EXPERIMENTAL STUDIES ON NON-LINEAR RESPONSE OF SOIL-PILE-STRUCTURE SYSTEMS SUBJECTED TO STRONG GROUND MOTION

C. S. Goit[1], M. Saitoh[2], H. Kawakami[3] and S. Nishiyama[4]

[1] *Student, Dept. of Civil & Environmental Engineering, Saitama University, Saitama 338-8570, Japan*
Email: zgoit@msn.com

[2] *Associate Professor, Dept. of Civil & Environmental Engineering, Saitama University*
Email: saity@mail.saitama-u.ac.jp

[3] *Professor, Geosphere Research Institute, Saitama University*
Email: kaw@kiban.civil.saitama-u.ac.jp

[4] *Nikken Sekkei Civil Engineering LTD. 2-23, Shimomiyabicho, Shinjyuku-ku, Tokyo 162-0822, Japan*
Email: nishiyama@nikken.co.jp

ABSTRACT:

Dynamic experimental studies of response curves of laterally loaded model soil-pile-structure systems subjected to strong ground motion possesses great importance in understanding the response of actual pile supported structures subjected to the earthquake loadings. Model tests on instrumented pile groups for the non-embedded footing case have been conducted for different configuration of the pile groups to study the response behavior accompanied by the bending and vertical strains subjected to strong ground motions. Two different cases with and without the embedment of piles in the bedrock have been studied. And a third category that comprised without any piles has also been taken in account. Test results reveal that the end-bearing pile system shows the least damping while the system without piles shows the highest damping accompanied by the highest rocking of all the systems studied. The bending and vertical strain profiles are also presented for the pile groups.

KEYWORDS: Response curves, Bending strains, End-bearing piles, Floating piles

1. INTRODUCTION

The response behavior in the form of study of resonance curves of the pile group systems subjected to dynamic loading bears immense importance in understanding the mechanism associated with the soil-pile-structure system. Limited experimental works have been carried out considering the soil-pile-structure interaction systems, like the experimental works on instrumented single piles and pile groups for lateral soil moments, reported by Poulos et. al. (1995) and Chen et. al. (1997). However, to analyze the soil-pile-structure system, along with the pile-soil-pile interaction, the effect of foundation motion and the inertial effect of the superstructure need to be considered. To this end, an experimental work involving shake table test consisting of model soil-pile-structure system for instrumented pile groups with non-embedded footing was conducted considering the base excitation and the results are presented in this paper. The main purpose of this paper is to investigate the effect of length of piles on the response of the system. One more system consisting of footing and superstructure was studied to understand the damping characteristics of the system without piles. Results for the bending and the vertical strain are also presented to understand the load carrying behavior of piles in pile groups.

2. SYSTEMS STUDIED

In the present work, all the experiments have been conducted without the footing embedment condition. Broadly, three systems have been studied. Two systems comprised of pile groups in which one system consisted of end-bearing conditions (referred as full-length piles) while the other consisted of without end-bearing i.e. the floating conditions (referred as half-length piles). The main objectives of these two systems are to study the effect of the embedment of the piles considering the end conditions or in other words, effect of the length of piles. The last type of the system, the third one, consisted of the footing simply resting on the surface of soil with the super-structure without being supported by piles. This system's performance has been focused for the rocking due to the lack of the piles. The major forms of study of the systems have been done in the form of resonance curves, bending strains and the vertical strains. Comparative charts of the all the systems studied are presented providing the response behavior of the systems subjected to the various amplitude of loading through a range of frequency. The bending and the vertical strains for each pile, in group, for different amplitude of loading are also presented.

3. EXPERIMENTAL SETUP

The experimental setup consisted of soil-footing-pile system cased by laminated shear box (1200mm x 800mm x 1000mm) bolted to the one degree of freedom shake table owned by Saitama University. A square acrylic footing (300mm x 300mm x 98mm) with nine piles having piles with center - center spacing of four times the diameter of pile was used in the experiment. Solid acrylic piles having the diameter of 30mm were embedded in the homogenous soil layer, modeled by dry Gifu sand, penetrating the bedrock layer for the end-bearing piles as shown in *Figure 1*. The superstructure system, comprising of steel plates of mass 37.52 Kg, was connected to the footing by means of two vertical thin steel plates. Four different amplitudes of lateral loadings – 20 Gal, 50 Gal, 100 Gal, and 200 Gal were utilized in the study, to analyze the system in the low-moderate-high value of the shear strain in the soil mass (1 Gal = 0.01 m/sec^2). The data for the frequency range of 4 ~ 35 Hz were recorded to capture the resonance of structure as well as of the soil.

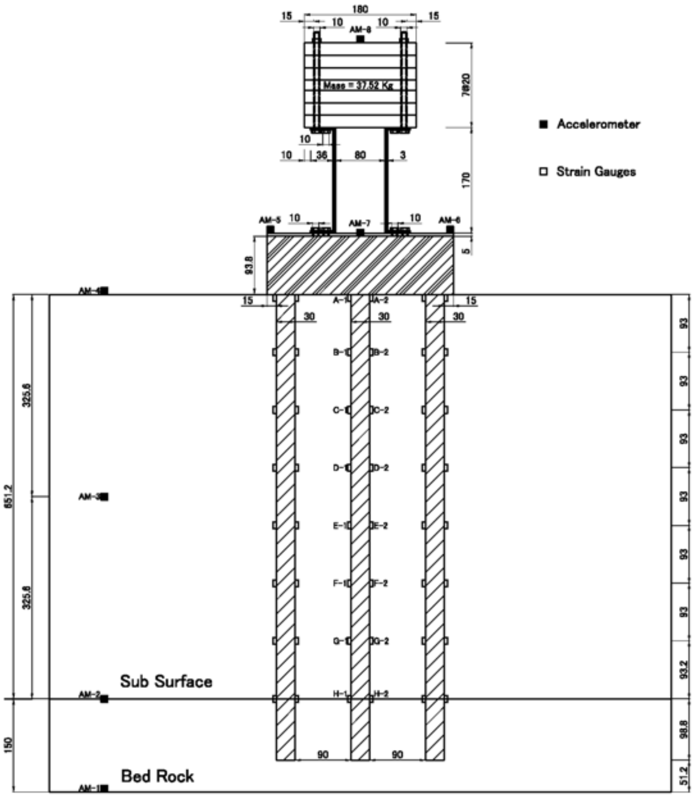

Figure 1: Experimental Setup for end-bearing piles

The experimental work was taken as the scaled model of a bridge-pier-footing system. The similitude law of *Kagawa (1978)*^{2} was used in deriving the model-prototype relations, considering the ratio of forces acting on the prototype and model, providing the law of similitude for the dynamic testing of a soil structure specimen by the statistical results of dynamic tri-axial tests suggesting that the loading frequency relationship between the model and the prototype as

$$\frac{\omega_m}{\omega_p} = \lambda^{3/4} \qquad \text{……………………………..} \; (1.01)$$

where, 'ω_m' is the loading frequency of the model, 'ω_p' is the loading frequency of the prototype and 'λ' is the ratio of prototype to model in linear dimension. The scaling factor for the model in comparison to the prototype was adopted as 0.0375, i.e. the model was 26.67 times smaller than the prototype.

The dry sand, as named earlier, used in this study was Gifu sand, commonly found in Japan. The standard properties of sand consisted of Poisson's ratio of 0.45, the specific gravity of 2.643, the coefficient of uniformity of 1.126, the internal angle of friction of 27.50° with maximum and minimum void ratio of 1.126 and 0.717 respectively. The gradation curve showed D_{60} = 0.350 mm, D_{30} = 0.310 mm and D_{10} = 0.220 mm with maximum diameter of particles being 0.840 mm. The soil was modeled as the two layer system namely the bedrock layer and the subsurface layer, both layer being consisted of the Gifu sand with different properties. The properties of these two layers are shown in the *Table 1*.

Table 1: Properties of Soil Layers

Particulars	Bed-Rock	Sub-Surface	Units
Height	150	750	mm
Mass of Sand	218.88	1052.16	Kg
Density	1520.00	1461.33	Kg/m^3
Void Ratio	0.74	0.81	-
Relative Density	94.67	77.60	%
Unit Weight	14.91	14.34	KN/m^3
Max. Shear	33323.90	9039.25	KN/m^2
Shear Wave	148.07	78.65	m/sec

Each set of experiments were instrumented with accelerometers and strain gauges to record the accelerations and bending strain at different locations in the shear box as well as along the model piles and superstructure. The data-recording unit used in the experiment was a digital data recording system NR-600, developed by *Keyence systems*. The software utilized for the recording the data was *Wave Logger Pro*, by the Keyence systems. In total 24 – data recording channels were utilized for the data acquisition at one time. Accelerometers were used to record the acceleration response of the shake-table and the model itself. The numbers of accelerometers utilized in each set of experiments were eight in number. Six out of the eight accelerometers were utilized to measure the linear acceleration whereas two of the accelerometers were used for measuring the rotational acceleration for the footing, to record the rocking mode. Strain gauges were used to record the bending strain imposed on the model piles during the testing. Sixteen strain gauges, 8 on each side of the pile, were used for a one pile's strain measurement, the number being multiplied by the number of piles in the pile group studied.

4. DATA PROCESSING

The recorded data comprised of the acceleration time histories and the bending strain time histories. The data of the acceleration time history has been converted from time domain to the frequency domain using the Fast Fourier Transform (FFT) technique to obtain the frequency response curve of the system. The recorded signals were filtered in the excitation frequency range multiplied by 0.95 to 1.05 to estimate the resonance curves. Finally, the resonance curves are presented in terms of amplification with respect to the respective amplitude of motion as the input motion, termed as the magnification ratio. For measuring the bending strain in real time, the data of bending strain were processed in the time domain. Total samples of 2000 data were analyzed for each pile, and the maximum value of the bending strain and vertical strain were calculated and are presented.

5. RESULTS

5.1 Soil Only

The free field response of soil was obtained in the form of accelerations in the time domain. To determine the resonance frequency of the soil, the test was conducted with only the soil in the shear box, where, a total height of 750 mm of dry Gifu sand was overlaid on the 150 mm of bedrock in the shear box and the testing was done with various amplitude of loadings of 20 Gal, 50 Gal, 100 Gal, and 200 Gal. *Figure 2* shows the response of this soil only case in the frequency domain.

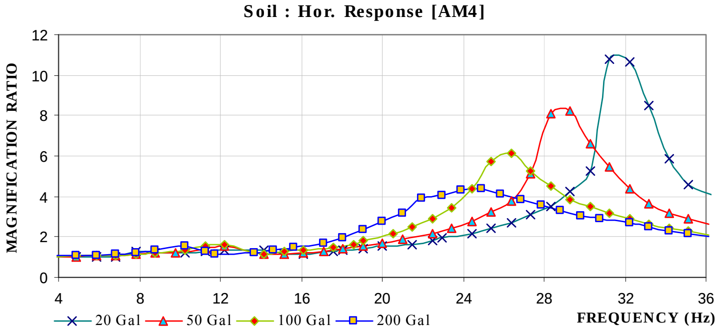

Figure 2: Lateral response of soil

As the shear moduli of soil is a function of the shear strain level, with the increase of the amplitude, the shear strain in soil mass increases, thereby causing the decrease in shear modulus and hence increase in the damping, as can be seen from *Table 2*. The result fits the established relation of the shear modulus and the damping with the increase in the shear strain for the Gifu sand by *Ishida et. al.*[3]. The stiffness of the system decreases with increasing level of shear strain and hence shift of the natural frequency is observed due to this phenomenon. The mean shear strain's value at lower amplitude of loading is of the order 10^{-5} which corresponds to the linear behavior of soil while with increasing amplitude of loading, the shear strain increases thereby showing that the amplitude of loading utilized in this present work is sufficient to induce the non-linear behavior of soil. The following table shows the mean shear strain of surface ground in each of loading amplitude and the corresponding damping and shear modulus of soil.

Table 2: Mean Shear Strain in Soil

Input Acceleration	Predominant Frequency	Magnification Ratio	Mean Shear Strain	Shear Modulus	Damping
Gal	Hz	-	-	KN/m^2	%
20	32.2	10.75	8.07E-05	15678.87	4.65%
50	29.3	8.25	1.87E-04	12981.90	6.06%
100	26.4	6.11	3.41E-04	10539.28	8.18%
200	24.9	4.35	5.46E-04	9375.66	11.49%

5.2 *Lateral Response Curves*

The *Figure 3* shows the lateral response curve of the soil-pile-structure system subjected to increasing amplitude of loading for different configuration of systems. Decrease in the natural frequency of the systems with the increase in loading can be clearly noted showing the strong effect of the amplitude of loading on the systems. This is attributed to the fact of decrease in the shear modulus of the soil with the increase in amplitude of loading accompanied by the increase in the mean shear strain thereby decreasing the stiffness of the systems and increasing the damping. Furthermore, the nature of the resonance curve in the higher amplitude of loading, 200 Gal, reveal that, with the higher shear strain in soil, the curve show flat peaks.

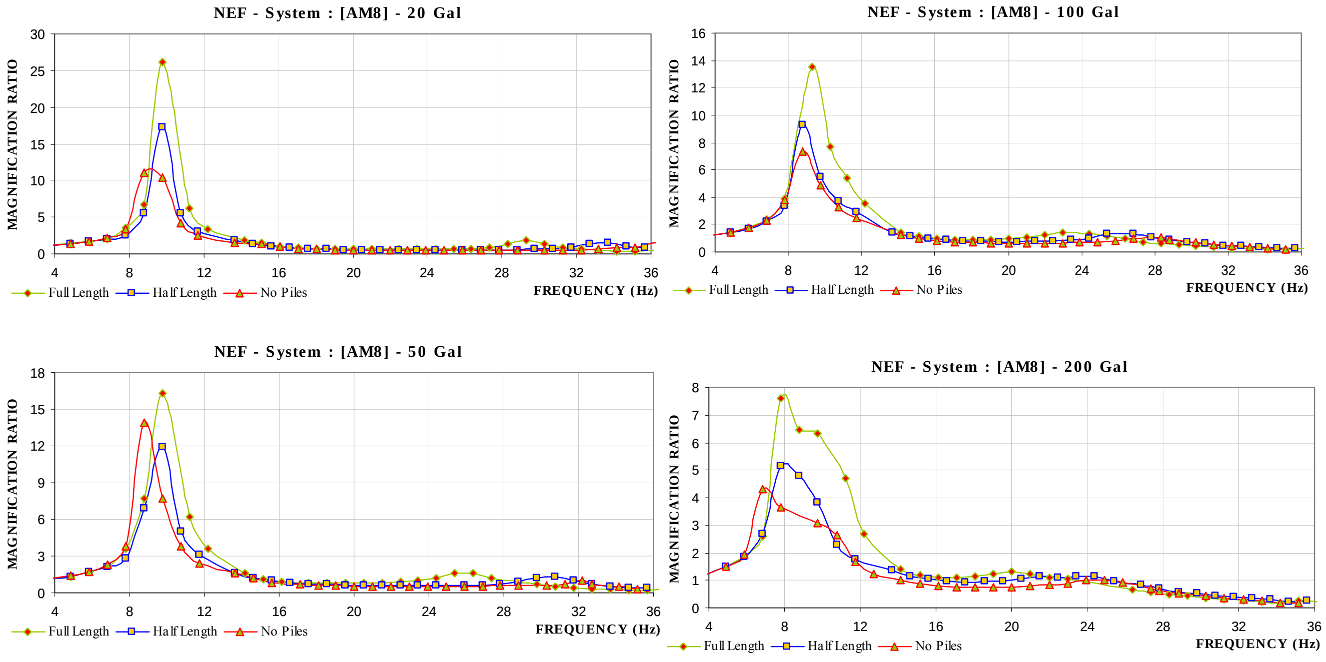

Figure 3: Lateral response curves

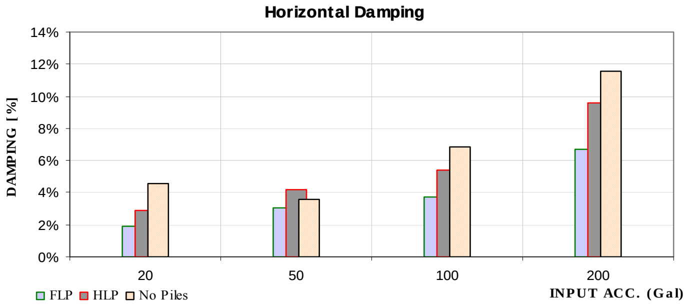

Figure 4: Lateral Damping of Systems

As the bedrock, does not support the half-length pile during all amplitudes of loading, the base of the footing remains in perfect contact with the surface of soil, accompanied by some level of settlement, insuring maximum radiation damping. Thus, at all amplitude of the loadings, the half-length piles show higher radiation damping than the full-length piles. Furthermore, the without pile case shows the maximum damping than the full-length and half-length piles except for the 50 Gal case, which is dominated by the rocking mode, as can be seen from the corresponding rocking response curves presented in proceeding section. Due to the absence of the piles, this system show maximum damping due to the perfect contact at all level of loading between the bottom face of the footing and the surface of soil. *Figure 4* shows a comparative view of damping offered by each system at different amplitude of loading.

Theoretically, in the case of end bearing piles, some component of the load of the superstructure and footing is transferred to the bedrock; the remaining load being taken by the shear force (friction) between the soil and pile. As the length of the pile is longer in comparison to half-length piles, the friction is higher. Thus, due to this, the confining pressure for the soil mass is not affected by the mass of the footing and superstructure and hence, the system shows lower natural frequency i.e. lower stiffness in comparison half-length piles. But, the response curves show that the natural frequencies of the full-length and half-length piles being almost same, without any significant change. Furthermore, the without piles case show lower stiffness, characterized by lower natural frequency, establishing that the stiffness provided by the confining pressure on the surface of soil is not significant in comparison to the stiffness provided by the presence of piles.

5.3 *Rocking Response Curves*

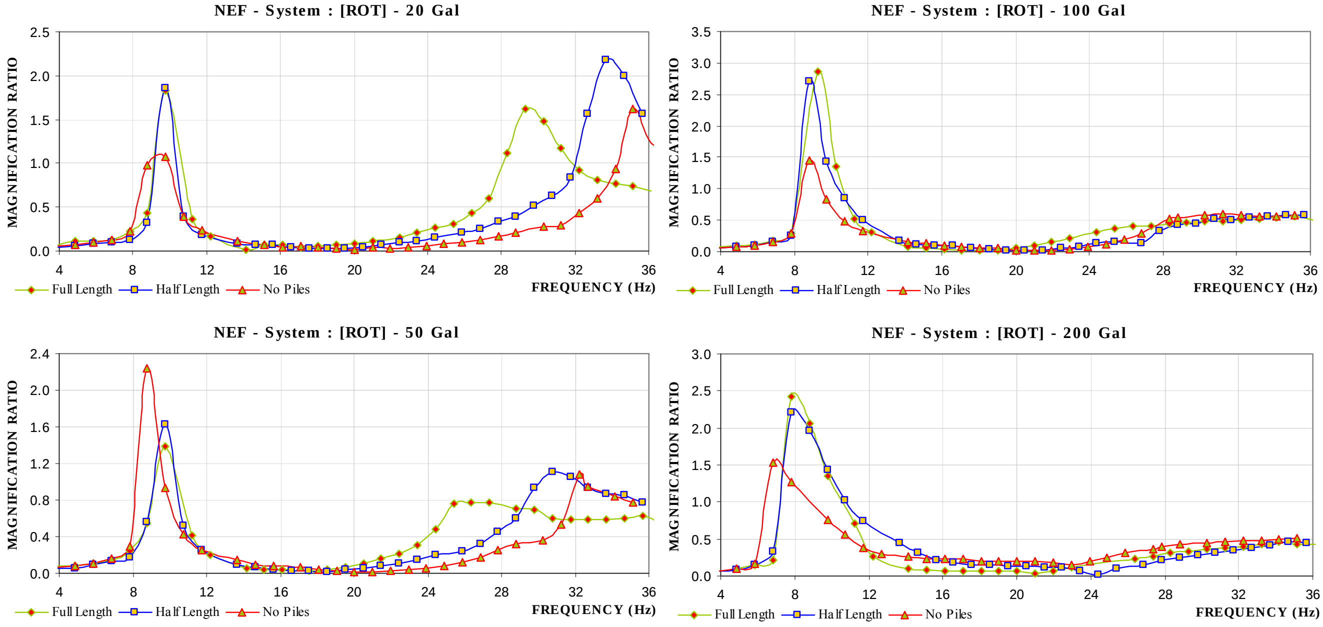

Figure 5: Rocking response curves

Figure 5 shows the rocking response curve of the soil-pile-structure system subjected to increasing amplitude of loading for different configuration of systems. The rocking of system in the region of resonance of the soil can be seen in the case of the 20 Gal and 50 Gal cases, with distinct peaks. But with the increase in the amplitude of the loading, the rocking effect in the resonance frequency of the soil diminishes, showing prominence of inertial effect. The rocking behaviors of the full-length and half-length piles show almost similar nature and almost same magnification ratio. The rocking of no piles case at 50 Gal shows higher value of magnification ratio, thereby showing least rocking damping of the systems analyzed. At all the amplitude except 50 Gal, the no-pile case shows higher rocking damping.

5.4 *Bending Strain Profiles*

As the footing used in this work was symmetric, only the piles marked as in *Figure 6* were used to measure the bending and vertical strain and the same numbering has been used in the proceeding sections of this paper, where the direction of loading in all the cases was maintained from left to right with the configuration as shown.

5.4.1 *End-bearing Piles*

Figure 6 shows the bending strain profiles for the end-bearing or the full-length piles for different amplitude of loadings where the corner pile, pile I shows the highest of the bending strain followed by the pile that is directly in the line of the loading, i.e. pile VI. The strain contrast due to the bedrock layer and the sub-surface layer is seen to have minimum effect on the strain profile, and is only insignificant value at 20 Gal and 50 Gal case.

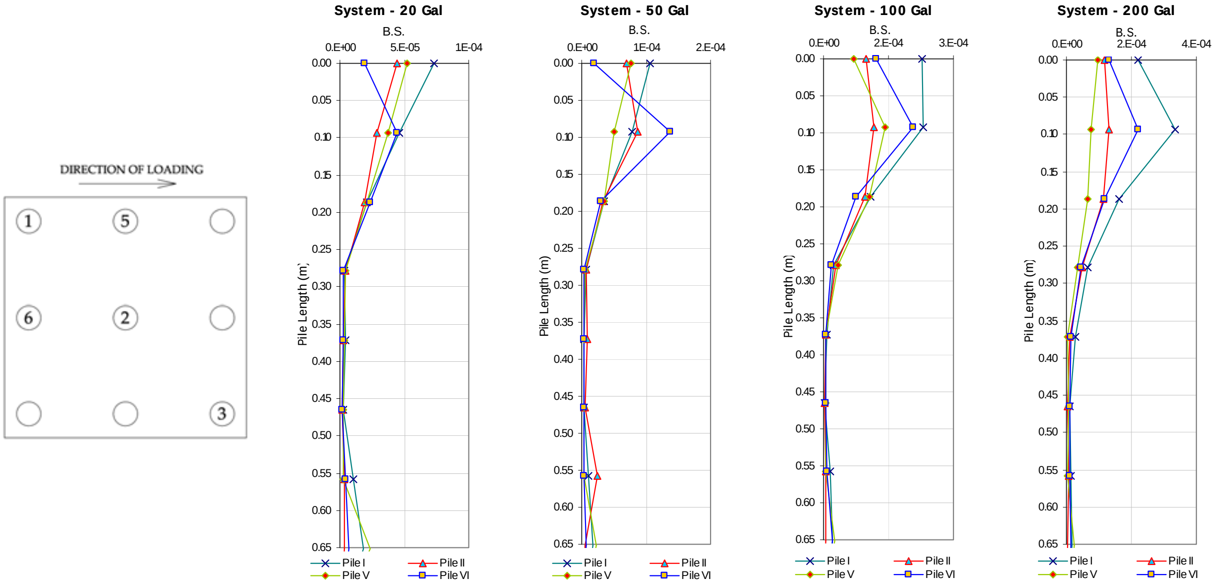

Figure 6: Bending strain profile for end-bearing piles

With the increase in the amplitude of the loading, the shift of the maximum value of the bending strain is seen towards the lower side as seen from the *Figure 6*. This is attributed to the change in the boundary condition at the head of the piles with the increasing amplitude. At the lower amplitude of loading, the soil supporting the superstructure and the footing mass shows higher resistance to the rocking of the footing, but as the amplitude of loading increases, the shear modulus of the soil decreases and the local non-linearity of soil near the footing facilitates the footing to rock. Due to this rocking of the footing, the shift in the maximum value of the bending strain is observed accompanied by higher bending moment acting at the base of superstructure.

5.4.2 *Floating Piles*

The half-length piles show lesser value of bending strain while in comparison with the full-length piles except for a single case of 200 Gal. In this case, as the pile is not embedded in the bedrock, the bending strain developed in the pile shows lesser value in comparison to the full-length piles. Furthermore, also in the half-length piles, the corner piles bear higher bending moment that the other piles in pile group.

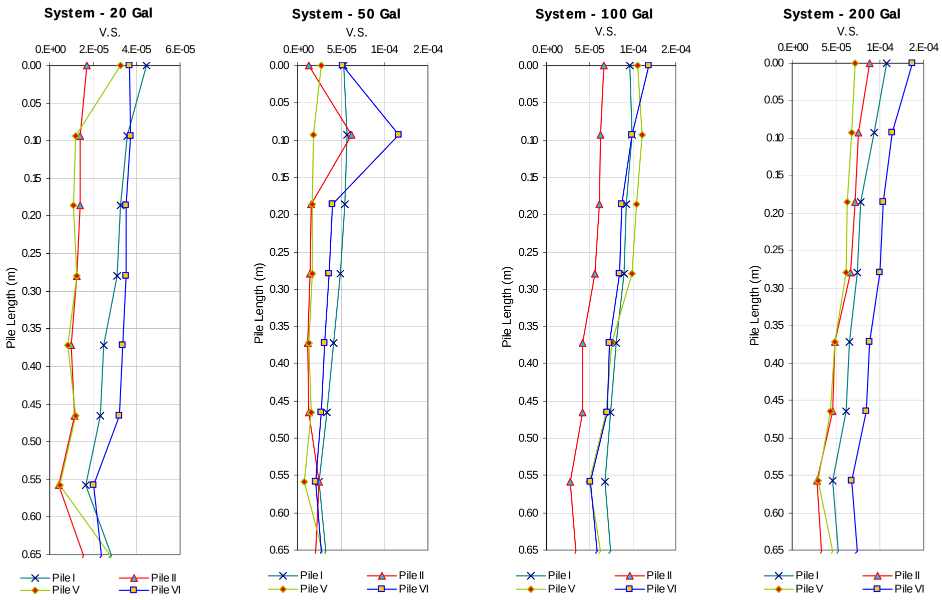

Figure 7: Bending strain profile for floating piles

5.5 *Vertical Strain Profiles*

5.5.1 *End-Bearing Piles*

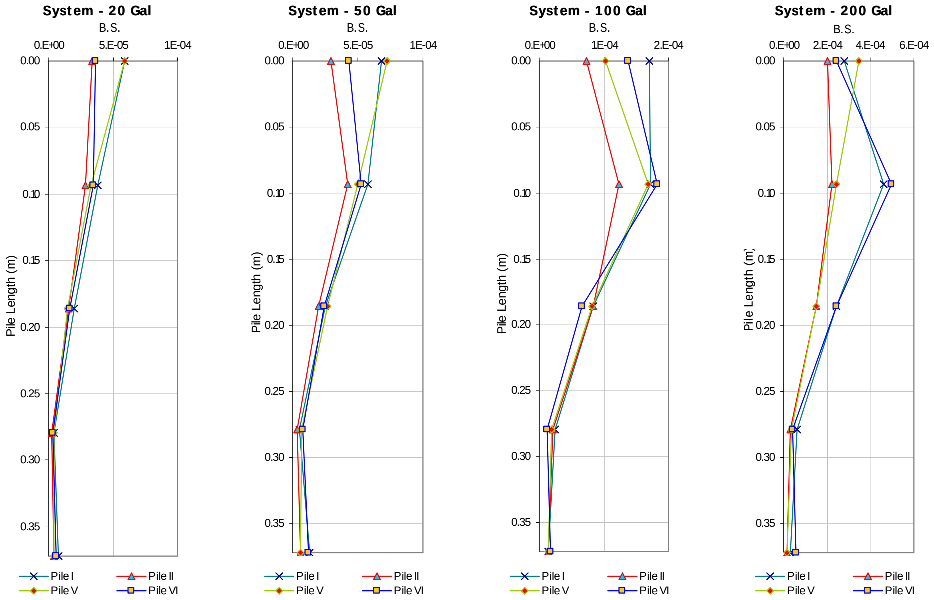

Figure 8: Vertical strain profile for end-bearing piles

The increase in magnitude of vertical strain is seen to be as a function of amplitude of increase in loading, with the maximum value being present at the head of the piles. As the center pile is the axis of the rocking of the footing, pile II shows the least value of the vertical strain in comparison to the others pile in the pile group. The first row of piles, directly perpendicular to the direction of loading, carry maximum load than the other rows. Thus, pile I and pile VI are seen to have maximum value of the vertical strains while comparing with remaining piles.

5.5.2 Floating Piles

As the rocking value is seen comparable with the end-bearing piles, the vertical strain for the half-length piles shows the comparable value with the full-length piles except for the 200 Gal, where, half-length piles show slightly lower value of the vertical strain than that of the full-length piles.

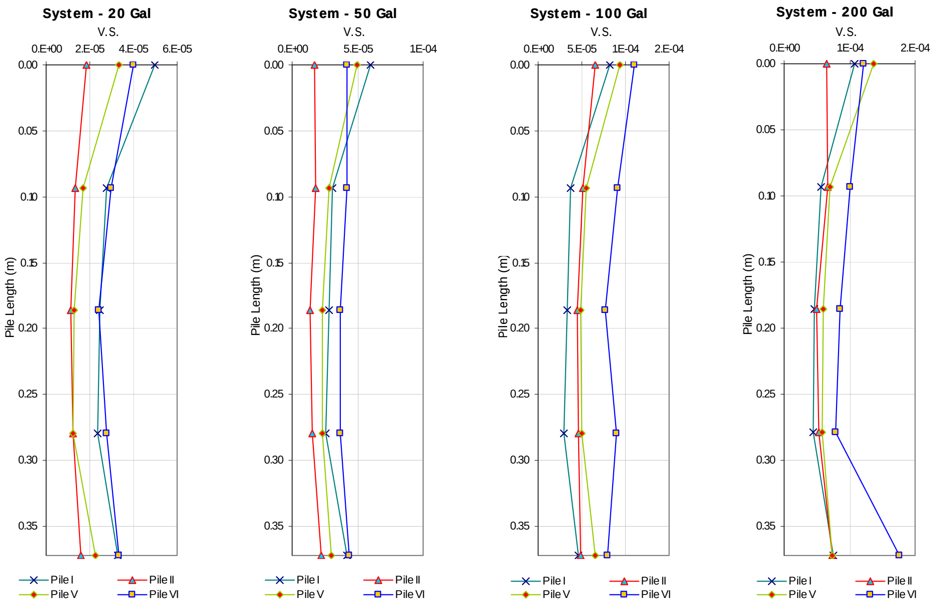

Figure 9: Vertical strain profile for floating piles

6. CONCLUSION

This study presented the experimental results targeted on the study of the effect of non-linearity arising on the soil-pile-structure systems due to the amplitude of loading and the configuration of piles. The wider peaks of the lateral and rocking resonance curves are obtained with increasing amplitude of loading and are found that the damping provided by the system without piles is higher than the half-length piles and the full-length piles, attributed to the radiation damping provided by the contact of base of the footing and the surface of soil, the damping provided by half-length pile being higher than that of the full-length piles. The bending strain profiles of the full-length pile signify that the corner piles carry maximum load, having the maximum value at head of piles at lower amplitude of loadings but the maximum value shifts for higher amplitude of loading due to the change in the boundary condition at the head, caused by the amplitude of loading itself. The center pile shows least bending strain. The half-length piles also follow the same pattern. While in the vertical strain, the center piles maintain the least value but the pile in line with the center pile shows the highest value of the vertical strain. Furthermore, with increasing amplitude, both the bending and vertical strain increases.

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