Group Efficiency Ratio of Pile Groups Subjected to Harmonic Vibration

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Abstract. This paper focus on understanding the behavior of dynamic Group Efficiency Ratio (GER) for different pile groups (3-pile, 2×2, 2×3 and 3×3) under harmonic vibration. The coupled vibration tests are conducted on the pile foundation in the field for varying eccentric moments (0.868, 1.269, 1.631, 1.944 Nm) to obtain the dynamic responses for all the pile groups considered. The pile groups are constructed in field with hollow steel piles of outer diameter 0.114 m and length 3 m. By utilizing continuum approach, theoretical studies are conducted for perceiving the frequency-amplitude responses of all the pile groups. The theoretical responses are found to be well-matched in comparison with the experimental responses. From numerical analysis, the stiffness and damping of all the pile groups has been also established and subsequently GER of the stiffness and damping has been computed which is the ratio of stiffness or damping of pile group to the sum of stiffness or damping of individual pile. The results exemplify that GER for stiffness is reduced below unity, which indicates the reduction in pile group stiffness due to dynamic pile-soil-pile interaction as the number of piles in group increases.

Keywords: Coupled vibration, Boundary zone parameters, Group Efficiency Ratio.

1 Introduction

Recent advancement in industries have upgraded the machine efficiency and thereby its vibration, which will ultimately demand an ideally suited foundation to ensure better stability. In-order to cope with heavy dynamic loads by machines, piles are generally arranged in groups, with varying spacing and configurations. This spacing and arrangement of pile chosen is having a significant role in its dynamic response. Designers generally culminate in dilemma during designing pile groups subjected to dynamic loading, as pile-soil-pile interactions have huge impact on its dynamic response. Therefore, safe and precise estimation of dynamic response of group pile is possible only by considering all contributing factors related to pile-soil-pile interaction in pile group.

Numerous theoretical approaches have been conducted to analyse piles subjected to dynamic loading, out of which boundary method, Winkler's method, continuum approach, finite element method, lumped soil mass model are some of the prominent ones. Continuum approach being a versatile method, several significant studies have been performed (Novak' et al., 1978), (Novak' et al., 1980), (Han & W. Sabin, 1995), (Sinha et al., 2015), (Biswas & Manna, 2018), (Biswas et al., 2022) for understanding the non-linear behaviour of soil-pile system. (Novak & Mitwally, 1990) has proposed a method for analysing group piles utilizing dynamic interaction factors. Later, (Kaynia and Kausel, 1982), put forward a method for estimating dynamic interaction factors using static interaction factors. Experimental studies are mandatory for checking the reliability of analytical response and for attaining the actual response. Several small scale tests had been performed as it is inexpensive. Recently manifold studies (Biswas & Manna, 2018), (Manna & Baidya, 2010), (Goit et al., 2016), (Choudhary et al., 2020) & (Choudhary et al., 2021) have been broadened over different aspects of pile groups to get a better intuition on the dynamic behaviour of group piles.

This paper focusses on the estimation of stiffness and damping of pile group, based on the studies by Choudhary et al., (2020) & Choudhary et al., (2021) for 3-pile, 2×2, 2×3 and 3×3, under coupled vibration. Subsequently, GER (Group Efficiency Ratio) which is referred as ratio of stiffness of pile group to sum of stiffness of individual piles is determined, to acquire an extensive idea about the dynamic pile-soil-pile interaction.

2 Background

2.1 Experimental Study

Field tests were done on pile groups (3-pile, 2×2, 2×3 and 3×3), with a spacing as, 3 times the diameter of pile, under coupled vibration, to estimate the response of soil-pile system. Forced vibration tests were done on hollow steel piles of outer diameter 114mm and length 3m with a thickness of 3mm, under static loads of 12kN. Pile and pile cap were connected using specially fabricated connectors and Fig.1 illustrates the same. As per the SPT test (IS:2131, 1981) performed, the soil around the pile was mostly characterized as clayey and silty soil and detailed soil properties are given in (Choudhary et al., 2020). Fig.2, illustrates the schematic diagram along with its original field set up.

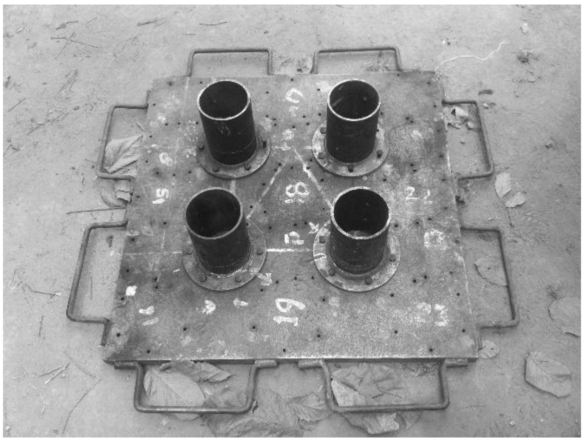
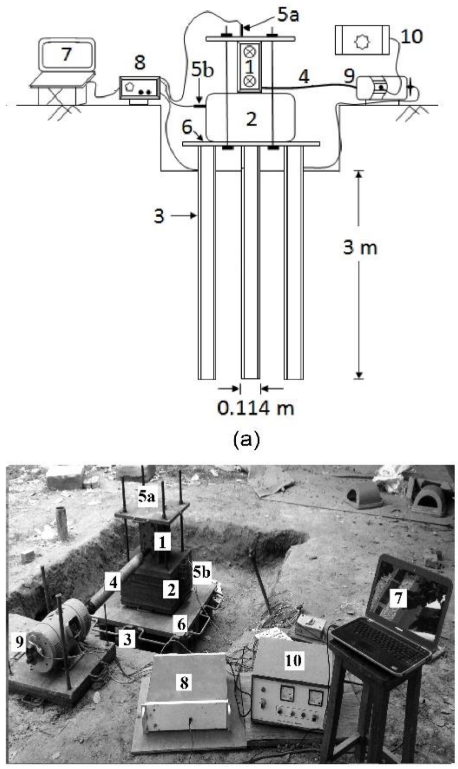


Fig. 1. Illustration of specially fabricated connectors for connecting pile cap with pile



(b)

(1) Mechanical oscillator (2) Static load (3) Hollow steel pile (4) Flexible shaft (5) Accelerometer (6) Pile Cap (7) Laptop with software package (8) Data logger (9) DC motor (10) Speed Control Unit

Fig.2. (a) Schematic diagram of test set up (b) Original field test set up.

From time versus acceleration response, frequency-amplitude responses were acquired for all pile groups under horizontal and rocking modes separately at various eccentric moments of 0.868, 1.269, 1.631, 1.944 Nm. The plots were exhibiting nonlinear behavior with an increased resonant amplitude and decreased resonant frequency for an increasing eccentric moments. Details of the experiments and results are expounded in Choudhary et al., (2020) & Choudhary et al., (2021).

2.2 Continuum Approach

Numerical analysis had been performed on group piles using software DYNA 5, which works based on continuum approach and superposition method. Novak et al., (1974), (Novak & Mitwally, 1990) had estimated stiffness of a single pile and group pile respectively in layered medium by assuming linear elastic behaviour of soil and a perfect bond between soil-pile. For indulging nonlinearity of soil into analysis, model proposed by (Novak and Sheta, 1980) has been used in this particular study.

With a motive on replicating the original field condition, soil-pile separation length was considered along with boundary zone parameters like shear modulus, thickness ratio and damping. Frequency-amplitude responses were obtained for each eccentric moments and boundary zone parameters were adjusted for acquiring a well harmonious behavior between analytical and experimental response. All the analytical assumptions and responses are given in concerned literature.

3. Results and Discussions

3.1. Stiffness and Damping of soil-pile system

Along with frequency-amplitude response, impedance functions of soil-pile system, which comprises of stiffness and damping were also being estimated for both modes of vibrations for all groupings and single pile. Fig.3 and Fig.4 illustrates the plot of impedance functions of single pile in horizontal mode and rocking mode respectively, for different eccentric moments along with frequency.

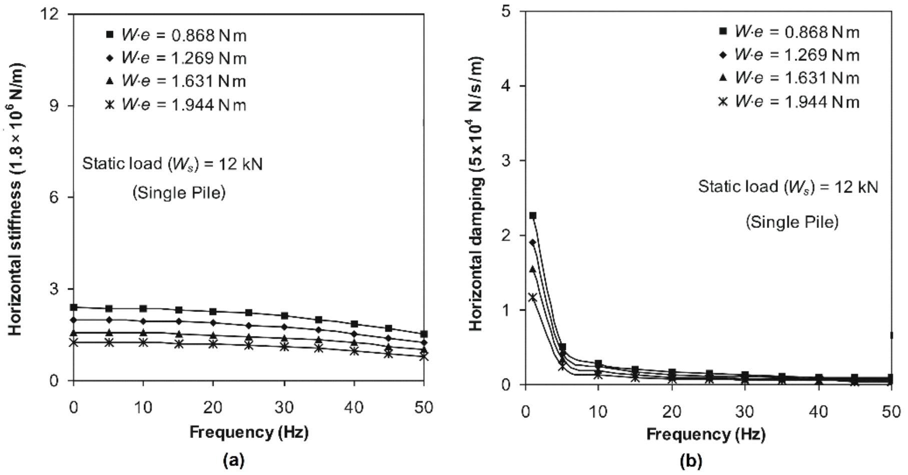


Fig.3. Variation of impedance functions of single pile with frequency for various eccentric moments in horizontal mode of vibration (a) stiffness (b) damping.

From Fig.3, it is noted that, with an increase in eccentric moments, both stiffness and damping is reducing. This reduction in stiffness can be inferred due to loosening of soil-pile bond at higher vibration. However, for an increased frequency, stiffness is exhibiting a gradual reduction and damping has showcased a rapid decrement, with maximum value at lower frequency. In case of rocking mode of vibration Fig.4, both stiffness and damping are decreasing with increasing eccentric moments and responses are similar to horizontal mode of vibration. But, the variation of damping with eccentric moment is found to be trivial, with peak value at lower frequency. Similar pattern has been also observed in all the other pile groups.

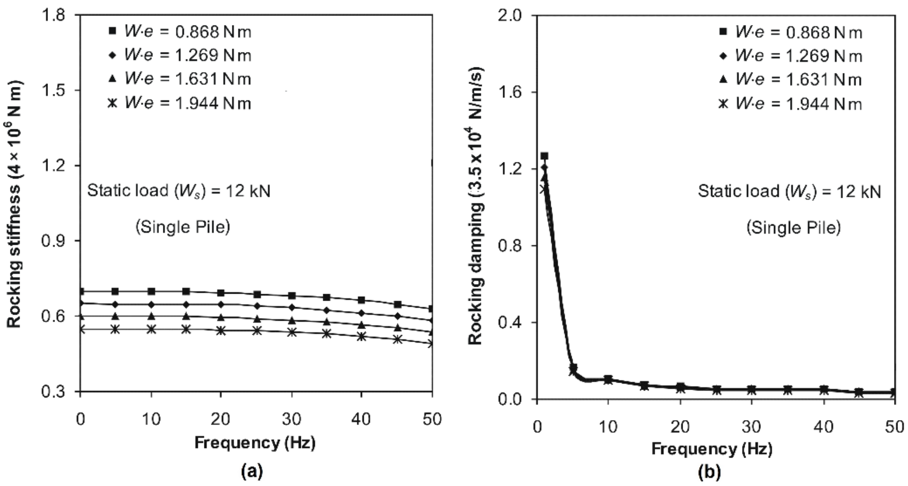


Fig.4. Variation of impedance functions of single pile with frequency for various eccentric moments in rocking mode of vibration (a) stiffness (b) damping.

Stiffness and damping of various modes of vibration for different pile groupings has been studied along with frequencies for a particular eccentric moment as illustrated in Fig.5. Fig.5a shows that, as the number of piles in a group increases, there observed an increase in horizontal stiffness, which is subsequently declining with increasing frequency. This decrement in stiffness can be interpreted due to the loosing of soil-pile bond at higher frequency. However, it is found that horizontal damping is maximum at lower frequency and rapidly decreasing, with an increase in frequency. This exemplifies that, for an increased frequency, frequency independent material damping is changing into frequency dependent viscous damping. The figure also expounds that, as the number of piles in group has a direct influence on damping.

From Fig.5b it is found that, rocking stiffness and damping exhibits same variation as that of horizontal mode of vibration, but in case of rocking stiffness, the response is almost steady for a particular pile group, in spite of frequency increment.

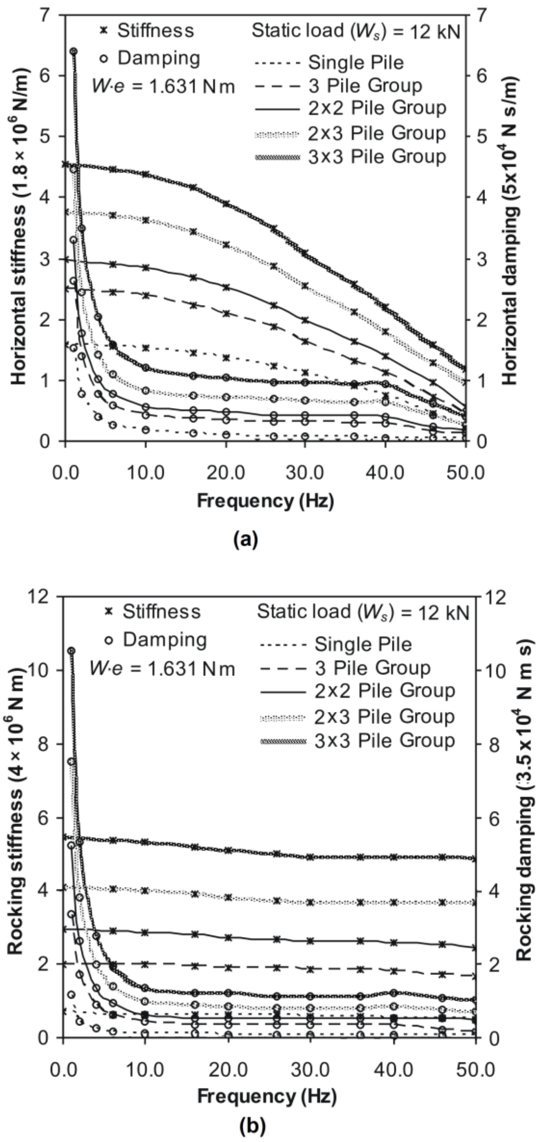


Fig. 5. Variation of soil-pile system stiffness and damping with frequency for various pile groupings (a) horizontal mode (b) rocking mode

3.2. Group Efficiency Ratio (GER)

Group Efficiency Ratio (GER) is a term used to get a better intuition for understanding the impacts of pile–soil-pile interaction on dynamic stiffness and damping in case of group piles. GER can be expressed as following:

$$GER = \frac{Stiffness\ of\ \ pile\ group}{Sum\ of\ stiffness\ of\ individual\ piles}$$

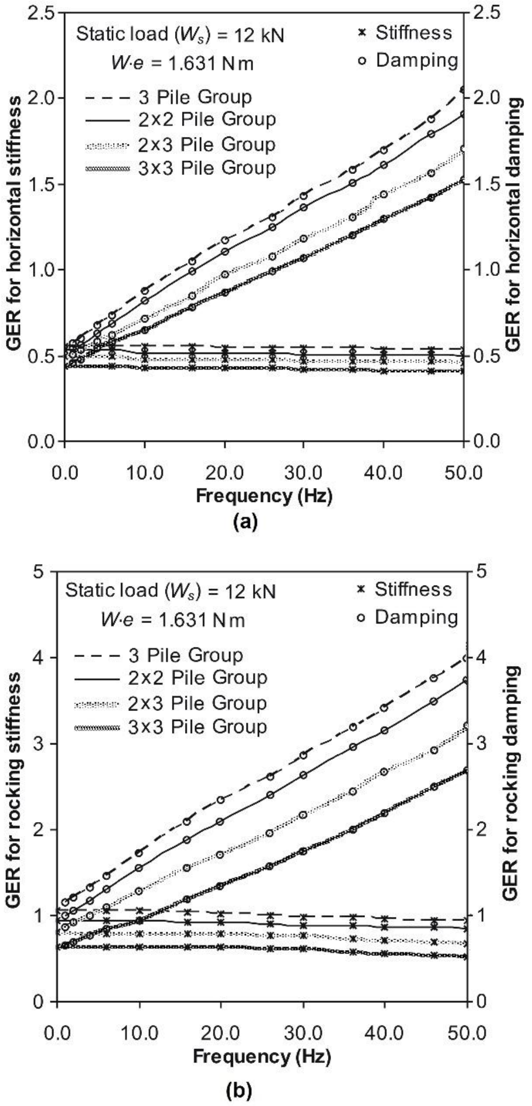


Fig.6. Variation of GER with frequency for different pile groups
(a) horizontal mode (b) rocking mode

The variations on GER for horizontal stiffness / damping and rocking stiffness / damping with frequency are shown in Fig.6. For both modes, plot exhibits decrement in GER with an increase in number of piles. From the plot, it is found that, GER for horizontal stiffness is exhibiting a value less than 1, which depicts that soil-pile interaction has significant impact on the stiffness of pile groups for horizontal motion. However, with regard to GER for rocking stiffness, it is found that values are close to 1, for the frequency range considered in the analysis.

For an increase in frequency, GER of stiffness is reducing and GER of damping is increasing for horizontal as well as rocking vibration, whereas the GER for damping in both cases is increasing to a value higher than 1, which infers that the damping of the group system is increased by pile-soil-pile interaction.

4. Conclusions

This paper has studied broadly about the dynamic response of various pile arrangements under coupled vibration along with its impedance functions. Field experiments and analytical studies to mimic the same response has been performed by Choudhary et al., (2020) & Choudhary et al., (2021). Additionally, this small scale tests details can be used for analysing responses of full scale piles by using appropriate scaling laws available. Further, this particular study has concentrated on understanding the behavior of piles arranged in different pattern. Some of the conclusions are being expounded below:

- Stiffness and damping for both modes of vibration is observed to be decreasing with an increase of eccentric moment. Stiffness reduction can be inferred owing to the loosening of soil-pile bond at immense vibration.
- For an increased frequency, stiffness has been exhibiting a gradual reduction and damping showcased a sudden reduction, with peak value at lower frequency. This can be inferred as the frequency independent material damping conversion into frequency dependent viscous damping.
- The stiffness and damping of the soil-pile system improves with the number of piles in a group for both horizontal and rocking modes of vibrations.
- GER concept is introduced to estimate the out-turn of pile-soil-pile interaction in group piles and it is found that GER for both impedance function decreases with an increase in number of piles in group.
- GER for horizontal stiffness is observed to be less than 1, due to intense soil-pile interaction on group piles, whereas GER for rocking stiffness is found close to 1.
- In case of GER for damping in both modes, it is noted that, with an increase in frequency, GER is increasing to a value more than 1.

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