ANALYSIS OF OFFSHORE GEOTHERMAL PILE FOR WIND TURBINES

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SEPTEMBER 2018

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by

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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 THAN KNOWLEDGE.
KNOWLEDGE IS LIMITED.
IMAGINATION ENCIRCLES THE WORLD.

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. Matsaga**r 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 amd 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) Laborator**y, 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. Niranjan 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 geotecnical 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 specrum, 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 मोनोपाइल 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 मोनोफाइल 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

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NOMENCLATURE

$[\boldsymbol{M}_{\mathbf{xx}}]$	Mass matrix
$[\boldsymbol{K}_{\mathbf{xx}}]$	Stiffness matrix
$[\boldsymbol{C}_{\mathbf{xx}}]$	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)
$\mathrm{K_s}$	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 seal level (MSL).
V_{m}	Intensity of characteristic wind speed at the reference height of 19.5 m above mean seal level (MSL)
V_{10}	Mean wind speed at10 m above sea level
z	Elevation (m)

k	Wave number
d	Depth (m)
$S_{vv}(z,f)$	Power spectral density function of the fluctuating wind velocity
υ_*	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_{vkvl}	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
$\{\ddot{u}\}$	Nodal acceleration vector
$\{\dot{u}\}$	Nodal velocity vector
$\{u\}$	Nodal displacement vector
$\{F(t)\}$	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
$\overline{K}$	Dynamic stiffness a
$\overline{C}$	Frequency dependent damping
K_h	Translational static stiffness coefficients for rigid embedded circular

	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
$[\boldsymbol{S}_{ss}]$	Stiffness matrix of the nodes on the structure
$[\boldsymbol{S}_{sb}]$	Stiffness matrix of the nodes of the structure that lies on the ground
$[\boldsymbol{S}_{bs}]$	Stiffness matrix of the nodes of the ground that lies on the structure
$[\boldsymbol{S}_{bb}]$	Stiffness matrix of nodes on the ground
(u_b^t)	Vector of the total displacement amplitude
$[\mathbf{S}\ (\omega)]$	Dynamic stiffness matrix
ρ	Mass density
G	Shear modulus
K_s	Static stiffness (for translation)
K_r	Static stiffness (for rotation)
z_o	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
$\varepsilon_{restrained}$	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
$P_{restrained}$	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
Fs	Drucker-Prager shear failure surface
β	Material friction angle, is its
c	Cohesion
σ	Stress tensor
q	von-Mises equivalent stress
$\boldsymbol{I}$	Identity matrix
$\boldsymbol{S}$	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