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# Machine-Induced Vertical Responses of Single and Pile Groups:
## Experimental and Theoretical Study

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## ABSTRACT

The main objective of this study is to understand the dynamic characteristic of pile foundations subjected to machine-based vertical vibrations. To accomplish this objective, forced vibration field tests are performed on hollow steel single and pile group to obtain the vertical responses of the pile foundations. It is found from dynamic frequency-amplitude response curves that the resonant frequencies are decreases and resonant amplitudes are not proportional when excitation forces are increases which indicate the nonlinear characteristics of soil-pile systems. The values of resonant frequencies are found higher and resonant amplitudes are found lower when the number of piles is increased due to an increase in soil-pile stiffness. For theoretical study, the continuum approach method is used to determine the analytical response curves of piles, and further, it is compared with the field test results. To understand the behavior of pile group, the variations of group efficiency ratio with varying frequencies are also predicted form the analysis.

## KEYWORDS

Continuum Approach, Dynamic Field Test, Nonlinear Responses, Pile Foundation, Vertical Vibrations

## 1. INTRODUCTION

In past few decades, the machine induced socioeconomic sector like hydro or nuclear power industries, petrochemical, oil refineries, cement and steel industries has increased. In these machine based industries, most often turbines, turbo generators, rotary compressors etc are used that produce vibratory forces on surrounding area which demands more stable foundation system. Due to stability requirement in the machine based foundation, the uses of piles are found easier and preferred solution. The main concern involved in the analysis of pile under dynamic loading is to predict the nonlinear soil-pile behavior and the impedance parameters (stiffness and damping) of soil-pile models. Now a day, many research works are still going on in the field of pile dynamics. However, limited dynamic field tests were performed on pile foundation under machine based vibrations. Number of analytical methods has been developed for the prediction of dynamic response of pile foundations. To verify the applicability and efficiency of these analytical methods, the experimental investigations are always

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necessary. Last few years, various types of dynamic pile tests were performed. They differ primarily according to the pile size, test medium, and technology. Field tests with full-scale piles were rarely done in practice due to the difficulty of dealing with heavy machinery and cost involvement in the test. However, the small-scale tests on model pile are a reasonably good option of checking the utility and applicability for various available theoretical approaches.

The dynamic vibration tests were performed by El Sharnouby & Novak (1984), Burr et al. (1997), Boominathan & Ayothiraman (2005), Bhowmik et al. (2016), and Elkasabgy & EI Naggar (2018) on piles under machine induced excitations to study the nonlinear behavior of soil-pile systems in terms of frequency-amplitude responses. Goit and Saitoh (2013) conducted an experimental test on single fixed head floating piles with the help of a uniaxial shake table and observed that the nonlinearity influences the response of the soil-pile system. Field and laboratory tests are further carried out by some other researchers (Elkasabgy & EI Naggar, 2013; Sinha et al., 2015; Biswas & Manna, 2018 and Choudhary et al, 2020) who worked in pile dynamics and performed dynamic field tests on piles and compared their results with the nonlinear analytical curves obtained using a continuum approach. It was observed that the analytical results provided a reasonable estimation of dynamic response curves as compared to the field results under machine vibrations. The analytical investigation is also important to predict and determine the necessary information of soil-pile under dynamic loading conditions. Among all analytical methods, continuum approach is found most promising and widely used method by many researchers due to inclusion of nonlinear function in terms of boundary zone and soil-pile separation under dynamic loading. Novak & Aboul-Ella (1978a, 1978b) provided an approximate analytical solution and improve continuum approach function to understand and determine the impedance functions (stiffness and damping) of piles under layered soil media. Novak & Mitwaly (1990) proposed a superposition method with use of dynamic interaction factor concept to determine the response of pile groups for different modes of vibration. Further Saitoh et al. (2016) proposed closed-form solutions based on the superposition method to determine the impedance functions of inclined-pile groups in horizontal and rotational direction using pile to pile interaction factors. Khalil et al (2020) investigated the soil-pile system under dynamic conditions and found that the Novak's approach yields similar trends to those obtained from the finite element model under vertical harmonic loading. From the results it was also observed that the loading frequency has a great impact on the dynamic impedance parameters and the induced amplitudes.

From the literature review, it is concluded that the response of pile foundation resulting from dynamic excitation is a complex phenomenon involving complex soil-pile interaction. Also, limited research and guidelines are available in the area of pile foundation subjected to machine induced vibration. It is also observed that the input soil parameters in terms of boundary zone are responsible for the nonlinear dynamic response of pile foundation when the nature of harmonic vibrations is in an axial or lateral direction, which has not been thoroughly investigated. Therefore, in this study, four different soil-pile setups (single pile, 3-pile group, $2 \times 2$ and $2 \times 3$-pile group) are used to investigate the dynamic behavior of soil-pile systems. The objective of the present study is to understand the rotating machines induced dynamic characteristics of pile foundations subjected to vertical excitations and to measure the boundary zone parameters around the pile and soil-pile separation lengths, which are the unique findings of this investigation. These studies include field tests as well as theoretical analysis. In the theoretical analysis, the dynamic influencing parameters (i.e., the boundary zone around the pile and soil-pile separation) responsible for the nonlinear response of soil-pile systems are thoroughly investigated under different intensities of forces. The machine induced dynamic pile-soil-pile interaction behavior of different soil-pile models is also investigated in terms of stiffness, damping, and group efficiency ratio (GER) with varying frequencies, which is a new addition in the domain of pile dynamics.