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Application of CFT Pile Foundation as an Energy Storage Media

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ABSTRACT

In the authors' previous study, the feasibility of a reinforced concrete (RC) deep pile foundation system with the compressed air energy storage (CAES) technology was examined, from which the limitation of an RC deep energy pile foundation was clearly found in its serviceability performances. To overcome such a limitation, in this study, a concrete-filled tube (CFT) pile foundation system was introduced as a dual functional system for an energy storage media and structural deep foundation. Extensive finite element analyses were conducted to estimate the overall structural responses of the CFT energy pile system considering the combined effects of structural loading, soil conditions, and internal air pressures. The finding obtained from this study indicates that the CFT deep energy foundation can provide improved serviceability performances.

1. INTRODUCTION

The reinforced concrete (RC) pile foundation with compressed air energy storage (CAES) system utilizes the structural pile with a hollow section wherein the compressed air can be stored. In the study reported by Zhang et al. (2017), the applicability of the RC deep energy pile foundation was adopted and analyzed based on the serviceability performances of the system using finite element analysis on ANSYS software. The results obtained from the study indicated limitations in its structural responses. To overcome these limitations, concrete-filled tube (CFT) pile foundation system was proposed as an alternative for its dual functions including energy storage medium and structural foundation. Its constructability, high stiffness and strength efficiency and resisting ability to high temperature and pressure make the proposed system practical; therefore, this pile foundation has been progressively applied to many building structures (Hsiao et al. 2015).

This paper presents an investigation of the application of CFT pile foundation system as an energy storage media with an analysis for structural performances. Finite element analyses were conducted to perform 3D model and elastic study on the structural responses using ANSYS Workbench software (Liang 2017). The analytical investigation considers four alternatives of CFT pile foundation with a hollow section that includes only concrete pile, concrete pile with the inner tube, concrete pile with the outer tube and concrete pile with double tubes. According to this study, the most feasible design is suggested to resist the combined structural loads, air pressure and soil effects.

As the basis of the parametric study, the inner radius variables of 150 mm, 200 mm, 300 mm and 400 mm are considered. The elastic concrete material properties including modulus of elasticity and Poisson ratio of 31 GPa and 0.2 are taken, respectively. Regarding steel tube properties, Young's modulus of 201 GPa and Poisson's ratio of 0.3 are considered. The structural loadings, air pressure, soil conditions and pile dimensions were similar to the study of Zhang et al. (2017): pile length of 16.5 m, the outer diameter of 1,000 mm, air pressure of 3.9 MPa, and axial force of 1,593 kN. The thickness of the steel tube is determined on the basis of allowable plate dimensions in which the steel tube for shaft should be minimum of 10 mm (Khaleghi 2012). In this study, inner tube thickness of 10 mm and outer steel tube thickness of 15 mm are taken because of construction process involvement.

The 3D model of the hollowed pile with 0.5 m top and 1.0 m bottom ends of solid sections are modelled as shown in Fig. 1. To make a soil, the solid section is designed with frictional contact conditions between soil and pile. Soil properties including elasticity, unit weight, shear stiffness and friction parameters are shown in Table 1. For the frictional contact condition, Augmented Lagrange approach is applied. Soil pressure, end bearing and other parameters are similar to the previous study of Zhang et al. (2017).

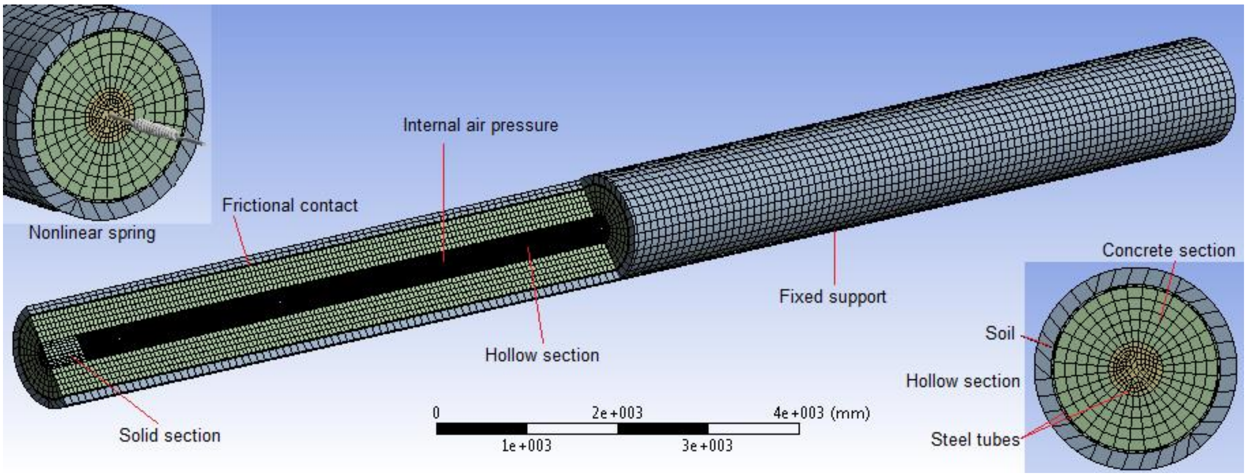

Fig. 1 3D model of the energy pile

Table 1. Soil and contact properties of the pile

Soil elasticity	Unit weight (γ)	Normal shear stiffness (k_N)	Friction angle (ϕ')	Friction coefficient	
				Soil and concrete	Soil and steel
31.55 MPa	18 kN/m^3	0.226 MPa	25º	0.466	0.3

2. ANALYTICAL RESULTS

The elastic analysis was conducted by applying all the loads including structural, soil effects and internal pressure. Stress states in vertical, circumferential and radial directions were drawn from the analysis. Fig. 2 shows the stress distribution of the concrete section based on the different pile design cases along the radial direction. As it can be seen, concrete pile with inner and double steel tubes have similar trend while only concrete and pile with outer tube show almost identical results. The radial and circumferential stresses decrease from inner to outer sections, while the vertical stress is uniformly distributed in tension.

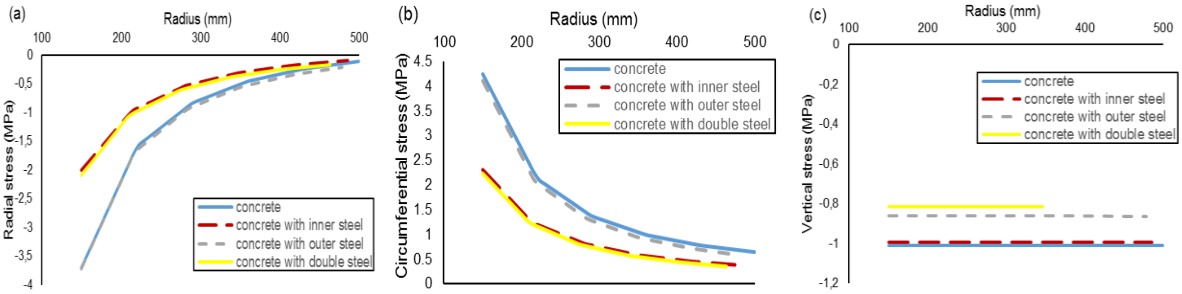

Fig. 2 Stress states of concrete along the radial direction

Fig. 3 presents radial, circumferential and vertical stresses of concrete at the inner section along the longitudinal direction. The circumferential stress of concrete with inner and double tubes are almost half the other two pile designs. Due to the soil lateral pressure increase, at the top of the pile, the circumferential stress slightly higher compared with the stress at the bottom side. From the Fig. 3(c), the vertical stress is in compression at the top then increases to the tensile direction along the depth. Around the solid sections, the stresses showed severe changes due to the transition between hollow and solid sections.

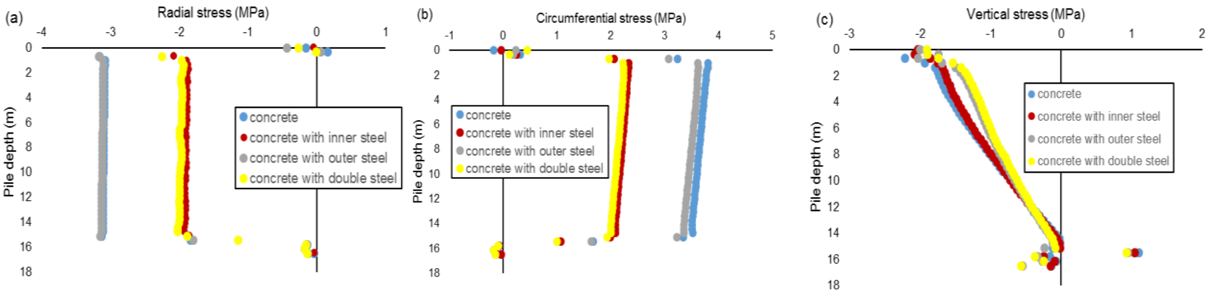

Fig. 3 Stress states of concrete along the longitudinal direction

Fig. 4 presents the parametric study of all four cases with inner radii of 150 mm, 200 mm, 300 mm and 400 mm. As it can be seen in Fig. 4(a), the circumferential stress of concrete pile for inner radii of 150 mm, 200 mm and 300 mm are higher than the tensile strength of concrete (2.6 MPa) that leads to the cracking. As the inner radius increases, pile thickness and cross-section area decrease that results in the increase of circumferential stress. Meanwhile, the internal air pressure decreases due to the increase of hollow section; however, axial load and air pressure are still induced to the pile. From the Fig. 4(b), it is clearly seen that the circumferential stress is less, except for the pile with the radius of 400 mm, because of the presence of the inner steel tube. Based on the analysis, it was found that the inner steel tube is more efficient compared with outer one since the circumferential stress of the inner tubes is ten times larger than outer steel tubes; therefore, inner steel tubes are preferred in the design of pile foundation system. The presence of only outer tube leads to the higher stress distribution that results in the occurrence of cracks as shown in Fig. 4(c). Regarding the concrete pile with both inner and outer steel tubes, the stress state is significantly less than the tensile strength of the concrete which makes it suitable. Moreover, considering the construction process of the piles, CFT pile foundation with double tube design is recommended to sustain service load state.

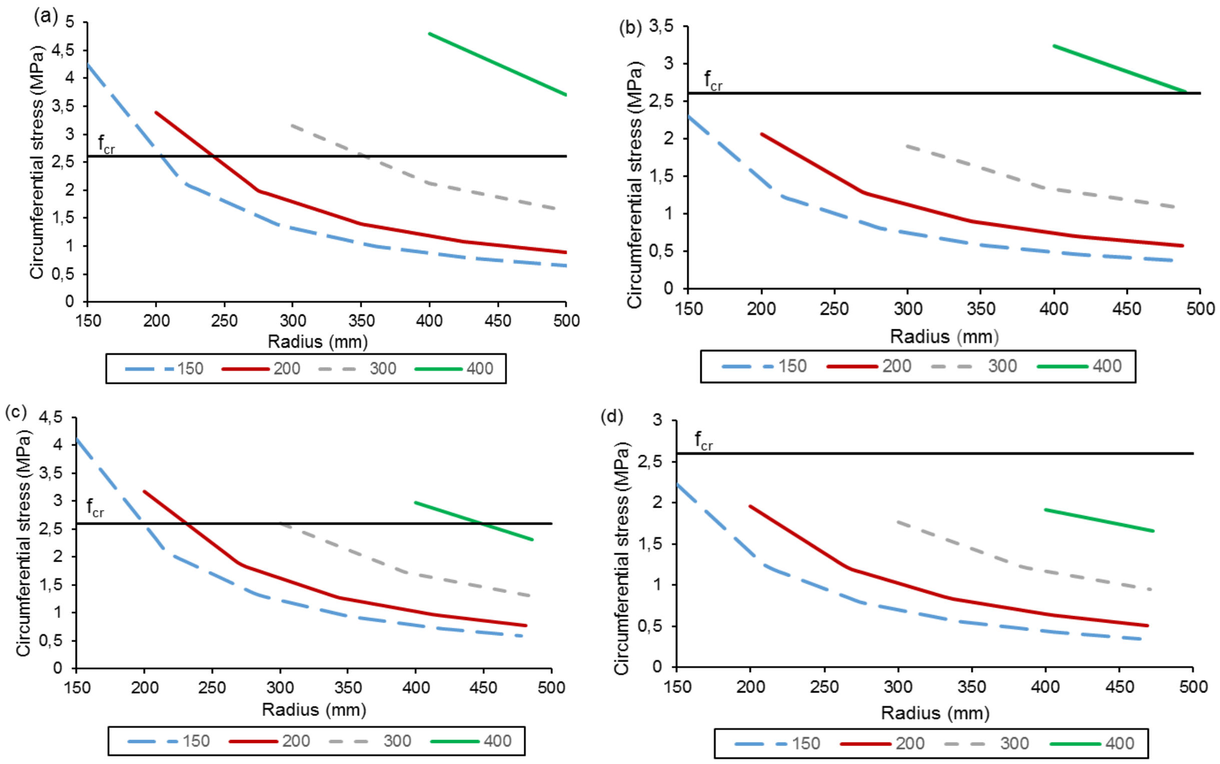

Fig. 4 Circumferential stress of along the radial direction for (a) concrete pile, (b) concrete pile with inner tube, (c) concrete pile with outer tube and (d) concrete pile with double tubes

3. CONCLUSIONS

The CFT pile foundation system was proposed as an energy storage media by investigating structural performances under structural loadings, soil effects, and air pressure. Finite element analysis was conducted for various pile type designs and the parametric study was performed. The findings are summed up as follows:

1. To prevent high-stress state distribution, the inner steel tube would be an efficient way of pile foundation design since it will significantly reduce the stress developed.
2. By analyzing various inner radii configurations, it was observed that with the increase of inner radius, the cross-section area and thickness decreases which leads to the high circumferential stress. Moreover, the increase of the void section results in the air pressure decrease; however, it should be noted that because of the axial force and soil lateral pressure, the maximum tensile stress increases.
3. The concrete pile with double steel tubes showed the advantageous results in structural performances of the building. In addition, considering the constructability of the piles, CFT pile with double tubes would be a better solution to the system.

ACKNOWLEDGEMENT

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