Use of digital correlation techniques for investigating behaviour of geothermal driven piles

Sreelakshmi G\textsuperscript{1} and Asha.M. N\textsuperscript{2}\textsuperscript{*}

\textsuperscript{1} Department of Civil Engineering (VTU RRC), CMR Institute of Technology, Bengaluru
\textsuperscript{2} Department of Civil Engineering, CMR Institute of Technology, Bengaluru
\textsuperscript{*}Corresponding author

E-mail address: sreelakshmi.g@cmrit.ac.in

Abstract. Geothermal energy has established its huge potential as renewable source of energy for general building establishments. A key feature here is the use of energy piles which serve as major energy exchange system which is sustainable and low-cost. Energy piles are basically driven precast piles employed to provide structural support to structures and act as heat exchange units to provide heating / cooling to buildings. The behaviour of energy piles is influenced by temperature, physical and engineering properties of soil. However, uncertainty still exists at pile soil interface irrespective of its heating or cooling conditions. The present study examines the suitability of using digital correlation technique (DIC) namely GeoPIV-RG software to study the soil deformation at pile soil interface in sandy soil. A rectangular test tank made of steel with a size of 60 × 20 × 45 cm is used for experimental studies. Hollow half section aluminum piles closed at the ends with two different pile length to outer pile diameter ratios viz., 10 and 15 of same flexural rigidity are used for the experimental studies. The piles are subjected to sustained loading simulated through Universal testing machine and movements of soil around the pile are captured using a digital camera. The image analysis software named GeoPIV-RG is used to determine the shear strains and soil displacements. Analysis of results indicated that this technique could capture deformation characteristics and surface heave formation in the surrounding infill medium.

1. Introduction

The human population on the planet earth is around 7.8 billion and need of over growing population has led to overconsumption of our depleting resources like water, coal, oil, natural gas and so on. So, it is important to manage our natural resources by developing other forms of energy such as solar energy, wind energy, hydro energy and geothermal energy. These sustainable forms of energy are clean, safe and does not pollute our environment. The energy which is produced beneath earth surface from rocks and fluids is termed as geothermal energy. Recently, geotechnical foundations like energy piles established its potential by offering sustainable and low-cost method of heating and cooling source for commercial and residential establishments. Energy piles are hollow driven precast piles with closed loop temperature control system to heat or cool any system by pumping liquid solution through pipes in contact with soil. These energy piles transfer the loads from superstructure to subsoil and also serve as a storage source of heat and cold energy during winter and summer seasons. So, these energy piles have to withstand stresses due to foundation loads as well as thermal stresses.
Recently numerous research works has been reported in literature based on heat transfer process, heating performance characteristics and thermal performance of energy piles [1-2]. Few researchers like [3-4] adopted numerical techniques like finite element and finite difference methods to simulate thermal behaviour in geothermal piles. But very few research works exist where in soil structure interaction behaviour is simulated through model or full scale studies. [5] carried out a comprehensive study to examine the structural interaction of geothermal pile and soil and concluded that skin friction resistance changes at the interface of embedded medium at varying soil depth. [6] developed soil-structure interaction model to measure strains, stresses, and displacements developed when piles are exposed to interaction loads due to its thermal and mechanical conditions in various types of soils. These researches concentrated only on thermomechanical behaviour of piles. The deformation characteristics at and around pile tip remains unexplored and techniques are required for visualisation of the same. In the year 1976, digital image correlation(DIC) methods emerged and it was used to determine strains developed on solid specimen surface [7]. Since then there has been vast progress made in field of digital imaging analysis and image processing techniques. GeoPIV-RG is a DIC technique developed by [8] and is based on Particle Image Velocimetry (PIV) method where in displaced position and strains developed in medium are analysed, based on change in the physical structure of the media under loading by capturing images for specific instant of time. Researchers like [9 - 13] adopted GeoPIV-RG to determine the behaviour of driven piles in different stress conditions by concluding that this technique could capture prefaileure strains, visualize soil movements and heave formation near pile soil interface. So, the current study aims to explore the suitability of image analysis software GeoPIV-RG based on DIC to estimate deformation characteristics and strain contours of infill medium under sustained loading conditions for driven piles which are used for construction of geothermal piles.

2. Methodology
The methodologies adopted to execute the study in order to attain the objectives are listed below:

- Characterization of materials
- Modeling of piles using scaling laws [11]
- Modeling and fabrication of test chamber [12]
- Seizing images at different time intervals during test using digital camera
- Perform analysis using GeoPIV-RG software to understand the deformation patterns and strain contours under pile length to outer pile diameter ratios of 10 and 15.

3. Experimental work
The present test tank made of steel has a size 60 cm × 20 cm × 45 cm with transparent sheet fixed on front face is used for filling infill material. The transparent sheet helps in image capturing during model tests. To simulate sustained loading conditions, uniform strain rate of 4.5 kN/min is applied using Universal Testing Machine. Infill medium is prepared using crushed stones of size 3.8 mm and pluviation technique is adopted to maintain even infill density of 1.46 g/cc. For pile soil interaction studies, scaling laws proposed by [11] is adopted to arrive at test pile sizes. Accordingly, aluminium half pile hollow section (closed ends) with an shaft outer diameter of 1.6 cm and shaft wall thickness of 0.4cm with a scale factor of 1/12 is selected as test pile for simulating original RCC pile of 40 cm diameter. Figure 1 shows the hollow pile section. For uniform application of sustained load and maintain verticality of pile position, a pile cap made of aluminium with 1.3 cm thickness is provided at pile head. The test is conducted on hollow half section piles (closed ends) with pile length to outer pile diameter ratios of 10 and 15 and deformation profiles of the embedded soil is captured using a single lens reflex camera.
The images collected from the model tests are used as source files in GeoPIV-RG and subsequent processing is completed using this DIC technique. The post processing files develops and plots deformation profile of infill soil under sustained pile loading. Figure 2 shows the complete test set up.

4. Results and discussions

For the present study, images are analyzed using two methods in the GeoPIV-RG Software. They are:

- Control points analysis: Locations of data sets of X and Y coordinates for image - object space calibration is created with respect to 1 cm grid spacing of perspex sheet.
- Mesh point analysis: Mesh of 50 × 50 pixels is created for selected region of interest.

After the image processing and analysis through DIC techniques, a relative study between piles is carried with respect to post processed results as listed below:

1. Soil particle movement vectors for pile length to outer pile diameter ratios of 10 and 15
2. Engineering shear strain contours for pile length to outer pile diameter ratios of 10 and 15

4.1 Soil particle movement vectors

The soil particle movement vectors are obtained for pile length to outer pile diameter ratios of 10 and 15 after analysing the 60 image frames are represented in Figure 3(a) and Figure 3(b). In Figure 3(a) and Figure 3(b), displacement vectors have different magnitudes along the depth of pile. It is evident that there is formation of strain localisation near the zone of penetration. But zones that are far off from pile penetration zones are not affected by influence of loading. For length/diameter ratios are 15, the observations are quite similar.
4.2 Engineering shear strain contours of hollow pile for pile length to outer pile diameter ratios of 10 and 15

Figure 4(a) and Figure 4(b) illustrates the engineering shear strain developed for pile length to outer pile diameter ratios of 10 and 15. It is construed from figure that hollow piles with its lesser mass density has increased disturbance of surrounding infill medium. This is one of interactive behaviour which needs to be investigated for energy piles when it is used for load bearing conditions. Figure 4(a) also shows the formation of surface heave when pile length to outer pile diameter ratio is 10 and for pile length to outer pile diameter ratio 15, there is a shift in heave zone due to slender behaviour of pile section.

When pile length to outer pile diameter ratio is increased to 15, it is observed that there is an expansion in areas of shear strain contours in both horizontal and vertical directions. This is mainly due to increase in buckling behaviour of pile section which has also contributed to increase in highest
shear contour value (red colour) from 25% to 65% as represented in colour scale strip. On analysis of the test results, it is found that the hollow piles considered in the present study depicts the case similar to that of an energy pile because it is hollow in cross section. The hollow sections, make the pile lighter, hence chances of bucking will be more. However, skin friction plays a key role and in the present study, cohesion less crushed stones that has an angle of friction of 32° is used. In real time, the infills will not necessarily be cohesion less and hence there are chances wherein frictional stress will decrease and chances of pile failure will increase. Hence, it is essential to carry out model studies to investigate the soil-pile interaction with respect to different infills.

5. Conclusions

- PIV technique is successful in capturing soil displacement characteristics around energy piles with pile length as a variable.
- Extraction of soil-pile interaction especially with reference to the functionality of the pile as an energy pile is explored in present study.
- Comparisons are made with reference to soil particle movement vectors and engineering shear strains for hollow piles having two different pile length to outer diameter ratios and it is concluded that phenomenon of buckling forms a critical parameter as far as design of an energy pile (hollow pile) is concerned.

6. References

[1] Gao J, Zhang X, Liu J, Li K S and Yang J 2008 Thermal performance and ground temperature of vertical pile-foundation heat exchangers: A case study Appl. Therm. Eng. 28 2295–304
[2] Brandl H 2006 Energy foundations and other thermo-active ground structures Geotechnique 56 81–122
[3] Bezyan B, Porkhial S and Mehrizi A A 2015 3-D simulation of heat transfer rate in geothermal pile-foundation heat exchangers with spiral pipe configuration Appl. Therm. Eng. 87 655–68
[4] Mehrizi A A, Porkhial S, Bezyan B and Lotfizadeh H 2016 Energy pile foundation simulation for different configurations of ground source heat exchanger Int. Commun. Heat Mass Transf. 70 105–14
[5] Li Q, Chen L and Qiao L 2017 Thermal Effect on Structural Interaction between Energy Pile and Its Host Soil Adv. Mater. Sci. Eng. 2017
[6] Chen D 2016 Soil Structure Interaction in Energy Piles (University of California, San Diego)
[7] Sutton M, Wolters W, Peters W, Ranson W and McNeill S 1983 Determination of displacements using an improved digital correlation method Image Vis. Comput. 1 133–9
[8] White D J and Take W a. 2002 GeoPIV: Particle Image Velocimetry (PIV) software for use in geotechnical testing vol 322
[9] White D J and Bolton M D 2002 Observing friction fatigue on a jacked pile Centrifuge Const. Model. Two Extrem. 346–54
[10] Sreelakshmi G, Asha M N and Viswanath D 2018 Investigations on Pile-Soil Interaction Using Image Analysis Geotech. Spec. Publ. 2017-Novem 466–75
[11] David Muir Wood, Adam crew C taylor 2002 Shake table testing of geotechnical models Int. J. Phys. Model. Geotech. 1 1–13
[12] Parkin A K and Lunne T 1982 Boundary effects in the laboratory calibration of a cone penetrometer for sand European symposium on Penetartion Testing (ESOPT II) (P.O. Box 40 Tasen Oslo 8, Norway: Norwegian Geotechnical Institute) pp 1–7