Numerical Analysis Of Machine Foundations on Infilled Geosynthetic Reinforced Soil Bed

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Abstract

Machine foundations require careful analysis and design as it involves severe dynamic loads in addition to the standard design loads of gravity. Furthermore, the magnitude and nature of the operating loads are mainly dependent on the type of machine. The foundation must aid the smooth functioning of machines during usual operation and also ensure structural integrity under unusual loading circumstances, especially during resonance. Such severe conditions may be avoided by varying the stiffness and the mass of the structure which alters the natural frequency of the system and demands revisit to the design of foundations. To expedite the process, a detailed 3D finite element analysis is carried out in the present study using a finite element software (ANSYS v 2021). Higher-rated machines now have greater tolerances and regulated behaviour thanks to advancements in manufacturing technology. To achieve greater efficiency in the machine performance, this study emphasizes the necessity of more vital collaboration between foundation designers and machine manufacturers. The paper presents the modal analysis of machine foundations resting on different ground conditions namely, Unreinforced and Reinforced with geocells . The findings are expressed in the form of vibration characteristics (i.e. natural frequency and mode shapes), which demonstrate how different elements of the structure respond under different dynamic loading situations. Furthermore, the influence of sloping ground near the machine foundations is highlighted in the study..

Keywords: Geosynthetics, Numerical analysis, Machine Foundations, Slopes, Vibration.

I. INTRODUCTION

Dynamic forces generated by machines are transferred to the soil beneath the foundation in such a way that all adverse consequences will be eliminated completely in a well-designed machine foundation itself. For several years, engineers have been concerned about minimizing the machine-induced vibrations [1]. Generally, the dynamic loads are smaller than static loads, and hence the supporting soils are considered to be in a linear elastic state. Consequently, the elasticity theory is employed to solve machine foundation problems [2]. Several researchers [3,4] demonstrated the significance of various parameters in the design and analysis of machine foundations supporting both reciprocating and rotating machines. The vibration of the foundation-soil system travels in the form of wave energy. Such vibration may displace the soil particles from their mean position, which must not exceed the permissible limits. Otherwise, the foundation which is designed for particular serviceable criteria will not serve the purpose. Hence, the excessive vibrations must be kept in check even though the magnitude of the dynamic loads is small. Besides, these excessive vibrations may also get amplified based on the nature of the soil and affect the nearby structures and people in the vicinity. Hence it is inevitable to understand the nature of the local soil condition. The interaction between the soil and the structures must be carefully assessed and incorporated into the design procedures. In most of the previous studies [5,6] the dynamic performance of the machine foundations is studied on the horizontal ground. The presence of uneven ground will also have a significant impact on the vibration amplification. Hence, this study attempts to understand the benefits of geosynthetics in mitigating the excessive vibrations due to machine foundations, using an extensive numerical investigation. Several critical parameters like soil types and geosynthetics might affect the performance of machine foundations laid on the soil reinforced with geosynthetics. Recently the use of geosynthetics in the field of geotechnical engineering has received greater attention from researchers [7-10]. In addition to the improvement in strength, these geosynthetics alter the dynamic behaviour of the founding soil beneath the machine foundations.

II. Problem Definition

In the design of a machine foundation, a large foundation base is generally preferred to handle the machine loads. Such a design will not only result in an uneconomical design but also not practical in many situations where the available land area is restricted to very minimum. In such conditions, the founding soil can be reinforced with tensile materials to provide additional strength similar to the usage of reinforcement in concrete. This paper aims to study the change in the dynamic performance of soil due to the inclusion of three-dimensional geosynthetic reinforcement (HDPE geocell) in the soil bed supporting the machine foundations as shown in Fig.1. Thus, a feasible solution for vibration mitigation is attempted by optimizing the placement of the soil reinforcement (geocell and geo-grid) under different dynamic loading conditions.

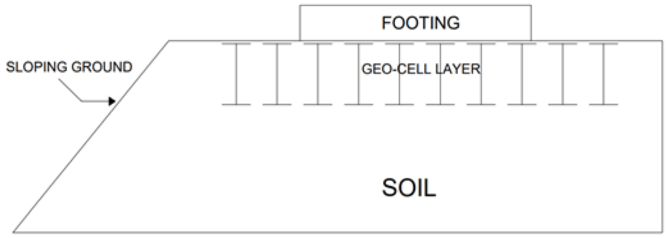


Fig. 1. Schematic Representation

III. BACKGROUND

Sujit Kumar Dash et al. [11] conducted a series of model tests followed by a numerical analysis to investigate the impact of geocell reinforcement on the performance of foundation beds. It was observed that the geocell reinforcement reduced the contact pressure on subgrade soil substantially. As a result, the subgrade soil remained undamaged until high loads were applied. As a result, the bearing capacity of the foundation bed increased significantly. As the width of the geocell mattress increases, the anchoring at both ends of the geocell reinforcement tends to increase dramatically. As a result, the footing load was efficiently supported, resulting in reduced contact pressure on the subgrade soil and improved performance.

Raja Sekhar et al. [12] utilized the finite element analysis to simulate the static and dynamic behaviour of machine foundations placed on the founding soil medium. The finite element results were found to be very beneficial in addition to the traditional tables and analytical methods used in the conventional design practice. The validation with the analytical solutions strengthened the findings reported in this study.

Vibhoosha et al. [13] explored the lateral deflection of a geocell reinforced sub-ballast system using a three-dimensional (3D) finite element method with full domain analysis. The results were compared with the 2D numerical models as well. The study witnessed the usefulness of 3D modelling as it was able to capture the interaction between the geocell and the filler material. It was reported that the horizontal mobility of geocell-reinforced soil is under-estimated in the ECA (Equivalent Composite approach), which can be effectively overcome by 3D modelling. Thus the proposed problem in the present study utilizes the 3D finite element software (ANSYS) to simulate the behaviour of the machine foundations resting on the reinforced soil.

Salahudeen et al. [14] presented a quantitative analysis using PLAXIS to understand the usage of geosynthetics as soil reinforcement in soft soils. The soil domain, along with the geosynthetics, was modelled in a commercial finite element package, PLAXIS. The results showed that the displacement of the unstable slope was reduced to a greater extent (more than 8 times) due to the use of geogrids.

Elif Cicek et al. [15] carried out laboratory tests with the creation of a reinforced road design model in order to produce simple equations. Various types of geosynthetic materials were used to investigate the impacts of vertical reinforcement layer distribution, total depth, and depth between each layer of the reinforced surface. To see the effect of changing material characteristics, the number of reinforcing layers was also changed. The model revealed that the behaviour of the reinforced layer changes with respect to the number of reinforcement layers. It was also observed that the lower consolidation yielded better results.

IV. NUMERICAL MODEL

The foundation soil used in this study was silty sand. As shown in Table 1, the material properties of soil, geocell and placement location of reinforcement were taken from the published work of Venkateswarlu et al. [10]. Additional parameters for the numerical analysis, such as geocell geometry, were adopted from Pokharel et al. [16]. Table 1 summarizes the details of the material properties.

Table I Numerical Modelling Material Properties

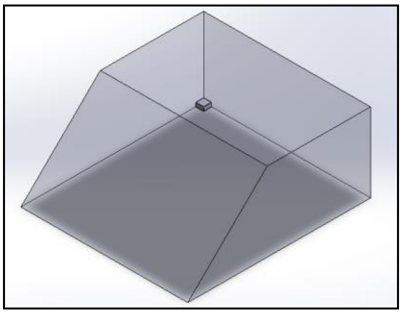
Material	**Parameter**	**Values**
Foundation soil	Density	1754.98 (kg/m^3)
	Poisson's ratio	0.3
	Youngs Modulus	20(Mpa)
Footing	Grade	M30
	Density	2300 (Kg/m^3)
	Poissons ratio	0.15
	Youngs Modulus	20 (Gpa)
Geocell	Density	940 (Kg/m^3)
	Poissons ratio	0.45
	Youngs Modulus	275 (Mpa)
	Material	HDPE

In the present study, a block machine foundation with a square of size 1.75 m and a depth of 0.75 m was modelled and placed on reinforced soil mass. To simulate the dynamic force created by machine vibrations, a harmonic load was applied over the foundation bed.

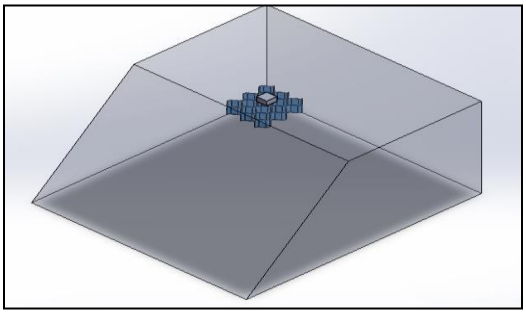
ANSYS, a finite element software, was used to carry out the numerical simulation. It was supposed that the block foundation machine base was lying on saturated silty sand, and the reinforcement was provided using geosynthetics called geocell. Two alternative scenarios, namely unreinforced and geocell reinforced, were explored to address the defined objectives. From the sensitivity analysis available in the literature [5], the boundary beyond 10B (where B is the foundation width) from the foundation edge along the x and y directions has no effect on the outcomes under dynamic excitations. As a result, 3.15m long and 1.5 m deep soil limits were explored to reduce boundary effects. The details of the geometry of the model are presented in Table II and Fig. 2.

Table II Geometric parameters of the model

Parameters	Values
Footing prototype (m)	1.5 x 1.5 x 0.75m
Model Footing (m)	0.15 x 0.15 x 0.075
Setback Distance (m)	0.300
Geocell Height (m)	0.015
Domain Width (m)	1.950
Geocell Length (m)	0.200
Sloping Angle (°)	45.00
Domain depth (m)	1.500



(a) unreinforced soil bed



(b) Geocell reinforced soil bed

Fig. 2. Finite element model of the foundation

The geometric properties of the geocell are portrayed in Fig. 3. The machine used in this investigation was supposed to be a low-frequency machine. The locations of reinforcement beneath the footing were examined to find the best one. The geocell was placed at varying depths from the ground surface: 0.01B, 0.025B, 0.05B, and 0.1B. A total of 5 models were considered in the present analysis with different locations of reinforcements along with the unreinforced case, as shown in Table III.

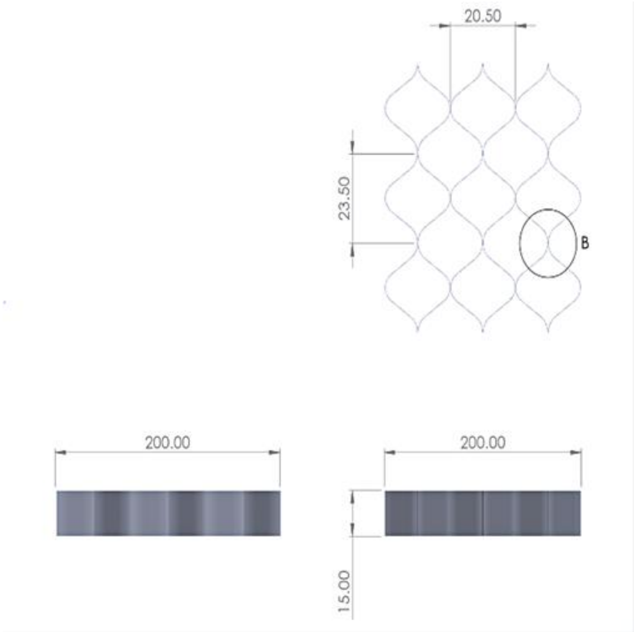


Fig. 3. Geocell modelled in the analysis (dimensions are in mm).

Table III Details of the numerical models

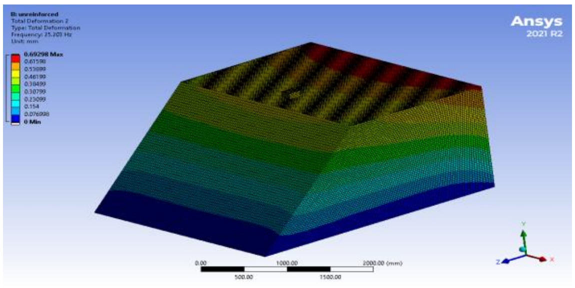
Case	Reinforcement placement(U)
Unreinforced	-------
Reinforced	0.01B,0.025B, 0.05 B, 0.1B

V. Results and Discussions

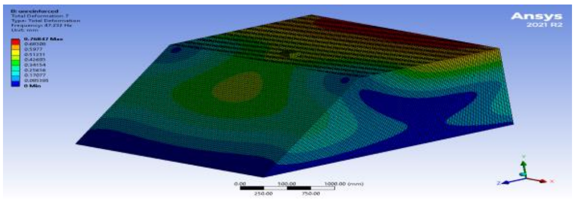
The performance of geosynthetics under dynamic stimulation was investigated in terms of reduction in displacement amplitude, optimum location, Amplitude Reduction Factor (ARF) and best suitable reinforcement.

A. Modal Analysis of Unreinforced Soil Bed

In this finite element analysis, the size of mesh was suitably taken from coarse to fine mesh based on the volume of the material like soil, footing and geocell (in descending order). To predict the stability of the modelled machine foundation during the modal analysis (natural frequency analysis), fixed boundary conditions were applied to the foundation soil. The results for the same are reported in Fig. 4.



(a) 2nd Mode



(b) 9th Mode

Fig. 4. Modal analysis of unreinforced soil bed

During this simulation, the frequency varied from 23.538 to 53.91 Hz, and the corresponding response, i.e., the deformation, was observed to be in the range of 0.693 to 1.575 mm. The maximum and minimum deformations occurred at modes 9 and 2, respectively, as reported in Fig. 4. The displacement variation in the unreinforced soil model is depicted in Fig. 5.

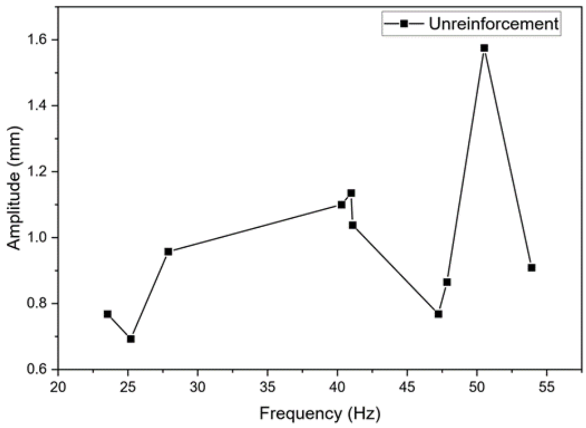
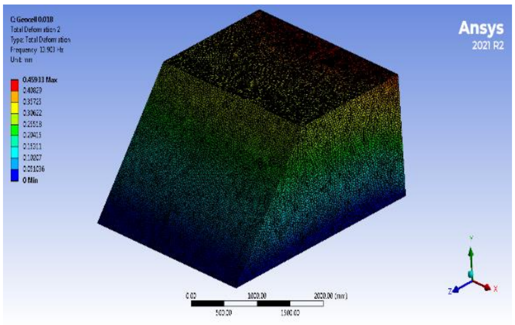


Fig. 5. Displacement variation in unreinforced case

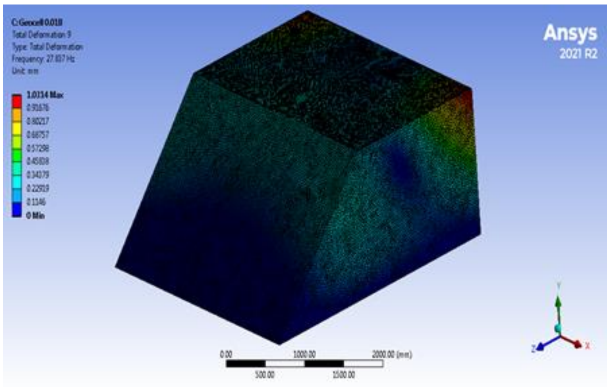
B. Modal Analysis of Reinforced Soil Bed

Following the free vibration analysis, the geocell was introduced in the soil model, and the modal analysis was carried out to understand the dynamic response of reinforced soil domain excited under the machine foundation. By varying the location of geocell reinforcement (as depicted in Table III), the optimum location of geocell reinforcement was identified. While carrying out the simulation, the frequency varied from 13.02 to 29.74 Hz, and the corresponding response, i.e., the deformation, was observed to be in the range of 0.459 to 1.031 mm when the geocell was placed at 0.01B from the base of the footing (Fig. 6). Also, the maximum and minimum deformations occurred at modes 9 and 2 in each case, similar to the unreinforced case.

It was also observed that there was no significant change in the minimum displacement when the placement of geocell was varied. However, the variation of displacement over a frequency range was observed in each case, which is reported in Fig. 7.



(a) 2nd Mode

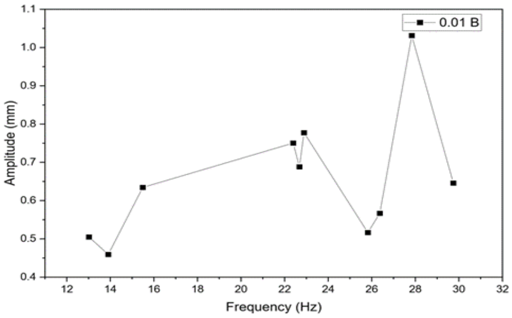


(b) 9th Mode

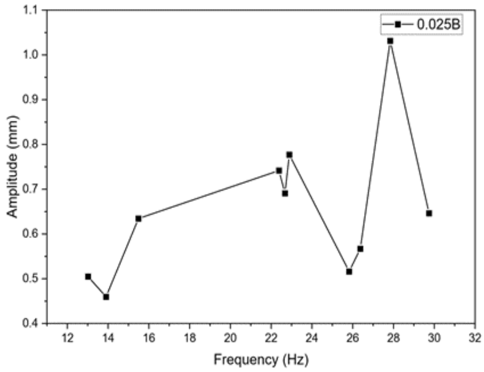
Fig. 6. Modal analysis of reinforced soil bed (0.01B)

Under dynamic excitation, severe disturbances were noticed in the unreinforced soil (Figs. 4-5). However, while employing the geocell in the soil bed, there was a considerable reduction in deformation (Figs. 6-7). It can be attributed to the fact that the three-dimensional confinement provided by the geocell within the soil domain. This confinement mechanism aids in restricting the soil from expanding laterally. Thus the geocell-soil composite layer serves as a barrier in limiting the excessive vibrations and cyclic stresses to be transferred downward.

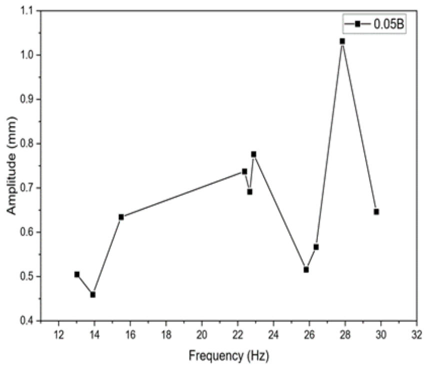
It must be noted that the highest displacement amplitude was observed when the soil bed was unreinforced. The amplitude was reduced when the geocell beneath the foundation was placed at various locations relative to the ground surface. As there was no significant difference in the maximum displacement in the amplitude for different locations, the geocell placed at a distance of 0.01B from the ground surface was recommended to be the best location for the geocell, keeping in view of practical aspects.



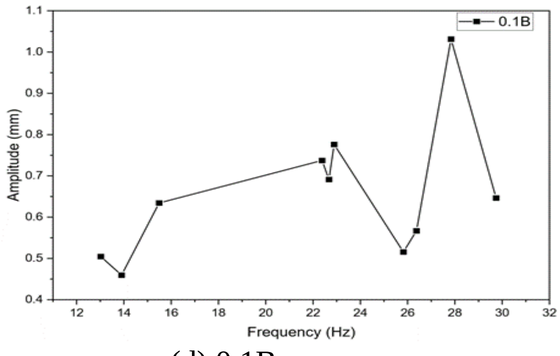
(a) 0.01B



b) 0.025B



(c) 0.05B



(d) 0.1B

Fig. 7. Displacement variation in reinforced case

Figure 8 portrays the significance of the geocell reinforcement in limiting the displacement amplitude to a greater extent (about 34%).

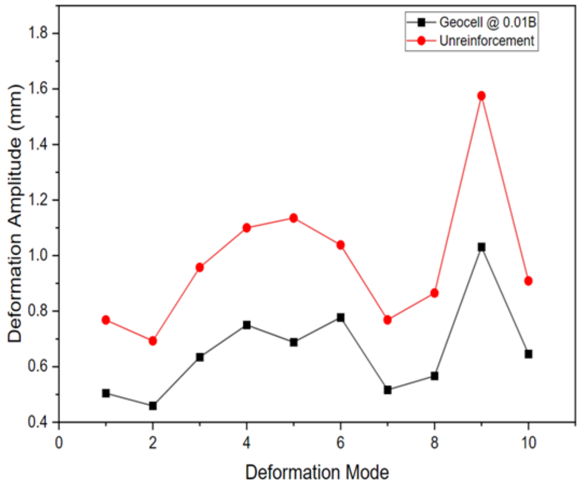


Fig. 8. Displacement variation in unreinforced case

The efficiency of the geocell can be better visualized by presenting the amplitude reduction factor (A_m). The amplitude reduction factor is the ratio of the maximum displacement amplitude in the unreinforced soil domain subjected to the excitation of machine foundations to that of the unreinforced soil bed. In general, the value of an amplitude reduction factor should be minimum for better vibration mitigation or screening. It can be seen from Table IV that the least amplitude reduction factor was recorded in the case of a geocell reinforced system.

Table IV Details of the numerical models

Soil bed	Peak displacement amplitude (m)	Amplitude reduction factor (A_m)
Unreinforced	0.0157	1.000
Reinforced	0.0103	0.656

VI. Nomenclature

A Contact area of the footing with soil (m^2)

A_m Amplitude reduction factor (dimensionless)

E Young's modulus (Mpa and Gpa)

f Frequency of the foundation soil system corresponding to peak displacement amplitude (Hz)

H Height of geocell (m)

L Length of the geocell layer (m)

U	Depth of placement of the geocell layer (m)
ν	Poisson's ratio (dimensionless)
ρ	Density (kg/m^3)
HDPE	High Density Polyethylene
ARF	Amplitude Reduction Factor

CONCLUSION

Various researchers have proposed several ways to strengthen the soil and other geotechnical constructions. The use of Geocells as reinforcement in geotechnical structures is one of the most commonly adopted technologies with several significant advantages over other methods. The dynamic response of geosynthetic-reinforced soil mass supporting the machine foundation was numerically investigated in this study using the finite element software (ANSYS). The confinement effect of Geocell was simulated in this 3D analysis. The performance of Geocell was observed to be superior in mitigating the vibrations in the soil. The reduction in the displacement amplitude was found to be a maximum of as much as 34% when a geocell was introduced into the soil domain. The optimal geocell position under the machine foundation was found to be 0.01B from the ground surface, in view of practical aspects. Overall, the findings of this study might help design the machine foundations supporting the type of machinery operated at a low-frequency range. It may be inferred that geosynthetics can be reasonably utilized beneath the machine foundations to limit the excessive vibrations passing on to the soil domain both in the downward and lateral directions. Since the research was conducted using only one type of foundation soil, further analysis of different kinds of soil and machines with different frequency ranges are recommended for further better understanding.

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