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BEHAVIOR OF MACHINE FOUNDATIONS ON REINFORCED SOIL

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Abstract

Foundations under heavy machinery can be subjected to periodic loadings and vibrations, which may cause excessive settlement or tilting of the supporting structure. The use of geosynthetics at the subsoil may enhance the strength and stiffness of the soil and reduce the vibration-induced deformations of the foundations. The present study aims to explore the utility of geogrid in improving the performance of machine foundations in reducing vibration-induced deformations, namely in the vertical direction. A series of field tests on a full-scale footing is conducted for this purpose. The biaxial geogrid reinforced bed is of size 2.2 m x 2.2m x 1.0 m, whereas the model footing is of size 1m x 1m x 0.3 m. The vertical vibration is generated using an eccentric mass shaker. The employed eccentric mass shaker consists of two shafts moving in a counter-clockwise direction to produce the dynamic force in the vertical direction. The foundation is excited with different eccentricities to provide a different level of vertical dynamic loading and also subjected to a range of frequencies for determining dynamic responses. The geogrid layers are placed in a single layer at varying depth. The dynamic responses are measured under using accelerometer sensors placed over the rigid foundation. The resonant amplitude and the resonant frequency is calculated. The response data are recorded at a sampling rate of 2000 samples per second and a baseline correction is applied followed by a Butterworth filtering of data. The processed acceleration data is then numerically double-integrated to obtain the displacement response of the footing. The resonant frequency and amplitude values of soil are determined, which helps in the identification of the parameters during resonance conditions, an essential criterion in the control of vibration. The resonant amplitude of the motion of the system increases with increased dynamic loading whereas the resonant frequency value has not much affected as the eccentric force level is kept low. The effect of geogrid reinforcement shows a significant influence on the vibration-induced vertical displacement of the machine foundation. However, resonant frequency characteristics are not much affected when subsoil gets reinforced with bi-axial geogrid.

Keywords: Machine foundation; eccentric mass shaker; dynamic properties; resonant frequency; damping.

1. Introduction

In the case of the foundation under machinery like turbines, compressors, etc. may be subjected to strong vibration under periodic or harmonic loading. The vibration induced by the machines may cause damage and ground settlement in the nearby vicinity. The design of the foundation is such that it can withstand the vibration caused by dynamic loading within the serviceable limits. The dynamic response of such a machine foundation is significantly affected by the soil foundation interaction. The soil foundation interaction is also governed by the dynamic properties of the underlying soil strata and it interacts to dissipate the energy due to the wave propagation in the underlying soil strata. To understand the soil foundation interaction, the large scale field studies are best suited as compared to the laboratory experiments which may have the boundary effects due to the presence of rigid or flexible boundary interface.

[1] provided the periodic displacement theoretical solution at the center of circularly loaded area. [2] has given the frequency-independent expression for the spring and damping constant also known as Lysmer's analog. [3] presented dimensionless formulas and charts for the value of dynamic damping and stiffness for both surface and embedded foundation of any arbitrary shape subjected to harmonic loading. The use of block vibration test in the field is reported by several researchers for the performance evaluation of machine footing subjected to the dynamic loading, [4,5,6,7,8,9]. [5] has conducted a series of block vibration tests on a model concrete footing under different modes of vibration subjected to harmonic loading. [5] has conducted a series of block vibration tests on the concrete footing of size 0.4m x 0.4m x 0.1m resting on the sand layer to understand the effect of layering of soil and the presence of a rigid layer on the dynamic

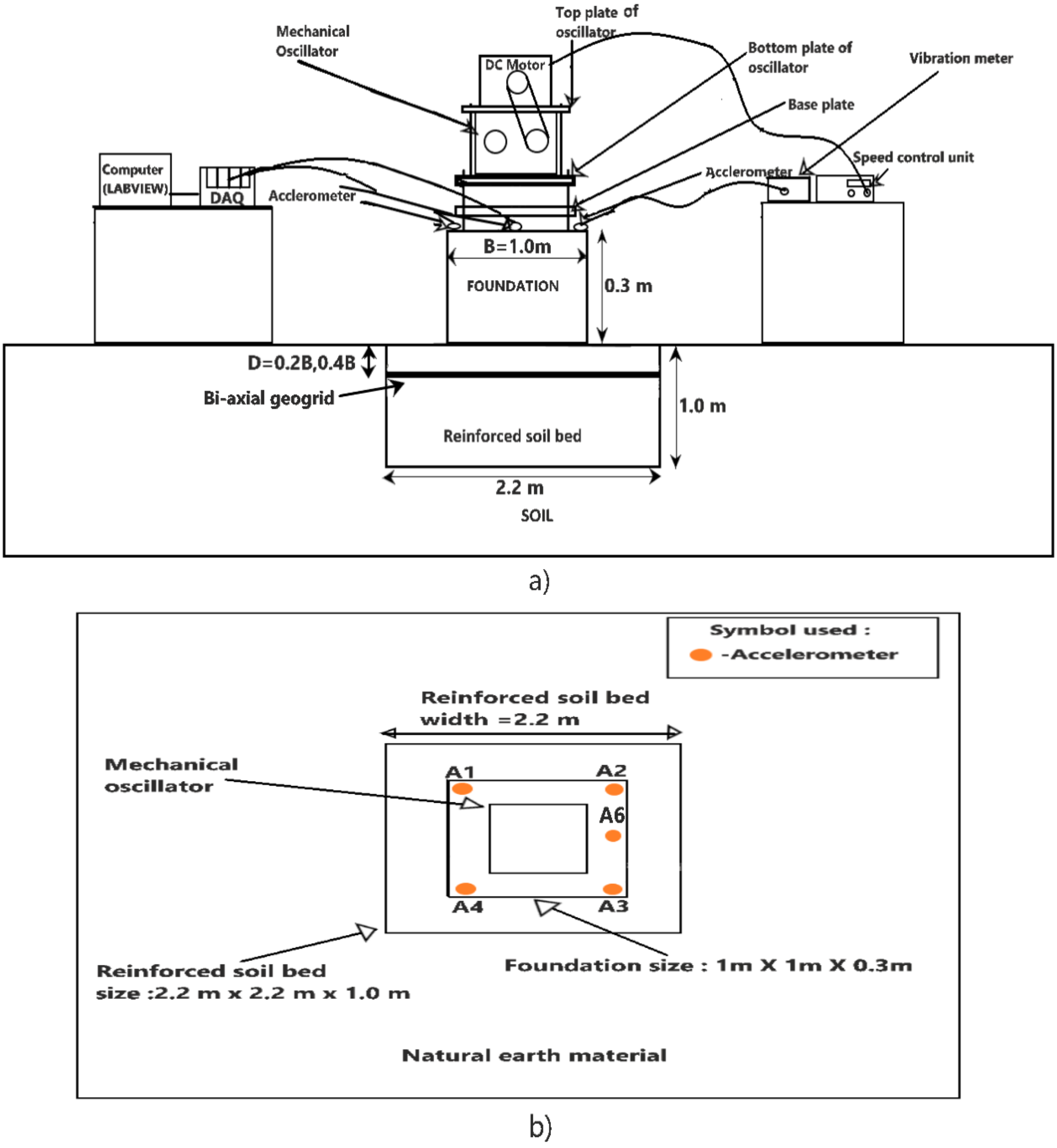
properties of the footing. [6] has conducted a series of block vibration tests on the foundation with the spring-mounted base resulting in the reduction of amplitude and resonant frequency of the foundation. [7] has studied the effect of layering of soil underlain by a rigid layer through block vibration test in the vertical direction. [8] has conducted a large number of experiments on a pair of footing at IIT Kanpur campus soil to understand the dynamic interference of footing. The study helps in the design of the machine foundation in case of a foundation in groups. The transmission ratio is plotted with frequency to predict the effect of active footing on the passive footing. [9] has conducted the block vibration test on the IIT Kanpur campus soil for the determination of displacement amplitude, resonant frequency, and damping and compared with the values earlier determined by [4,8]. The proper understanding of the dynamic parameters primarily at resonance condition and nature of the foundation bed is indeed helpful. There is a gradual increase in the amplitude with frequency and at resonance, there is rapid shoot in the amplitude values because of matching between the frequency given to the mechanical oscillator with the natural frequency of the soil-foundation system.

Geosynthetics products are widely used in slope stability, erosion, ground improvement, retaining wall and many other mega construction projects. There is plenty of literature available on the use of biaxial geogrid (Geosynthetics product) in the case of static loading [10,11,12]. [10] has conducted tests on the performance of geogrid in the slope stability case. [11] has performed tests on small scale model footing and validated with the finite element analysis for finding the optimum depth for the full utilization of reinforcement strength. [12] studied the use of geosynthetics in case of slope stability problems in cohesive backfills. However, there are limited studies on the performance of geogrid under the application of dynamic loading for the case of the machine foundation bed. [13] has conducted block vibration test on reinforced soil bed with geotextile and geogrid under vertical vibration. There is a reduction in the value of displacement amplitude, an increase in shear modulus and a slight increase in the frequency at resonance condition. [14] has conducted laboratory test namely free vibration and forced vibration on geogrid reinforced dense sand bed. [15] studied the geocell combined with geogrid reinforced soil by conducting a series of cyclic plate load tests. Significant increase in bearing capacity, reduction in settlement and increase in stiffness of the soil bed. [16] studied the use of geocell and geogrid reinforced soil bed under machine foundation and reported improvement in reducing the amplitude.

In the present study, an attempt is made to understand the performance evaluation of geogrid reinforced soil bed under the machine foundation. A series of block vibration tests are conducted where the bi-axial geogrid is laid at a different depth to find the optimum location for the significant reduction of the peak displacement amplitude.

2. Experimental program

The block vibration test setup was based on [17] code provision guidelines and the experimental program used by [4,5,6,7,8,9]. The block vibration test setup is consisting of an eccentric mass shaker equipment (MX 100A), Micron Industries Limited. The eccentric mass shaker is the mechanical oscillator that is capable of producing 10000 kgf. The principle mechanism of the eccentric mass shaker to produce a sinusoidal harmonic variation is due to the counter-clockwise rotating shafts which can able to produce periodic vertical force. The eccentricity angle inside the mechanical oscillator can be set up to from zero to 180 degrees. The shaft of the oscillator is driven by the help of 5HP DC motor and it can run up to 3000 rpm. The base plate (MS plate) is connected to the foundation through the help of guide bars. Then the square-shaped bottom plate is connected to the four guide bars. After the calibration, the mechanical oscillator is placed on the bottom plate of the oscillator so that the whole system vibrates as a single entity. The layout of experimental test setup in layout (front view) and the plan is shown in Fig. 1a) and b).



a)

b)

Fig. 1- Layout of block vibration test setup a) front view (elevation); b) plan of the experimental program

2.1. Preparation of reinforced foundation bed

The site is first cleaned and then excavation is done to remove the topsoil up to a depth of 1m so that the pit size being 2.2m x 2.2m x 1.0m as shown in Fig.2a). The soil specimen from various depth is checked for the in-situ density through the core cutter sample. The optimum amount of water content and density were determined from the standard Procter test. As a thumb rule, the pit length greater than two to three times the width of the footing is sufficient to get a similar dynamic response, [18]. Therefore, pit length is taken as 2.2B where B is the width of the foundation. The soil was air-dried for 48 hours. The water is added as per the optimum moisture content. The pit was prepared with 95 % of the in-situ density as shown in Fig. 2b).

The manual mode of compaction was considered with compaction effort equal to the standard Procter test. A steel rammer of weight 12.17 kg is utilized for that purpose. The pit was prepared in ten layers each of 10 cm depth. Then, bi-axial geogrid as a reinforcement being introduced to the well-compacted soil strata at the required depth as shown in the Fig. 2c). The bi-axial geogrid used is made from fine grades of polypropylene with carbon black content. The bi-axial geogrid has high tensile strength and stiffness. The properties of the biaxial geogrid are given in Table 1. The depth of the single layer (D) of the bi-axial geogrid reinforcement chosen as 0.2B and 0.4B for finding the optimum location of the geogrid reinforcement where B is the width of the footing. Finally, the foundation bed is prepared for the experimentation as shown in the Fig. 2d).

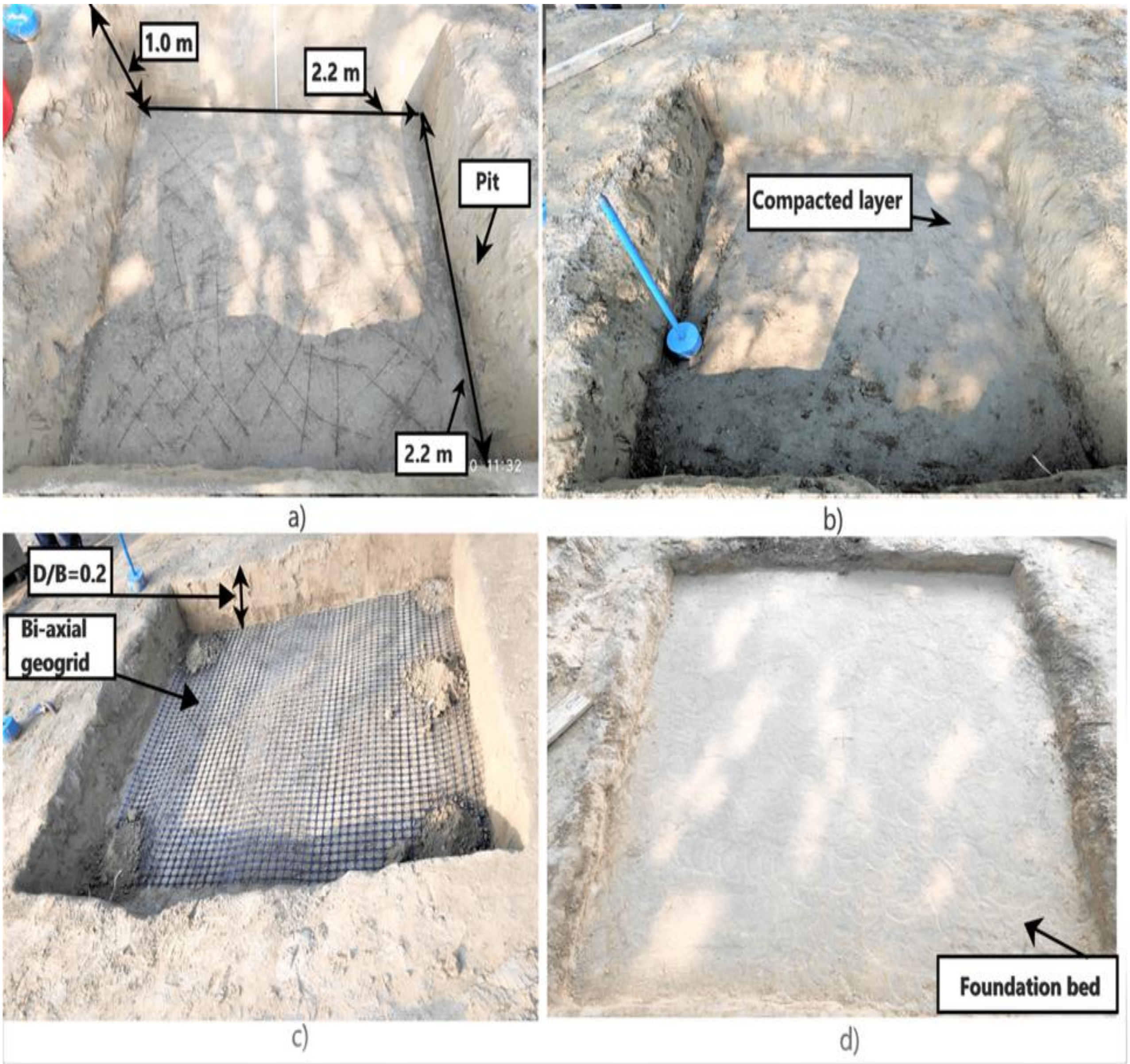


Fig. 2 -The preparation of the foundation beds a) excavating a pit of size 2.2m x 2.2m x 1.0m b) preparing the compacted layers to Procter density c) Bi-axial geogrid reinforcement at D/B=0.2 and D/B=0.4 d) pit is ready for experimentation

Table 1 – Properties of the reinforcement material

Property	**Quantity**
Bi-axial Geogrid	
Pitch size (MD x XMD) (mm)	40 x 40
Shape of the aperature	Square
Material	Polyproplene

Overall three cases of foundation bed are prepared, the first one is unreinforced foundation bed, second one is single layer of bi-axial geogrid at D= 0.2B and third one is single layer of bi-axial geogrid at D= 0.4B as shown in Fig.3a), b) and c) where B is the width of the model footing.

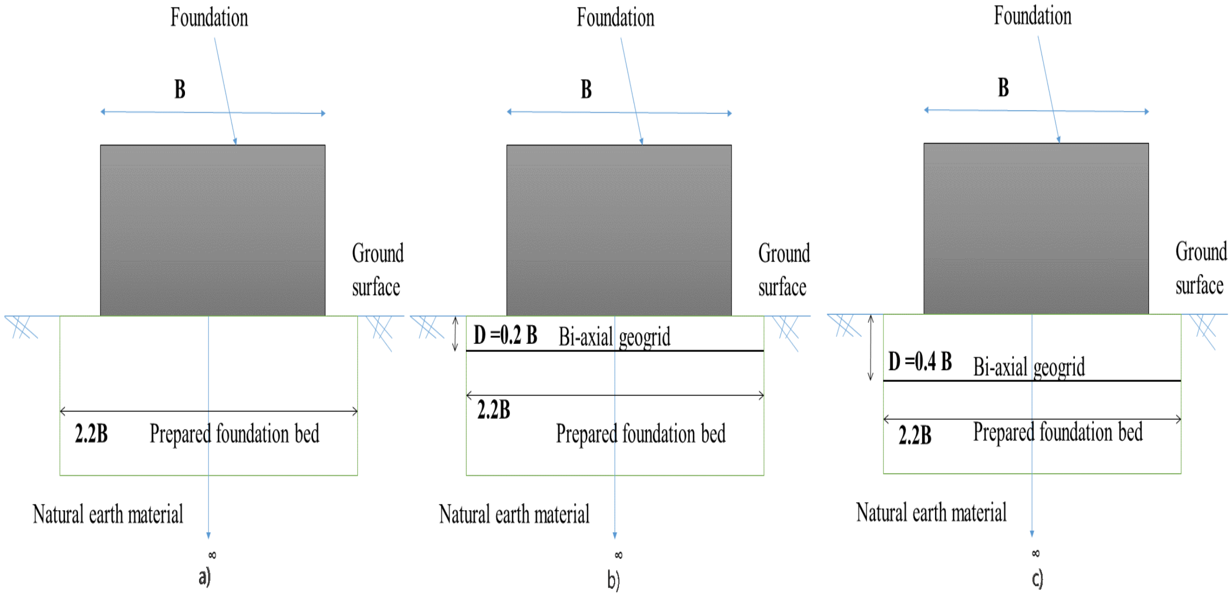


Fig. 3- The different cases for the foundation bed preparation a) unreinforced; b) reinforced foundation bed with single layer of bi-axial geogrid at D/B =0.2; and c) single layer of bi-axial geogrid at D/B =0.4

The block vibration test was conducted through the use of eccentric mass shaker on model isolated shallow foundation of size 1.0m x 1.0m x 0.3m. For that purpose, the model reinforced concrete foundation is designed and cast. The four guide bars are welded to the reinforcement so that the model foundation can be later attached to the eccentric mass shaker. A concrete with characteristics strength of 20 MPa was designed for the casting of foundation as per [19].

After preparing the cast-in-situ foundation and proper setup of the mechanical oscillator the placement of sensors like accelerometer was done. Overall five accelerometers were connected to the foundation. The four strain gauge based accelerometer is placed on the outer four edges (numbered A1, A2, A3, and A4 as shown in Fig. 1b) in the clockwise direction from Southside direction). The accelerometer sensor is connected to the 32-bit data acquisition system (DAQ). The DAQ is further connected to a computer having LABVIEW installed in it for recording the raw data. The MEMS accelerometer (numbered A6 as shown in Fig. 1b)) is placed on the centerline of the foundation. This MEMS based sensor is further connected to the vibration meter which gives a direct reading of acceleration, velocity, and displacement. The placement of accelerometer sensors along with the block vibration test setup is as shown in Fig. 1b).

The soil strata at the field site are clayey silt. The water table is 6.5 m below the ground table so that it is well below the zone of influence ie. B depth below the base of the footing where B is the width of the foundation. The specific gravity of the soil is 2.67. The dry density of the soil is 16.42 kN/m^3. The liquid limit is found to be 26.70 %. The plasticity is found in the range of low to medium.

2.2 Experimental procedure

The block vibration test for the vertical vibration case is conducted on an isolated square foundation of size 1m x 1m x 0.3m for different values of eccentric force and with a range of forcing frequencies. The power is fed into AC to DC converter to run the 5HP DC motor which causes the two shafts of the eccentric mass shaker to run in counter-clockwise direction thereby canceling the horizontal forces and addition of forces in the vertical direction. The desired forcing frequency is set by setting the revolution per minute (rpm) by the speed control unit. The eccentricity angle range is from 0 to 180 degrees. The speed control unit range is from 300 rpm to 3000 rpm thereby the forcing frequency range is from 5Hz to 50 Hz. The capacity of the mechanical oscillator is 10000 kgf. The eccentric force depends upon the angle of eccentricity between the unbalanced mass inside the mechanical oscillator and the speed of rotation. The eccentric force generated is given by following Eq.(1) as follows

$$F= m_e \text{ x } e \text{ x } \omega^2 = 0.85624 \text{ x } \sin(\theta/2) \text{ x } \omega^2 \tag{1}$$

where F is the force generated in Newton, m_e is the unbalanced mass rotating with the radius of e inside the mechanical oscillator in meters, and θ is the angle between the eccentric masses. The eccentric force level is calculated by following Eq.(2) as follows

$$F_e= m_e \text{ x } e \text{ x } \omega^2 = 0.85624 \text{ x } \sin(\theta/2) \text{ x } \omega^2 \tag{2}$$

The eccentric force corresponds to the 5-degree eccentricity is 0.037349 N-sec^2. The experimental study was conducted for three eccentricity angles of 5, 13 and 20 degrees. The eccentric force level corresponding to the eccentricity angle of 5, 13 and 20 degrees is 0.037349, 0.096929 and 0.14868 N-sec^2. For each eccentric force level, the forcing frequency range is from 5 Hz to 41 Hz in the increment of every 2 Hz.

First the calibration of the accelerometer sensor was performed so to record the response (g values) with accelerometer sensors with the help of LABVIEW software using a data acquisition system connected with the accelerometer sensor. The micron MEMS accelerometer sensor (A6) connected to the vibration meter which gives the direct value of acceleration, velocity and displacement values. After recording the data in LABVIEW software from different accelerometers (A1, A2, A3, and A4), the recorded data are multiplied with 9.81 so to convert it in m/s^2. Then the raw data is processed with MATLAB. The samples are recorded at 2000 samples per second so that the Nyquist frequency of the system is 1000 Hz. The baseline correction is made to the acceleration values. The Butterworth filter of the 4th order is applied in the selected frequency bandwidth to capture the fundamental mode of the present system. The velocity is calculated by integrating the acceleration values and displacement is calculated by integrating the velocity values. The displacement for every forcing frequency is noted and accordingly the graph between displacement and forcing frequency is plotted. The peak displacement value is calculated by taking the average of the peak displacement as obtained from the sensor placed on the edges.

3. Result and discussion

The block vibration test is conducted on the model shallow foundation of size 1m x 1m x0.3m resting on field site near field laboratory, IIT Kanpur. After attaining the steady-state, the reading from the accelerometer sensors is recorded. The displacement values are calculated from numerically double integration of the acceleration values for each forcing frequency. Finally, the response curve is plotted with the function of frequency from each of the peak displacement amplitude at different frequencies, thereby finding the resonant displacement amplitude and resonant frequency from the observed response curve.

The peak displacement response is plotted with frequency as shown in Fig. 4a), b) and c) for each of the three eccentric angles of 5, 13 and 20 degrees. A total of 12 tests are conducted for the unreinforced, reinforcement foundation bed at D/B=0.2 and D/B=0.4 particularly at three eccentricity angle settings including three trial tests.

When the forcing frequency approaches the natural frequency of the soil the rate of increase in the dynamic response ie. displacement amplitudes is rapid as shown in Fig. 4a), b) and c) (displacement amplitude). This is mainly due to the propagation of surface waves (Rayleigh wave) and when the operating frequency matching with the natural frequency of soil foundation system which can cause vibration induced ground deformation. After reaching the resonant frequency, the dynamic responses started decreasing. That's the typical case of the response curve obtained from the block vibration test, [4,7,8].

First discussing the unreinforced foundation bed case as per Fig. 4a), as the eccentricity angle is 5 degrees, the peak displacement amplitude at resonance condition is ie. 169.770 µm (ie. 0.169mm) as shown in Table 2 where µ refers to the usual mathematical power of 10^{-6}. As the eccentric angle is increased thus resulting in larger dynamic loading, the peak displacement increased to 190.705 µm thus creating larger ground amplitude as shown in Fig. 4a) and in Table 2.

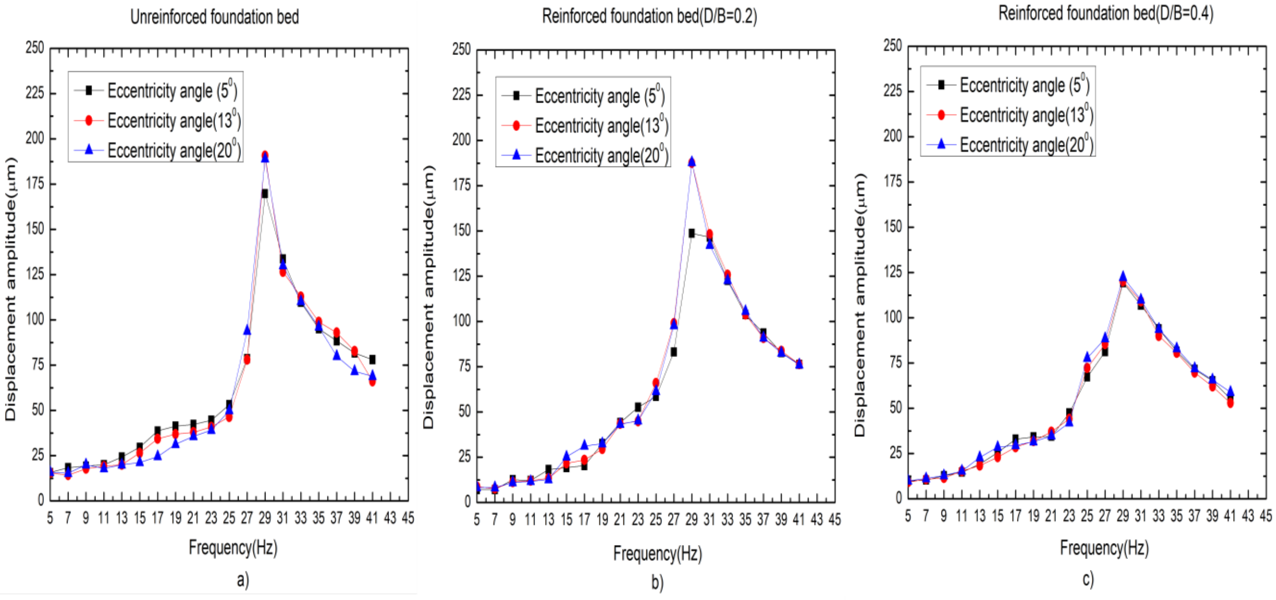


Fig. 4 -Displacement amplitude variation with forcing frequency at different eccentric force settings a) Unreinforced foundation bed; b) Reinforced foundation bed at D/B=0.2; and c) Reinforced foundation bed at D/B=0.4 respectively

A factor δ is defined to depict the effectiveness of the biaxial geogrid reinforcement in reducing the vibration induced displacement amplitude thereby changing the interaction of the soil foundation system. The improvement factor δ is defined in Eq (3) as the ratio between the peak displacement amplitude at resonance condition in case of reinforced foundation bed to the unreinforced foundation bed case.

$$\delta=(Disp)_{Rf}/(Disp)_{Unrf} \tag{3}$$

where $(Disp)_{Rf}$ refers to the resonant displacement amplitude during reinforced foundation bed at D/B=0.2 and D/B=0.4 and $(Disp)_{Unrf}$ refers to resonant displacement amplitude during unreinforced foundation bed

The inclusion of bi-axial geogrid to the foundation bed at D/B=0.2, there is a decrease in the displacement amplitude as shown in Fig. 4b) in case of an eccentricity angle of 5 degrees. The peak displacement amplitude at resonance condition is reduced to 148.681μm (ie. 0.148 mm). The reason behind it is the improvement in the frictional resistance of the soil as offered by the strength of biaxial geogrid. However, the natural frequency is kept almost the same with 0.2m geogrid inclusion. With the increase in the dynamic loading, the eccentricity angle is increased from 5 to 13 and 20 degrees, the decrease in the peak displacement amplitude value is less. The inclusion of a single layer of bi-axial geogrid did reduce the vibration induced displacement amplitude.

With the inclusion of bi-axial geogrid to the foundation bed at D/B=0.4, the significant decrease in the peak displacement amplitude, as shown in figure 4c). The decrease in the displacement amplitude is due to the lateral resistance offered by the bi-axial geogrid inclusion. The resonant displacement amplitude from Fig. 4c) and Table 2 decreased to 119.403 μm (ie. 0.119mm) which is significant in terms of as reinforced foundation bed is changing the interaction of soil foundation system. Further increasing the dynamic loading, at an eccentricity angle of 13 degrees, the decrease in peak displacement amplitude from 190 μm to 120.080 μm is much larger. As seen in Fig. 4c) and Table 2, the amplitude reduction is very significant. Increasing further the dynamic loading, at eccentricity angle of 20 degrees, there is also greater amplitude reduction from 189.08 μm in unreinforced foundation bed to 122.455 μm in reinforced foundation bed at D/B=0.4. Thus it can be said the inclusion of a single layer of bi-axial geogrid improved the foundation bed such that the ground vibration got reduced to a significant amount. Indeed, it can be said that at D/B =0.4 is the optimum depth of placement of bi-axial geogrid in reducing the vibration-induced deformation for the present study.

Table 2- Test results for the present study for vertical vibration case on model machine foundation under unreinforced and reinforced foundation bed with a single layer of bi-axial geogrid inclusion

Eccentric settings	**Unreinforced foundation bed**		**Reinforced foundation bed (D/B=0.2)**		**Reinforced foundation bed (D/B=0.4)**	
Angle	**Resonance displacement amplitude**	**δ**	**Resonance displacement amplitude**	**δ**	**Resonance displacement amplitude**	**δ**
(Degree)	(μm)	-	(μm)	-	(μm)	-
5	169.770	1	148.681	0.875	119.403	0.703
13	190.705	1	187.590	0.983	120.080	0.587
20	189.018	1	187.890	0.99	122.455	0.647

It is clear from the results as seen from Fig. 4a), b) and c) and Table 2, that the inclusion of the single layer of bi-axial geogrid at different depth can reduce the ground vibration to a significant amount thereby altering the soil foundation interaction. The bi-axial geogrid has greater tensile strength and stiffness and causing greater friction resistance between geogrid and soil thereby improving the lateral resistance of the reinforced foundation bed. The present study confirming the utility of bi-axial geogrid in improving and controlling the vibration-induced deformation.

4. Conclusion

Due to urbanization and an increase in the construction activity, near to residential buildings, the use of multi-story buildings and installation of heavy machines which may create strong vibration during its operation at high frequency. This experimental study is an attempt to understand the vertical vibration problem of machine foundation and that should be duly acknowledged in the design for machine foundation. Large scale field model test was conducted on a model foundation of square section over reinforced soil bed with the inclusion of the biaxial geogrid at different depth. The problem of soil-foundation interaction is visible from the test results as the value of displacement amplitude of the soil gets significantly reduced with geogrid reinforced foundation bed under the variation of dynamic loading. The use of bi-axial geogrid in controlling the vibration-induced vertical displacement of the reinforced foundation bed is clearly evident from the present study. Further research, is needed in this direction, to fully understand the soil foundation interaction under a reinforced foundation bed.

5. Acknowledgements

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