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DYNAMIC ANALYSIS OF SINGLE BATTER PILE USING DIFFERENT SOIL MODELS

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Abstract

Modelling of dynamic soil-pile interaction behavior is very complex. Different soil models have been proposed to model the complex soil-pile behavior under dynamic loading. Applicability of different soil models for dynamic loading is very limited for batter piles. To study the dynamic response of batter pile, three different soil models are used; (i) Linear Model : This model that considers no slippage between the pile and soil; (ii) Nonlinear Model 1: This model that includes a cylindrical zone around the pile with less inner zone soil modulus than outer zone and neglects the inner weak zone soil mass to avoid the wave reflections between the inner zone and outer zone; (iii) Nonlinear Model 2: Nonlinear soil model that uses a nonreflective boundary formed between the inner zone and outer zone to account for the mass of soil in the cylindrical boundary zone.

In this present study the frequency dependent stiffness, damping and amplitude of soil-pile system under vertical vibrations are calculated using continuum approach by Novak with three soil models. A series of vertical field vibration tests were also conducted on a single batter driven pile (L/d =26) of inclination 10 degrees for different eccentric moments (0.449, 0.670, 1.664 and 1.830 Nm) with static load of 12 kN. The effectiveness of the soil models has been checked by comparing the test results with the analytical results obtained using three soil models. It has been observed that the frequency amplitude responses obtained from Nonlinear Model 1 for a precise range of boundary zone parameters are found close to the experimental results. So it can be concluded Nonlinear Model 1 predict the dynamic response of batter pile under vertical vibrations more accurately than Linear Model and Nonlinear Model 2.

Keywords: Batter piles; Soil models; Dynamic loading; Stiffness; Damping; Amplitude; Vertical vibration; Field vibration test; Boundary zone.

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1. INTRODUCTION

Pile foundations are often used to support structures that are exposed to dynamic loads such as earthquakes, wind, wave and machine induced vibrating machines. They are used to large vertical or lateral or combined loads which may be static or dynamic in nature. In situations, where there are excessive lateral and vertical loads coming from the superstructure, batter piles in combination with vertical piles are used to increase the stiffness of soil-pile system.

For the evaluation of the dynamic response of pile foundation involves the calculation of stiffness and damping values of soil-pile system considering the actual soil conditions. Several researchers [1,2,3,4] contributed to formulate and postulate the continuum approach to analyse the dynamic response of pile foundation. The continuum approach was mainly given by Novak and Aboul-Ella [5] for deriving the complex stiffness of soil-pile system of single pile in layered medium [6]. Novak and Sheta [7] later contribute with the development of weak boundary zone around the pile with less shear modulus ratio and increase damping to account for the nonlinearity of the soil-pile system while neglecting the mass of the inner zone to prevent the spurious reflections between the inner and outer zone around the pile. Later Velestos and Doston [8] overcome the assumption given by Novak and Sheta [7] by introducing the mass of the inner zone. Han and Sabin [9] proposed a new model of boundary zone with nonreflection interface in which parabolic variation of the medium properties in assumed (the boundary zone has properties smoothly approaching those of outer zone). Based on this model Han [10] done a parametric study on boundary zone parameter under vertical vibration.

Extensive studies have been done by various researchers on the dynamic behavior of single vertical and group piles under machine induced vibrations. To investigate the dynamic behavior of vertical pile and pile groups and to understand the soil-pile interaction, various full scale and model-prototype tests were conducted by various researchers [11,12,13,14,15,16,17].

From the literature review it is understandable that both the analytical and experimental study on the batter pile under rotating machine induced vertical vibrations are rarely performed. Hence, in this paper with the help of the continuum approach by Novak for different soil stiffness models [6,7,9] are used to analyse the complex soil -pile stiffness of batter pile. To verify the applicability of the proposed model, dynamic forced vibration tests were performed in the field on a hollow steel pipe (*L/D = 26*) with angle of inclination of 10 degrees.

2. CONTINUUM APPROACH

The dynamic response of batter pile is governed by complex interaction phenomenon between the soil and the pile. This complex soil-pile interaction phenomenon can be modeled by using the complex impedance functions where the real and imaginary parameters represent the stiffness and damping of the soil-pile system. The stiffness and damping are calculated based on the assumption that the soil is perfectly bonded to the circumference of the pile and the behavior of the soil is governed by the law of viscoelasticity. The complex stiffness of vertical pile is calculated by using the methodology given by Novak and Aboul-Ella [5].

There is no analytical solution for the calculating the impedance function (stiffness and damping) of the battered pile but they can be established by using the observations made by Poulos and Madhav [20]. They theoretically investigated the static displacement of the battered pile by using the Mindlin’s equation. They applied the axial loads (longitudinal direction) to the battered pile and found out that that axial displacements are almost unaffected by the batter of pile. Only 4 percent was the maximum effect for pile with batter angle up to 30 degrees. So, it can be concluded that the impedance function of the battered pile up to 30 degrees can be calculated using the impedance function by means of dynamic solution available for vertical piles [21]. , the complex stiffness of the batter pile-soil system can be calculated using the stiffness along the local axes of the single vertical pile then transforms the stiffness into the local axes by multiplying the stiffness by a transformation matrix [21] which is given by

$$[K^1_{vb}] = [T]^T [K^1_w] [T] \quad (1)$$

where K^1_{vb} = complex dynamic stiffness of batter pile, [T] is the transformation matrix which depends on direction cosines and K^1_w is the complex stiffness of the vertical pile. With the stiffness and damping of the batter pile, the vertical response of the batter pile is calculated.

To account for the nonlinearity and slippage, the consideration of linear viscoelastic medium can be divided into an outer infinite zone and inner weak boundary zone with reduced shear modulus and higher soil damping as compared to the outer zone. Without any modification in theory, the soil reactions of the composite medium are introduced into the dynamic analysis of batter pile foundation. In this study, three different soil models are used to analyze the nonlinear behavior of batter pile foundation.

- Linear Model: In this model the dynamic complex stiffness function of the soil medium in calculated considering no slippage between the pile and the soil. The complex stiffness of the soil is derived using the solution of the equation of the motion of viscoelastic medium using the hysteric damping which is obtained from the solution of wave propagation of elastic medium [6].
- Nonlinear Model 1: In this model, Novak and Sheta [7] considered a cylindrical annulus of soft soil around the pile which has less shear modulus and high damping than the outer zone. The mass of the inner weak zone is considered as zero ($\rho = 0$) to avoid any wave reflection between the interface of inner and outer zone. This soil model with continuum approach is available in the computer software package DYNA 6 [18].
- Nonlinear Model 2: This model assumes the boundary zone has a nonzero mass and a smooth variation into the outer zone by introducing the parabolic variation function [9]. This type of soil model with continuum approach is programmed in a software named DYNAN [19].

3. EXPERIMENTAL INVESTIGATION

The test site was situated in between Block II and Block III at the Indian Institute of Technology Delhi, Hauz Khas, New Delhi, India. The soil properties were determined by laboratory and in situ tests. Standard penetration tests (SPT) were conducted in the field to determine the N values of soil layers. It is found that soil is predominately sandy silt up to depth 6.0 m. Piles were made of hollow steel pipes of outer diameter (d) 0.114 m and length (L) of 3 m. Initially, a borehole of 0.1 m diameter was made to reduce the resistance of pile driving. The pile was then driven into the ground by dropping of SPT hammer of weight 65 kg from a height of 0.3 m. During driving, the batter angle was maintained with the help of guide rod fixed at required batter angle. A steel plate of dimension 0.9 m × 0.9 m × 0.037 m was used as a pile cap which was connected rigidly with the pile. Forced vertical vibration tests were conducted on model single batter pile (β = 10°). The dynamic forces are produced by Lazan type mechanical oscillator in the form of harmonic motion. Two counter rotating-mass are moved inside the oscillator to develop the dynamic forces on the pile. The amplitude of the dynamic force was controlled by adjusting the eccentricity (θ) of the rotating masses. The excitation force, $P(t)$, is given by

$$P(t) = m_e.e.\omega^2 sin\ \omega t = (W_e/g).e.\omega^2\ sin\ \omega t \quad (2)$$

where, W_e and me are the weight and mass of eccentric rotating parts of the oscillator, respectively, e is the eccentric distance of the rotating masses, g is the acceleration due to gravity and ω is the circular frequency of vibration. The magnitude of the exciting force was changed by adjusting the angle of eccentric mass. The mechanical oscillator was connected by means of a flexible shaft with a DC motor and the speed of DC motor was controlled by a speed control unit. The oscillator was run slowly through a motor using speed control unit. Mild steel plates of size 0.5 m × 0.5 m × 0.022 m were placed on the pile cap to provide

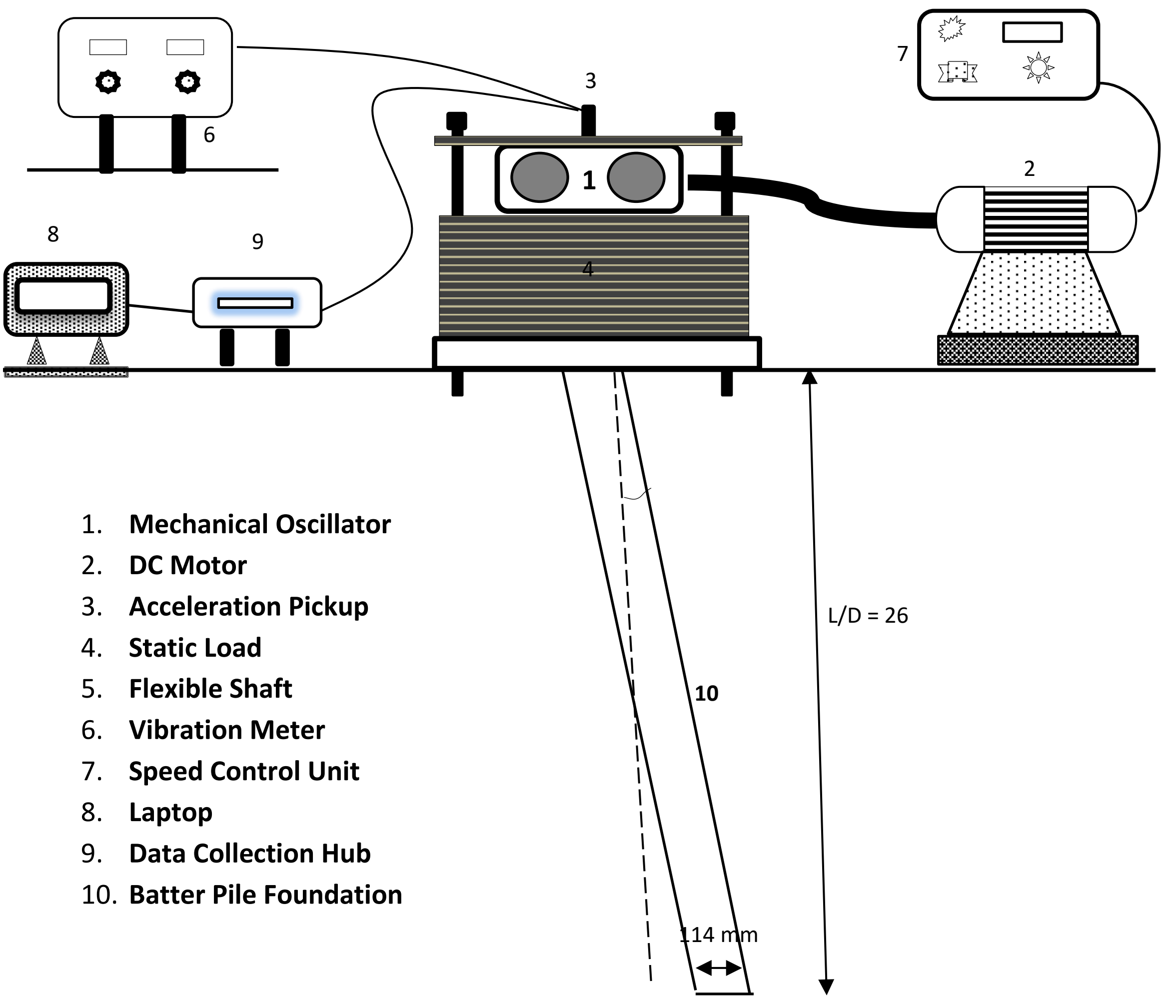

Figure 1: Schematic diagram of vertical vibration test setup in batter pile (L/D = 26, β = 10°)

desired static weight. Then the mechanical oscillator assembly was mounted on the top of the steel plates in such a way that the oscillator imposed a vertical harmonic excitation force on the pile foundation. The whole assembly was properly tightened with the pile cap using four bolts so that it could act as a single unit. The accelerometer was attached vertically on the top of the plate over the center of the pile cap. Tests were conducted for four different eccentric moments ($W_e.e$ = 0.449, 0.670, 1.664, and 1.830 N m) with the static load (Ws) of 12 kN. The complete vertical vibration test set up is shown in Fig. 3. The experimental frequency-amplitude response curve of single batter pile for different eccentric moment is shown in Fig.

2. It is observed from the dynamic test results that the measured frequency-amplitude response curve exhibits nonlinear behavior by showing decrement in resonant frequencies and disproportional increment in resonant amplitudes with the increase in excitation moments.

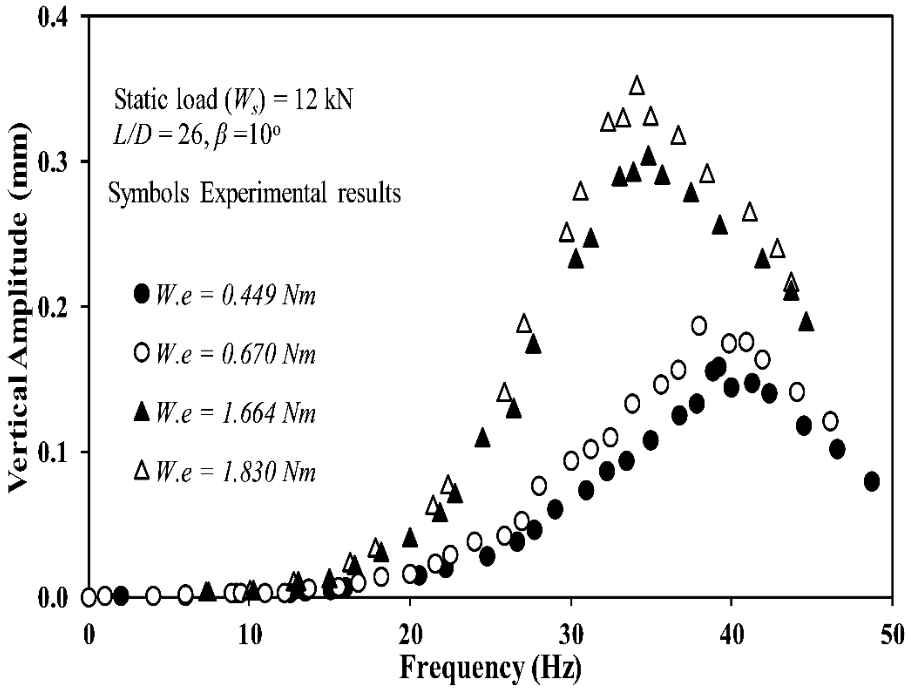

Figure 2: Experimental frequency versus vertical amplitude response of single batter pile

4. COMPARISON BETWEEN THE EXPERIMENTS AND THEORETICAL RESULTS

The test pile on the field has been analysed with all the soil models i.e. Linear Model, Nonlinear Model 1 and Nonlinear Model 2 to get the frequency-amplitude response of the batter pile-soil system. The soil material damping has been assumed 10 percent for the analysis. For different eccentric moments the weak boundary zone parameters were adjusted so that the nonlinear theoretical response curves match closely to dynamic field test data. For the current soil conditions and applied dynamic load, G_{ws}/G_s varied from 0.015 to 0.22, T_{ws}/R_i varied from 0.5 to 1, D_m varied from 0.2 to 0.35. The results obtained from the field experiments are compared with the theoretical analysis for eccentric force (*W.e =1.644 Nm*) as shown in Fig. 3.

- Linear Model: It can be well comprehended from the figure that the theoretical resonant frequency is higher and resonant amplitude are lower than the dynamic test result on the single batter pile (L/D = 26, β = 10°). This is due to the assumption that the soil is perfectly bonded to the pile and that the soil behaviour is primarily governed by laws of linear elasticity explicating no weak inner zone resulting in larger stiffness of batter pile-soil system which produces higher resonant frequency and lower resonant amplitude values.

- Nonlinear Model 1: From the comparison, it is observed that Nonlinear Model I show a well-defined match with the test results. Nonlinearity of batter pile foundation is also exhibited from the figure with the increase in the resonant amplitude and decrease in the resonant frequency with the increase in excitation levels.

- Nonlinear Model 2: It can be observed that the Nonlinear model 2 produces high resonant frequency and high resonant amplitude when compared to dynamic test result.

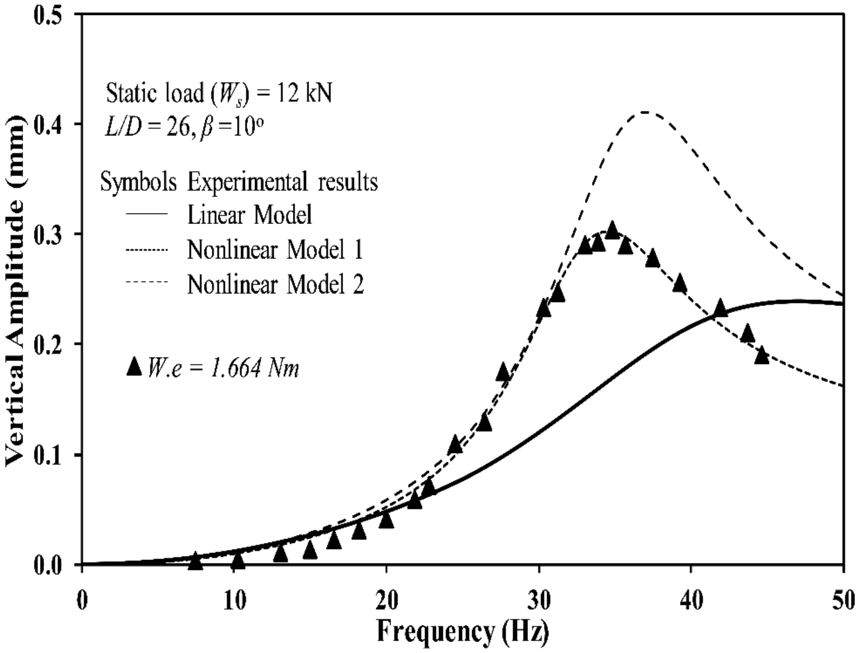

Figure 3: Comparison between the response curve obtained from vertical vibration test and Linear Model analysis

5. STIFFNESS AND DAMPING OF BATTER PILE

The vertical stiffness and damping of single batter pile (*L/d = 26, β = 10°*) with frequency were determined using three models i.e. Linear model; Nonlinear model 1 and Nonlinear model 2 for all eccentric forces. The comparison of variation of stiffness and damping for different models are shown in Fig. 4a and Fig. 4b for eccentric force (*W.e = 1.664 Nm*) respectively. It is found that Linear model highly overestimates both the stiffness and damping of single batter pile. It also shows that frequency dependent stiffness and damping of single batter pile **is** not varied with different eccentric moments showing a single stiffness and damping curves. In Nonlinear Model 1 the frequency dependent stiffness and damping values are decreased with increase of excitation force. This phenomenon occurs due to the development of weak boundary zone between pile and soil. For low frequency range, the stiffness values tend to remain linear showing the dynamic stiffness of batter pile close to static stiffness. However, the damping values of the batter pile increases rapidly as frequency approaches to zero due to the conversion of soil material damping to the frequency-dependent equivalent viscous damping. In Nonlinear model 2 the frequency dependent stiffness is

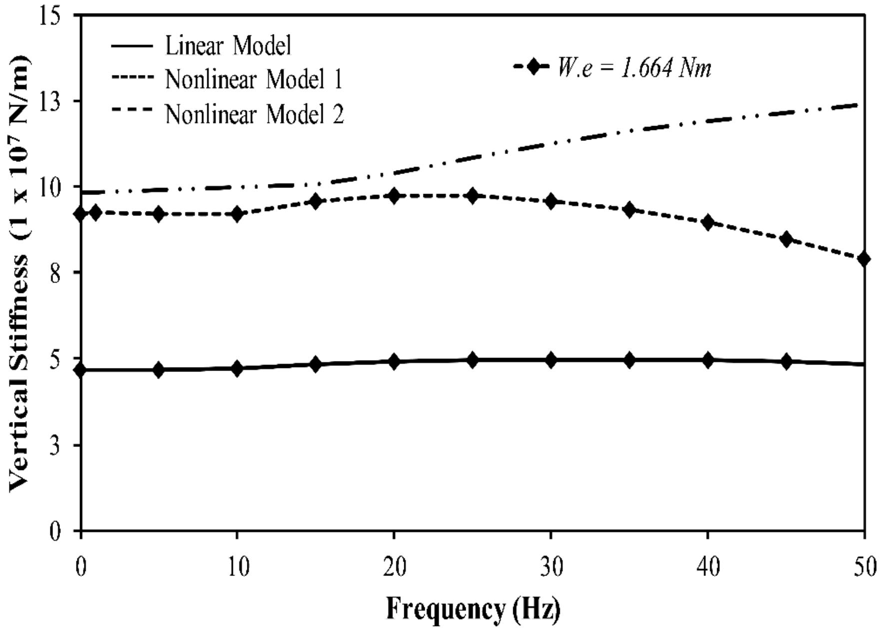

Figure 4a: Comparison of stiffness of soil-pile system obtained from Linear Model, Nonlinear Model 1 and Nonlinear Model 2b

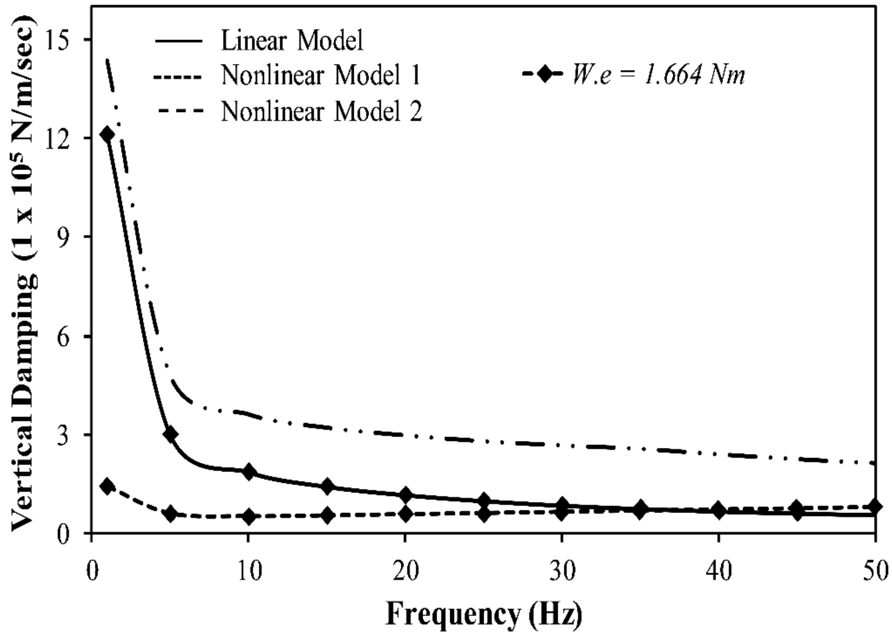

Figure 4b: Comparison of stiffness of soil-pile system obtained from Linear Model, Nonlinear Model 1 and Nonlinear Model 2b

decreased with the increase in the excitation force and the damping values tends to give a small change (overlapping) with the excitation force.

6. CONCLUSIONS

The main objective of the present study is to compare the different soil model i.e. Linear model; Nonlinear model 1 and Nonlinear model 2 to evaluate the frequency-amplitude response of the batter piles subjected to machine induced vertical vibrations. The study also includes the characterization of different soil model and variation of boundary zone parameters of the batter pile-soil system. A field vertical vibration test was also conducted on a on a single batter driven pile (L/d = 26) of inclination 10 degrees for different eccentric moments (0.449, 0.670, 1.664 and 1.830 Nm) with static load of 12 kN. On the basis of the dynamic test result, the effectiveness of different soil models is monitored. The major conclusions for the present study are as follows

- From both the dynamic test data and analysis results it is observed that the measured frequency-amplitude response curves for batter pile ($L/d = 26,\ \beta = 10^o$) shows marked nonlinearity which was manifested by the reduction in the resonant frequency and disproportional increment in resonant amplitudes with the increase in excitation intensity.
- Nonlinear Model 1 accurately predicts the response of the batter pile reasonably well as compared to Linear Model and Nonlinear Model 2 with dynamic test results.
- The stiffness and damping of the batter pile system are decreased for vertical mode of vibration with increase in excitation level. This reduction is primarily due to the development of weak boundary zone around the pile.
- The Nonlinear Model 1 is found capable of predicting the stiffness and damping value of single batter pile reasonably well for vertical mode of vibration with reasonable estimation of nonlinear parameters. On the other hand, the Linear Model and Nonlinear Model 2 was found to be unsatisfactory in this study.
- The nonlinear parameters like shear modulus reduction (G_m/G), damping factor (D_s), thickness ratio (t_m/R) and separation length plays a major role for actual nonlinear response of soil -pile system.

REFERENCES

1. Kobori T, Minai R, Baba K (1975) Dynamic interaction between an elastic cylinder and its surrounding visco-elastic halfspace. In: proceedings of the 25th japan national congress of applied mech, university of tokyo press, tokyo, japan, pp 215–226.
2. Nogami T, Novak M (1976) Soil–pile interaction in vertical vibration. Int J Earthq Eng Struct Dyn 5(3):277–293
3. Novak, m. 1974. Dynamic stiffness and damping of piles. Canadian geotechnical journal, 11(4): 574–598. Doi:10.1139/t74-059.
4. Tajimi H (1966) Earthquake or foundation structures. Report of the Faculty of Science and Engineering, Nihon University, Tokyo City, Japan, pp 1.1–3.5
5. Novak M, Aboul-Ella F (1978) Impedance functions of piles in layered media. J Eng Mech Div 104(3):643–661.

6. Novak M, Nagomi T, Aboul-Ella F (1978) Dynamic soil reaction for plain strain case. J Eng Mech Div ASCE 104(EM4):953–959
7. Novak M, Sheta M (1980) Approximate approach to contact problems of piles. In: O'Neill M (ed) Proceedings of the dynamic response of pile foundations: analytical aspects, New York, ASCE, pp 53–79
8. Veletsos AS, Dotson KW (1988) Vertical and torsional vibration of foundations in inhomogeneous media. J Geotech Geoenviron Eng ASCE 114(9):1002–1021.
9. Han YC, Sabin GCW (1995) Impedances for radially inhomogeneous viscoelastic soil media. J Eng Mech Div ASCE 121(9):939–947.
10. Han YC (1997) Dynamic vertical response of piles in nonlinear soil. J Geotech Geoenviron Eng ASCE 123(8):710–716.
11. Novak M, Grigg RF (1976) Dynamic experiments with small pile foundations. Can Geotech J 13(4):372–385
12. Novak, M., and El Sharnouby, B. (1984). "Evaluation of dynamic experiments on pile groups." Journal of geotechnical engineering, asce, 110 (6): 738-756.
13. Puri, V. K. And Prakash, S. (1992). "Observed and predicted response of piles under dynamic loads." In: piles under dynamic loads (gps 34), asce, 153-169.
14. Manna B, Baidya DK (2010) Dynamic nonlinear response of pile foundations under vertical vibration-theory versus experiment. Soil Dyn Earthq Eng 30:456–469
15. Elkasabgy, M., and El Naggar, M. H. (2013). "Dynamic response of vertically loaded helical and driven steel piles." Can. Geotech. J., 50: 521–535.
16. Biswas, S., Choudhary, S.S., Manna, B. (2013). Prediction of nonlinear characteristics of soil-pile system under vertical vibration. Geomechanics and engineering, an international journal. 5(3) - 2013,223 - 240,
17. Elkasabgy, M., and El Naggar, M. H. (2017). "Lateral vibration of helical and driven steel piles installed in clayey soil." Journal of geotechnical and geoenvironmental engineering, © asce, issn 1090-0241.
18. El Naggar, M.H., Novak, M., Sheta, M., El Hifnawi, L., and El Marsafawi, H. 2011. DYNA 6 –a computer program for calculation of foundation response to dynamic loads. Geotechnical Research Centre, The University of Western Ontario, London, Ont.
19. ENSOFT INC, (2004). DYNAN user's manual, Version 2.
20. Poulus H. G. and Madhav M. R. Analysis of the movement of battered piles. Proc. 1st australia-newzealand conf. Geomechanics, maelbourne, 1971, 1, 268-275.
21. Novak, M. 1980. Soil-pile interaction under dynamic loads. Institution of civil engineers, numerical methods in offshore piling, ice, london 1980, 59-68
22. Han Y, Novak M (1988) Dynamic behavior of single piles under strong harmonic excitation. Can geotech j 25:523–534
23. Vaziri H, Han Y (1992) Nonlinear vibration of pile groups under lateral loading. Can geotech j 29:702–710.