FLAC based 3D numerical analysis of machine foundations resting on geosynthetics reinforced soil bed

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ABSTRACT: The behavior of the machine foundation resting on the geosynthetic reinforced soil bed is not well understood yet. The present study investigates the efficacy of geosynthetics reinforcement in supporting the machine foundations. 3D numerical studies have been performed using the explicit finite difference package FLAC^{3D}. The behaviour of a square footing, 0.6 m wide and 0.5 m deep resting on a non-homogeneous foundation bed has been analysed. Three different cases, namely, unreinforced, geogrid reinforced and geocell reinforced conditions were considered. The analysis was carried out by varying the frequency of the excitation. The depth of placement of geogrid and geocell was varied. From the results, the optimum depth of placement of geogrid and geocell was found to be 0.4*B* and 0.1*B* respectively from the ground surface. Similarly, the optimum width of placement of geocell and geogrid was found to be 4*B*. In overall, the performance of geocell was found to be better than other conditions. In the presence of geocell, displacement amplitude and peak particle velocity were reduced by 44% and 42% respectively as compared to the unreinforced condition. Further, the geocell reinforcement improved the stiffness as well as the resonant frequency by 1.8 and 1.3 times as compared to unreinforced condition.

Keywords: Machine foundations; Non-homogeneous soil; Dynamic response; Geogrid; Geocell; FLAC^{3D}.

1 INTRODUCTION

The vibrations generated by the machine foundation can adversely affect the surrounding structures and the people working near the area. The motion and direction of the machine vibration depends on nature and deformability of the supporting ground. The response of soil under dynamic loads is non-linear and irreversible even at very low strain levels (Borja and Wu 1994). The current theoretical solutions were developed with the assumption that the soil is an elastic material. In practice, soils are rarely homogeneous and having the strata with different soil properties. In this regard, Baidya (1992) has studied the effect of non-homogeneity on the vibration response through the experimental investigation. Baidya and Muralikrishna (2001) have studied the influence of layering effect in the presence of rigid boundary through model vertical block vibration tests. The results revealed that the layering position and thickness have a significant influence on natural frequency of the system. The similar observations were reported from the field study of Mandal et al. (2012). Few studies have proposed theoretical solutions for the evaluation of foundation vibration resting on non-homogeneous soil system (Jaya and Prasad 2002, Wolf and Deeks 2004, and Pradhan et al. 2004). Baidya and Rathi (2004) studied the foundation response of homogeneous soil layer resting over the rigid base. The results revealed that the increase in layer thickness leads to reduction in resonant frequency of the system. Later on, few attempts were made to study the behavior of reinforced homogeneous soil under machine vibration (Boominathan et al. 1991, Sreedhar and Abhishek 2016).

It is evident from the literature that the effect of non-homogeneity of the soil on the response of foundation has not been adequately addressed yet. Further, none of the study has discussed the behavior of reinforced soil underlain by non-homogeneous soil medium supporting the machine foundations. In the present study, an attempt has been made to analyse the machine foundation resting on non-homogeneous soil reinforced with different geosynthetics. The depth of placement and width of geogrid and geocell was varied in order to quantify the optimum location to arrest the machine vibration.

2 NUMERICAL ANALYSIS

The present dynamic analysis was performed by using a three dimensional finite difference program FLAC^{3D}. It uses explicit solution to solve initial and boundary value problems. It contains a powerful built-in programming language called FISH, which enables it to model wide range of complex problems. A square footing of size 0.6 m × 0.6 m × 0.5 m resting on a layered foundation bed has been analysed. Initially, the Standard Penetration Test (SPT) was conducted up to a depth of 10 m at IIT Patna campus to obtain the properties of foundation bed. Three different soil layers were observed in the vicinity as shown in Figure 1. The different properties of individual soil layers were determined through laboratory tests.

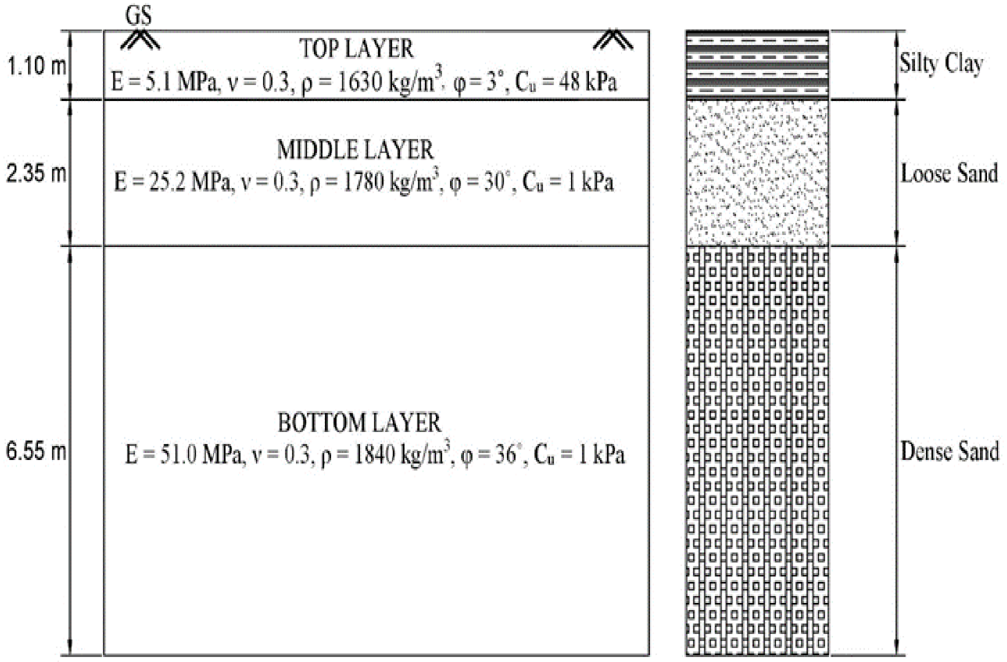

Figure 1. Soil profile with their properties

The modulus of elasticity (E) for various layers has been determined based on SPT-N value as per the recommendations of Bowles (1996). The Poisson's ratio (v) for all the layers has considered as 0.3. The soil profile shown in Figure 1 has been considered as the foundation bed in the present analysis. The foundation bed was modelled with brick element, having the dimensions of 25 m × 25 m × 10 m. The dimensions of the foundation bed was selected so as to minimize the boundary effects. The sensitivity analysis was carried out to determine suitable mesh density. The course mesh was selected in the present study as the mesh density had minimum influence on the results. The foundation soil was modelled as to follow the Mohr-Coulomb criteria with non-linear failure envelope. The concrete footing was modelled as linear elastic material. The bottom plane of the foundation bed was restrained in all the three directions. The vertical faces of the model were restrained in horizontal direction. In addition, the quiet boundaries were applied to the vertical faces to minimize the wave reflections and energy radiation from the boundary. The material damping of the soil was considered as 5 % in the present analysis (Richart et al. 1970). The machine foundation was considered to be made with M20 grade concrete. The FLAC^{3D} model with non-homogeneous soil layering conditions is shown in Figure 2.

The vertical harmonic excitation with a constant force amplitude was applied over the footing. It can be determined by,

$$X(t) = a_o \sin(\omega t) \tag{1}$$

where $X(t)$ is the dynamic load intensity in kN/m^2, a_0 is the force amplitude in kN/m^2, ω is the circular natural frequency in rad/second and t is the dynamic time in seconds. The typical values of force amplitude for high-speed rotary machines ranging from 25 to 100 kPa, with the frequency ranges between 5 to 50 Hz (Fattah et al. 2015). Hence, the force amplitude of 100 kPa was selected to represent a high-speed machine.

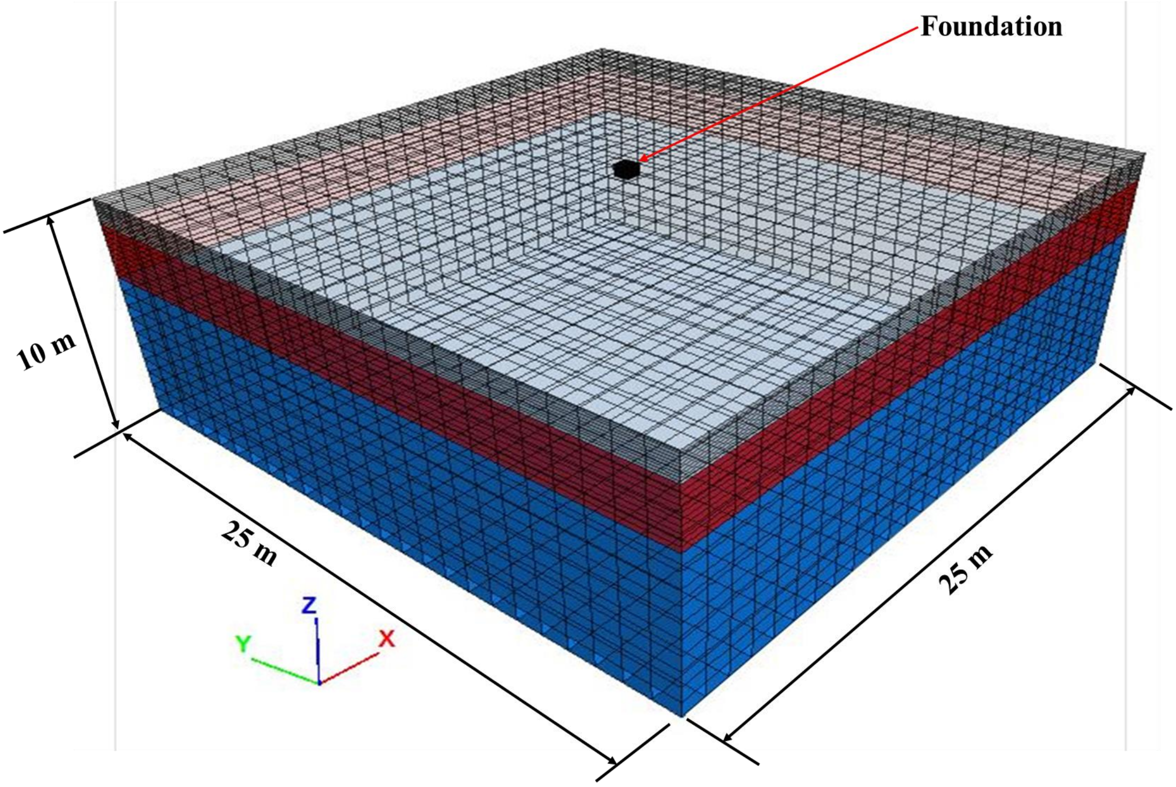

Figure 2. FLAC^{3D} numerical model

Before starting the analysis, the numerical model was validated with the results of Ghosh (2012). While validating the model, the model size, material properties and the constitutive model behavior similar to Ghosh (2012) were adopted. The result of dynamic settlement at the foundation base along the centre line of isolated square footing was validated. Figure 3 shows the good agreement between the results of Ghosh (2012) and the present study. The validated model was employed for the further investigation.

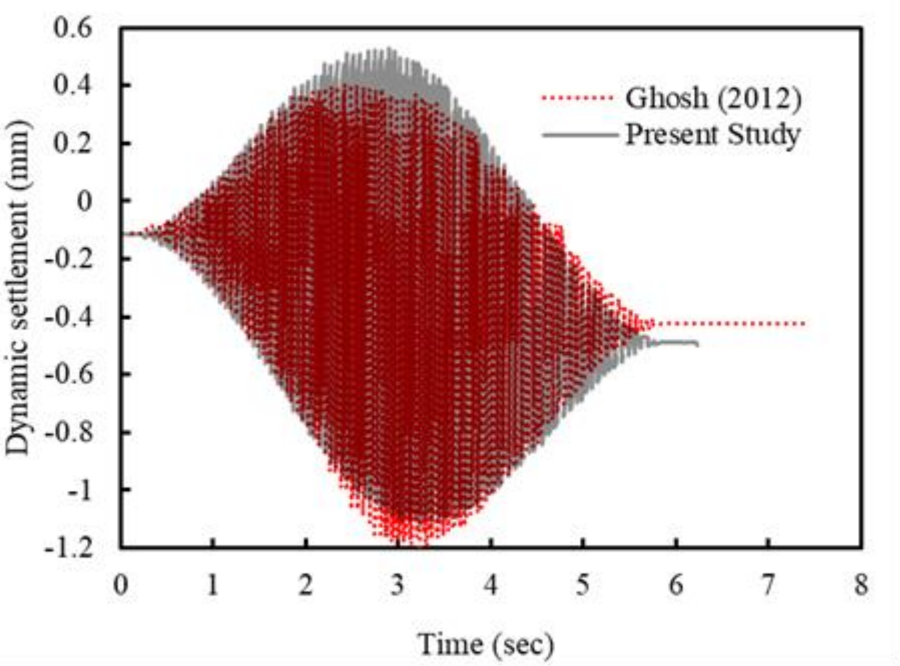

Figure 3. Validation of the numerical model

Two types of geosynthetics, namely, geogrid and geocell were used to reinforce the foundation bed. The geogrid was modelled using the geogrid structural elements, available in FLAC^{3D}. Linear elastic model was used to simulate the behavior of the geocells and geogrid. Tensile strength test was conducted to determine the tensile strength of the geosynthetics materials. The tensile strength of geocell and geogrid was determined based on the recommendations of ASTM D-4885 (2011) and ASTM D-6637 (2011) respectively. Figure 4 shows the stress-strain behavior of geocell and geogrid used in the present study. From the figure, the secant modulus of the geocell was determined as 435 kN/m at 2% strain. The equivalent diameter of the geocell was observed as 0.25 m. The interface properties between geogrid and soil, namely, interface shear modulus, interface cohesion and interface friction were considered from Hegde and Sitharam (2015a).

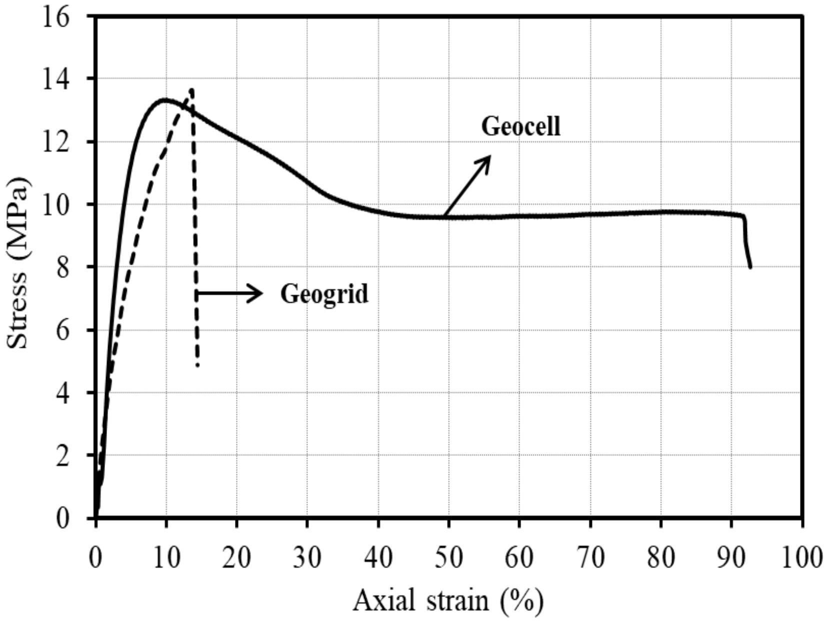

Figure 4. Stress-strain behaviour of geosynthetics materials

The poorly graded sand was used as the infill material. The properties of geocell-soil composite layer were determined based on Equivalent Composite Approach (Latha and Somwanshi 2009, Hegde and Sitharam 2015b). According to ECA, the cohesion of composite layer increases without any change in angle of internal friction (Bathurst and Karpurapu 1993, Rajagopal et al. 1999). The properties of the materials used in the numerical modelling have been listed in Table 1.

Table 1. Properties of materials used in numerical modelling

Material	Parameter	Values
Foundation	Modulus of elasticity of concrete, E (MPa)	2×10^4
	Unit weight of concrete, γ (kN/m^3)	24
	Poisson's ratio of concrete, v	0.15
Geogrid	Mass per unit area (g/m^2)	250
	Young's modulus, E (MPa)	210
	Poisson's ratio, v	0.33
	Thickness, t_i (mm)	1.5
	Interface shear modulus, k_i (MPa/m)	2.36
	Interface cohesion, c_i (kPa)	0
	Interface friction angle, φ_i (°)	18
Geocell-soil composite layer	Cohesion (kPa)	34
	Internal friction (°)	35
	Poisson's ratio, v	0.3
	Shear modulus, G (MPa)	25

The dynamic behavior of non-homogeneous foundation bed was analysed by varying the depth of placement (*u*) and width (*b*) of reinforcement materials. The details of the numerical analysis have been presented in Table 2. Initially, the depth of placement of geogrid was varied from 0.2*B* to 0.6*B* with an increment of 0.2*B* from the ground surface. Similarly, the depth of placement of geocell was varied from 0.1*B* to 0.3*B* with an increment of 0.1*B* from the ground surface (where *B* is the width of the foundation). The width of reinforcement was varied from 2*B* to 6*B* at the optimum location. In addition, the frequency of the dynamic excitation was varied from 2 to 40 Hz in unreinforced and 2 to 45 Hz in reinforced conditions. The dynamic response of the foundation bed was analyzed at the centre of the foundation base.

Table 2. Details of the numerical analysis

S. No.	Condition	*u/B*	Optimum *u/B*	*b/B*	Frequency (Hz)
1	Unreinforced	N/A	N/A	N/A	2 to 40
2	Geogrid reinforced	0.2,0.4 and 0.6	0.4	2, 4 and 6	2 to 45
3	Geocell reinforced	0.1,0.2 and 0.3	0.1	2, 4 and 6	2 to 45

3 RESULTS AND DISCUSSIONS

Figure 5 represents the variation in displacement amplitude with the change in depth of placement of geogrid and geocell under the machine foundation. From the figure, the maximum reduction in displacement amplitude was observed at 0.4*B* in the case of geogrid-reinforced condition. With the increase in the depth from 0.4*B* to 0.6*B*, the increment in displacement amplitude was observed. Similarly, the minimum displacement amplitude was observed, when the geocell placed at 0.1*B* distance from the ground surface. As compared to geogrids, the maximum reduction in displacement amplitude was observed in the presence of geocell reinforcement.

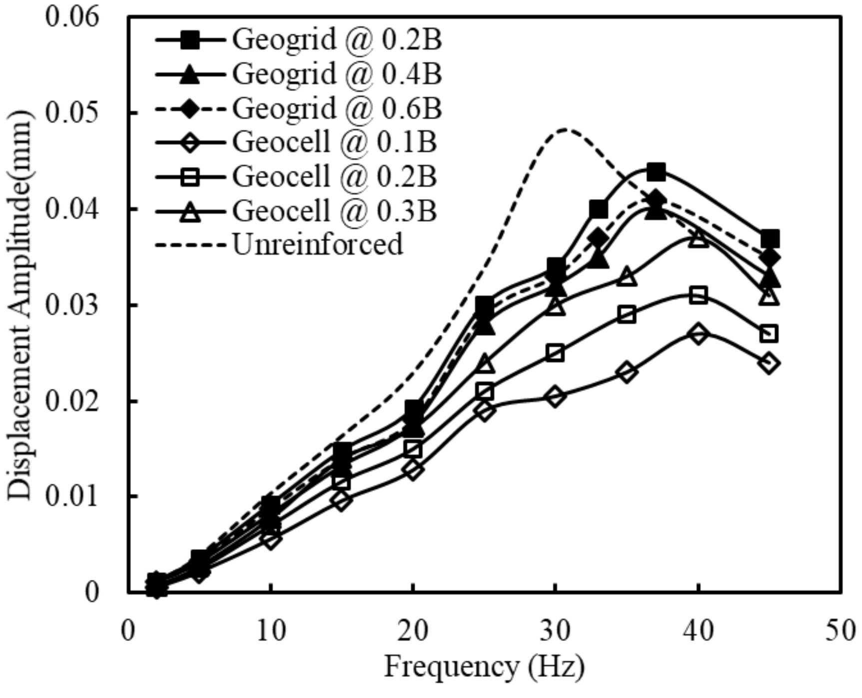

Figure 5. Displacement amplitude Vs. frequency response with variation in depth of placement of geosynthetics

Figure 6 shows the variation of displacement amplitude with the change in width of geogrid and geocells. The width of reinforcement was varied from 2*B* to 6*B*, with an increment of 2*B*. In this case, the geogrid and geocell was placed at its optimum location. From the figure, it was observed that the reduction in amplitude was more up to a width of 4*B* in geogrid and geocell conditions. The rate of reduction was less with the increase in reinforcement width beyond 4*B*. Hence, the 4*B* was considered as an optimum width for controlling the machine vibration.

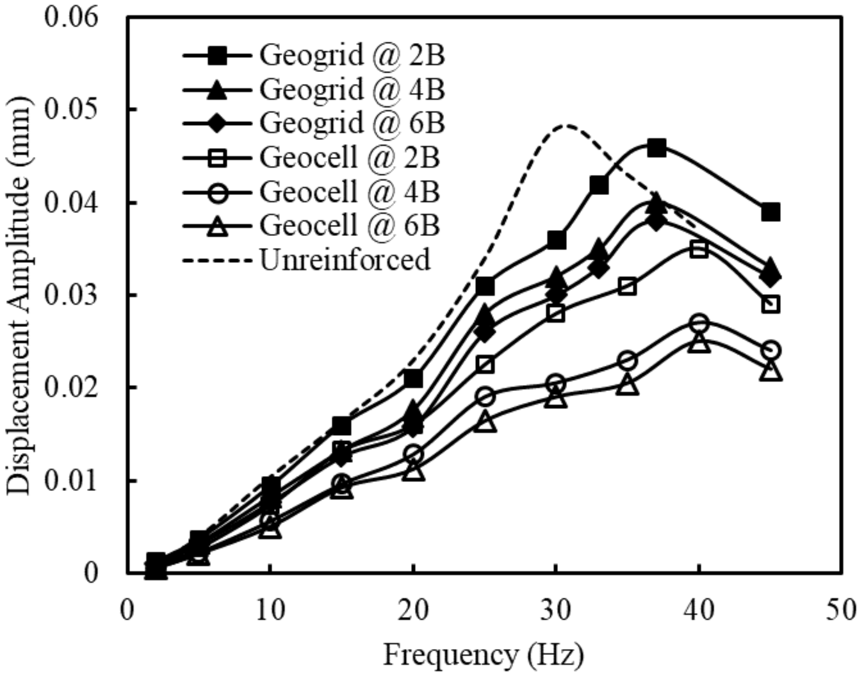

Figure 6. Displacement amplitude Vs. frequency response with the change in width of geosynthetics

The comparison of resonant amplitude between unreinforced and reinforced conditions (at their optimal depth and width) are presented in Figure 7. Resonant amplitude is the maximum displacement amplitude developed at resonance condition. Resonance is the critical phenomenon in the case of machine foundations, at which the natural frequency of the foundation soil system matches with the operating frequency of the machine. It leads to maximum amplitude and eventually reduces the machine performance. From the figure, it was observed that the effect of resonance was least in the case of geocell reinforced condition. In addition, the resonant frequency was improved by 1.3 times in the presence of geocell reinforcement. It indicates the efficacy of geocell for controlling the displacement amplitude of non-homogeneous soil bed, even at resonance as compared to the other two conditions.

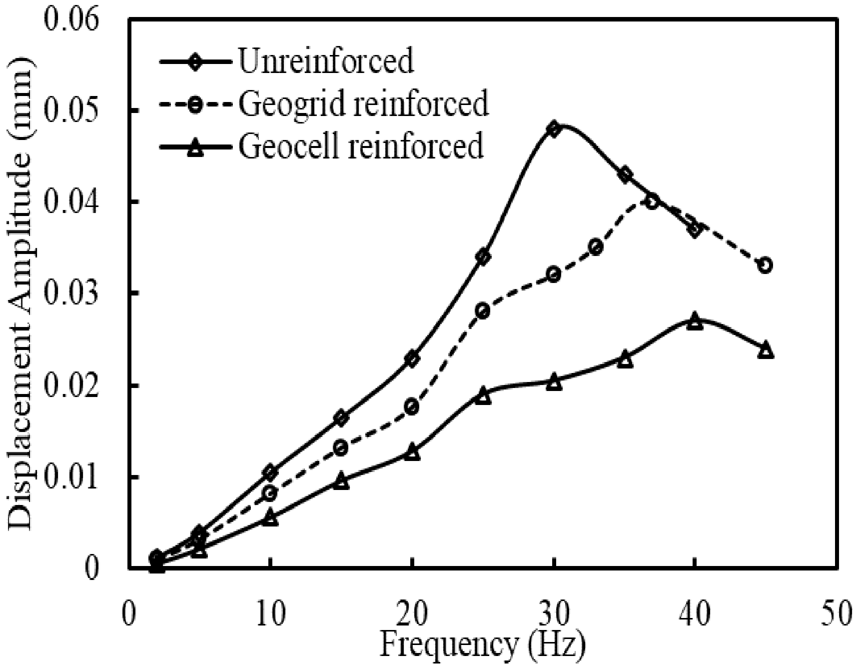

Figure 7. Comparison of displacement amplitude Vs. frequency response between unreinforced and reinforced conditions

The comparison of Peak Particle Velocity (PPV) between unreinforced and reinforced conditions (at their optimum depth and width) is shown in Figure 8. The variation in PPV was observed up to the distance of 10 m from the vibration source, with an interval of 1 m along the soil surface. PPV is the parameter, which represents the rate of displacement of the particle in the ground under the dynamic excitation.

From the figure, 42% and 31% reduction in PPV was observed in the presence of geocell as compared to the unreinforced and geogrid reinforced conditions respectively, at 1 m distance from the vibration source.

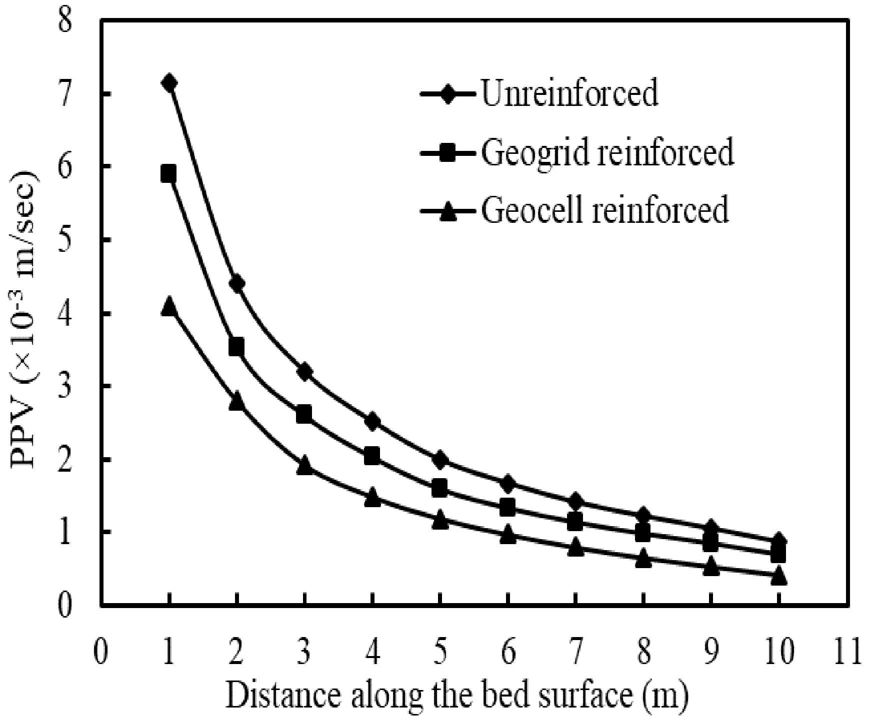

Figure 8. Comparison of PPV between unreinforced and reinforced conditions

Further, the dynamic properties such as, coefficient of elastic uniform compression (C_u) and stiffness (K) of all the cases were determined. Based on C_u, the other dynamic elastic constants were determined by using the equations suggested by Barkan (1962). The C_u can be determined by,

$$\mathrm{Cu} = 4\pi^2 \mathrm{f}_{\mathrm{nz}}^2 [M/A] \quad (2)$$

where f_{nz} is the frequency of the foundation soil system at which maximum amplitude occurs, M is the mass the foundation block and A is the contact area of the footing with soil. The stiffness of the soil was determined by multiplying the contact area of the footing with soil and coefficient of elastic uniform compression. The different dynamic properties of all the conditions were listed in Table 3. From the Table, it was observed that the dynamic properties of the non-homogeneous foundation bed were significantly improved in the presence of geocell.

Table 3. Summary of the dynamic properties obtained from the numerical study

S. No.	Dynamic Property	Unreinforced foundation bed	Geogrid reinforced bed	Geocell reinforced bed
1	Coefficient of elastic uniform compression, C_u (MN/m^3)	43	66	77
2	Coefficient of elastic uniform shear, C_τ (= 0.5 C_u) (MN/m^3)	22	33	39
3	Coefficient of elastic non-uniform shear, C_Ψ (= 0.75 C_u) (MN/m^3)	33	50	58
4	Coefficient of elastic non-uniform compression, C_φ (= 2 C_u) (MN/m^3)	87	132	154
5	Soil stiffness, K (MN/m)	16	24	28

4 CONCLUSIONS

The present study highlights the efficacy of geosynthetics in supporting the machine foundation resting on non-homogeneous soil layer. Three different conditions, namely, unreinforced, geogrid-reinforced and geocell reinforced conditions were considered. From the numerical results, optimum depth of placement of geogrid and geocell was found at 0.4*B* and 0.1*B* respectively, from the ground surface. Similarly, the optimum width of 4*B* was observed in both the cases to control the machine vibration. The dynamic behavior of non-homogeneous foundation bed was improved in the presence of geogrid and geocell. As compared to geogrid, the maximum improvement was observed in the presence of geocell reinforcement. In the presence of geocell, stiffness of the soil was improved by 1.8 times as compared to the unreinforced condition. In addition, 44% reduction in resonant amplitude and 1.3 times increase in natural frequency of the system was observed in the presence of geocell reinforcement. Further, 42% reduction in peak particle velocity was observed in the presence of geocell as compared to the unreinforced condition. In this way, the present study highlights the new application of geosynthetics in improving the dynamic behavior of non-homogeneous foundation bed.

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