Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Evaluation of Non-linear Response of Block Foundation Subjected to Vertical Vibration

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Abstract. Dynamic tests subjected to vertical vibration were conducted on a small-scale block footing of aspect ratio (L/B = 1.0) and depth of 0.5 m resting on the ground surface. The tests were conducted under a static load of (W_S) 6.6 kN to determine the dynamic amplitude responses for different excitation intensities. The theory of non-linear vibrations was used to back-calculate the dynamic non-linear responses from the experimental response curves. The non-linear responses indicate the disparity in the undamped natural frequencies with vertical translational amplitudes. It was observed that the approach well anticipates the non-linear characteristics of the frequency amplitude responses of the soil-foundation machine oscillator system.

Keywords: vertical vibration; machine foundations; non-linear response; field tests.

1 Introduction

Developing effective and economical designs for footings subjected to dynamic loads has become more critical in recent years. The detrimental effects of vibrations emanating from larger machines and industrial installations have been the primary concern for industrialists and geotechnical engineers. In this regard, various studies have been reported on the dynamic response of machine foundations for the last 60-70 years. However, several researchers conducted analytical and experimental investigations over the previous few decades. The vibration of soils and foundations has led to the development of fundamental methods for formulating soil-foundation systems. The conceptual machine foundation design limits the vibrational amplitudes so that the satisfactory operations of the machines and the people working in the immediate vicinity remain unaffected by the impact of vibrations. The vibration studies are essential as the dynamic properties of the soil play a crucial part in the overall response of foundations (shallow and deep). Various researchers have made significant contributions to geotechnical engineering, considering the dynamic soil properties of foundations subjected to machine-induced vibrations (Gazetas 1983; Novak 1987; Baidya 2000; Baidya and Rathi 2004) that showed the non-linear behavior in the dynamic response of the block foundations.

The small-scale field tests help to examine the behavior of block foundations subjected to dynamic loads. The field tests are also conducted to avoid spurious reflection of waves often present in the laboratory tests in the tank due to the boundary zone effect. Among various researchers and experimental studies reported in the literature, Novak and Beredugo (1972) conducted field tests on two blocks at different embedment ratios and densities of the backfill soil under vertical vibration. Beredugo (1971) observed strong nonlinearity in the soil-foundation system. The experimental results were compared with Baranov's analytical approach, and it was reported that the analytical approach overestimates the resonant amplitude. In the current research work, an attempt has been made to analyze and investigate the dynamic non-linear response of the small-scale surface block foundation subjected to machine-induced vertical vibrations. The non-linear approach proposed by Novak (1971) was used to evaluate the effective mass with dynamic impedances, i.e., stiffness and damping from the experimental response curves. The dynamic frequency-amplitude curves were back-calculated by the theoretical approach and compared with the field test results.

2 Geotechnical Characterization of Site Soil

The test location identified between Block II and Block III at IIT Delhi, New Delhi, India, was characterized with the help of various field and laboratory tests. SPT and MASW tests obtained the geotechnical properties of the site, and it was found that the subsurface consists of sands with fines (SM- silty sands and silt mixtures). The soil properties explored to the depth of 5.0 m are presented in Table 1.

Table 1 Geotechnical Characterization of Soil with Depth

Depth (m)	Dry Unit Weight (kN/m^3)	Particle Size Distribution (%)	In-situ SPT-N	*Vs* (m/s)
1	15.23		11	113.36
2	15.34	Sand = 80,	14	113.36
3	16.27	Silt = 18,	15	113.36
4	17.08	Clay = 2	18	128.21
5	17.20		18	128.21

3 Experimental Investigations

The forced vibration tests subjected to vertical loading were conducted on a square (*L/B*) block foundation under a static load of (W_S) 6.6 kN. The dynamic tests were carried out for four excitation intensities (*W.e* = 0.221 Nm, 0.868 Nm, 1.450 Nm, and 1.944 Nm). The dynamic forces were induced on the block foundation using a Lazan-type mechanical oscillator connected with a flexible shaft to the DC motor. The vibration responses were recorded using the data acquisition system connected with the uni-directional accelerometers for frequency intervals of 5Hz. The vertical vibration test setup for the surface block foundation is shown in Fig. 1.

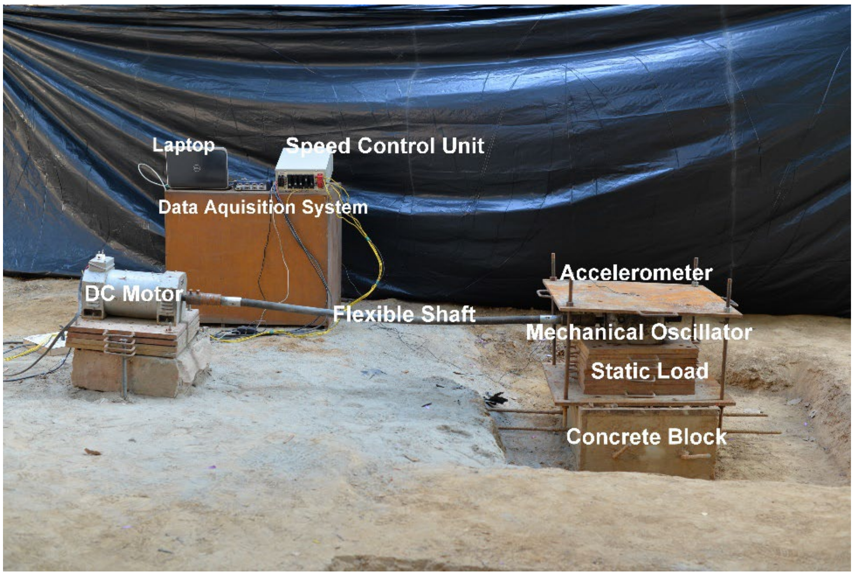

Fig. 1. Experimental Test Setup for Vertical Vibration

4 Theoretical Investigations

A typical feature of non-linear vibration is the resonant frequency and amplitude change with different excitation intensities. The experimental frequency amplitude responses determine the effective mass and dynamic impedances. The non-linear dynamic responses were back-calculated using Novak's theory of non-linear vibration from experimental response curves. It can be established from experimentally obtained frequency response curves that the undamped natural frequency of the soil-foundation oscillator system reduces with the increasing amplitudes of vibration. The undamped natural frequency was calculated from restoring force and the damping force. The restoring force was assumed to be non-linear, whereas the damping force was linearly viscous. The restoring force was calculated using Eq. 1

$$\Omega = \sqrt{\omega_1 \omega_2} \tag{1}$$

where, ω_1 and ω_2 are the undamped frequencies corresponding to the interaction points between the experimental response curve and a line passing through the origin.

The present study considers the non-linear frequency-amplitude response obtained from dynamic field tests (L/B = 1.0 and h/H = 0) for a static weight of 6.6 kN. The backbone curve $\Omega(A)$ for each frequency amplitude curve is constructed by intersecting the response curves by a trace of lines, as shown in Fig. 2. It is observed from each response curve that the impedance of the machine-foundation soil oscillator system varies with the degree of eccentricity and its respective excitation moment. The results reported are based on the equivalent linearization of both damping and restoring forces, known as the first approximation accuracy. The steady-state harmonic force excitation amplitude proportional to the square of the frequency was considered, and the vertical stiffness was expressed for the translational amplitudes A. The vertical damping and effective mass were determined (Novak 1971) using the geometrical properties of the non-linear response curves. The effective mass (m_{eff}) was found to be greater than the mass of the foundation loading system ($m_s = W_{st}/g;$ W_{st} is the total mass of the foundation, including steel plates, ingots, and the exciter) as the surrounding soil participates in the dynamic analysis of the foundation. The apparent additional mass in terms of the mass coefficient is expressed as

$$\xi = \frac{m_{eff} - m_s}{m_s} \tag{2}$$

The restoring force characteristics and effective mass were also calculated from the backbone curve Ω for each response curve. The typical non-linear force-displacement characteristic curve is shown in Fig. 3. The effective mass, stiffness, and damping for different eccentric moments determined from the backbone curves are given in Table 2. It can be observed from Table 2 that the vertical stiffness of the soil-foundation oscillator system decreases with an increase in the excitation force. It can also be seen from Table 2 that with the increase in the eccentric moment, the vertical damping values increased; however, the vertical stiffness values and the effective mass reduced with higher eccentric moments. The frequency amplitude curves are back-calculated using the non-linear theoretical approach. The curves are obtained from the calculated soil-foundation oscillator system mass, vertical damping, and restoring force characteristics. The calculated response curves using the inverse problem are then compared with the dynamic field test results, as shown in Fig. 2. It can be noticed that the theoretical back-calculated response curves match well with the test data obtained from the vertical vibration test. So, it can be concluded that the non-linear parameters obtained from the theoretical analysis for foundations resting on the ground surface and partially or fully embedded (Novak 1971) are accurate enough to be considered in the response analysis.

Table 2 Non-linear parameters of block foundation soil-oscillator system under vertical vibration

Exciting Moment (Nm)	Mass of the Soil-foundation system, m_s (kg)	Mass m_{eff} (kg)	Mass Coefficient, ξ	Damping	Stiffness (kN/m)
0.221	1008	1182.559	0.17317	0.147	4.33E+07
0.868	1008	1173.645	0.16433	0.135	4.00E+07
1.450	1008	1165.511	0.15626	0.136	3.97E+07
1.944	1008	1124.959	0.11603	0.138	3.42E+07

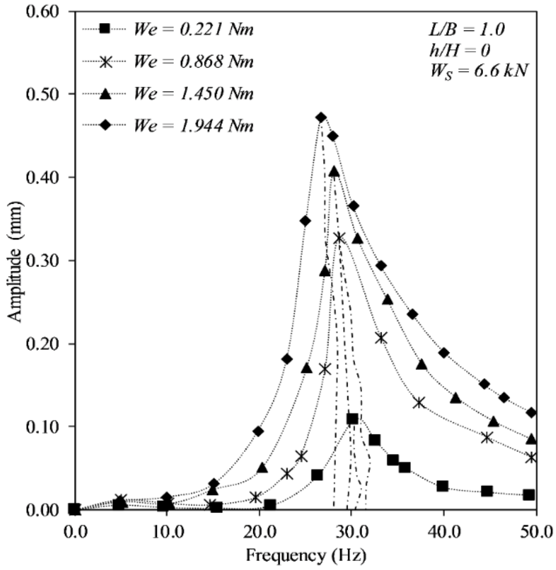

Fig. 2. Experimental and back-calculated response curves of block foundation (*L/B* = 1.0) subjected to vertical vibration

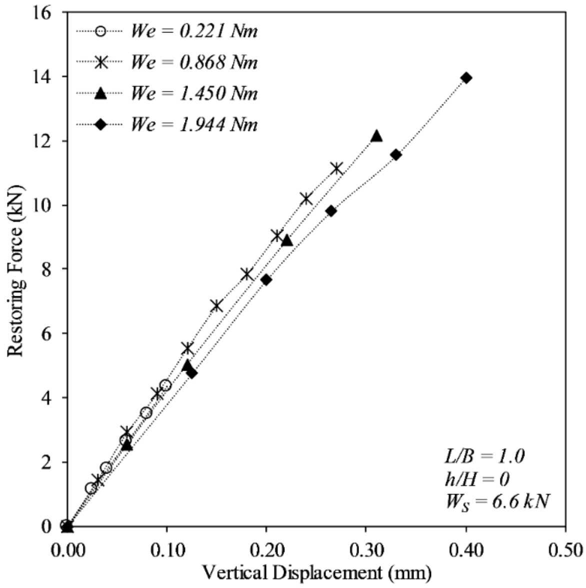

Fig. 3. Non-linear force characteristic curve for square block foundation resting on the ground surface (W_S = 6.6 kN)

5 Conclusions

The present study measured the dynamic responses, and the frequency-amplitude response characteristics were evaluated for machine-induced vertical vibration. Based on the vertical vibration test results on the surface block foundation, the following interpretations were drawn:

1. The experimental response curves agree with the theoretically obtained response curves.
2. The force characteristics curve represents the non-linear behavior of the foundations as the decrease in resonant amplitudes and increases in resonant frequency is observed with the increase in excitation level.
3. The impedance characteristics, i.e., dynamic stiffness and damping parameters obtained from the frequency-amplitude curves, also indicate the non-linear behavior of the foundation.

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