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A Numerical Study on Laterally Loaded Single CFG Pile Embedded in Layered Soil

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Abstract. Soil having low bearing capacity is one of the greatest problems for the construction of civil engineering structures. Many techniques have been adopted to get rid of the troubles faced from such soil, among them, Cement Fly-ash Gravel (CFG) pile technique is an emerging one. It has been used in highways, railways, bridges, embankments, high-rise buildings, and many other places due to its congruous engineering properties. CFG piles were mainly analysed for transmitting vertical loads in single layered soil. But practically, piles are always installed in layered soil and the pile may also experience several lateral loads. This paper aims to address the behaviour of a laterally loaded single CFG pile embedded in layered soil. In order to achieve the objective, a numerical analysis is conducted using finite element method based software PLAXIS 3D and it is validated with the laboratory experimental results. In this study, the load-displacement behaviour and bending moment characteristics are determined by varying the length to diameter (L/D) ratios as 8, 10 and 12 where the length is kept constant. It is noticed that due to an increase in diameter by 1.2 and 1.5 times, the lateral load carrying capacity is increased by 1.4 and 1.9 times respectively. In consideration of strength and economy, CFG pile can be a suitable one for carrying vertical as well as lateral load that comes on the foundation.

Keywords: CFG Pile, Lateral Loading, Numerical Analysis, Horizontal Displacement, Bending Moment.

1 Introduction

Constructing agencies often meet with the difficulties during construction on sandy soil. These problems proliferate when the sand is very loose. Loose sand has natural shifting characteristics and the bearing capacity is also low to carry heavy loads from superstructures. That's why, deep foundations become necessary to carry the heavy loads in such soils. Piles are the most common examples of deep foundations which are being used now-a-days. But, the construction cost of such conventional piles is high enough. In these places, CFG piles can be used with lesser installation cost. The reinforcement is not required in CFG piles and the use of by-product i.e., fly-ash also reduces its cost of manufacturing. CFG piles can firmly carry heavy vertical loads and reduce the settlement of structures [1].

A fair number of research works has been carried out experimentally, analytically, and numerically to perceive the behaviour of the CFG pile. The consolidation characteristics of an embankment for a road built on a compound foundation was studied using finite element method (FEM) based software PLAXIS 2D [2]. The foundation was composed of multiple columns. It was found that in the long run the durability of the embankment is improved by the combination of CFG lime columns because the compression modulus of CFG columns is noticeably higher than that of stone columns. The mechanical behaviour of CFG pile foundation in consolidating saturated mine tailing dam was studied experimentally and numerically [3]. It was stated that the maximum stress value was found near pile bottom and the decrease of pile-soil stress ratio occurs with the increase of load. A numerical analysis was done to study the performance of geosynthetics reinforced granular piles in soft clays [4]. It had been observed that the ultimate load intensity of floating granular piles increases up to a certain stiffness value of geotextile, and then it remains constant for higher stiffnesses. But a linear relationship was found between the increase of ultimate load intensity of end bearing granular piles and the increase in stiffness of geotextile. The combined effect of ultimate axial compression load and lateral load in soft soil were computed by conducting experiments in the laboratory to obtain the behaviour of a CFG single pile [5]. It was observed that the CFG pile substantially improves the soil properties under combined loading and its use is very much economical for the design of foundations.

The numbers of analyses on CFG pile are not quite less. But these analyses were mainly on single layer soil. The behaviour of CFG pile only under the action of lateral load was not also studied properly by the previous researchers. As the analysis of lateral load on CFG pile is rare, hence, in the current study, the impact of lateral load on a CFG pile embedded in homogeneous and layered soil is investigated experimentally and numerically.

2 Numerical Model Validation

The numerical analysis is validated with laboratory test results. A small scaled laboratory model test is performed for that purpose. The boundary conditions and dimensions for numerical model are kept exactly similar to that of experimental one. The data obtained from lateral load test performed in laboratory are compared with the prepared numerical model and plotted in Fig. 1. It shows that results from PLAXIS 3D software agree very well with the results of experimental analysis.

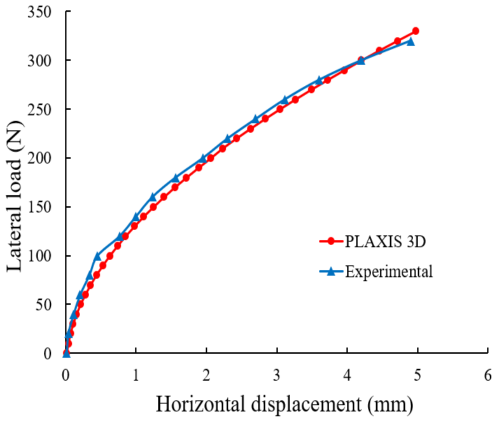


Fig. 1. Load-displacement curve for experimental test data and developed numerical model.

3 Experimental Study

3.1 CFG Pile

The CFG pile foundation is a special type of subsoil improvement technique. It was developed by the Foundation Institute of China Academy of Building Research and the manufacturing process was first published in 2008 [6]. In the present experimental study, the cement of OPC 53 Grade has been used and the fly ash was of Grade I as per IS 3812 (part 1): 2003 [7]. The gravel sizes are taken in between 4.75 mm to 10 mm. The dimensions L and D of the pile constructed in laboratory are 400 mm and 40 mm respectively. The testing tank where the pile is installed has a square cross-section. Its base dimension is 36.5 cm × 36.5 cm and the height of this tank is 60 cm.

3.2 Soil Properties

There are three types of soil materials used in the current study. These are loose sand, silty-sand and dense sand. The features of the soil samples are found performing laboratory tests as per proper techniques demonstrated by the Indian Standard (IS) codes. The properties of soil materials evaluated in the laboratory tests and used in numerical modelling are summarized in Table 1.

3.3 Preparation of Soil Bed

The test is executed on three-layered soil. The top most layer of the soil bed consisted of loose sand; the silty-sand soil is placed as the second layer of soil; and dense sand is kept in the bottom layer. The relative density (RD) of bottom layer soil is kept 85%. To maintain a homogeneous density throughout the soil bed, the ‘sand-raining technique’ is applied [8]. The RD of the sandy soil is based on the height from where the sand particles are dropped and, hence, a correlation between the RD and the height of the free fall is attained, and is represented in Fig. 2. The height of free fall of the sand particles corresponding to the RD of 85% is found to be 400 mm.

For the middle layer, i.e., for the silty-sand soil, it is placed with a bulk density (γ) of 17 kN/m^3 at a water content (w) of 15.7%. To get the necessary bulk density, the silty-sand layer is parted into three equal sub layers. The dry weight of the silty-sand soil is evaluated and mixed with 15.7% water content, and then filled uniformly in the respective layers. Each layer is tamped thoroughly to achieve the desired density. The density is inspected by gathering samples in various containers of previously known volume kept at several places of each layer of the silty-sand soil during the filling of the soil.

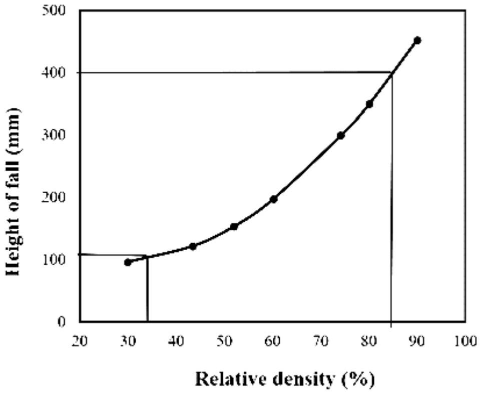


Fig. 2. Calibration of height of free fall vs. relative density

The top layer of soil is prepared adopting the same process as the lower most soil layer is filled. But the relative density is maintained as 35%. In this case, the height of free fall of the sand particles is kept 103 mm which again has been obtained from the Fig. 2.

3.4 Model Pile Installation

The sand is poured into the tank from the certain height using previously mentioned technique. The tank is filled up to the height of 20 cm from bottom surface. Then the pile is kept vertically on sand deposit and fixed at its top so that the pile does not move during preparation of soil layers. The observation for the inclination of pile is done cautiously with a level. Afterwards, the tank is filled up with the second layer of soil i.e., the silty-sand which occupies a depth of 24 cm above the bottom most layer and covers 60 percent depth of pile from its toe. The remaining part is filled up with the loose sand.

3.5 Test Program

After complete installation of the pile, two dial gauges are fitted with both sides of the collar attached at the pile head. These dial gauges have recorded the lateral displacement of pile head due to the application of lateral loads. The average reading from these two gauges is considered as the actual one. Fixing the high-tension wire with collar, the lateral load is imposed gradually on the loading platform. The lateral displacements are recorded after 15 minutes of imposing each load [9]. The load increment is continued till the maximum displacement reached at 5 mm. The complete experimental set-up is presented in Fig. 3.

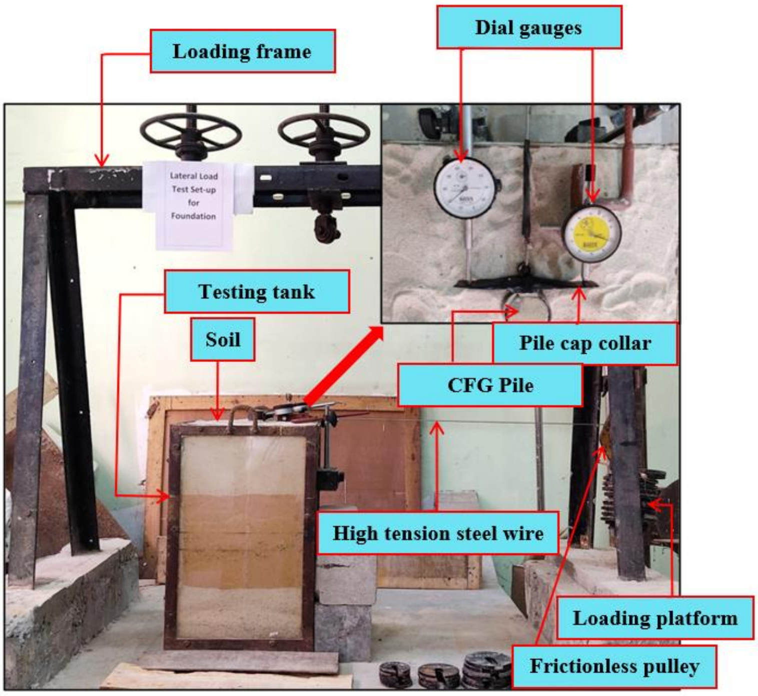


Fig. 3. Experimental test set-up

4 Numerical Study

The numerical analysis is done through FEM based software PLAXIS 3D. The dimensions of the numerical model are increased by a scale factor of 25 from the experimental model. The Hardening soil model is chosen for the modelling of soils [10]. The analysis is performed in double layered (DL) soil and triple layered (TL) soil models to see the effect of soil layering. The pile is regarded to be composed of linearly elastic material having poisson's ratio 0.2 and modulus of elasticity 25×10^6 kN/m^2. The properties of soil introduced in numerical analysis are presented in Table 1. The 3D meshing for the numerical model of present study is shown in Fig. 4. During the mesh generation, the geometry of the model is divided into wedge elements of 15 nodes. There are 6-noded triangular faces in the work planes of these elements. These are the volume elements to model the soil and pile. In addition to that, 16-node interface elements are generated for the soil-structure interaction. Total number of elements and nodes generated are (8850 ± 150) and (14770 ± 250) respectively. Keeping the length of pile (L) as 10 m in the whole analysis, the modelling is done with length to diameter (L/D) ratios 8, 10, and 12. As a result, the diameters come out as 1.25 m, 1 m and 0.83 m respectively for the aforesaid L/D ratios. To see the effect of this load, its value is increased gradually with an increment of 50 kN. The maximum displacement is evaluated for each load increment. The load that is responsible for the maximum displacement of 12 mm has been regarded as the lateral load carrying (LLC) capacity of pile [11].

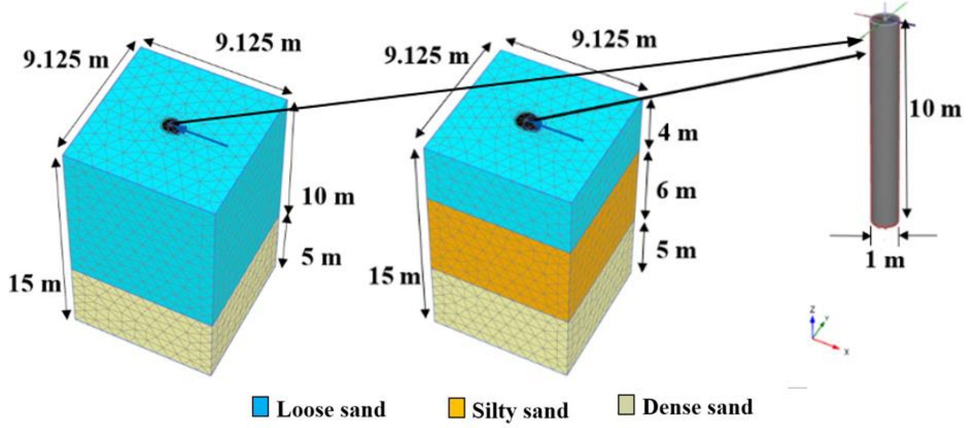


Fig. 4. 3-D meshing and numerical model boundaries

Table 1. Properties of soil used in the present study.

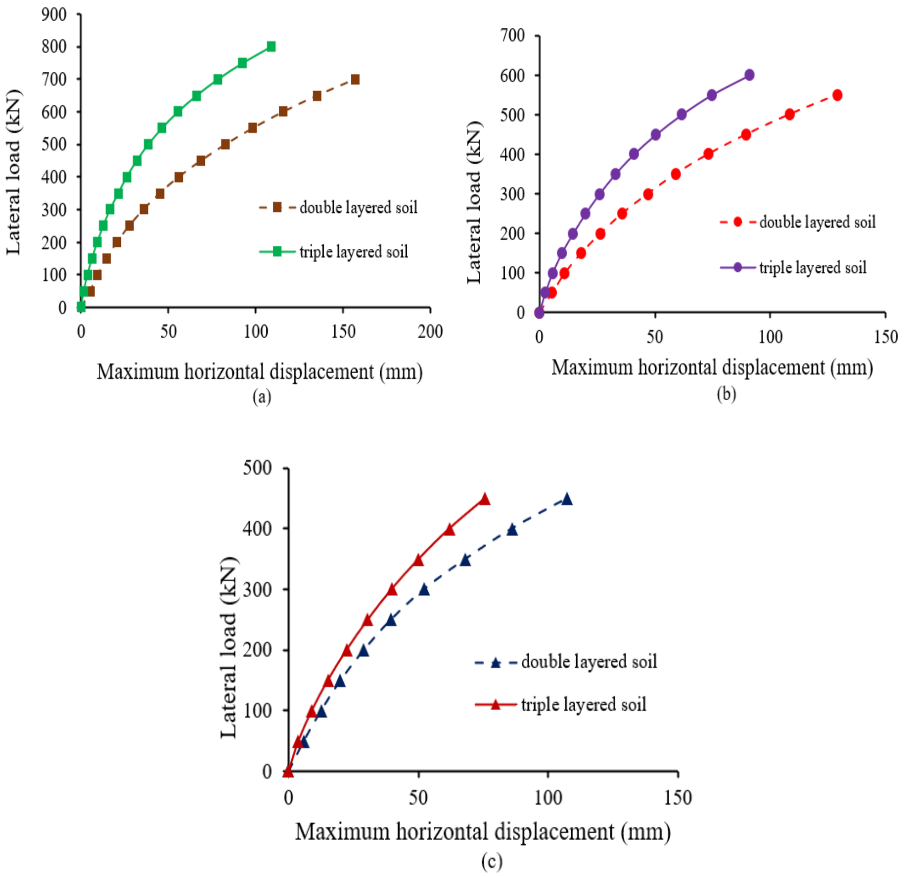
Parameters	Loose sand	Silty-sand	Dense sand
Material model	Hardening soil	Hardening soil	Hardening soil
Drainage type	Drained	Undrained	Drained
γ_{unsat} (kN/m^3)	16.3	17	18
E_{50}^{ref} (kN/m^2)	12000	15000	35000
E_{oed}^{ref} (kN/m^2)	12000	15000	25000
E_{ur}^{ref} (kN/m^2)	36000	45000	105000
Permeability, k (m/day)	2.5	0.775	1
Cohesion, *c* (kN/m^2)	0.5	16	0.5
Angel of internal friction, φ (degree)	31	23	37
Dilatancy angle, ψ (degree)	1	0	7
Interface reduction factor, R_{inter}	0.65	0.7	0.75

5 Results and Discussions

5.1 Load-Displacement Behaviour of CFG Pile

The LLC capacity of a single CFG pile is considered as that very load which causes 12 mm displacement of the pile head. It is noticed that LLC capacity increases with the increase in diameter of the pile. Fig. 5 shows the variation of lateral load with maximum horizontal displacement of pile having different L/D ratios in DL and TL soil. The load-displacement curve found is non-linear for all the cases. It has been observed that the LLC capacity of CFG piles in TL soil are 1.3, 1.6, and 1.9 times of this in DL soil for L/D ratios 12, 10, and 8 respectively.

Fig. 6 depicts that the LLC capacity increases with the decrease in L/D ratio in both DL and TL soil. This is because the surface area of the pile increases due to decrease in L/D ratio. The LLC capacity corresponding to 12 mm displacement is obtained to be 127.43 kN, 178.21 kN, and 241.78 kN for L/D ratios of 12, 10, and 8 respectively for DL soil and for TL soil this load carrying capacity is found to be 98.67 kN, 110.01 kN, and 125.89 kN for L/D ratios of 12, 10, and 8 respectively. Fig. 7 shows displacement of pile along its depth in TL soil for the load value of 400 kN, which gives the most perceptible values of differences between the horizontal displacements in Fig. 6. These curves tell that maximum displacement occurs at the pile head.



(a)

(b)

(c)

Fig. **5.** Variation of lateral load with maximum horizontal displacement of pile in DL and TL soil for (a) L/D = 8, (b) L/D = 10, and (c) L/D = 12.

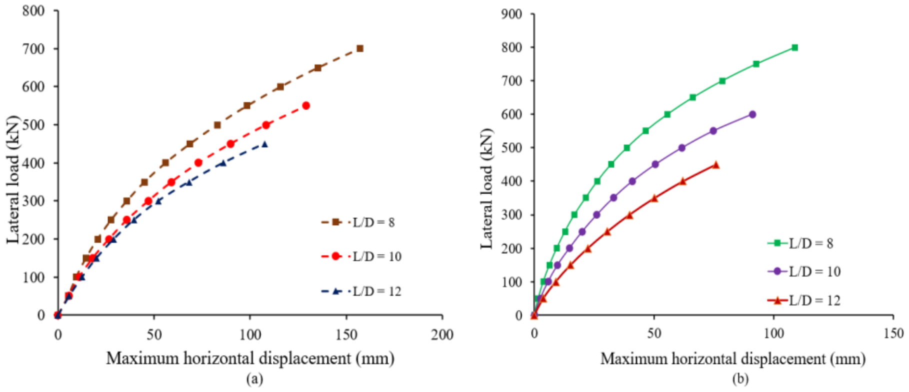


Fig. 6. Variation of lateral load with maximum horizontal displacement of pile in (a) DL soil and (b) TL soil.

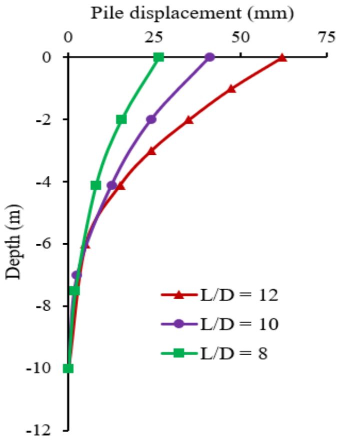


Fig. 7. Displacement of pile along the depth in TL soil.

5.2 Bending Moment Characteristics of CFG Pile

Fig. 8 shows the bending moment (BM) of pile corresponding to applied lateral load of 400 kN in DL and TL soil. From Fig. 8, the maximum BM for both DL and TL soil is found at a depth of 0.4 to 0.55 times the whole length of pile and as the diameter of pile increases the maximum BM also increases. The depth at which the maximum value of BM is achieved also shifts downward with the increase of diameters.

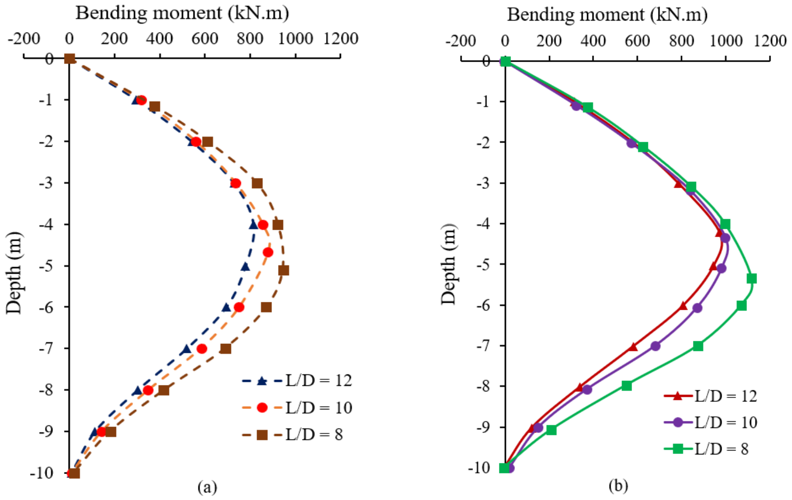
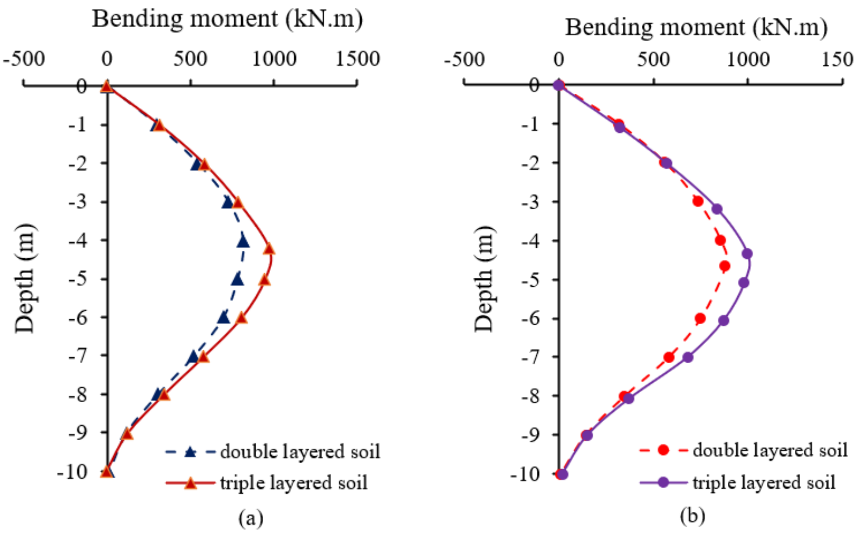


Fig. **8.** BM along the depth of pile in (a) DL soil and (b) TL soil.

The maximum BM of pile in TL soil is nearly 1.15 to 1.2 times the maximum BM of pile in DL soil for the application of same lateral load i.e., 400 kN. Fig. 9 shows the maximum BM is found higher in TL soil compared to DL soil for all the three L/D ratios of pile.



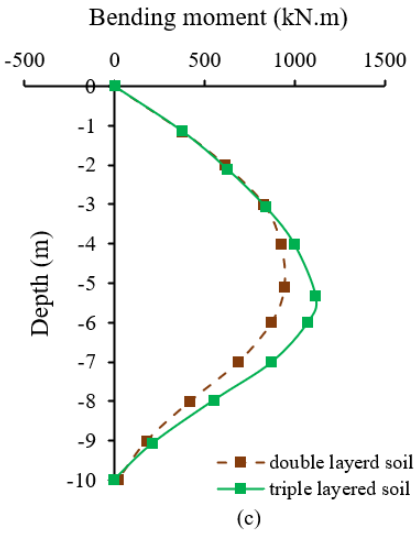


Fig. **9.** BM along the depth of pile in DL and TL soil for (a) L/D = 12, (b) L/D = 10, and (c) L/D = 8.

BM is directly proportional to the stiffness (EI) of piles [12]. As the modulus of elasticity (E) is constant for all the piles, the BM increases with the increase of moment of inertia (I) which depends on the diameters of the piles. The increase in diameter also leads to the increase in surface area. These are the reasons for increasing BM with the increase in diameter of pile.

6 Conclusions

This paper represents the numerical study of CFG pile in layered soil strata and the following conclusions from this analysis can be drawn.

- An increase in diameter of CFG pile increases the LLC capacity. It is found that the LLC capacity is increased by 1.4 and 1.9 times in TL soil and 1.1 and 1.3 times in DL soil due to increase in diameter of pile by 1.2 and 1.5 times respectively.
- The LLC capacity is increased by 1.3, 1.6, and 1.9 times for L/D ratios 12, 10, and 8 respectively due to the inclusion of silty-sand soil layer.
- For applying the concentrated load at the top of the pile which is at ground surface, the maximum and minimum displacement of pile occurred at pile head and at toe of the pile respectively.
- The depth of maximum BM shifts downward due to an increase in the diameter of the pile. But this depth is limited in between 0.4 to 0.55 times the length of pile.
- The maximum BM is increased by nearly 15 to 20 percent when silty sand layer of soil is placed in between loose sand and dense sand.

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