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Thermal induced response in energy storage pile

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ABSTRACT

A multi-disciplinary research project focuses on development of a new pile foundation system for renewable energy storage. It uses compressed air energy storage technology to store energy inside of the hollowed reinforced concrete sections. The compressed air can result in high air pressure to which the structural response of the pile foundation has been studied. In addition to this, the temperature in the pile foundation can also affect the structural response if sufficient cooling is not provided. Therefore, temperature distributions inside concrete section were investigated through non-steady state heat transfer analyses. Further, the obtained data were used for investigation of the stresses inside the pile foundation.

1. INTRODUCTION

Renewable energy obtained from solar panels and windmills attached to the buildings have been widely used to supply electrical power for the daily operations of buildings (Hayter and Kandt 2011). However, it cannot provide uninterrupted energy supplies due to its intermittent nature (Rugolo 2012). To solve this problem, compressed air energy storage (CAES) technology can be applied to store extra renewable energy for later usage (Zhang et al. 2012). Based on this technology, a new pile foundation system is being developed for renewable energy storage under a multi-disciplinary research project (Tulebekova et al. 2017). In this system, reinforced concrete pile foundation configured with hollowed sections is used as a storage space of a renewable energy.

This study focuses on investigation of thermal effects and thermal induced response in energy storage pile. First, temperature distributions inside the concrete section for the pile foundation through non-steady state heat transfer analyses were studied. Temperature change due to compressing and releasing air was calculated based on thermal dynamic processes of the CAES. After that, the heat transfer analysis was conducted using an analytical 2D plane strain model discussed below. The obtained temperature distributions were used for the investigation of thermal stresses inside the foundation using an axisymmetric model of the concrete pile.

2. BACKGROUND

The CAES technology follows the advanced-adiabatic process (Energy Storage Association 2020). It consists of four parts: (1) compression, (2) cooling, (3) heating, (4) expansion. First, the ambient air goes through a compression process driven by the renewable energy available for storage. After this process, the pressure and temperature of the air considerably increase so that it is not possible to store inside the concrete sections. Thus, the cooling process should be performed to extract the heat from the compressed air and store it in a heat storage medium, albeit the temperature will not drop back to the initial temperature. Therefore, there are two options available. Option 1 is to provide an extra cooling, while Option 2 is to directly store the air inside the pile foundation. This paper focuses on thermal effects from latter option. Detailed explanation for the advanced-adiabatic process is provided in Zhang et al (2018).

3. ANALYTICAL MODEL

The numerical model for the pile foundation and surrounding soils was built using the general-purpose finite element software ABAQUS as shown in Figure 1. The 2D plane strain model was developed to represent a quarter of the pile. Symmetrical boundary conditions without heat flux passing through were applied. Small heat transfer through the bottom of the pile foundation were ignored. The temperature change from the compressed air was applied at the inner surface of the pile foundation. For a concrete section 10 to 20 mm mesh were applied, while for soils mesh size gradually increases along radial direction.

Thermal conductivity of k = 2 W/m·°C and specific heat of c = 940 J/kg·°C were assigned to the concrete. For the soil, these values were k = 1.0W/m·°C and c = 1220 J/kg·°C, respectively. Taking into account that complete contact between concrete and soil is impossible, thermal conductance of 25 W/m^2·°C was assigned to an interface element.

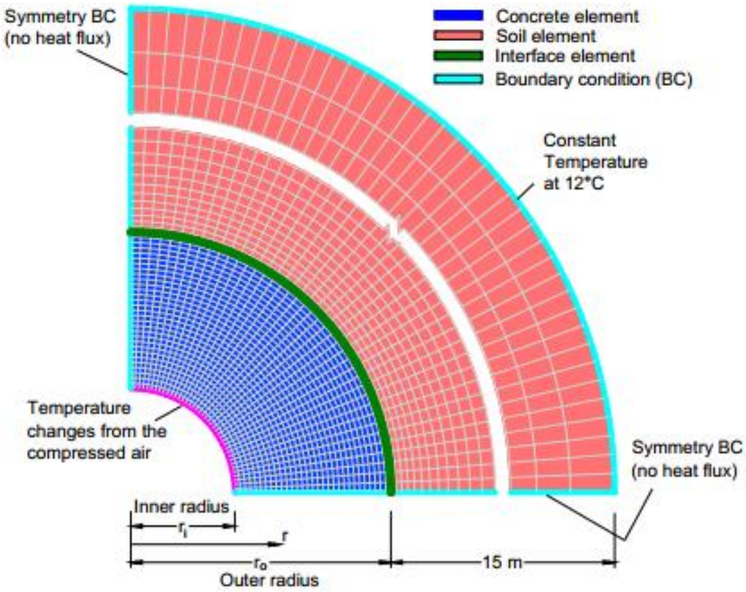

Fig. 1. The 2D plane strain model.

An axisymmetric model of the pile foundation was built using the same software. For better and more precise representation of stress and strain distribution along radial and longitudinal direction a comparatively fine mesh of 20 mm by 20 mm was applied to the model. The structural loads calculated in accordance with chosen pile design were applied. The temperature distributions inside concrete sections were also applied into corresponding node sets along radius direction. These temperature distribution data were obtained from a heat transfer analysis discussed above.

For thermal-mechanical analysis of energy storage pile, ultra high performance concrete (UHPC) referred as C150 were used. The modulus of elasticity and Poisson ratio of C150 concrete were taken to be 45.55 GPa and 0.2, respectively (Tulebekova et al. 2019). This type of concrete has a tensile strength of 8.5 MPa and compressive strength 150 MPa. Coefficient of thermal expansion was chosen to be $0.9 \cdot 10^{-5}$/°C (Mehta and Monteiro 2017). For this study, inner and outer diameters of the pile are 200 mm and 1000 mm, respectively. The length of the pile is 6 meters.

4. **RESULTS AND DISCUSSION**

4.1. Temperature distributions inside concrete section

Figure 2a illustrates the maximum temperature of each loading cycle at different locations of the concrete section. The maximum temperature increases with the loading cycle due to the cumulative effect of the residual temperature from the previous cycles. This is applied for all locations, except for the inner surface of the pile (r=0.1 m) which has constant maximum temperature because of the input temperature change. Moving further from the center of the pile, the maximum temperature decreases, which shows the lowering effect of the thermal input with increasing radius. In addition, the temperature continues growing for the points located further from the pile center, which indicates that as radius increases more cycles are required for the maximum temperature to be converged.

Figure 2b shows the temperature distribution inside the concrete at the end of different loading cycles. As seen, at the end of the first loading cycle, the considerable residual temperature is stored in the pile section. As time goes by, temperature along the radius increases with cycles following similar shapes except for the inner surface (r=0.1m) of the pile. This indicates that the cumulative residual temperature has a greater influence on the magnitude of temperature along the radius than the shape of the curve.

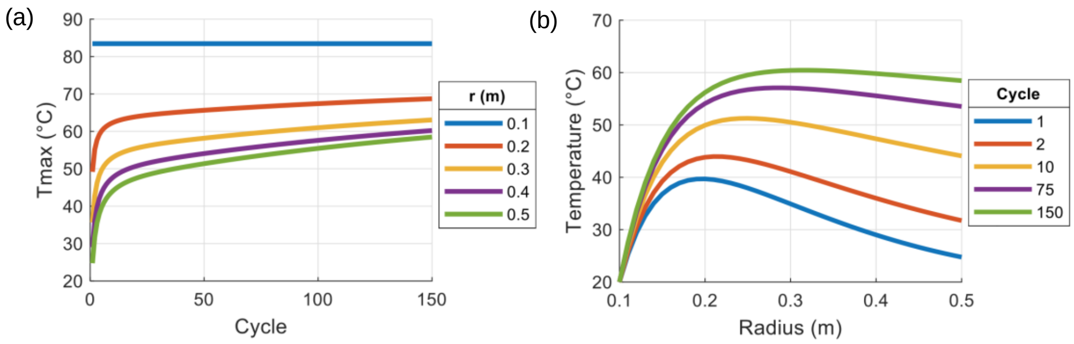

Fig. 2. (a) Maximum temperature of each loading cycle inside the pile;
(b) Temperature distribution inside the pile at the end of different loading cycles.

4.2. Maximum stress distribution per cycle

Figure 3a and 3b illustrate the maximum circumferential stress at the bottom of the pile at inner and outer directions of the concrete section varying with each cycle. Tensile stresses are observed in the circumferential direction, albeit these stresses do not exceed cracking strength of 8.5 MPa for UHPC. The similar picture can be observed for the other parts of the pile as well. Since radial and shear stresses were mostly negligible, the results discussed here were mostly based on circumferential and vertical stresses.

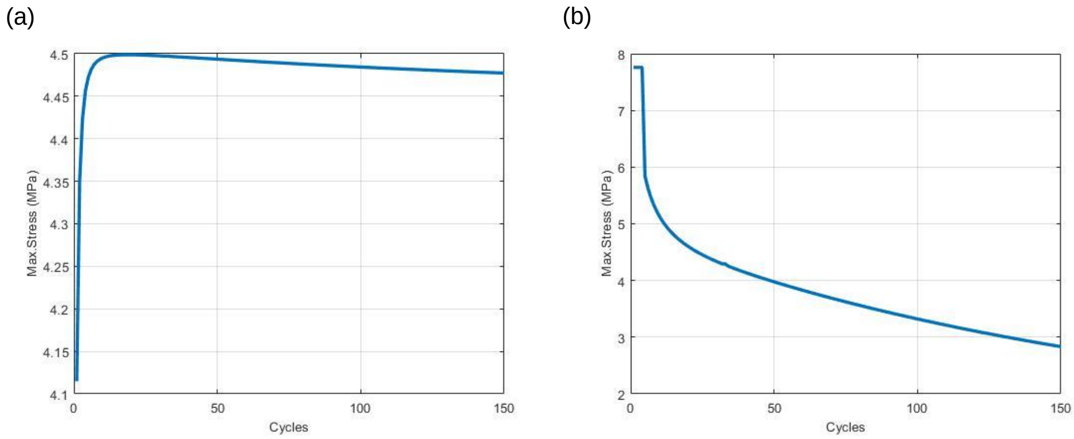

Fig. 3. Maximum circumferential stress distribution with cycles at the bottom of the pile at (a) r = 0.110 m and (b) r = 0.490 m.

4.3. Stress distribution along radial direction

Figure 4a and 4b show circumferential and vertical stress distributions along the radial direction from the inner to outer surface at the middle of the pile length. It can be seen that under thermal effects, both circumferential and vertical stresses develop compressive as well tensile stresses from the inner surface to the outer surface. However, it can be clearly observed that both do not exceed the tensile strength of concrete.

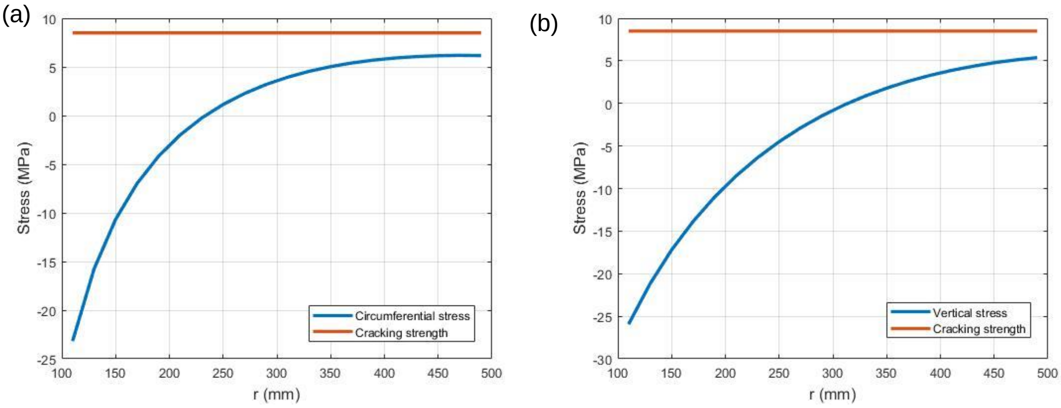

Fig. 4. Stress distribution along radial direction at the middle of the pile: (a) circumferential and (b) vertical stress.

4.4. Stress distribution along longitudinal direction

Figure 5a and 5b demonstrate circumferential and vertical stress distributions along z-direction of the pile at the inner side. Compression stress can be clearly observed, and the distribution is almost uniform except for top and bottom parts of the pile foundation. Compression stresses caused by thermal effects are by far less than the given compressive strength of the concrete.

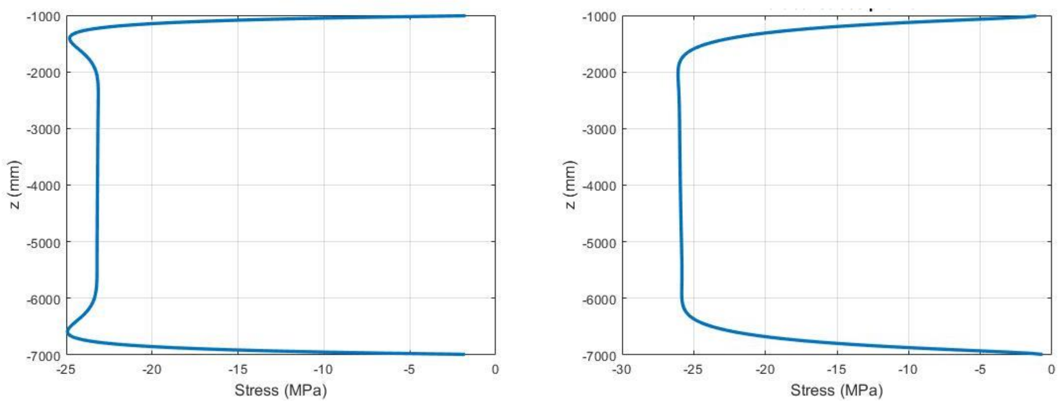

Fig. 5. Stress distribution along longitudinal direction at the inner skin of the pile: (a) circumferential and (b) vertical stress.

5. CONCLUSION

The following conclusion can be made for the thermal analysis of the concrete pile foundation:

- The temperature inside the concrete section gradually increases with cycle because of the cumulative effect of the residual temperature. As moving away from the pile center, the maximum temperature decreases due to the lowering effect of the thermal input from compressed air.
- Under thermal effects, circumferential and vertical stresses at different locations of the pile do not exceed compressive and tensile strengths.

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