Preliminary analytical study on the feasibility of using reinforced concrete pile foundations for renewable energy storage by compressed air energy storage technology

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Abstract. Compressed air energy storage technology is one of the promising methods that have high reliability, economic feasibility and low environmental impact. Current applications of the technology are mainly limited to energy storage for power plants using large scale underground caverns. This paper explores the possibility of making use of reinforced concrete pile foundations to store renewable energy generated from solar panels or windmills attached to building structures. The energy will be stored inside the pile foundation with hollow sections via compressed air. Given the relatively small volume of storage provided by the foundation, the required storage pressure is expected to be higher than that in the large-scale underground cavern. The high air pressure typically associated with large temperature increase, combined with structural loads, will make the pile foundation in a complicated loading condition, which might cause issues in the structural and geotechnical safety. This paper presents a preliminary analytical study on the performance of the pile foundation subjected to high pressure, large temperature increase and structural loads. Finite element analyses on pile foundation models, which are built from selected prototype structures, have been conducted. The analytical study identifies maximum stresses in the concrete of the pile foundation under combined pressure, temperature change and structural loads. Recommendations have been made for the use of reinforced concrete pile foundations for renewable energy storage.

1. Introduction
Over the past decades, a huge number of technologies for the production of so-called "green" energy have been developed, but none of them has reached the proper level of development for a full large-scale industrial application [1]. The main reason for that is the high cost of renewable energy in comparison with the financial and environmental benefits of its use. However, taking into account the inevitable depletion of traditional energy sources, developed countries continue to invest in further research in the field of renewable energy, which leads to a gradual reduction in the cost price of green energy production.

Another serious obstacle for the full-scale use of renewable energy is the lack of reliable and effective means for its storage as energy received from the sun, wind or water should be used immediately, otherwise it will be wasted [2]. Nowadays, the new methods for the partial accumulation of renewable energy by using various technologies are being developed. One of them is the conversion

of electricity into compressed air through the pressurization of the reservoir for the subsequent generation of electricity [3]. This technology is widely known as Compressed Air Energy Storage (CAES).

Currently, the application of CAES technology is limited to pressurization of large scale underground caverns using compressors driven by power plants [4]. This paper explores the possibility to apply CAES into small scales. Renewable energy, generated from the solar panels or windmills attached to building structures, is proposed to be stored inside the pile foundation with hollow sections via compressed air. Given the relatively small volume of storage provided by the foundation, the required storage pressure is expected to be higher than that in the large-scale underground cavern. The high air pressure typically associated with large temperature increase, combined with structural loads, will make the pile foundation in a complicated loading condition, which might cause issues in the structural and geotechnical safety. Therefore this paper presents a preliminary analytical study on the performance of the pile foundation subjected to high pressure, large temperature increase and structural loads. The study is conducted using finite element analyses on pile foundation models which are built from selected prototype structures. The analytical study identifies maximum stresses in the concrete of the pile foundation under combined pressure, temperature change and structural loads. Recommendations have been made for the use of reinforced concrete pile foundations for renewable energy storage.

2. Background

The proposed compressed air energy storage system shown on simplified scheme (See figure 1) is designed to store compressed air inside reinforced concrete pile foundations with hollow sections. The advanced-adiabatic (AA-CAES) process is used for thermodynamic cycles of energy storage [5]. The process includes compression of air, extraction of heat from it, separate storage of heat and compressed air, and expansion with preceding heating.

Heat storage is critical for CAES as it directly affects the total efficiency of the system. The air temperature increases during compression and drops down while expanding. Hence, the temperature has to be controlled at compression, storage and expansion as extreme temperatures may damage equipment and pile foundation.
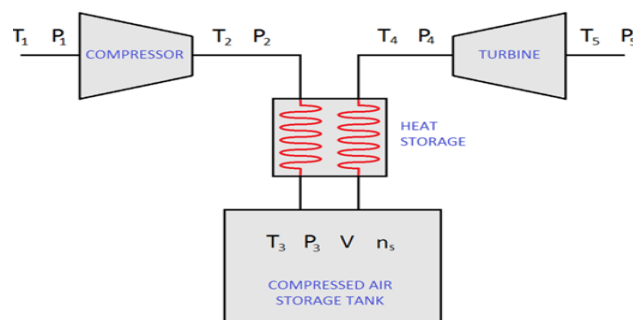

Figure 1. Compressed air storage simplified scheme.

2.1. Compression process

The compression process model is based on the energy conservation principle. For simplification purposes, the isentropic adiabatic compression is assumed as in equation(1) [6].

$$\dot{w} = \frac{7}{2\eta_1} \dot{n} R (T_2 - T_1) \tag{1}$$

where $\dot{w}$ is the electric power consumed by the compressor; $\dot{n}$ is the rate of air flow through the compressor; η_1 is the compressor efficiency; T_1 is the ambient air temperature; T_2 is the compressed air temperature; R is the universal gas constant. The adiabatic temperature to pressure relation for air is

shown in equation(2) [6].

$$T = CP^{\frac{2}{7}}$$ (2)

where C is the constant. Considering the volume of the storage tank, V, and initial amount of air stored, $n_{s,i}$, the time required to charge the tank to a pressure P_2, can be obtained as given in equation(3) [6].

$$t = \frac{3.5}{\dot{w}\eta_1}\left(VP_2 - n_{s,i}RCP_2^{\frac{2}{7}} - \frac{T_1 V}{C}P_2^{\frac{5}{7}} + n_{s,i}RT_1\right)$$ (3)

2.2. Storage

During compression, the extra heat is extracted from the air with certain efficiency,η_2, hence, temperature and pressure decrease. The heat is accumulated in a separate storage for subsequent air heating at an expansion stage. Pressure and temperature at heating and cooling processes may be assumed to have the isochoric relation as shown in equation(4) [6].

$$\frac{P}{T} = \frac{n_s R}{V} = const$$ (4)

Also, heat extracted with zero work is directly proportional to temperature change. Then, storage temperature and pressure can be determined as in equation(5) and equation(6) [6].

$$T_3 = T_2 - \eta_2(T_2 - T_1)$$ (5)

$$P_3 = \frac{n_s R T_3}{V}$$ (6)

2.3 Expansion process

The expansion process can be assumed to be a reverse of compression with power generation with efficiencyη_3. Considering the heat losses inside the air storage tank and heat storage tank with heat storage efficiencies η_4 andη_5 respectively, the total efficiency of the system is given as in equation(7) [6].

$$\eta_T = \eta_1\eta_3\frac{\eta_4 + \eta_5}{2}$$ (7)

2.4. Energy generation and consumption

This paper uses solar energy as an example for study the energy storage. Accumulation of solar energy is of a high importance as energy generated at daylight is to cover the day and night consumption. The data acquired from National Laboratory of Astana for solar panel performance was used to obtain different electricity generation patterns in 24 hours period per square meter of solar panel [7]. Also, for the same time period, the electricity consumption patterns were obtained per square meter of area based on different building occupation types. Figure 2 shows the example of electricity generation and consumption patterns for 100 m^2 of prototype residential area with 20 m^2 of solar panels. The area of solar panels was adjusted based on the total efficiency of the energy storage system.
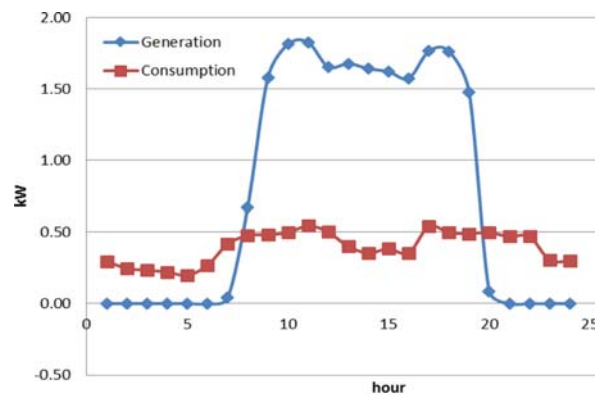
Figure 2. Electricity generation and consumption.

2.5. Required storage pressure and temperature

One of the prototype residential buildings was assumed to have 4 stores and 5m x 5m column grid, which implies 25 m^2 of tributary area for the column and 100 m^2 of total tributary consumption area. As will be shown further, the column was designed to be supported by four 20 m long piles with cap. The internal hollow region in each pile has 200 mm in diameter and 18 m in length, resulting in the total volume of 2.26m^3 available for storage. Using the energy surplus (the difference between generation and consumption shown in figure 2 and the given storage area, the thermal cycle processes are calculated for the CAES via equation (1) to equation (7). The CAES processes results in maximum storage pressure of P_3=3.125 MPa and maximum temperature increase inside the pile ofT_3=60.27^{0}C. The change of the storage pressure and temperature inside the pile for a 24-hour cycle are shown in figure 3.
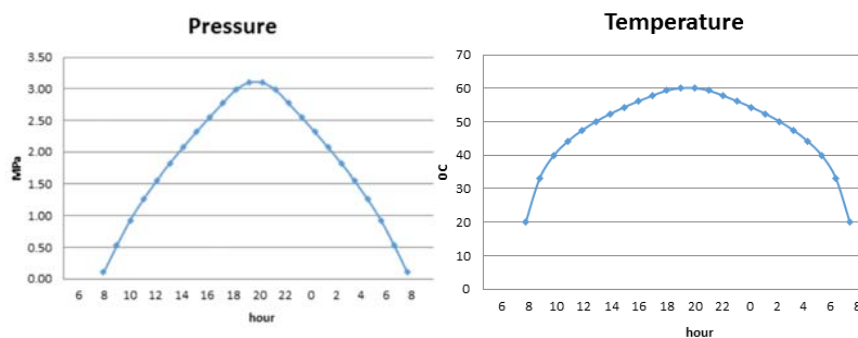

Figure 3. Pressure and temperature variations in a pile.

3. Analytical Study

The main objective of this paper is to conduct the preliminary study on the behavior of the pile foundation subjected to combined air pressure, temperature change and structural loads through finite element analyses.

3.1. Structural and geotechnical design

Superstructure above the pile foundation is a 4-story moment frame building with column grid of 5m x 5m. The loads are assumed to be as shown in table 1. The pile dimensions have been determined based on the factored structural load and soil conditions shown in Sec.3.2. Table 2 shows the summary of the factored structural load and pile dimensions.
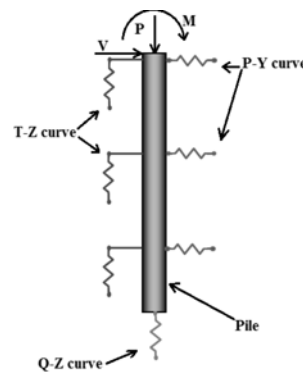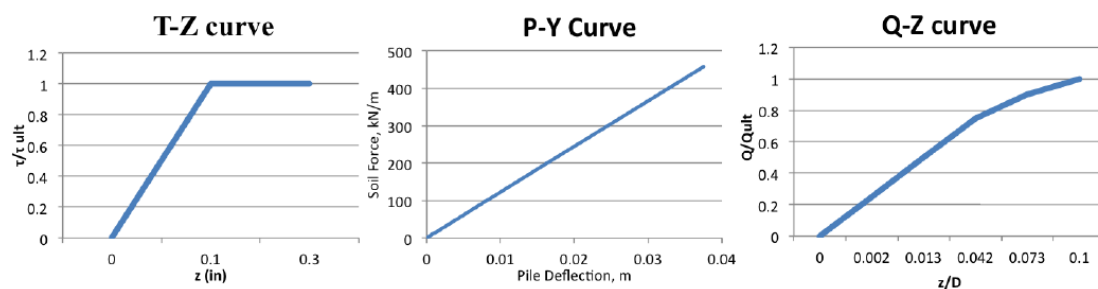
Table 1. Loads.		
Load type	Value	
Dead Load	10	kN/m^2
Live Load	3	kN/m^2
Total Gravity Load	18	kN/m^2

Table 2. Pile Parameters.		
Parameter	Value	
Structural vertical load	900	kN
Length	20	m
Outer diameter	0.5	m
Inner diameter	0.2	m

3.2. Soil-structure interaction

The modeling of the soil-structure interaction involves formulating the soil-pile resistance through the set of uniformly distributed independent springs with nonlinear properties [8]. Figure 4 shows the diagram of the soil-pile interaction model. The spring properties in the model, such as normal and lateral stiffness, are governed by load-displacement curves, which are obtained from the empirical tests and are discussed further (See figure 5). Skin friction on the pile is governed by T-Z curve springs; horizontal soil pressure is determined by P-Y curve; end-bearing is governed by Q-Z curve.

Figure 4. Spring model of a pile.

Figure 5. Load-displacement curves [8, 9]

Soil model for calculating vertical load-displacement curve (skin friction and end-bearing) has been obtained through American Petroleum Institute (API) recommendations [9]. In this study, sandy soil that is homogeneous across the depth is considered. API recommendation for skin-friction in the sand is linear elastic perfectly plastic transfer curve from which shear stiffness can be obtained. Shear stiffness coefficient value depends on the depth of the pile. End-bearing stiffness can be determined from API load transfer curve presented in [9]. For lateral load-displacement curve the provisions presented by Reese and Van Impe [10] have been applied. From this curve the normal stiffness of soil can be obtained, which is constant throughout depth of the pile. Table 3 presents the summary of the

soil properties for the model.

Concrete foundation pile has been modeled as a cylinder with the hollow section with linear elastic properties. Since the study is to check the maximum stress in the concrete, at this stage the nonlinear concrete model is not needed. The nonlinear concrete model will be used for further analytical investigation. The amount of the concrete that can be removed from the inner section of the pile has been determined based on the axial load capacity of the reinforced concrete section. Table 4 shows the summary of the properties of concrete material used for the pile.

Table 3. Soil Properties.

Soil Properties	Values
Soil Type	Medium Sand
Unit Weight	18 kN/m^3
Internal Friction Angle, φ	30°
Soil-Pile Friction Angle, δ	25°
Normal stiffness, K_N	1220 kN/m

Table 4. Concrete Properties.

Concrete Properties	Values
Grade of Concrete	C-40
Young's Modulus, E_c	3.6 GPa
Poisson's Ratio, μ	0.15
Density of Concrete, ρ	2307 m^3

3.3. Finite element model

In this study, finite element models for the pile and surrounding soil have been developed in ANSYS. The pile has been modeled as a 3D solid element using SOLID45 element and material properties of elastic concrete have been assigned to it. The interface between structure and soil has been modeled using CONTAC52. Predefined negative gaps were used to model the lateral static earth pressure, and they increased linearly with the depth of the pile. The skin friction resistance has been defined through shear stiffness K_s and coefficient of friction μ using Coulomb friction model. The end-bearing of the soil has been modeled using nonlinear springs. Figure 6 shows the model of the cylindrical hollow pile cross-section with CONTAC52 elements uniformly distributed along the circumference of the outer layer. Figure 7 shows the perspective view of the pile with spring elements uniformly distributed at the bottom of pile.
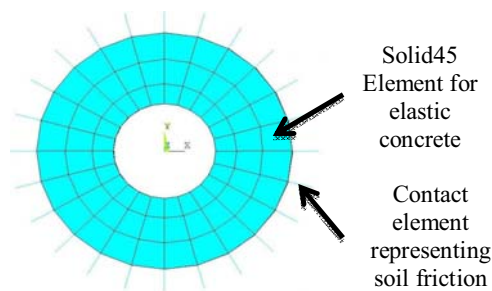

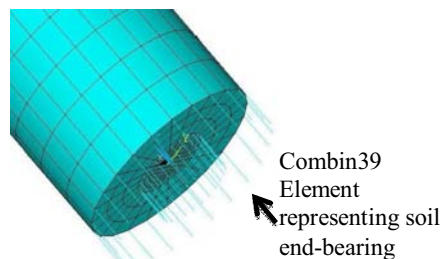**Figure 6.** Pile cross-section with contacts.

Figure 7. Pile with end-bearing elements.

4. Analytical results

In this study, the response of the pile structure to the air pressure and temperature change combined with structural loads is investigated. For the purpose of investigating the effect of each load on the pile foundation separately, three different load combinations are considered: case (a)structural load (refer to Table 2) + pressure load (refer to Figure 3a); case (b) structural load+ temperature load (refer to Figure 3b); case (c) structural load+ pressure load+ temperature load.

The results obtained from the finite element analysis show that significant stress in the concrete of the pile foundation is caused by high air pressure and temperature change. Figure 8 shows the circular

tensile stress diagrams for the three cases. As it can be seen, the combination of the temperature change and pressure loading causes significant circular tensile stress (about 6.1MPa) on the pile.
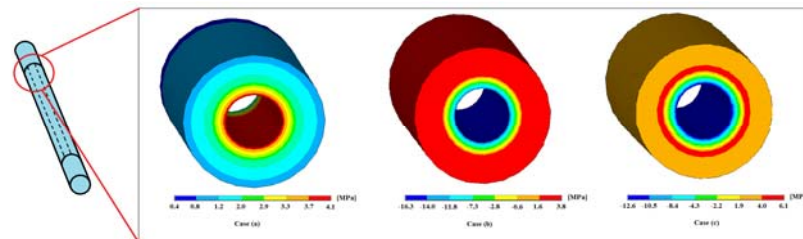

Figure 8. Circular tensile stress diagrams for three cases.

Since the pile is modeled with elastic elements, it is important to check the critical stresses in the pile. The maximum compression, tension and shear stresses have been obtained and are shown in the figures 9, 10, and 11 respectively. The summary of the critical stresses on the pile foundation is shown in Table 5.

Table 5. Summary of critical stresses.

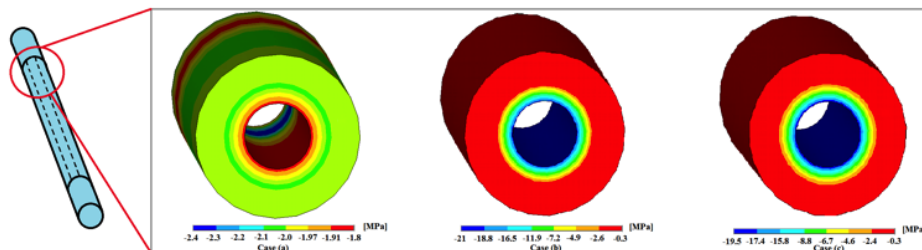| Stress type	Value	
Maximum compression	21	MPa
Maximum tension	6.1	MPa
Maximum shear	0.6	MPa

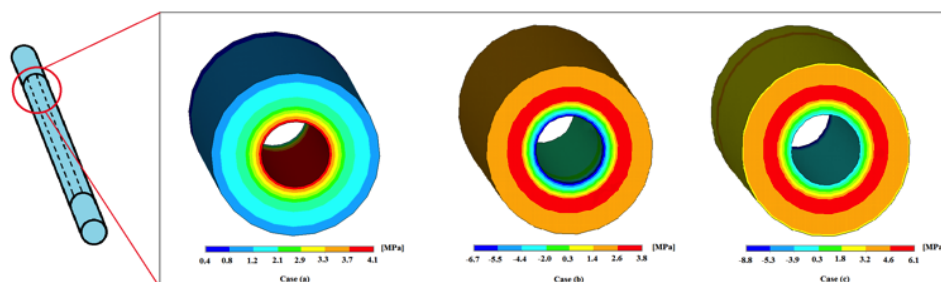**Figure 9.** Maximum compression stress for three cases.

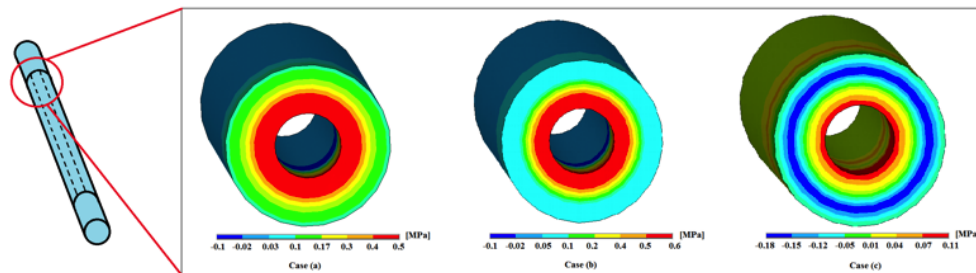**Figure 10.** Maximum tension stress for three cases.

Figure 11. Maximum shear stress for three cases.

As it can be seen from the comparison of three loading cases, the temperature increase causes larger stresses in the concrete than the air pressure. However, the simulation for the temperature load does not consider the thermal conductivity of the concrete. This assumption creates a conservative structural demand of the pile foundation due to the temperature change. Coupled thermal and structural analyses will be performed in detailed studies.

As seen in table 5, the maximum compression stress (21MPa) and shear stress (0.6MPa) is within the capacity of the normal concrete used in this study. However, the maximum tensile stress (6.1MPa) exceeds the tensile strength of normal concrete and will cause cracks in the concrete, which might not be suitable for retain the air pressure and heat inside the pile. Thus it might require higher strength concrete for the construction of the pile foundation. The nonlinear inelastic behavior as well as the effects of reinforcement cannot be investigated using the elastic pile foundation model. Further studies will be performed using the concrete model to consider the concrete cracking and effects of reinforcement.

5. Conclusion and future work
A new pile foundation system is being proposed to storage the renewable energy using compressed air. This paper presents the preliminary study on the structural behavior of the pile foundation subjected to combined high air pressure, large temperature increase and structural loads. The maximum compression, tension and shear stresses inside the concrete caused by these combined loadings are obtained through finite element analyses. The analytical results indicate: (1) the temperature increase leads to a larger structural stress demand than the high air pressure does; (2) the compression and shear stresses caused by the combined loading can be resisted by the normal strength concrete; and (3) the tensile stress might cause cracking in the normal concrete. The cracking might cause the leakage of the pressure and heat. Thus it is recommended to adopt high strength concrete and high insulation material for the proposed pile foundation system.

The preliminary study has several limitations: (1) the concrete material for the pile foundation is modeled as elastic material; (2) the reinforcement inside the concrete is ignored; (3) thermal conductivity of concrete is not considered; and (4) the soil-structure interaction is modeled as simple springs. All these limitations will be addressed in a more detailed analysis to fully understand the behavior of the new pile foundation system.

6. References
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