The 2018 Structures Congress (Structures18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Feasibility of RC Pile Foundation as an Energy Storage Media

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ABSTRACT

The use of energy storage technologies has become one of the promising methods in the sense of its high reliability, economic feasibility, and low environmental impact. The deep reinforced concrete (RC) pile foundation with the compressed air energy storage (CAES) technology was proposed as an efficient solution to optimize a power distribution during peak and non-peak periods. The main characteristic of this technique is that the compressed energy obtained from solar panels or wind turbines can be kept inside the deep pile foundation. This paper presents the preliminary analytical investigation results on the maximum compressed air pressure from thermodynamic cycles and corresponding structural responses of a deep pile foundation under various combined loading scenarios. The study identifies the critical tensile stresses of the proposed pile system using finite element analysis, and some recommendations were made for the proper practical design of a deep energy storage pile foundation system.

1. INTRODUCTION

The renewable energy storage mechanism is a relatively new configuration system of efficient utilization of the energy received from solar panels and windmills. Due to the dependence on the climate conditions and diurnal traffic of the building, there has been a significant demand on efficient energy storage systems (Chela and Kaushik, 2017). Reinforced concrete (RC) pile foundation with compressed air energy storage (CAES) was proposed as a dual system for optimizing the operation of energy technologies. Its working principle lies upon the energy that kept inside the RC pile foundation using compressed air. In terms of economic feasibility, reliability and environmental impact, the CAES technology goes beyond the expectations; however, currently, the application of it is restrained due to the shortage of analytical investigations in building structures. Hence, this study presents the investigation on the structural responses of the pile foundation with a hollow section inside where compressed air is stored.

The RC pile foundation undergoes complex stress states due to subjected structural loadings, soil conditions that include the soil shaft friction, the end bearing and soil lateral pressure, and applied internal air pressure as shown in Fig. 1 (Tulebekova et al. 2017). These loadings cause radial, circumferential and vertical stresses.

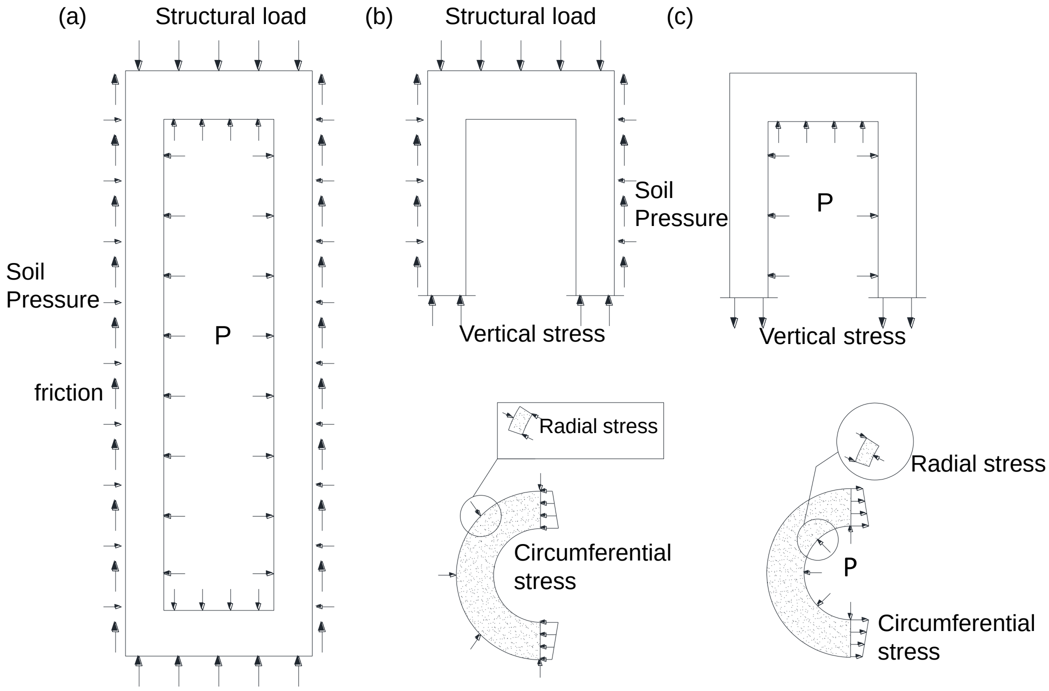

Fig. 1 Stress states under (a) applied loads, (b) structural load, (c) internal air pressure.

Compressed air energy storage (CAES) method considers the advanced-adiabatic process that consists of four thermodynamic cycles: compression, cooling, heating, and expansion (Budta et al. 2016). The compression involves the isentropic adiabatic compression condition and uses energy balance principles. After compression, the high temperature of the compressed air is cooled until initial state is achieved and the heat is stored in a heat storage medium. In heating, accumulated air absorbs the heat from the heat storage medium. Finally, in the expansion process, the power is generated by the turbine.

The detailed energy supply and demand calculations can be found in Zhang et al. (2017) in which the power supply was measured by field tests at National Laboratory of Astana while energy demand was taken based on the day-and-night energy consumption data of the typical residential building (NLA, 2016). The energy that will be kept in the storage tank is determined by the subtraction of demand from supply. Based on the investigations, the most critical condition occurs at peak hours when the storage pressure is the highest.

The pile foundation design was performed based on the number of floors and spacing of columns. Pile dimensions including the length, inner and outer diameter of the pile were designed taking into consideration design practices and load conditions. When the inner diameter of the pile is larger, the volume increases which means the pressure exerted will decrease; however, the axial load and soil effects should be carefully considered. Based on the analyses performed, 10 story building with the column spacing of 7x7 m were taken and pile dimensions are as follows: L_p = 16.5 m, d_i = 300 mm, d_o = 1,000 mm where L_p is the pile length, d_i and d_o are the inner and outer diameters, respectively. The internal air pressure and axial force applied are taken as $P_{\max}$ = 3.9 MPa, and N_p = 1,593 kN.

The storage pressure is calculated based on the thermodynamic cycles described above by entering the energy pile volume and input energy. By analyzing different energy patterns with the number of stories and column spacing, the maximum pressure was determined as shown in Fig. 2.

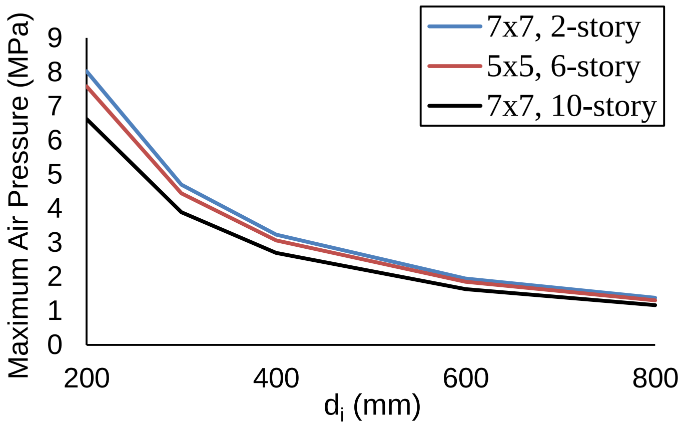

Fig. 2 Maximum Air pressure based on energy cycles

2. ANALYTICAL RESULTS

The model of the pile foundation was developed using finite element analyses in a software ANSYS. The design of the pile has solid sections at the ends and hollowed part in the middle. Elastic and inelastic analyses were considered to investigate structural performance of the pile. For the elastic analysis, FE concrete model with the following properties was taken: elasticity modulus and Poisson’s ratio of 31GPa and 0.2. For the inelastic analysis, concrete pile and hoop reinforcement model was developed based on the smeared crack approach (Zhang et al. 2017).

The soil-structure interaction including shaft friction and soil lateral pressure was modelled using point-to-point contact elements (Tulebekova et al. 2017). The necessary parameters consist of the normal and shear stiffness, coefficient of friction and initial gap. The normal and shear stiffness can be determined based on the soil lateral and friction response curves, respectively (API 2002, Loehr and Brown 2008) while the coefficient of friction and the initial gap can be calculated by equations $\mu = \tan(\phi' - 5°)$ and $g_0 = (1 - \sin\phi')\gamma z / k_N$. The end bearing was introduced as nonlinear springs and input parameters of the springs were determined using soil bearing response curve.

The analysis results of the energy pile model indicated valid stress distributions under both longitudinal and circumferential directions. Based on the elastic FE analysis, it was determined that the vertical compressive stress value decreases along the depth and tensile and circular stress values decrease too from inner to outer surfaces. The maximum circumferential stress shown in Fig. 3 varies based on the different inner pile radii at the mid-depth. It can be observed that stress at the inner surface for all three cases is higher than the tensile strength of the concrete which means the crack will occur from the inside section. For piles with larger inner radius (>320 mm), cracks will even spread to the outside surface of the pile.

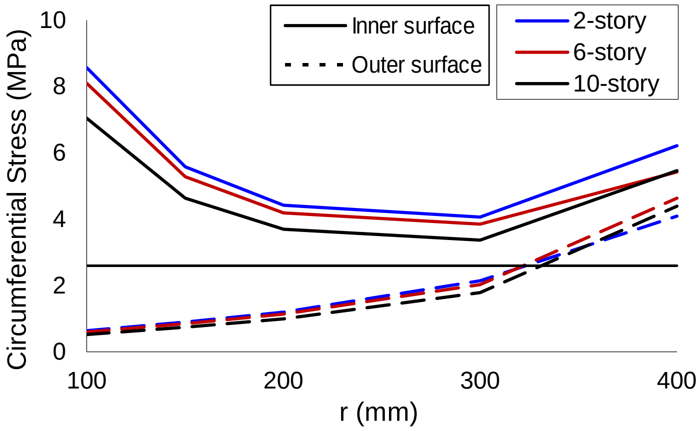

Fig 3. Stress distribution of the pile along the circumferential direction

Consequently, the hoop reinforcement with the ratio up to 6% was considered in the study of Zhang et al. (2017) to control the tensile stress in the pile section. Fig. 4 presents the crack propagation according to different hoop reinforcement ratios from the inelastic nonlinear analysis. As it can be seen in Fig. 4a, the cracks in the pile with minimum reinforcement ratio of 2.3% were fully penetrated while piles with 2.5% and 3.1% (Fig. 4b, c) were partially cracked. Hence, for the practical design of the energy piles, proper pile dimensions with sufficient amount of hoop reinforcements should be provided.

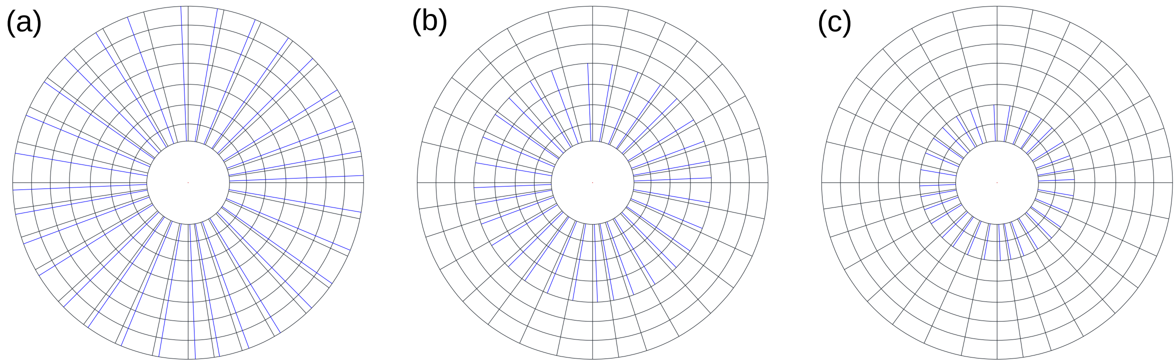

Fig. 4 Crack penetrations with hoop reinforcement ratio of
(a) 2.3%, (b) 2.5% and (c) 3.1%.

3. CONCLUSIONS

The RC pile foundation was proposed as an innovative and promising solution for optimizing the renewable energy storage systems. The study presented applicability of the system based on the analytical investigation of serviceability performance under combined structural loads, soil conditions and internal air pressure. The storage air pressure was determined by thermodynamic cycles and energy pile geometry. The finite element analyses were performed to investigate the critical stresses and crack patterns of the system. The findings obtained from this study can be summarized as follows:

1. The proposed system was appropriate for 10 story buildings or less, due to the insufficiency of renewable energy to be stored with more than 10 story buildings. Moreover, it was observed that the energy demand patterns and pile foundation dimensions determine the compressed air pressure capacity.
2. The applied loads induce the non-uniform distribution of circumferential tensile stresses that lead to the cracks in the pile. The highest stresses were observed in the inner surface and decrease to the outer surface.
3. The air pressure from the energy storage medium can decrease the shaft friction at the top of the pile; however, at the bottom, it can be increased. Overall, the effect of the internal pressure on the shaft friction was insignificant.
4. To control the crack distribution in the pile section, the hoop reinforcements were introduced as well. The hoop reinforcement ratios of 2.5-3.5% should be considered to prevent the full crack of the pile section. Moreover, it was determined that small inner diameter pile is preferred to have the practical and cost-effective design of foundation system.

ACKNOWLEDGEMENT

This research was supported by the Nazarbayev University Research Fund, and the authors are grateful for this support.

REFERENCES

American Petroleum Institute. 2002. Recommended practice for planning, designing and constructing fixed offshore platforms- working stress design. American Petroleum Institute, 21st Ed.

Budta M., Wolf D., Spanc, R. and Yan J. (2016). “Compressed Air Energy Storage – An Option for Medium to Large Scale Electrical-energy Storage”. Energy Procedia, 88: 698-702

Chela A., Kaushik G. (2017). “Renewable energy technologies for sustainable development of energy efficient building”. Alexandria Engineering Journal. https://doi.org/10.1016/j.aej.2017.02.027

Loehr E.J. and Brown D.A. (2008). “A Method for Predicting Mobilization Resistance for Micropiles Used in Slope Stabilization Applications”, A Report Prepared for the Joint ADSC/DFI Micropile Committee.

National Laboratory of Astana. (2016). Solar panel performance data sheet. Nazarbayev University. Research Institute of Renewable Energy, Energy Saving, Efficiency and Future Energy.

Tulebekova S., Saliyev D., Zhang, D., Kim JR., Karabay A., Turlybek A., Kazybayeva L. (2017). “Preliminary Analytical Study on the Feasibility of Using Reinforced Concrete Pile Foundations for Renewable Energy Storage by Compressed Air Energy Storage Technology”. Global Congress on Construction, Material and Structural Engineering, Johor Bahru, Malaysia, August 27-28.

Zhang D., Kim J., Tulebekova S., Saliyev D., and Lee D. (2017). “Structural Responses of Reinforced Concrete Pile Foundations Subjected to Pressures from Compressed Air for Renewable Energy Storage”. International Journal of Concrete Structures and Materials, Under review. Nazarbayev University, Astana, Kazakhstan.