Dynamic Analysis of Heat Exchanger Piles in Offshore Environment

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Abstract

In order to secure the future generations from energy crisis, it is widely accepted that implementation of renewable energy resources is the urgent need of the day. Renewable energy resources, e.g. wind, ocean wave and geothermal energy provide substantial benefits towards our climate, health, and economy. Heat exchanger piles are deep foundations that combine the structural function as a foundation with a heat exchanger for extracting heat from the earth's crust. In the proposed study, a novel concept of combined offshore wind turbine-heat exchanger pile foundation technology will be investigated. Coupled temperature-displacement analysis of geothermal energy pile foundations will be carried out using finite element (FE) software ANSYS to understand the interaction between geothermal pile and the surrounding soil subjected to random wave loading and thermal loading-unloading cycles. In this paper, thermal characteristics are evaluated in the ground thermal energy system with steel foundation pile. The average effective thermal conductivity of the surrounding offshore soil is estimated by conducting an extensive literature survey. Pile will be modeled using the linear elastic model where as the soil is modeled using Drucker Prager constitutive model. The thermal loading-unloading cycle will be applied on the pile using temperature cycles. The random wave loading on the pile would be modeled using the Pierson-Moskowitz spectrum. The results of the analyses will be studied for stress, strain and displacement response of the heat exchanger pile foundation for offshore wind turbine and the surrounding soil. Temperature changes in steel and surrounding soil during thermal pile operation will lead to additional steel stresses and displacements within the pile-soil system. Hence proper care has to be taken that the temperatures remain within acceptable limits, while the pile geotechnical analysis should demonstrate that any adverse thermal stresses are within design safety factors and that any additional displacements do not affect the serviceability of the offshore structure.

Keywords: ANSYS, Coupled temperature-displacement analysis, Drucker Prager Cap Model, Offshore Wind Turbine.

1. Introduction

Renewable energy is derived from natural sources that are replenished constantly. In its various forms, the renewable energy may be derived directly from the sun, wind or from heat generated deep within the earth. Moreover, electricity and heat may be generated from different types of renewable energy, e.g. solar, wind, ocean wave, hydropower, biomass, geothermal resources and biofuels. As per the world energy consumption report [1], the consumption of wind energy is only 0.51% and the consumption of geothermal energy is only

0.12%. The energy consumption from ocean wave is even lesser, only 0.001%. Thus there is lot of scope in increasing the consumption of these energy resources.

In offshore environment, the wind energy may be captured through offshore wind turbines whereas the geothermal energy may be extracted from the heat stored in the earth's crust and sea water. Thus, the total world energy consumption combining wind, ocean wave and geothermal energy comes down to a value which is even lesser than 1% of the total energy consumption. Hence, it is necessary to explore the possibilities of deriving electricity and heat from the renewable energy. In the proposed work, the possibility of using both the offshore wind turbine and its foundation in deriving energy from wind, ocean wave and geothermal resources will be investigated. A combined offshore wind turbine-geothermal pile technology will be studied for its response under random wind and wave loading on the turbine along with thermal loading-unloading of the geothermal energy pile foundation.

2. Combined Offshore-Geothermal-Wind Turbine System

A mono-pile foundation consists of a large-diameter steel pile, which is in principle simply a prolongation of the tower shaft into the ground. The mono-pile must be able to transfer both lateral and axial loads from the structure into the seabed. The steel piles are of simple tubular construction which is inexpensive to produce and provide a low cost fabrication option. In the present work, mono-pile foundation in form of energy pile extracts the geothermal heat from the sea crust and the heat is utilized in generating electricity. Energy piles in general contain high-density polyethylene pipes for carrying the fluid used for heat transfer as shown in Figure.2. The pipes circulate the geothermal fluid from the surface to the targeted depth and brings the heated fluid back to surface where a heat exchanger converts the temperature difference between the fluids and finally goes into a thermoelectric generator which works on the principle of Seebeck effect [2] and converts this temperature difference to power as shown in Figure.3. In the present study, a single tube is considered instead of a U-tube loop used in conventional energy piles for simplicity as shown in Fig.2 and the thermal loading is applied on the tube. Finally Lot of research has been reported in the literature [3-8] related to the response of the geothermal energy piles under heating and cooling operations. It is observed that the use of geothermal energy piles affect the load-displacement response of the piles, the axial stresses generated in the pile and the relative displacement at the pile-soil interface. Also, these piles may undergo significant uplift when subjected to heating. However, none of these studies have focused on the dynamic stress-strain response of the geothermal piles used in offshore applications.

3. Modeling of the Structure

3.1 Steel-Monopile-Heat Exchanger

A steel hollow monopile of diameter 7.5 m with 9 cm thickness is embedded 30 m below sea bed as shown in Fig. 1 has been considered as the energy pile. The steel hollow casing overlies the concrete grout with its mechanical properties shown in Table 1. The soil bed is considered to be heated upto 200^{o}C which is the minimum temperature required for extracting heat out of a geothermal reservoir and then cooled as the fluid is removed from the system. More details about the heating- cooling cycle has been discussed in section 4 of the paper. The time history of heating - cooling cycle has been presented in Figure 3. Assuming a water depth of 30 m and a maximum design wave height of 14.5 m, the design horizontal load for a monopile with a diameter of 7.5 m amounts to about 8 MN, the resultant horizontal force acting about 30 m above sea level, i e. nearly at still water level. Additionally a vertical load of 10 MN representing the own weight of the turbine, the blades and the tower was assumed. Such loads have to be considered analyzing the behaviour of monopiles. The current model which involves characteristics of both offshore monopile and an energy pile has arrived after the successful validation of two separate models by Laloiu [3] and Achmus [9]. Appropriate offshore soil thermal parameters have been chosen after devoting significant amount of time in going through a large number of parameters of sea sediments.

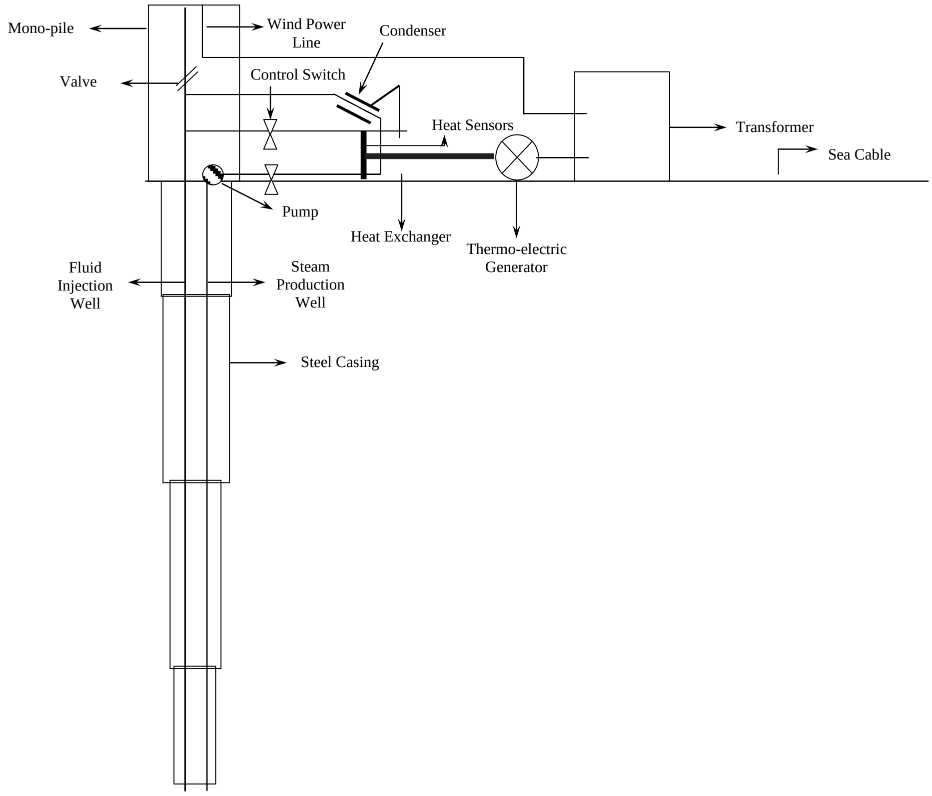

Figure 1. Schematic representation of offshore wind turbine geothermal system.

3.2 Finite Element Modelling

To simulate the behavior of the heat exchanger pile and the surrounding saturated soil, a numerical model, coupling the mechanical behavior to the thermal and hydraulic phenomena is needed. Here, a thermo-hydro-mechanical (THM) model for saturated porous media is used. Fully-coupled equations govern the evolution of pore water pressure, solid displacement and heat flow under mechanical, hydraulic and thermal loading. This can be implemented in ANSYS using the coupled poro-pressure element CPT215 which is based on Biot's theory of consolidation. The pile is modeled as a thermo-elastic solid using an eight noded SOLID185 brick elements. The thermo-mechanical data of steel has been presented in Table 4. Soil is assumed to have the thermo-poro-elastic properties of sand. The software used for model simulations in thermo-hydro-mechanical analysis is able to calculate simultaneously heat transfer from the grout to steel pile shaft and surrounding soil and the mechanical behavior of domains. An initial value of 80^{o}C was selected based on the ambient ground temperature at the targeted depth of geothermal energy heat extraction. Infinite boundary is simulated using spring and dashpots derived from Lysner[10] to simulate radiation damping of the soil. Only half of the pile and soil domain was considered as axi-symmetric condition. Soil and the pile domain is meshed using an element size of 0.75 m. The soil layer below the pile is modeled using a finer element size of 0.5 m. Element sizes coarser than 0.75 m gives an element shape distortion error. The structural and thermal properties of the steel pile has been presented in Table 1.

Initial stresses are generated in the soil medium using the INISTATE command in ANSYS. The computations were done using the finite element program system ANSYS .In order to carry out many calculations for loading conditions, a large computer system with parallel processor technology was used to minimize the time effort. The aim of the investigation was to analyse the behaviour of a large monopile under thermal loading-unloading cycle for energy storage.

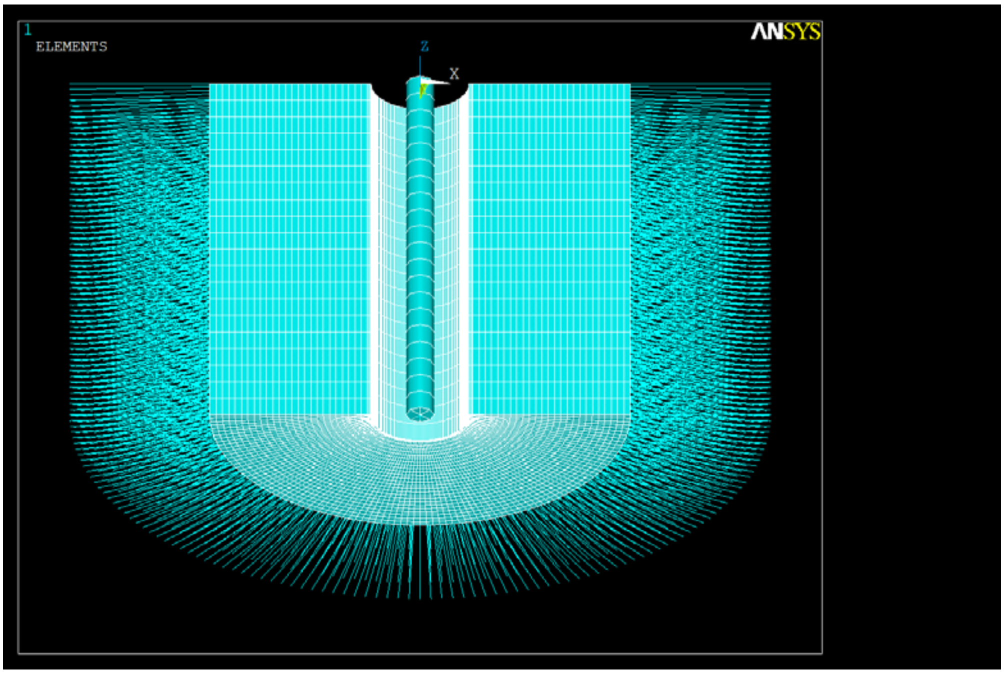

Figure 2. Finite element model in ANSYS.

Table.1 Summary of properties.

Steel density ρ	7850 kg/m^3
Thermal expansion coefficient steel	1.6 × 10^{-4}
Specific Heat Steel	419 J/kgK
Thermal conductivity	43 W/mK
Foundation radius r_0	3.75 m
Foundation depth z_0	40 m
Moment of inertia I_0	4.1368 m^4
Thermal expansion coefficient of sand	3.33 × 10^{-5}
Specific Heat of Sand	1090 J/kgK
Thermal conductivity of Sand	6 /mK

4. Thermal Loading

The load-settlement behavior of foundation piles directly impacts on the serviceability and safety of the structure above it. To determine the amount of pile displacement associated with cyclic thermal loading of energy piles, finite element simulation of an energy pile has been performed. The validity of the numerical analysis has been ensured by comparing the numerical simulation results with the field pile load test data and the results of numerical simulations performed by Laloui et al.[3]. Axisymmetric finite element analysis of piles in marine sand have been performed in two steps - (i) a static step to apply the gravity loading and to bring the model in geostatic equilibrium and (ii) a coupled temperature-displacement step to apply the thermal loading (iii) pore pressure loading. The thermal load is applied on the steel pile is generated by convection load due to fluid circulating through pipes. The heating-cooling load applied to the steel pile has been presented in Fig.3a.

5. Results and Discussion

Results are presented in the form of plots predicting changes in displacement, radial strain and axial stress in the steel pile under heating-cooling period.

Analysis has been carried out in three parts, where firstly an initial state load has been applied. Secondly a thermal loading has been applied for a duration of 16 days of heating and cooling cycle as shown in Fig.3a. Thirdly the pore pressure load has been applied on the steel pile structure. It is seen from Fig.3b that under thermal loading, the pore pressure keeps fluctuating with the highest value at the beginning of the heating period and then it keeps decreasing. The value of the pore pressure increases again in the beginning of the cooling period. After the initial loading has been applied, thermal load is applied on the structure and the thermal strain is shown in Fig.3c. The minor fluctuations in the curve shows the expansion and contractions throughout the heating and cooling period in the steel pile. Fig.3d shows the axial stress in the steel pile at three different depths of 0 m (pile head), 9 m and 36 m. It is seen from the figure that the highest axial stress occurs at the base of the pile. Fig.3e and 3f shows the translational and axial displacement in the steel pile throughout the heating and cooling period. The axial displacement at a depth of 9 m is almost half of that at the base of the steel pile. The axial displacement at the base of the pile follows a negative pattern as compared to that at the depth of 9m and that at the pile head. The radial displacement shown in Fig.3e shows that the displacement is almost same without too much of change for all the different depths.

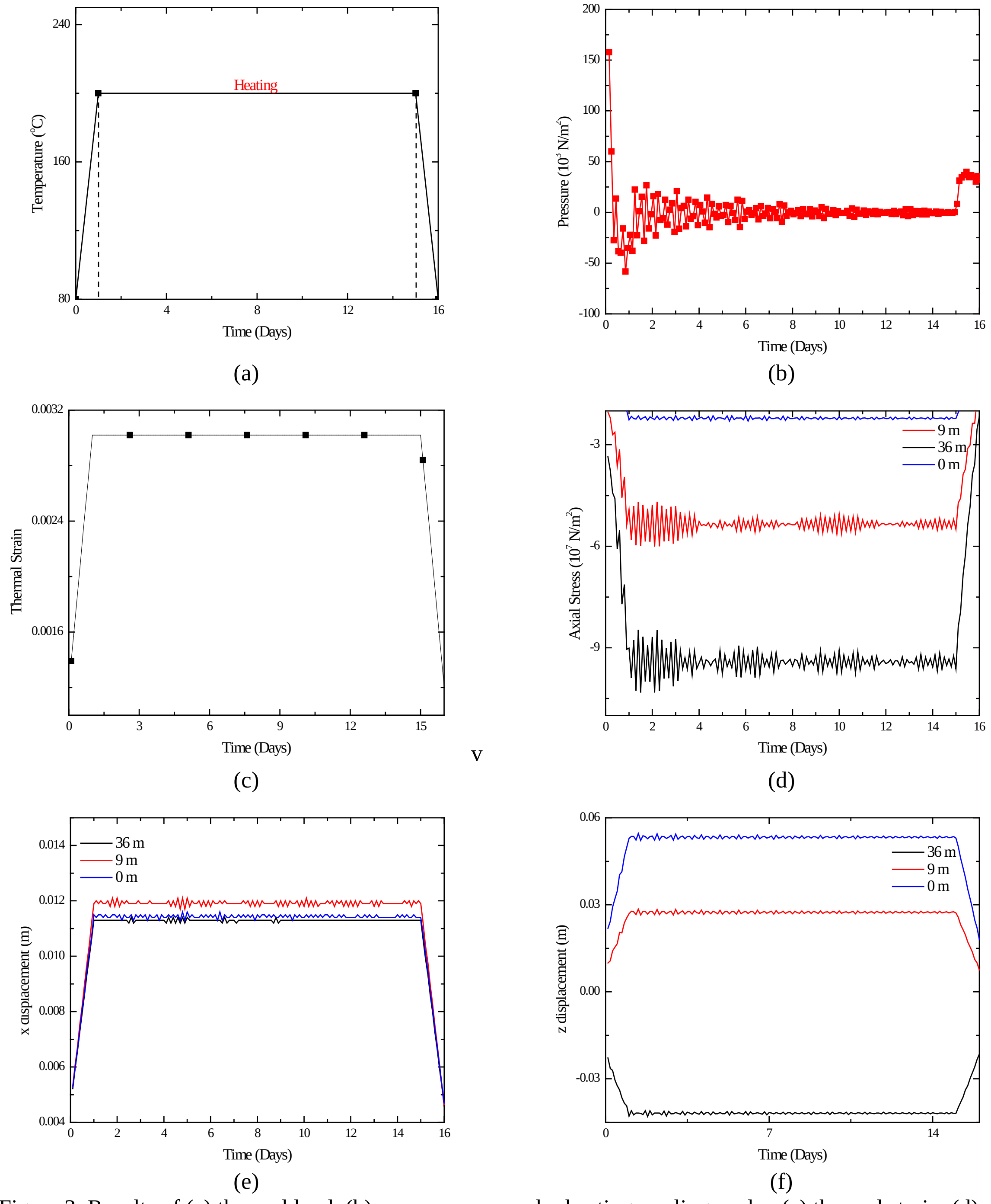

Figure 3. Results of (a) thermal load, (b) pore pressure under heating-cooling cycle , (c) thermal strain, (d) axial stress, (e) radial displacement, and (f) axial displacement.

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