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ENERJİ KAZIKLARININ DEPREM ETKİSİ ALTINDAKİ TEPKİSİ

RESPONSE OF ENERGY PILES UNDER EARTHQUAKE MOTION

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ÖZET

Bu çalışmada, örnek bir enerji kazık temelin deprem hareketi altındaki davranışı sonlu elemanlar yöntemi kullanılarak incelenmiştir. Kazıklar, zemin sahalarının geoteknik mühendislik parametreleri üst yapıdan aktarılan yükleri taşımak için yeterli olmadığında yaygın olarak kullanılan derin temellerdir. Bu tür temel tipleri, yüklerin zemin yüzeyinden daha derindeki daha sert zemin katmanlarına aktarılması ve ya yüklerin kazık yüzey sürtünmesi ile karşılandığı sistemler olarak kullanılabilir. Bir tür derin temel olan enerji kazıkları, hem taşıyıcı eleman olarak hem de pompa sistemleri aracılığıyla zeminle ısı alışverişi sağlayan bir yapı olarak kullanılmaktadır. Böylece kazık ve çevresindeki zemin sıcaklık değişimlerine maruz kalır. Eğer kazık çevresinde bir sıcaklık artışı varsa, bu sıcaklık değişimleri, çevredeki zeminin elastisite modülünde ve kohezyon değerinde azalmalara neden olur. Bu sıcaklık değişimlerinin etkileri göz önüne alındığında, enerji kazıklarının deprem hareketi altındaki tepkisinin sıradan kazıklardan farklı olması beklenebilir. Bu çalışmada 1995 Kobe Depremi hareketi altında sabit mekanik yüklemeye maruz kalan bir kazığın tepkisi, aynı özelliklerdeki enerji kazık temel tepkisiyle karşılaştırılmıştır. Sonuçlar, kazıkların üzerinde ölçülen maksimum yer değiştirme ve ivme açısından elde edilmiş ve sıcaklık etkisi sonlu elemanlar analizleriyle gösterilmiştir.
Anahtar Kelimeler:*Enerji kazıkları, sonlu elemanlar, deprem etkisi*

ABSTRACT

In this study, the response of an energy pile under earthquake motion was investigated using the finite element method. Piles are deep foundations commonly used when geotechnical engineering parameters of soil sites are not satisfactory to resist the loads transferred from the superstructure. Such foundation types can be employed when piles are required to transfer the loads to deeper and stiffer soil layers or resist the loads by surface friction. A type of deep foundation, energy piles are used as load-bearing and ground heat exchangers via pump systems. Thus, the pile and the surrounding soil are subjected to temperature variations. If the temperature around the pile is increased, these temperature variations induce decreases in elasticity modulus and cohesion in the surrounding soil. Considering the effects of temperature variations, the response of energy piles under earthquake motion is expected to differ from that of regular piles. The response of a conventional pile subjected to constant mechanical loading under the 1995 Kobe earthquake motion was compared to that of an identical energy pile. The results are obtained in terms of maximum displacement and acceleration measured on top of the piles, and the effect of temperature change was observed in the finite element analyses.
Keywords: *Energy piles, finite element method, earthquake effect*

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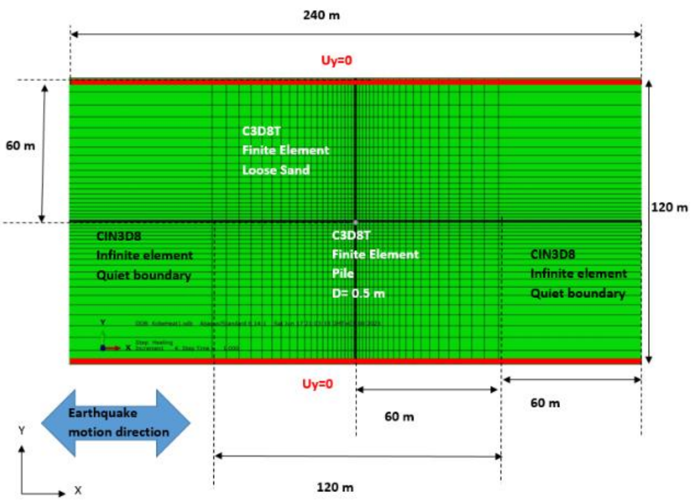
1. INTRODUCTION

Sustainability has gained importance in engineering applications; thus, studies on sustainable solutions have become prevalent. One of the developments resulting from these studies is the energy pile foundations. Energy piles are deep foundations that are used for both load-bearing and heat exchanging from the ground via heat pump systems. After reaching a depth below ground of approximately 10-15 m, the temperature profile is constant (typically 15°C) throughout the year (Brandl, 2006). High-density polyethylene pipes are attached to the reinforcement cage of the pile, and a heat-transferring fluid is circulated through the pipes. The fluid temperature is adjusted so that the desired heat flow for heating-cooling is achieved (Abuel-Naga et al. 2014). According to the investigations on energy pile applications, it is observed that energy piles satisfy the energy demand for the heating-cooling process of a building (Brandl, 2006), and carbon dioxide emissions are decreased as a result of the increasing number of energy pile installations (Amis and Loveridge, 2014). Considering the benefits of energy piles, such as energy efficiency and eco-friendliness, the use of energy piles should be encouraged in Turkey. However, thermal expansion/contraction occurs due to temperature variations during the operation of an energy pile; therefore, thermal strains and corresponding additional load and displacements occur on the pile and soil (Bourne-Webb et al., 2009). Moreover, other effects are anticipated by many researchers, such as an increase in creep effect and irreversible displacements in long-term (Akrouch et al., 2014) and temperature effects on some engineering properties of soils, such as the elastic modulus and cohesion (Yavari et al., 2016; Arzanfudi et al., 2020; Heidari et al., 2022). Elastic modulus and cohesion are especially emphasized in studies since they are directly related to the stiffness and strength of the soil, while friction angle is assumed to be independent of temperature variations (Yavari et al., 2016; Heidari et al., 2022).

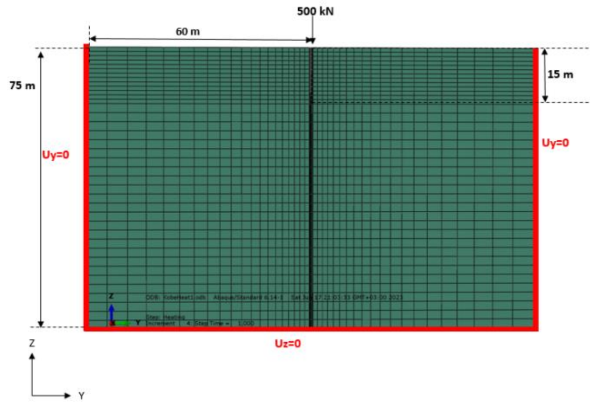
Thermo-mechanical behavior of energy piles under various loading conditions has been investigated in the literature by various researchers (Laloui et al., 2008; Akrouch et al., 2014; Saggu and Chakraborty, 2014; Arzanfudi et al., 2020; Heidari et al., 2022). However, the literature lacks a detailed investigation of the performance of such foundation types in earthquake-prone regions. This study aims to present the preliminary results of the analysis of a heated pile response under an earthquake motion and compare them to those of regular piles. Thus, an insight into the applicability of energy piles in seismic zones can be obtained, and a better understanding of the effect of the heating process after an earthquake motion for such piles can be achieved.

2. METHODOLOGY

To evaluate the earthquake response of energy piles, a 3D finite element model is constructed, as given in Figure 1.



(a)



(b)

Figure 1. Model geometry and boundary conditions on a) XY plane, b) YZ plane

The model consists of a 75 m deep mainly loose sand layer and a 15 m deep axially loaded pile with a diameter of 0.5 m. Figure 1-(a) shows the top view of the model in which the pile is placed in the center of the finite element domain. The boundary conditions applied to the model are marked with the red line. In addition, Figure 1- (b) shows the mid-section of the model and also the bottom boundary condition. The earthquake motion was given in the $\pm$ x-direction for the dynamic analysis. The Infinite elements were constructed by extending the boundaries on the direction of motion about half-length (60 m) of the finite element domain based on the ABAQUS User's Manual, as shown in Figure 2.

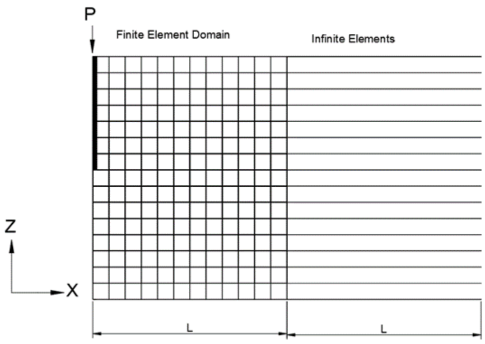


Figure 2. Infinite element size requirement based on the ABAQUS User's Manual

Infinite elements provide a quiet boundary that prevents wave reflections. Thus, far-field behavior under the earthquake motion can be simulated. The ground motion duration applied in the example is 48 seconds, with a peak acceleration of 0.82 g at t=8.54 s. Hussein and Albusoda (2021) took the Rayleigh damping coefficient β=0.06884 and α=0 based on the predominant frequency of the 1995 Kobe earthquake (KJMA Station of Japan Meteorological Agency) and assumed 5% material damping (ξ); we followed the same approach for the finite element soil domain in this study and also employed the parameters used by Saggu and Chakraborty (2015) as given in Table 1.

Table 1. Material properties (Saggu and Chakraborty, 2015)

Parameter	**Loose sand**	**Pile**
Density, ρ (kg/m^3)	1478	2500
Young's modulus, E_0 (Pa)	10x10^6	27.38x10^9
Poisson's ratio, ν	0.2	0.2
Cohesion, c (Pa)	500	-
Friction angle, ϕ (^{o})	27	-

Dilation angle, ψ (°)	2	-
Thermal conductivity, λ (W/m°C)	1.8	2.1
Thermal expansion coefficient, α_t (1/°C)	10^{-4}	10^{-5}
Specific heat capacity, c_s (J/kg°C)	1600	800

Table 1 shows the material properties used in this study. The pile was modeled as thermo-elastic material. Mohr-Coulomb plasticity was chosen for the soil behavior. Since friction angle is assumed to be independent of temperature (Yavari et al., 2016; Heidari et al., 2022) and cohesion has a negligible influence on the shear strength of sand, temperature dependency of shear strength parameters was ignored for this study. Heidari et al. (2022) suggested that the elastic modulus of sand can be assumed temperature-dependent for their study on laterally loaded heated piles in sandy soils. Similarly, Arzanfudi et al. (2020) used a temperature-dependent elasticity modulus to analyze a heated pile embedded in layered soil, including sandy gravels. Therefore, building on these prior studies, we also adopted a temperature-dependent elasticity modulus approach for this study. Arzanfudi et al. (2020) proposed Eq. (1), which denotes a temperature-dependent elastic soil modulus to model freezing and thawing in porous media domains; this preliminary study applies their equation to account for temperature-dependency of the elasticity modulus as an initial approach.

$$E_{s(T)}=E_{s,0}e^{-b.\Delta T} \quad (1)$$

where $E_{s\,(T)}$ is the elastic modulus of soil at a specific temperature (MPa), $E_{s,0}$ is the elastic modulus of soil at a reference temperature (MPa), ΔT is the temperature change (°C), and b is a material parameter (1/°C), set to 0.1 for sand and clay layers by Arzanfudi et al. (2020). The analysis of the finite element model of the energy pile comprises five steps in this study: *i*) Initial step: Predefining initial geostatic stress and temperature, applying displacement boundary conditions; *ii*) Geostatic step: Applying gravity loading to bring the model into geostatic equilibrium; *iii*) Static step: Applying an axial load of 500 kN to the pile head; *iv*) Transient coupled temperature-displacement step: heating the pile body to 36°C over 12 days; and *v*) Dynamic step: Applying the 1995 Kobe earthquake acceleration history to the base of the finite element domain.

The entire model, including the pile, initially had a temperature of 15°C. During the heating phase, pile temperature was increased from 15°C to 36°C and heated for 12 days (Laloui et al., 2006). After this heating period, the response of the pile under the earthquake motion was analyzed. The analysis of a regular pile followed the same steps, excluding the heating step. Thus, the temperature does not affect the response of the regular pile.

3. RESULTS

Temperature distribution on the model at the end of the heating is shown in Figure 3. The increase in temperature due to heating extended in all directions to a radial distance of nearly 4.5 m from the pile center, which shows a clear temperature distribution from the pile surface to the soil domain. Similarly, it reached nearly 3.5 m vertically from the pile toe. The observed temperature distribution is similar to that of Laloui et al. (2006), with minor differences caused by different temperature boundary conditions on the ground surface.

Accelerations induced by the earthquake motion on the pile head are plotted in Figure 4 for the energy pile and regular pile. The difference in the responses of the piles is minor. The maximum lateral accelerations were 0.11g for the regular pile and 0.12g for the energy pile.

Figure 5 compares the lateral top displacement in the direction of the motion. Figure 5 also illustrates that the heated energy pile undergoes slightly larger lateral displacements than the regular pile under the specified earthquake loading. The maximum lateral displacement of the energy pile was approximately 86.7 mm, whereas the maximum lateral displacement of the regular pile was 85.9 mm. As anticipated, the heating operation causes, although slight, an increase in lateral displacement under earthquake motion due to reduced elastic modulus.

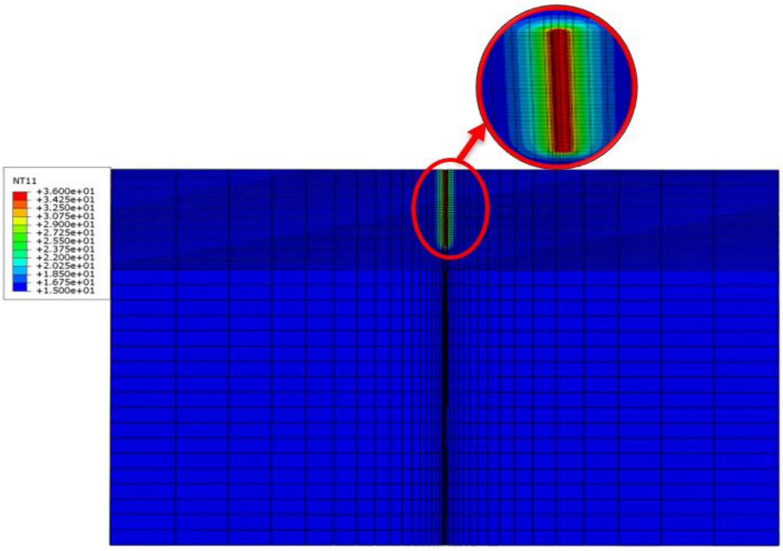


Figure 3. Temperature distribution on the model at the end of heating

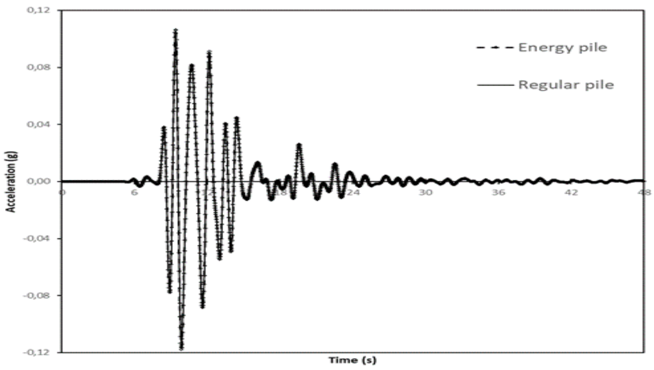


Figure 4- Comparison of earthquake-induced accelerations at the pile head

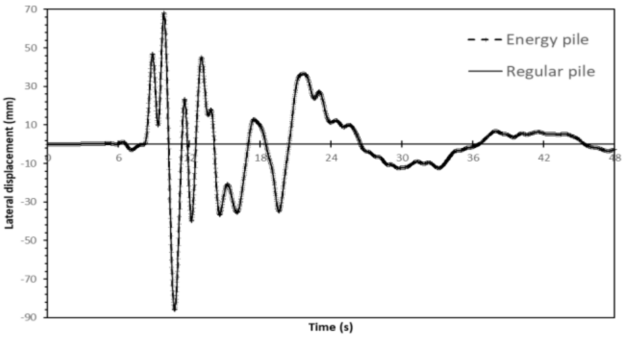


Figure 5- Comparison of lateral displacements on x-direction at the pile head

A comparison of the vertical displacements on the pile head during earthquake motion is shown in Figure 6. In the case of the regular pile, the initial vertical pile displacement observed at the pile head is 5.7 mm due to vertical loading without heating, reaching a final settlement of approximately 7 mm by the end of the earthquake motion. On the other hand, the energy pile undergoes larger settlements, reaching around 15.5 mm at the end of heating and reaching a final vertical displacement of 22.8 mm by the end of the earthquake motion, primarily due to the temperature-induced modulus reduction. The differences in the total vertical displacements of the piles were found to be substantial for the model used in this study.

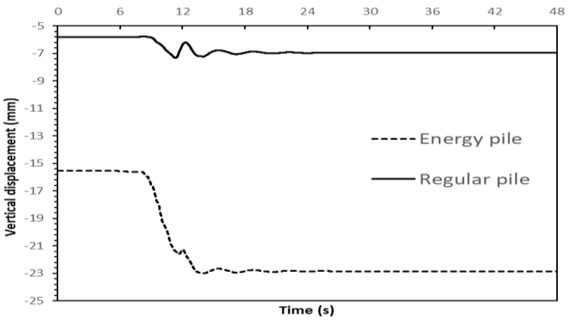


Figure 6- Vertical displacements at the pile head after the earthquake loading

4. CONCLUSION

The results demonstrate the impact of the heating process, causing a slightly larger lateral displacement and acceleration on the pile head during the earthquake loading. Since no lateral load is applied to the pile, close lateral displacements for both cases are reasonable. The substantial vertical displacement differences in the results under the vertical constant load indicate that the heating process can cause larger displacement for energy piles under vertical loads combined with earthquake motion due to the reduced elasticity modulus.

The model can be applied to various scenarios to generate maximum displacement relative to pile length-to-pile diameter ratios for different temperature variations and durations. In summary, these results indicate the significant effect of the heating operation and the necessity of considering such effects on the earthquake response of energy pile foundations in seismically active regions.

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