Numerical Analysis of Machine Foundation Resting on the Geocell Reinforced Soil Beds

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ABSTRACT: The foundation beds are often subjected to dynamic loads due to many circumstances, such as earthquakes, traffic loads, and the machine vibrations in the case of the machine foundations. Excessive vibrations caused by the dynamic sources can lead to the structural damage of the foundation soil. Over the years, geosynthetics have been effectively used in reducing the settlement of the foundations under static loads. However, the performance of geosynthetics is not fully analyzed under the dynamic loads. In the present study, the numerical analyses have been carried out to understand the performance of the machine foundations resting on the geocell reinforced beds. The analyses were carried out by using finite element software PLAXIS 2D. The hypothetical case of the circular machine foundation of 1 m diameter resting on the saturated silty sand was analyzed. Mohr-Coulomb failure criteria was used to simulate the behavior of the soil. Initially, the numerical model was validated with the existing results reported in the literature. The validated numerical model was further used to investigate the performance of the machine foundations. Three different cases, namely, unreinforced, geogrid reinforced and geocell reinforced were considered. The response of all the cases was studied by varying the frequency of dynamic excitation and maintaining the constant force amplitude. The depth of the placement of the geocell and geogrid was also varied. At the optimum location of geocell, 61% reduction in the displacement amplitude was observed as compared to unreinforced foundation bed. Similarly, as compared to geogrid, more than 50% reduction in the displacement was observed in the presence of geocell. In addition, 40% reduction in peak particle velocity was observed in the presence of geocell at the center of the footing. The resonant frequency was found to vary with the reinforcement system. Furthermore, 163% increase in the damping ratio of the soil was observed in the presence of geocell. In this way, the study highlights the possible new applications of geocell in supporting the machine foundations.

KEYWORDS: Dynamic response, Machine Foundation, Geocell, Amplitude, PLAXIS 2D.

1. INTRODUCTION

The design of machine foundation considered to be complex due to the involvement of dynamic loads generated from the moving parts of the machine. The stresses generated from the machine parts are repetitive in nature and leads to settlement of foundation soil. The settlement due to cyclic stresses can be controlled by improving the dynamic properties of the soil. The major properties influences the behavior of soil are stiffness and elasticity of the soil. Coefficient of elastic uniform compression (C_u) is the parameter used to represent elasticity of soil. It is obtained from field tests like cyclic plate load test and block vibration tests. The coefficient of elastic uniform compression can be obtained by,

$$C_u = 4\pi^2 {f_{nz}}^2 \frac{M}{A} \tag{1}$$

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. Generally, spring coils, felt, rubber and cork sheets are placed under the foundation to enhance the elasticity of the soil (Gazates 1983). Hegde and Sitharam (2016) opined that the elastic properties of the soil can also be improved using the soil reinforcements.

Over the years, soil reinforcement technique has gained popularity in providing the efficient solutions for various geotechnical engineering problems. The concept of reinforced earth is to improve the properties of soil by the inclusion of metallic strips, fibers and synthetic materials, etc. into the soil. Among several materials, soil reinforcement with geosynthetics is the most sought after technique to enhance stiffness properties of soil (Dash et al. 2001, Hegde and Sitharam 2013, Hegde and Sitharam 2015a). Out of the different forms of the geosynthetics available, geocells are best suited for the protection and stabilization applications (Hegde and Sitharam 2015b). Geocells are the three dimensional expandable panels made of polyester, polyethylene and novel polymeric alloy, etc. The applications of geocell include foundations, pavements, embankments, retaining walls and buried life lines, etc. Several studies have shown that the efficacy of geogrid and geocell in improving the stiffness and elasticity of the soil (Tafreshi et al. 2008, Pokharel et al. 2010, Sireesh et al. 2013, Dash et al. 2013 and Hegde and Sitharam 2016). However, limited studies have been performed to understand the performance of geosynthetics under machine foundations. Boominathan et al. (1991) performed forced block resonance tests on reinforced silty sand beds. Test results revealed that the increment in coefficient of elastic uniform compression and shear modulus in the presence of high tensile wire grid. The study of Sreedhar and Abhishek (2016) has shown that the drop in peak amplitude and rise in resonant frequency in the presence of geogrid. In addition, the studies of cyclic plate load tests on geogrid reinforced sand have shown that the improvement in coefficient of elastic uniform compression (Verma and Bhatt 2008, Sreedhar and Goud 2011). Hegde and Sitharam (2016) studied the cyclic response of geocell reinforced soft clay beds through laboratory cyclic plate load tests. From the test results, it was observed that the stiffness and natural frequency of the foundation soil system was increased by 8 times in the presence of geocell and geogrid. Azzam (2015) carried out the numerical studies on the performance of confined cell supporting the machine foundation. From the numerical results, it was observed that the placement of geocell below the foundation improved the subgrade damping by 230%. From the available literature, it is evident that the limited studies have performed to understand the efficacy of geosynthetics in supporting the machine foundation. In the present study, an attempt has been made to enhance the present knowledge on the possible use of the geosynthetics in supporting the machine foundations.

2. NUMERICAL MODELLING

2.1 Modelling details

The hypothetical case of the circular machine foundation of 1 m diameter, resting on reinforced soil mass has been analyzed in the present study. The harmonic excitation was applied over the foundation bed to represent the dynamic force generated from the machine vibrations. The study has been carried out using finite element software PLAXIS 2D. It uses a finite element scheme to solve initial and boundary value problems. The circular machine foundation was assumed to be resting on the saturated silty sand. Geosynthetics such as geogrid and geocell were used as the reinforcements. In order to achieve the objective, three different cases, namely, unreinforced, geogrid reinforced and geocell reinforced were considered and compared. Figure 1 shows the schematic diagram of three different cases considered in the study.

The behavior of foundation soil used in the present study was simulated using Mohr Coulomb yield criterion. The sensitivity analysis carried out by Ghosh (2012) suggested that the boundary beyond 10*B* (where *B* is the width of the foundation) from the foundation edge along x and y directions does not influence the results under dynamic excitations. Hence, the soil boundaries of 30 m long and 15 meters deep were considered to reduce the boundary effects. Medium mesh was adopted for describing the system as shown in Figure 2. The present problem is symmetric in nature and hence, the only half portion was modelled to reduce the computational effort. The entire soil domain was discretized using the 15 node triangular elements. Vertical side boundaries were completely restrained in the horizontal direction by allowing the settlement only in vertical direction, i.e., u_x=0. The bottom side of the model was restrained in both vertical and horizontal directions, i.e., $u_x = u_y$ =0. In the elastic wave propagation, the normal boundary conditions may not suffice to prevent the wave reflections back into the soil, arising from edges. Hence, as a special measure, absorbent boundary conditions were applied to the extreme boundaries. The absorbent boundary is also known as a non-reflecting boundary. These boundary conditions help to prevent the wave reflections in the soil medium (Lysmer 1969). The material damping for the soil was assumed as 5% as described by Richart et al. (1970). The PLAXIS 2D has several built in models to model the geogrid elements. Length of the geogrid was considered as 2 m from the axis of symmetry (shown in Figure 2) as suggested by Basudhar et al. (2007).

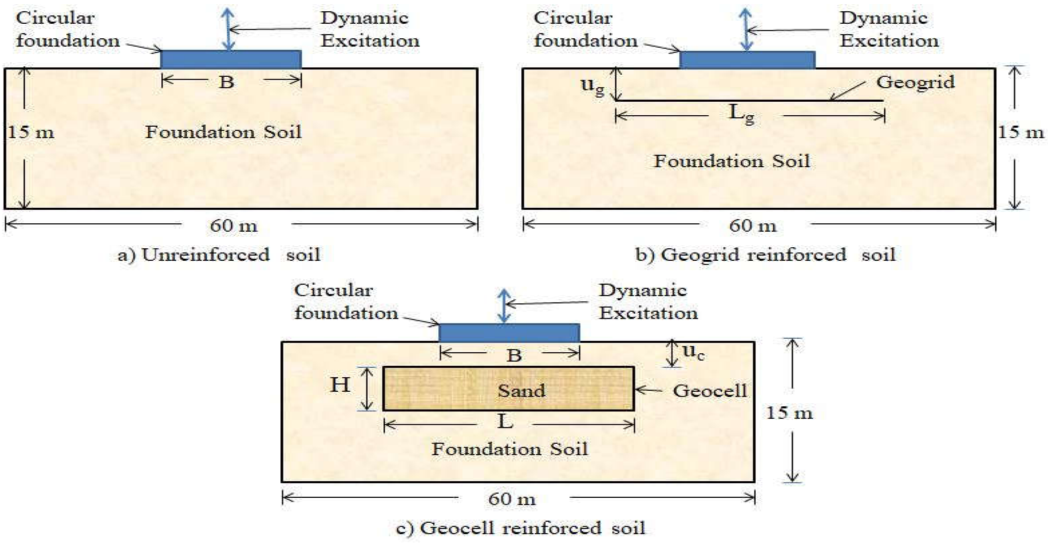

Figure 1 Schematic representation of the different reinforced soil bases

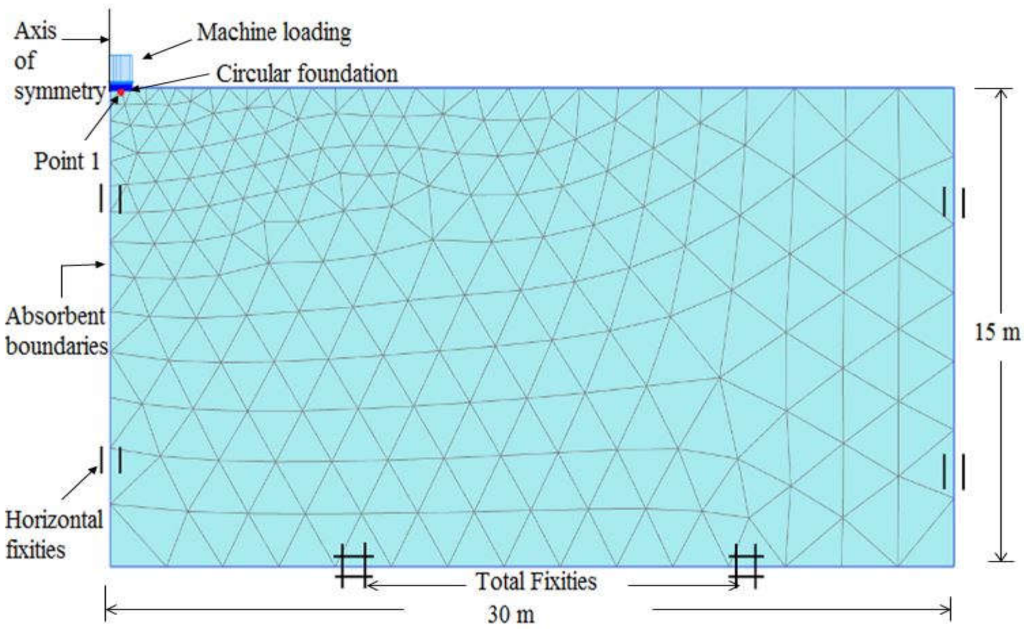

Figure 2 Mesh generation and boundary conditions adopted in the mod

In the present study, all the cases were analyzed for a period of 0.5 s with five numbers of cycles. The foundation is assumed to be subjected to a vertical harmonic excitation with constant force amplitude as represented below.

$$\mathrm{X}\,(\mathrm{t}) = a_0\,\sin\,(\omega t) \tag{2}$$

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. Al-sherefi (2000) suggested that the force amplitude for low to medium frequency machines is in between 25 kPa-100 kPa. In the present study, machine was assumed to be a low frequency machine and hence, the force amplitude of 50 kPa were selected. Figure 3 represents the oscillations released from the machine with the frequency 10 Hz and force amplitude of 50 kN/m^2.

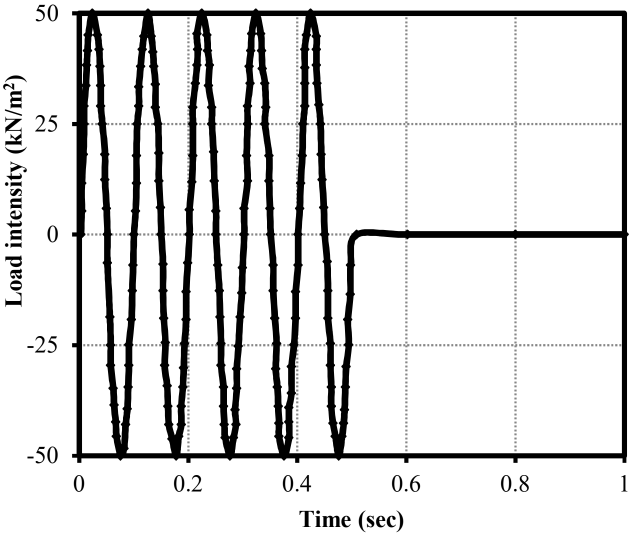

Figure 3 Input load vs. time curve

The positions of reinforcement below the footing were varied to determine its optimum location. The geogrid was placed at different depths, 0.25*B*, 0.4*B*, 0.5*B* and 0.6*B* (where *B* is the diameter of the foundation) from the ground surface. Geogrid structural element was used to model the geogrid. The behavior of the geogrid was assumed to follow the linear elastic law. On the other hand, geocell with 0.15 m height and 0.25 m equivalent diameter was used in the study. The length of the geocell considered was same as that of the geogrid. Depth of placement of the geocell was varied at 0.01*B*, 0.025*B*, 0.05*B*, 0.1*B* and 0.2*B* from the ground surface. The modelling of geocell in 2D framework is a difficult task because of its curvature and honeycomb structure. In the present study, equivalent composite approach has been adopted to model the geocell. The equivalent composite approach is a simple way to model the geocell in two dimensional framework. In this approach, geocell in filled with sand is considered as a composite soil layer with improved stiffness and strength characteristics (Hegde and Sitharam 2013, Hegde and Sitharam 2015a, Latha and Somwanshi 2009). The geocell confinement around the sand enhances the cohesion value without any change in its angle of internal friction (Bathurst and Karpurapu 1993, Rajagopal et al. 1999). The improvement in apparent cohesion (C_r) due to increase in confining pressure is obtained by using the following equation.

$$C_r = \frac{\nabla\sigma_3}{2}\sqrt{K_p} \tag{3}$$

where K_p is the coefficient of passive earth pressure and $\nabla\sigma_3$ is the increase in confining pressure due to the provision of geocell reinforcement. Increase in confining pressure is determined by,

$$\nabla\sigma_3 = \frac{2M_g}{d_0}\left[\frac{1-\sqrt{1-\xi_a}}{1-\xi_a}\right] \tag{4}$$

where M_g is the secant modulus of the geocell material calculated from stress-strain response curve at the axial strain ξ_a and d_o is the equivalent pocket diameter of the geocell material. The details of the numerical analysis have been summarized in Table 1.

Table 1 Details of the numerical analysis

S.No	Type of reinforced base	Placement of reinforcement	Frequency (Hz)
1	Unreinforced base	……….	0,5,10,15 and 20
2	Geogrid reinforced base	0.25*B*,0.4*B*, 0.5*B* and 0.6*B*	0,5,10,15 and 20
3	Geocell reinforced base	0.01*B*,0.025*B*,0.05 *B*, 0.1*B* and 0.2*B*	0,5,10 and 15

The modelling procedure followed in this study consisted of three phases. In the initial phase, the footing was constructed and static load was applied. The magnitude of the static load was equal to the static stresses generated due to self-weight of footing and machine parts. In the second phase, dynamic excitation was applied by considering selected force amplitude and the frequency. It represents the vibrations transmitted by the machine. These vibrations are transmitted into the soil through the footing. In the third phase, dynamic excitation is turned off at the estimated time interval and the soil was allowed to vibrate freely. Finally, before running the analysis, the nodal points were selected in the required positions (point 1 shown in Figure 2) at the surface of the bed to measure the response of the foundation. Geosynthetics performance under dynamic excitation was studied in terms of reduction in displacement amplitude, peak particle velocity and improvement in resonant frequency and dynamic elastic constants.

2.2 Material properties

In the present investigation, locally available silty sand was considered as foundation soil. The unit weight and shear strength properties of the foundation soil was obtained from the laboratory studies. The Young's modulus and Poisson's ratio of the soil were adopted from Bowles (1996). The dilatancy parameter was considered, $\psi = \varphi$ - 30^0 as suggested by Baranov (1967). The circular foundation of 1 m diameter was assumed to be made with M20 grade concrete. The weight of the machine was selected as per the guidelines given by Leonard (1962). As per the guidelines, the ratio between the weight of the foundation to the weight of the machine was maintained equal to 2.1, resulting the weight of the machine equal to 10kN. A similar procedure was adopted by Fattah et al. (2015) for the selection of weight of the machine. In this study, concrete foundation was modeled as a linear elastic material. Geogrid made up of polyester and geocell made up of high density polyethylene have been used in this investigation. The tensile strength of the geogrid and geocell were determined as per the guidelines of ASTM D-6637 (2011) and ASTM D-4885 (2011) respectively. The stress-strain behavior of geogrid and geocell are shown in Figure 4. The secant modulus of the geocell was determined as 410 kN/m corresponding to 2% axial strain from the stress-strain curve. Sand was used an infill material to fill the geocell pockets. The properties of the sand were considered from Hegde and Sitharam (2013). Table 2 summarizes the properties of the different materials used in the numerical modelling.

Table 2 Properties of different materials used in numerical modelling

Material	Parameter	Value
Foundation soil (silty sand)	Unit weight, (kN/m^3)	19
	Young's modulus, E (kN/m^2)	20,000
	Poisson's ratio, υ	0.3
	Angle of internal friction, φ (^{0})	32
	Cohesion, C (kN/m^2)	0
	Dilatancy angle, ψ (^{0})	2
Foundation	Young's modulus of concrete, E (kN/m^2)	2×10^7
	Unit weight of concrete (kN/m^3)	24
	Poisson's ratio of concrete, μ	0.15
Geocell	Young's modulus, E (MPa)	275
	Poisson's ratio, μ	0.45
	Geocell height, H (m)	0.15
	Length of the geocell, L (m)	2
Geogrid	Young's modulus, E (MPa)	210
	Poisson's ratio, μ	0.33
	Length of the geogrid, L_g (m)	2
Infill material (sand)	Unit weight, (kN/m^3)	20
	Elastic modulus, E (kN/m^2)	50,000
	Poisson's ratio, υ	0.3
	Angle of internal friction, φ (^{0})	36
	Cohesion, C (kN/m^2)	0

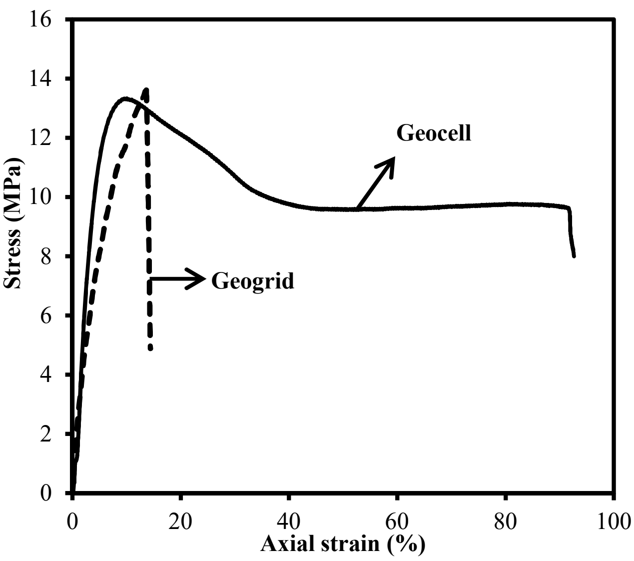

Figure 4 Stress-strain response of reinforcement materials

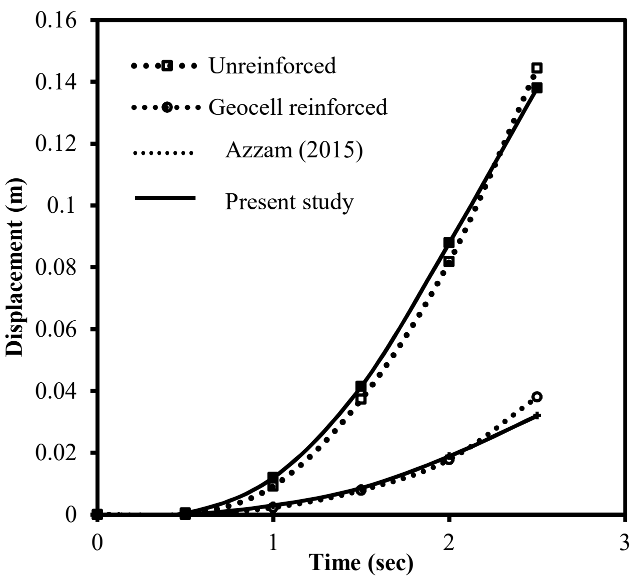

Figure 5 Results of validation of unreinforced and geocell reinforced conditions

2.3 Validation of numerical model

Initially, the model was validated with the results of the numerical studies performed by Azzam (2015). In the validation, material properties similar to Azzam (2015) were adopted. The results of unreinforced and geocell reinforced conditions were validated. Figure 5 compares the present study results with Azzam (2015). In overall, a good agreement was observed. Further, the validated model was utilized in the remaining investigations.

3. RESULTS AND DISCUSSIONS

Figure 6a-c shows the displacement vectors for the different reinforcing conditions. Severe disturbance was observed in unreinforced soil under the dynamic excitation. Formation of heave was also observed at the ground surface. Lack of shear strength of the unreinforced soil was the reason for the formation of heave. In case of the geogrid, significant reduction in the heave was observed.

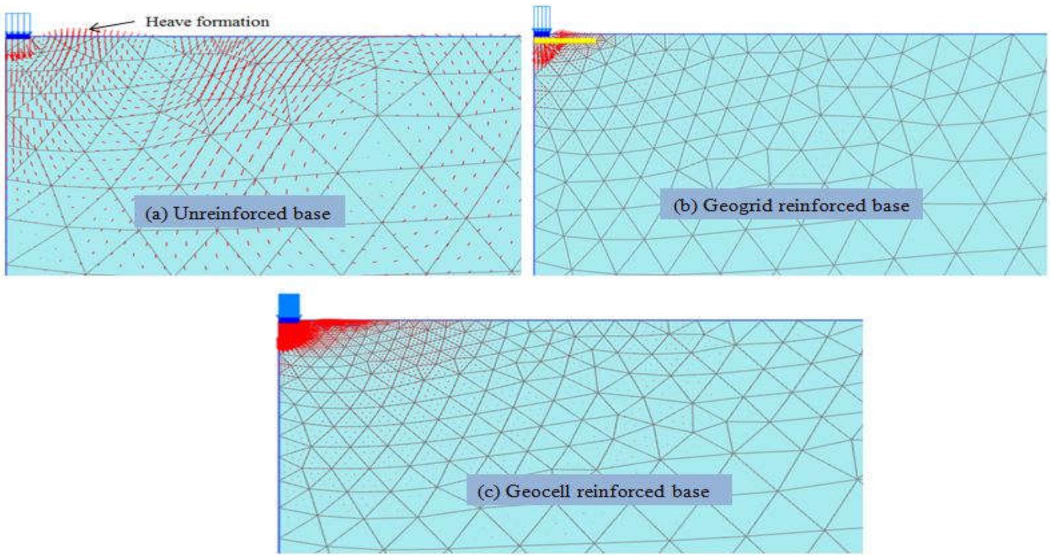

Figure 6a-c Displacement vectors; (a) Unreinforced; (b) Geogrid reinforced and (c) Geocell reinforced

On the other hand, no heaving was observed in the case of geocell reinforced soil bed as shown in Figure 6c. It was attributed due to the provision of all round confinement around the soil by the virtue of its three dimensional structure (Hegde and Sitharam 2016). The confinement mechanism of geocell arrests the lateral spreading of soil under dynamic excitation. The geocell-soil composite layer acts as the barrier to control the vibrations and transfer the cyclic stresses in a downward direction. Figure 7 shows the variation of displacement amplitude with a frequency of a geogrid reinforced foundation bed. The location of geogrid below the foundation was varied from the ground surface. The maximum displacement amplitude was observed in case of the unreinforced condition. The optimum placement of geogrid was observed at a distance of 0.4B from the ground surface.

The small decrement in displacement amplitude was observed in the presence of geogrid at its optimal location. The provision of geogrid alters the tensile strength and natural frequency of the foundation soil, might be the reason for the decrease in displacement amplitude. The similar pattern was observed in experimental study results of many researchers (e.g., Boominathan et al. 1991, Sreedhar and Abhishek 2016 and Kirar et al. 2016).

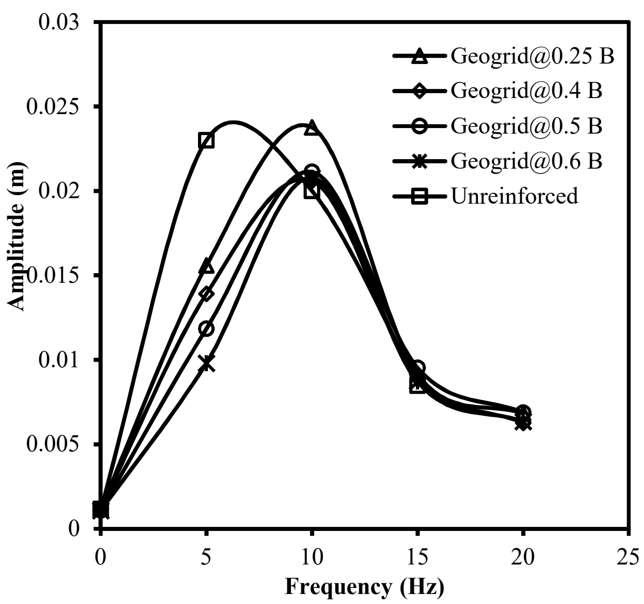

Figure 7 Variation of displacement amplitude with geogrid location

Figure 8 represents the variation in displacement amplitude of geocell reinforced foundation bed. The reduction in displacement amplitude was maximized when the placement of geocell is nearer to the ground surface. The minimum displacement amplitude was observed when the geocell was placed at 0.01B from the ground surface. The reduction in displacement amplitude of reinforced sections (at its optimum location) was compared with unreinforced case and shown in Figure 9. From the figure, it is evident that the maximum reduction in displacement amplitude occurs in the presence of geocell reinforcement. In addition, improvement in resonant frequency was observed with the provision of geocell reinforcement.

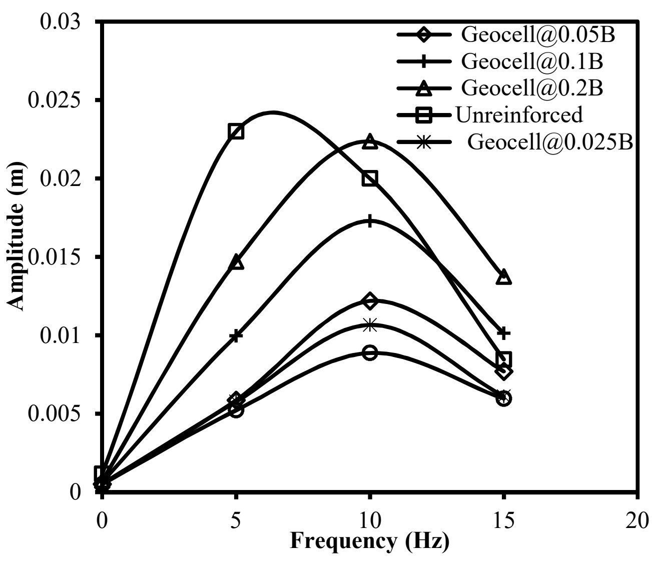

Figure 8 Variation of displacement amplitude with depth of placement of geocell

The effectiveness of the reinforcement as vibration isolation system can be expressed in terms of amplitude reduction factor (A_m). Amplitude reduction factor is defined as the ratio between the displacement amplitude of the reinforced section to the displacement amplitude of the unreinforced section. Generally, for better migration or screening of vibrations, the value of an amplitude reduction factor should be minimum. The minimum amplitude reduction factor was observed in the presence of geocell. Hence, it is an effective isolation

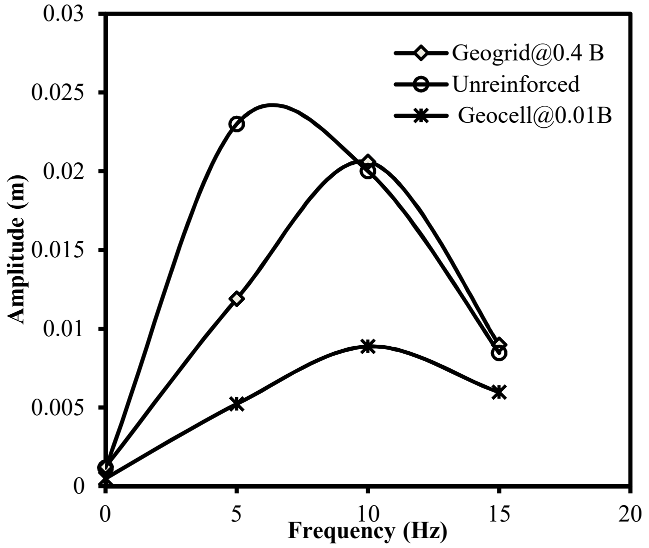

Figure 9 Comparison of displacement amplitude between unreinforced and reinforced bases at its optimum location

system for the screening of vibrations. The similar observations have been reported by Majumder and Ghosh (2015). The variation in amplitude reduction factor, peak particle velocity and resonant frequency of different soil bases was presented in Table 3.

Peak particle velocity (PPV) can be defined as the velocity of a particle through soil media as similar to wave transmission. It is the ground motion parameter, which has great significance in the analysis of underground structures, ground blasting techniques and buried life lines, etc. In the present study, peak particle velocity was observed at the ground surface along the length of the bed. Total nine nodal points were considered. Figure 10 represents the response of peak particle velocity of unreinforced and reinforced conditions at its optimal location. About 40% reduction in PPV was observed in the presence of geocell reinforcement as compared to the unreinforced case at a point 1 (shown in Figure 2). From the figure, it is evident that the role of geocell is significant in reducing the PPV. The reason can be attributed due to the densification of the foundation bed in the presence of geocell.

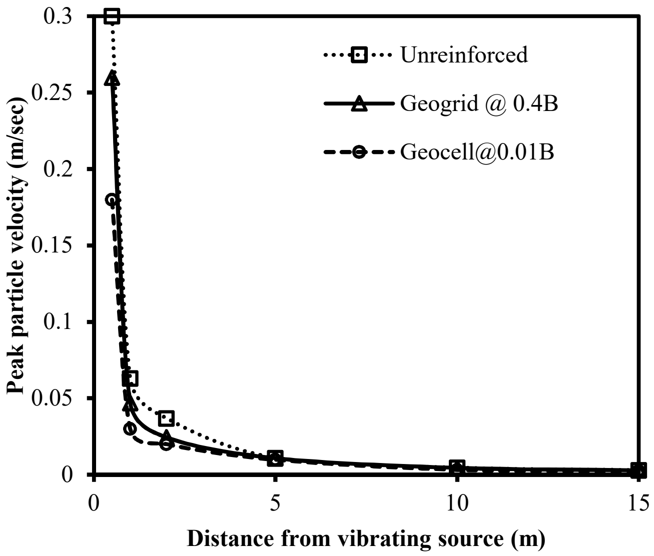

Figure 10 Variation of peak particle velocity along the ground surface for unreinforced and reinforced cases

Performance of geosynthetics on dynamic properties of foundation soil was also studied. Dynamic properties of the soil such as the shear modulus (G), stiffness (K) and damping ratio (ξ) were considered. The damping ratio (ξ) is defined as the ratio between the damping coefficient of the reinforced system to the damping coefficient of unreinforced system. The various dynamic properties of the unreinforced and reinforced soil bases were determined by using the following relations.

$$G = \frac{E}{2(1+\upsilon)} \tag{5}$$

$$E = \frac{C_u(1-\upsilon^2)\sqrt{A}}{C_s} \tag{6}$$

$$K = \frac{4\,G\,r_0}{1-\upsilon} \tag{7}$$

$$\xi = \frac{\zeta_R}{\zeta_U} \tag{8}$$

where ζ_R and ζ_U are the damping coefficients of the geocell reinforced and unreinforced foundation soil systems respectively. The damping coefficient (ζ) under vertical vibration mode can be determined by using the following equation as suggested by Hardin and Drnevich (1972).

$$\zeta = \frac{3.4\,r_0^{\,2}\sqrt{G\rho}}{1-\upsilon} \tag{9}$$

where r_o is the equivalent radius of the circular foundation, υ, G and ρ are the Poisson's ratio, shear modulus and density of the soil respectively. Shear modulus of the soil can be calculated by using the Eq. 5. Where, E, K and C_u are the elastic modulus, stiffness and coefficient of elastic uniform compression of the soil respectively, A is the contact area of the foundation block with soil and C_s is the coefficient of damping. C_u can be determined by using the Eq.1. Based on this value the remaining secondary dynamic properties can be evaluated by using suitable relationship between them. In addition, the variation of dynamic elastic constants and damping ratio for unreinforced and reinforced (at its optimal location) conditions was presented in the Table 4. From the Table, it can be observed that, 163% improvement in the damping ratio was observed in the presence of geocell reinforcement. It shows that the geocell and infill material acted as a compacted mass, which not only improved the damping ratio of the system, but also decreased the soil disturbance as shown in Figure 6c. The results of improvement in the damping ratio with geocell reinforcement followed the findings of the numerical study conducted by Azzam (2015). In addition, the elastic constants were significantly improved in the presence of geocell reinforcement. The dynamic elastic constants (C_u, C_τ, C_ψ, C_φ) were improved by 2.7 and 1.27 times in the presence of geocell as compared to unreinforced and geogrid reinforced systems, respectively.

4. PRACTICAL SIGNIFICANCE

In general, there are three possible methods to prevent the failure of foundation bed under dynamic excitation, namely, controlling the vibrations transferred from machine foundation to the soil, improving the elastic properties of the soil and avoiding the resonance. Ground borne vibrations released from the transit systems and industrial machines may destroy the performance of the foundations.

In such cases, foundation performance can be improved by adopting the suitable isolation system (either active or passive). From the present study, it was found that the role of geocell was significant as an active isolation system.

Table 3 Comparison of performance of different soil bases

Sl. No	Type of foundation bed	Resonant frequency (Hz)	Peak displacement amplitude (m)	Amplitude reduction factor (A_m)	Peak particle velocity (m/sec)
1	Unreinforced soil base	6.4	0.023	1	0.3
2	Geogrid reinforced soil base	9.3	0.0206	0.89	0.26
3	Geocell reinforced soil base	10.5	0.0088	0.38	0.18

Table 4 Summary of the dynamic properties obtained from the numerical study

Sl. No	Dynamic property	Unreinforced soil base	Geogid reinforced soil base	Geocell reinforced soil base
1	Coefficient of elastic uniform compression (C_u) (kN/m^3)	1928	4070	5188
2	Coefficient of elastic uniform shear (C_τ= 0.5 C_u) (kN/m^3)	964	2035	2594
3	Coefficient of elastic, non- uniform shear (C_ψ = 0.75 C_u) (kN/m^3)	1446	3052	3891
4	Coefficient of elastic, non- uniform compression (C_φ = 2 C_u) (kN/m^3)	3856	8140	10376
5	Elastic modulus (E) (kN/m^2)	1471	3093	3942
6	Shear modulus (G) (kN/m^2)	565	1189	1516
7	Soil Stiffness (k) (kN/m)	1614	3396	4331
8	Damping ratio	1	1.41	1.63

The current study suggested that the provision of geocell helps to decrease the amplitude reduction factor of the system. Which indicates the effectiveness of the geocell in vibration isolation. In addition, the role of geocell was found effective in reducing the peak particle velocity.

The second important method is improving the elastic properties of the soil. In order to avoid settlement, soil should be elastic such that it regains its original position before the application of the next cycle. Coefficient of elastic uniform compression (C_u) is the parameter used to represent the elastic nature of the soil. In this study, it was observed that the provision of geocell significantly improves the elastic compression of soil. Table 4 shows the improvement in the elastic uniform compression of the soil with the provision of geocell reinforcement. The present study suggested that the geocell can be utilized for improving the elastic nature of the soil.

The third major method for the safe design of machine foundation is to avoid resonance. Resonance is the phenomenon at which operating frequency of the machine matches with the natural frequency of the foundation soil system. In order to avoid the resonance, the frequency ratio should be very high or low. Frequency ratio is defined as the ratio between operating frequency of a machine to the natural frequency of the foundation soil system.

In the case of low frequency machines the frequency ratio less than 0.5 is required for avoiding the resonance. Similarly, for the high frequency machines, it should be greater than 1.5. The present study suggested that the natural frequency of the foundation soil system increases with the provision of geocell reinforcement. As the natural frequency increases, the frequency ratio reduces. Which helps to maintain the frequency ratio less than 0.5 in case of the low frequency reciprocating machines.

5. CONCLUSIONS

In this investigation, dynamic response of geosynthetic reinforced soil mass supporting the machine foundation has been studied numerically using the finite element software PLAXIS 2D. Under the action of dynamic excitation, the performance of geocell was more effective than unreinforced and geogrid cases. The optimal location of geocell was found to be 0.01B from the ground surface under the machine foundation. At its optimal location, the maximum improvement in the elastic properties of soil was observed. Presence of geocell has improved the coefficient of elastic uniform compression (C_u), 2.7 times as compared to the unreinforced condition. In addition, 1.64 times improvement in the natural frequency of the foundation soil system and 61% reduction in displacement amplitude was observed in the presence of geocell. The peak particle velocity was found to be reduced by 40% in the presence of geocell. The densification of foundation soil in the presence of geocell caused the improvement in subgrade damping by 163%. With these lines, the current study highlighted the efficacy of geocells in supporting the machine foundations. In overall, the outcomes of the study are useful in the design of foundations to support the low frequency machines. The work has its own limitations. The study has been carried out using only one type of foundation soil. Hence, the presented results are applicable to limited cases.

6. NOMENCLATURE

A Contact area of the footing with soil (m^2)
A_m Amplitude reduction factor (dimensionless)
a_0 Force amplitude (kN/m^2)
B Diameter of circular foundation (m)
C_u Coefficient of elastic uniform compression (kN/m^3)
C_τ Coefficient of elastic uniform shear (kN/m^3)
C_ψ Coefficient of elastic, non-uniform shear (kN/m^3)
C_φ Coefficient of elastic, non-uniform compression (kN/m^3)
C_r Apparent cohesion (kN/m^2)
ζ_R Damping coefficient of reinforced foundation (dimensionless)
ζ_U Damping coefficient of the unreinforced foundation system (dimensionless)
d_0 Equivalent pocket diameter of geocell (m)
E Young's modulus (kN/m^2)
f_{nz} Frequency of the foundation soil system corresponding to peak displacement amplitude (Hz)
G Shear modulus (kN/m^2)
H Height of geocell (m)
K Soil stiffness (kN/m)
Kp Coefficient of passive earth pressure (kN/m^2)
L Length of the geocell layer (m)
L_g Length of geogrid (m)
M Mass of the foundation block (kN)
M_g Secant modulus of the geocell material corresponding to 2% axial strain (kN/m^2)

PPV Peak Particle velocity (m/sec)
r_0 Equivalent radius of circular foundation (m)
t Dynamic time (sec)
U_g Depth of placement of the geogrid from the ground surface (m)
U_c Depth of placement of the geocell layer (m)
u_x, u_y Horizontal and vertical displacement of foundation (m)
$X(t)$ Dynamic load intensity (kN/m^2)
$\Delta\sigma_3$ Increase in confining pressure (kN/m^2)
ξ_a Axial strain (dimensionless)
γ Unit weight (kN/m^3)
φ Angle of internal friction (°)
ψ Dilatancy angle (°)
v Poisson's ratio (dimensionless)
ω Circular natural frequency (rad/ sec)
ξ Material damping (dimensionless)
ρ Density of the soil (kg/m^3)

7. REFERENCES

ASTM D-4885 (2011), Standard test method for determining performance strength of geomembranes by wide strip tensile method; ASTM International, West Conshohocken, PA, USA.

ASTM D-6637 (2011), Standard test method for determining the tensile properties of geogrid by the single or multi-rib tensile method; ASTM International, West Conshohocken, PA, USA.

Al-Sherefi, M. H. J. (2000). "Non-Linear Dynamic Response of Soils (Doctoral dissertation." MSc. thesis, Civil Engineering Department, University of Baghdad).

Azzam, W. R. (2015). "Utilization of the Confined Cell for Improving the Machine Foundation Behavior-Numerical Study." *Journal of GeoEngineering*, 10 (1), pp. 17-23.

Bathurst, R.J., Karpurapu, R., (1993). "Large scale triaxial compression testing of geocell reinforced granular soils." Geotech. Test. J. 16 (3), 296-303.

Baranov, V. A. (1967). "On the calculation of excited vibrations of an embedded foundation." *Voprosy Dynamiki Prochnocti*, 14, pp. 195-209.

Basudhar, P. K., Saha, S., & Deb, K. (2007). "Circular footings resting on geotextile-reinforced sand bed." *Geotextiles and Geomembranes*, *25* (6), pp. 377-384.

Boominathan, S., Senathipathi, K., & Jayaprakasam, V. (1991). "Field studies on dynamic properties of reinforced earth." *Soil Dynamics and Earthquake Engineering*, 10 (8), pp. 402-406.

Bowles J.E. (1996). Foundation Analysis and Design, 5th edn, pp. 1175. McGraw-Hill Companies, Inc.

Dash, S.K., Rajagopal, K. and Krishnaswamy, N.R. (2001). "Strip footing on geocell reinforced sand beds with additional planar reinforcement." *Geotext. Geomembr*., 19 (8), pp. 529-538.

Dash, S.K. and Bora, M.C. (2013). "Improved performance of soft clay foundations using stone columns and geocell-sand mattress." *Geotext. Geomembr*., 41, pp. 26-35.

Fattah, M., Salim, N., & Al-Shammary, W. (2015). "Effect of Embedment Depth on Response of Machine Foundation on Saturated Sand." *Arabian Journal for Science & Engineering (Springer Science & Business Media BV)*, 40 (11).

Gazetas, G. (1983). "Analysis of machine foundation vibrations: State of the art. *Soil Dyn. Earthquake Eng.* 3 (1), pp. 2–42.

Ghosh, P. (2012). "FLAC based numerical studies on dynamic interference of two nearby embedded machine foundations." Geotechnical and Geological Engineering, 30 (5), pp. 1161-1181.

Hardin, B. O., & Drnevich, V. P. (1972). "Shear modulus and damping in soils: measurement and parameter effects." *Journal of Soil Mechanics & Foundations Div*, *98* (sm6).

Hegde, A., Sitharam, T.G. (2013). "Experimental and numerical studies on footings supported on geocell reinforced sand and clay beds." Int. J. Geotech. Engg. 7 (4), pp. 347-354.

Hegde, A.M. and Sitharam, T.G. (2015a). "Effect of infill materials on the performance of geocell reinforced soft clay beds." *Geomech. Geoeng*., 10 (3), pp. 163-173.

Hegde, A. and Sitharam, T.G. (2015b). "Experimental and numerical studies on protection of buried pipelines and underground utilities using geocells." *Geotext. Geomembr*., 43 (5), pp. 372-381.

Hegde, A., & Sitharam, T. G. (2016). "Behaviour of geocell reinforced soft clay bed subjected to incremental cyclic loading." *Geomechanics and Engineering*, 10 (4), pp. 405-422.

Kirar, B., Krishana, A. M., & Rangwala, H. M., (2016). "Dynamic properties of soils for the design of machine foundations." *Proceedings of Indian Geotechnical Conference*, Chennai, India, December, pp. 1-4.

Latha, G. Madhavi, Somwanshi, A., (2009). "Effect of reinforcement form on the bearing capacity of square footing on sand." Geotext. Geomembr. 27, pp. 409-422.

Leonards, G. A.: (1962) Foundation Engineering. McGraw-Hill Book Co., Inc., New York.

Lysmer, J. and Kuhlmeyer, R.L. (1969)." Finite dynamic model for infinite media." *Jl. Eng. Mech. Division*, Proceedings of *ASCE*., 95 (4), pp. 859-877.

Majumder, M., & Ghosh, P. (2015) "Screening of machine vibration with geofoam barriers considering soil non-linearity." Indian Geotechnical Conference IGC 2015. pp .1-4.

Pokharel, S.K., Han, J., Leshchinsky, D., Parsons, R.L. and Halahmi, I. (2010). "Investigation of factors influencing behavior of single geocell reinforced bases under static loading." *Geotext. Geomembr*, 28 (6), pp. 570-578.

Rajagopal, K., Krishnaswamy, N.R. and Madhavi Latha, G. (1999). "Behaviour of sand confined with single and multiple geocells." *Geotext. Geomembr*, 17 (3), pp. 171-181.

Richart, F. E., Hall, J. R., & Woods, R. D. (1970). "Vibration of Soils and Foundations." International Series in Theoretical and Applied Mechanics.

Sireesh, S., Sailesh, P., Sitharam, T.G. and Puppala, A.J (2013). "Numerical analysis of geocell reinforced ballast overlying soft clay subgrades." *Geomech. Eng., Int. J.*, **5** (3), pp. 263-281.

Sreedhar, M.V. and Goud, P.K. (2011). "Behavior of geosynthetic reinforced sand bed under cyclic loading." *Proceedings of Indian Geotechnical Conference*, Kochi, India, December, pp. 519-522.

Sreedhar, M.v.s., Abhishek J.(2016). "Effect of geosynthetic reinforcement on dynamic characteristics through model block resonance tests." Indian Geotechnical Conference IGC 2016. pp. 1-4.

Tafreshi, S. M., Zarei, S. E., & Soltanpour, Y. (2008). "Cyclic loading on foundation to evaluate the coefficient of elastic uniform compression of sand." In *The 14th World Conference On Earthquake Engineering, October*, pp. 12-17.

Verma, A.K. and Bhatt, D.R. (2008). "Design of machine foundations on reinforced sand." *Proceedings of 12th International Conference of IACMAG*, Goa, India, October, pp. 3583-3589.