Renewable and Sustainable Energy Reviews 92 (2018) 685–700

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Evaluation of possibilities in geothermal energy extraction from oceanic crust using offshore wind turbine monopiles

Arundhuti Banerjee, Tanusree Chakraborty*, Vasant Matsagar

Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi 110016, India

ARTICLE INFO

Keywords:
Finite element method (FEM)
Ground heat exchanger (GHE) System
Offshore wind turbine (OWT) monopile
Thermoelectric generator

ABSTRACT

This paper proposes a novel concept of extracting geothermal power from the oceanic crust, using an offshore wind turbine structure, combined with an active heat exchanger system comprising of fluid pipes. The offshore monopile system uses a thermoelectric generator with the working principle of Seebeck effect that converts the temperature difference between the fluids in the inlet-outlet pipe to produce electricity. Thermal analysis of steel monopile with fluid-carrying-pipes has been carried out using finite element method through a heat flow analysis, taking into account the complex heat transfer process of convection through fluid pipes and conduction between the pipe-soil-monopile system. The effects of temperature variation in the fluid, the mass flow rate of the fluid in the outlet pipe, and the thermal conductivity of soil on the offshore monopile and the surrounding soil have been studied in detail. It is observed that a maximum power output of 242 kW (kW) could be extracted out of the system using thermoelectric generators.

1. Introduction

Searching for new sources of sustainable energy is of utmost concern for the present generation. Scientists and researchers are constantly exploring renewable energy resources, e.g. solar, wind and geothermal, to name a few. The utilization of these readily available resources on earth in an appropriate way for human welfare has become an important research and development topic over the past few years [1]. Technological advances have taken place in extracting oceanic renewable energy which exists in the forms of ocean waves, tidal currents and thermal gradients [2–10]. However, geothermal energy from the oceanic crust, stored underground in the form of hot rocks and water, deep within the Earth, has possibly been the area receiving the least attention. Underground deep rock masses and higher rock temperatures may become accessible by deploying a suitable geothermal piping system in the oceans, and thus providing great opportunities for geothermal energy production. So far, the offshore geothermal energy resources have not been considered as a viable option to fulfill the energy demands because of the challenges involved in the rough sea environment. However, with the rising energy costs and increasing knowledge in utilizing the alternative energy resources, the choice of offshore geothermal energy would soon become a more attractive energy option [11]. Fig. 1 shows the potential regions for offshore geothermal energy extraction globally, by highlighting the tectonic plates and oceanic ridges across the world map [12]. It also highlights the areas with high wind potential for energy harvesting. Divergent tectonic plate boundaries, as shown on the map, can have high geothermal gradients [13]. Areas away from the tectonically active zones have lower geothermal gradients. Divergent plate boundaries occur, when two tectonic plates are moving away from each other. This causes magma to flow in the upward direction and generate new crust along the boundary [13]. This upward flowing magma creates higher geothermal gradient because it is of a much higher temperature than the surrounding rock at the same depth. These boundaries are commonly associated with the mid-oceanic ridges, where temperature increases quickly with depth. For example, Iceland has a divergent plate boundary above sea-level where geothermal energy extraction is feasible. Indonesia is another country that lies on the ring of fire and currently has 11 water-dominated geothermal power plants extracting a total of 1533.5 Mega-watt (MW) of power. By 2018, Indonesia plans to increase the geothermal capacity by 634 MW for a total of 2478.5 MW [14–16].

The benefits of using an offshore geothermal plant at sea are immense. Firstly, the presence of infinite recharge of water (sea) acts as a potentially unlimited geothermal fluid for energy extraction. The system to be used for energy extraction can be an old unused oil reservoir, or it may be an offshore wind turbine structure founded on a monopile foundation, as proposed in this paper. Secondly, availability of unlimited cold seawater can be used as a limitless condenser for the heat exchanger system (this has also been utilized in the study). Lastly, the earth's crust is thinner towards the ocean i.e. 7 km on an average and for the continental crust (land), it is 20–65 km. The average heat flow from the continental crust is 57 W/m^2, and through the oceanic

* Corresponding author.
E-mail addresses: arundhuti.banerjee@civil.iitd.ac.in (A. Banerjee), tanusree@civil.iitd.ac.in (T. Chakraborty), matsagar@civil.iitd.ac.in (V. Matsagar).

https://doi.org/10.1016/j.rser.2018.04.114
Received 7 June 2017; Received in revised form 18 April 2018; Accepted 24 April 2018

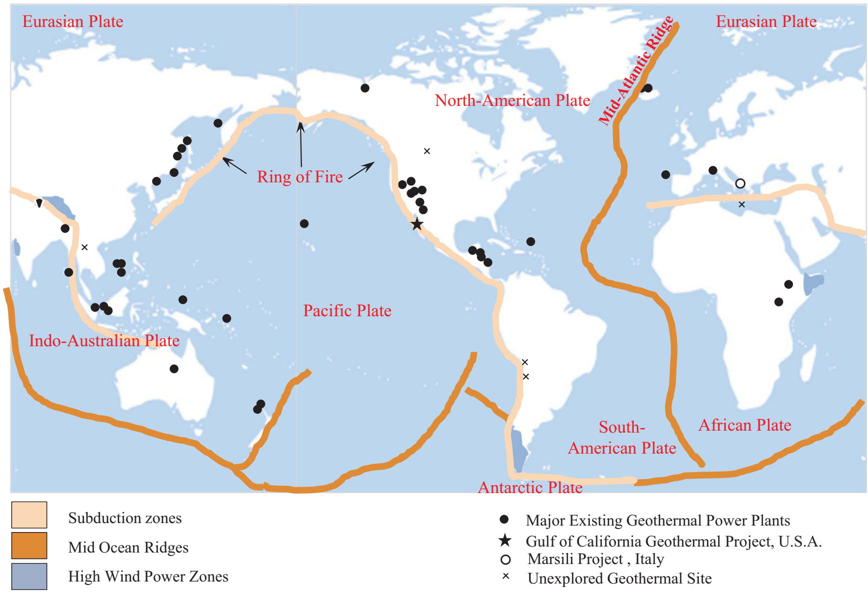

Fig. 1. World map for high-temperature zones highlighting tectonic plates, oceanic ridges and existing geothermal power plants [12].

crust, it is 99 W/m^2 [11]. Therefore, higher heat sources can be tapped as compared to that on land with lesser drilling.

The disadvantages of using an offshore geothermal system would include higher costs of construction, exploration and operation. However, exploiting the deep offshore geothermal resources would compensate for some of the costs by supplying green energy to the communities living in and around the coast. Hence, generating electricity from offshore geothermal resources could prove to be highly beneficial for the future. 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. No such studies presently exist on offshore geothermal structures for higher depths. By modelling an offshore energy pile foundation, equipped with pipes embedded in concrete/soil with a heat carrier fluid circulating into them to exploit the geothermal flow in the upper crust of the seabed, the authors of this paper are offering an innovative concept which can be used in the near future for efficient energy extraction.

The objectives of the present work are to investigate (i) the power output of an offshore wind turbine structure when combined with geothermal heat exchanger system using thermoelectric generators, (ii) the temperature distribution in the heat exchanger system which comprises of the marine saturated soil, pipes that carry the hot and cold water and the steel monopile, and (iii) the effects of thermal interactions between the pile and surrounding soil on the system efficiency. To fulfill the objectives, a series of thermal finite element (FE) analyses have been carried out on an offshore monopile foundation using finite element software Ansys Mechanical [17]. In the paper, first, a short introduction on offshore geothermal projects have been provided, following which the working principle of the offshore-geothermal system used in the present study has been elaborated upon. Next, the mathematical modelling of the system has been described briefly. Subsequently, the three-dimensional (3*D*) FE model used in the numerical simulations is described and the details of the simulation are provided followed by the results and discussion of the analyses.

2. Background literature

2.1. Onshore geothermal application

Different novel methods of low-temperature geothermal energy applications have been reported, for example, the use of stable water temperature in closed mines which are no longer functional can reportedly be used for exploiting geothermal energy by employing geothermal recovery loops coupled to the heat pumps [18]. Municipal solid waste landfills can also be a potential source of thermal energy extraction due to their elevated temperatures associated with decomposition of organic materials within the waste [19]. Application of solar panels combined with ground source heat pumps [20], and removal of snow from bridge decks and pavements using ground source heat pump systems [21,22] are a few other examples of shallow geothermal energy usage. Shallow energy geothermal resources have been extensively utilized in heating-cooling applications of buildings on land. The utilization of the ground and underground structures as heat storage mediums, termed as ground heat exchangers (GHE), has long been studied and written about in the literature. A typical vertical GHE system comprises of one or multiple U-type pipes through which heat exchange fluid is circulated, and grout that fills the space between the pipe and the soil around. Recently, utilization of pile foundations of buildings as ground heat exchangers, have attracted much attention. It is often regarded as an energy pile in the literature and several types can be found in practical applications for heating or cooling of building spaces, mostly because of their cost-effective benefits compared to those of other conventional systems, e.g. air-conditioning or heating devices. In the geothermal systems, the pile foundations with heat-exchanger fluid carrying pipes inside, are used as vertical GHEs.

Several numerical studies on vertical GHEs have been reported in the literature. The ground temperature response of a GHE in a horizontal two-dimensional (2*D*) cross-section assuming constant fluid temperature using finite volume method was studied by [23]. The coefficient of performance (COP) for heating and cooling modes of operation of a geothermal pile for different heat exchange rates per unit length for both the heating and cooling purposes are compared using a finite element model simulated in [24]. Similarly, in [25–27] numerical analyses was performed and they computed the variation of fluid temperature along the length of a geothermal pile. Two dimensional analysis of a geothermal pile foundation using finite element method, as reported in [28] showed that the temperature gained from the ground is higher for lower fluid circulation velocity. Thermal response of geothermal piles was also numerically studied in [29] using COMSOL Multi-physics finite element software. Thermal response tests of geothermal piles and boreholes under constant heat injection scenarios were reported in [30]. He compared the ground temperature response, fluid temperature variation along the circulation tube, and pile and