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Numerical Analysis of the Lateral Behavior of Geogrid Strengthened Pile Foundation System Subjected to Machine Induced Vibration

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Abstract. This paper presents a numerical study of the dynamic lateral behavior of geogrid strengthened pile foundation systems embedded in layered soil medium subjected to rotating machine induced vibration. Lateral dynamic responses of the single and 2 × 2 group pile foundation systems are studied without and with geogrid reinforcement using Finite Element software Plaxis 3D for different intensities of dynamic force (0.01,0.02 and 0.03kg-m). For geogrid reinforced pile foundations, the geogrid is placed at a depth of L/8 (L = length of the pile = 0.6m) from the top surface of the soil. The Mohr-Coulomb soil model is used to simulate the elastoplastic behavior of soil. The model is validated using the existing results presented in the literature. Results of the numerical analysis are presented in terms of frequency versus lateral displacement amplitude of the pile foundation. From the results, it is found that, the inclusion of geogrid in the pile foundation system has improved the performance of both the single and group pile foundation system by reducing the amplitude of vibration. This is because of the increase in the stiffness of the foundation system due to the interlocking effect between the soil-pile geogrid systems.

Keywords: Pile Foundation, Lateral Vibration, Finite Element Analysis, Geogrid

1 Introduction

Pile foundation system comes under the category of deep foundation. The purpose of pile foundation is to transfer the load from the heavily loaded structures to the deeper layers of soils present in the ground. These heavily loaded structures include high rise buildings, chimneys, power plants, oil refineries and nuclear facilities etc. These kind of structures create lateral loads on the pile foundations due to wind action, wave actions etc. [1]. Use of pile foundation is necessary in the case of soft soil or heavily loaded structures in the field. The lateral load carrying capacity of pile foundations depends on the strength of top soil layers up to certain depths (generally 5m to 10m) [2]. In some cases, there is a chance of dynamic forces taking place in the ground due to seismic actions or machine loading. For such situations, the design of pile foundations should be done accordingly. However, pile foundations alone cannot resist the dynamic loads coming from the structure in some cases due to poor soil strength.

Geogrids are the mesh like structured polymeric materials. These are widely used in many of the geotechnical applications like embankment fills, reinforced earth retaining walls, reinforced soil slopes and construction over soft clays etc. [3]. Apertures or the openings of geogrid provide interlocking effect between the soil and the geogrid material. This will provide sufficient tensile strength for the structure. Stiffness of geogrid also plays an important role in providing the strength to structure [4].

To improve the tensile strength of the top soil layers and the lateral load carrying capacity of the soil, geogrids can be placed in the top soil layer. For the purpose of this study, geogrids modeled as layer of reinforcement in the top soil layer of a three-layered soil deposit.

2 Numerical Modeling

A 2x2 pile group foundation was modeled in a three-layered soil deposit using a three-dimensional finite element software Plaxis 3D. Soil layers were modeled by considering Mohr-Coulomb failure model which is a linear elastic perfectly plastic material model. Piles were modeled as beam elements and the pile cap was modeled as plate element. Geogrid was modelled using the default option of geogrid available in Plaxis3D.

The numerical model was constructed by taking the study conducted on small-scale geogrid reinforced pile foundation as a reference [5]. Hence, the material and soil properties were also given as the same used in that study. Input properties for the soil layers were presented in the table 1. Properties of the model piles and pile cap were presented in table 2. Geogrid type used for this model study was NeltonCE121 whose stiffness was taken as 110kN/m [5]. Since the literature suggests that effect of lateral behavior of foundation is more dependent on the top soil layers, geogrid was placed at a depth of *L*/8 (*L* = embedded length of the pile) from the ground surface.

In the practical applications of this kind of foundation system, necessary geometric scaling factors λ can be used for each parameter of the materials to simulate the prototype foundation system. Table 3 shows the scaling factor for the various parameters of material.

Table 1. Input properties of soil layers in the model

Soil type and properties	Aggregate	Modified glyben layer	Sand
Thickness(m)	0.08	0.23	0.36
Density(kN/m^3)	1.61	1.38	1.75
Elasticity Modulus(kN/m^2)	2746	2623	8377
Cohesion(kN/m^2)	0	10	0
Friction Angle(degree)	50	0	40

Table 2. Input properties of pile and pile cap in the model

Property	Pile	Aggregate
Material	Acrylic	Aluminum
Density(kN/m^3)	1.5	2.7
Elasticity Modulus(kN/m^2)	3.2×10^6	7×10^7
Poisons ratio	0.4	0.32
Size(mm)	20×600	200×200×6

Table 3. Scaling factors for each parameter used in modeling

Parameter	Scaling factor
Length	λ
Density	1
Elasticity Modulus	λ
Stiffness	λ^2
Force	λ^2
Frequency	$\lambda^{-1/2}$
Time	$\lambda^{1/2}$

Fixed boundaries were selected at the bottom and the sides were taken as roller supported boundary. The soil sides boundaries are provided far away from the pile to reduce the effect of wave reflection from the soil boundary. Damping property of soil was simulated by considering Raleigh damping coefficients α and β using the input option available in the Plaxis 3D. These damping coefficients can be calculated by entering damping ratio as 5% which is usually taken for the general problems on dynamic loading due to machine foundations. To simulate the field interaction between soil and geogrid and the soil and pile cap, default interface elements were given at the bottom and top of geogrid layer and also at the bottom of the pile cap i.e., plate element. For the numerical model, 10 nodded tetrahedral elements were used in the meshing operation. Fine mesh elements were selected to have better accuracy in the calculations. Fig. 1 shows the three-dimensional finite element mesh of the numerical model developed using Plaxis 3D. Fig. 2 shows structural elements present in the numerical model which include the location of piles, geogrid, pile cap and the direction of the load application onto the foundation model. Interfaces elements were also shown in the figure on top and bottom of geogrid to simulate the interface between geogrid and soil layers.

Dynamic lateral loading was applied at the center of pile cap on the ground surface in the form of sinusoidal waves to simulate the rotating machine induced vibration loading. Magnitude of dynamic loading was calculated for different frequencies of the running machine. The following equation was used to calculate dynamic loading applied on the foundation system.

$$F = me\omega^2 \sin(\omega t) \tag{1}$$

In the above equation, *F* is the magnitude of dynamic loading, *me* is the eccentric moment induced by the rotating machine, ω is the operating frequency of machine and *t* is the dynamic time interval of the machine loading.

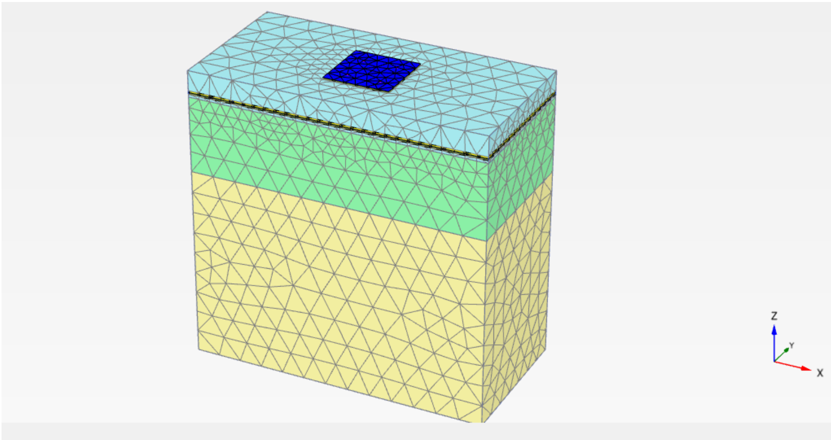


Fig. 1 Finite element mesh of the numerical model

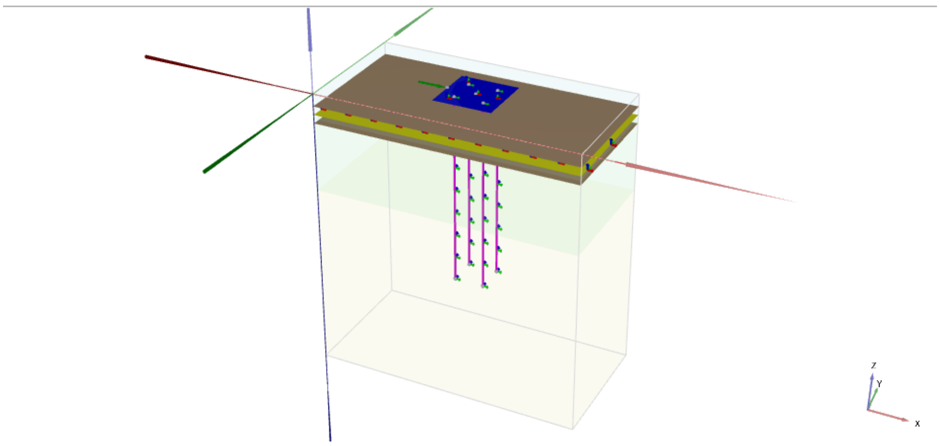
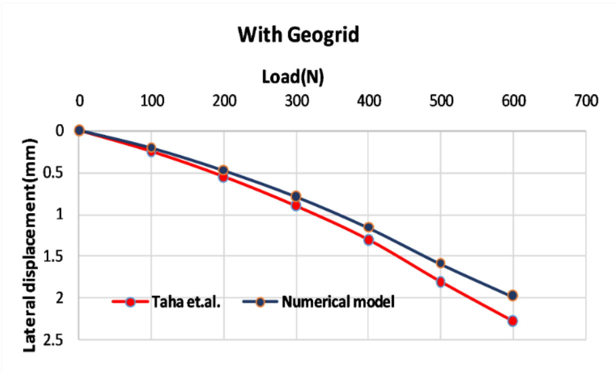


Fig. 2 structural elements of the numerical model (pile, geogrid, pile cap and interface elements)

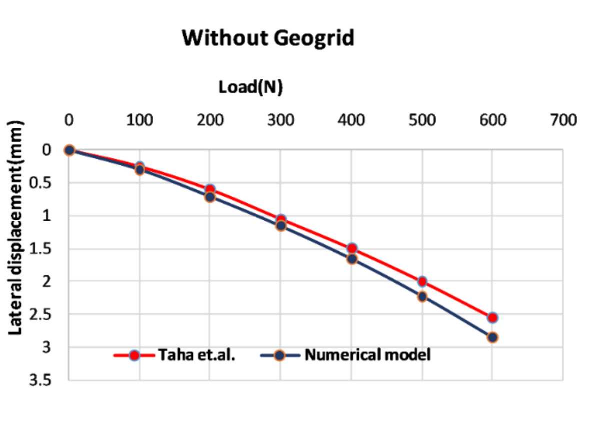
3. Results and Discussion

3.1 Validation of numerical model

Validation of the numerical model was done by considering the results obtained from the small-scale laboratory study of geogrid reinforced pile foundation system under static lateral loading conducted by Taha et. al. [5]. In that study, the test was conducted on both the foundations without geogrid reinforcement and with the geogrid reinforcement. To know the effect of geogrid reinforcement on the foundation system, single pile and group pile foundation system numerical models were constructed. Models were also generated for both the foundation systems (without and with geogrid) for single and group pile foundation system. Load versus lateral deformation of the foundation system were plotted for both the cases. The results obtained from numerical model were having a good agreement with the results obtained from the experimental study. The comparison of load-displacement behavior of pile group obtained for numerical analysis and experimental results were shown in Fig. 3.



(a)



(b)

Fig. 3 Comparison of load-displacement behavior of the pile group (a) with geogrid (b) without geogrid

3.2 Dynamic Response

After validation of the numerical model under static loading, dynamic analysis was carried out by applying different magnitude of dynamic load (0.01kg-m, 0.02kg-m, 0.03kg-m) at the pile cap. The time versus lateral displacement amplitude responses of single as well as group pile were obtained at each operating frequency. From these graphs, frequency versus lateral displacement amplitude were plotted. Fig. 4 shows the results of dynamic analysis on pile group under an eccentric moment of 0.02kg-m from 0Hz to 70Hz frequency range. From the graph, it was observed that, with the inclusion of geogrid reinforcement to the foundation system, the magnitude of dynamic lateral displacement amplitude was reduced. The improvement in the performance of foundation system is because of the interlocking effect between the geogrid and the soil layers and pile foundation.

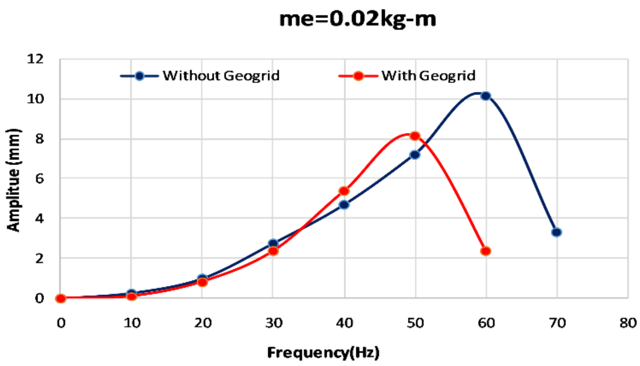


Fig. 4 Frequency versus lateral displacement amplitude group pile

3.3 Non-linear behavior of piles

To study the non-linear behavior of pile foundation system, the model was subjected to three different eccentric moments. Responses of the foundation were presented in terms of frequency versus lateral displacement amplitude for both the foundation systems without and with geogrid reinforcement. Fig. 5 shows the frequency versus lateral displacement amplitude of the single pile foundation system when it is subjected to different eccentric moments. From the graphs, it was observed that the lateral displacement amplitude was increased with the increase of eccentric moment in both the system. But, the amount of displacement amplitude is observed to be less in the case of foundation with geogrid reinforcement compared to the normal foundation system.

4 Conclusions

In this study, numerical analysis on the single and group pile foundation system was carried out without and with geogrid reinforcement. Nonlinear behavior of pile group system was also studied by subjecting it to different eccentric moments. The findings of this study are stated below.

- From the results of the dynamic analysis, it was observed that, magnitude of lateral displacement amplitude was found to be reduced with the addition of geogrid reinforcement in both the cases of single as well as group pile foundation system.
- It was observed a decrease in the magnitude of foundation system even under the variation in eccentric moments which shows nonlinearity of the system.
- Amount of improvement in the performance was more in the case of single pile foundation system over the group pile foundation system. This is because of the complexity involved in the reaction between soil and piles in the case of group system rather in single pile foundation system.

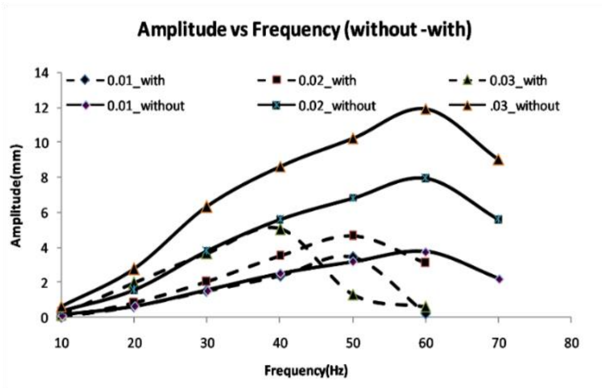


Fig. 5 Frequency versus lateral displacement amplitude of single pile for different eccentric moments

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