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論文の要約

Advancements in the methods of analysis and design of pile foundations have been a subject of much research interest over the years. Various solutions for predicting the response of piles that range from very complex formulations to simple approximate equations are available, providing varying levels of accuracy. However, whether it is a complex formulation or just a simple approximate equation, most of the solutions to predict the behavior of piles are based on the assumption that both the pile and soil behave elastically. Assumption of a pile being an elastic material can be viewed as a valid reasonable approximation, however, consideration of soil as elastic or viscoelastic material might not be a reasonable assumption for all levels of strain in soil, as soil exhibits strain-dependent nonlinear behavior.

A significant amount of work has been carried out for the dynamics of vertical piles, as undoubtedly they are a popular choice for a wide range of structures. Inclined piles (also referred as ‘batter piles’ or ‘raked piles’), on the other hand, are particularly desired for structures demanding substantial lateral stiffnesses, such as offshore structures, bridges, towers etc. The distinct advantage of these piles is that they transfer the imposed load not only through shear and bending as those by vertical piles, but also through axial compression. Nonetheless, for a considerable length of time, the use of inclined piles has been considered detrimental in seismic conditions and is restricted by design codes like AFPS and Eurocode. Encouraging findings about the positive aspects on the performance of inclined piles in recent years, however, have attracted much research interest on the topic. Despite such, till date, the virtues and drawbacks concerning the use of inclined piles are largely unknown.

For such, the present study focuses on the effects of soil nonlinearity on the response of both the vertical and inclined piles, encompassing a broad aspect of pile dynamics. Experimental investigations through instrumented model soil-pile systems on a shaking table are carried out. Response of both the solitary piles and pile groups with various configurations including the angle of inclination, spacing between the piles, and loading types, are studied. A range of lateral loading amplitudes at the pile-head levels of floating single piles and pile groups embedded in cohesionless soil layer is considered to induce varying levels of soil strain, and in turn the soil nonlinearity. A wide range of frequency is considered to encompass the typical structural and soil periods. Practical pile inclinations of 5° and 10° besides vertical pile in the direction of loading are considered for the effects of batter.

Specifically, the dynamic response of single piles and pile groups are investigated through the measure of three distinct quantities: (a) active length of piles, (b) horizontal pile-to-pile interaction factors, and (c) horizontal impedance functions. The experimental results suggest that the behavior of soil-pile systems becomes highly nonlinear with increasing amplitude of loading, as the extent of local nonlinearity around the pile increases. Moreover, the results also indicate that the resonance of soil-pile system has a profound impact on the behavior of piles.

Comparisons between experimentally measured values of active length of pile and available approximate solutions reveal the closeness in values for very low amplitude of loadings, but for intermediate-to-high amplitude of loadings, the experimental values are smaller than those predicted by the approximate equations. Furthermore, both the static and dynamic active lengths of pile converge to an approximately identical value of six times the diameter of pile for intermediate-to-high amplitude of loadings. This suggests that the active lengths are, in fact, the same for both the static and dynamic loadings, under nonlinear conditions. Additionally, results also suggest that the passive-type failures of soil induced by applied lateral loadings in front of the pile govern the active lengths. The dynamic active lengths of pile do not show any significant dependency on the resonance of soil.

The horizontal pile-to-pile interaction factors, on the other hand, show a strong dependency on both the soil nonlinearity and resonance of the soil-pile systems. The experimental results indicate that the nonlinear effects decay with distance and become insignificant beyond spacing to the diameter ratio greater than 5. To account for such nonlinear behavior and resonance in soil, new semi-empirical equations are proposed in computing the horizontal interaction factors, as an extension to elasticity-based available approximate equations for both the close and ample pile spacings.

As for the horizontal impedance functions, horizontal impedance functions of inclined single piles are found smaller than the vertical pile and the values decrease with the increase in angle of pile inclination, contrary to the general understating that inclined piles show higher stiffnesses. Validation of such obtained experimental results is carried out through three-dimensional nonlinear finite element analyses, and the results from numerical models are in good agreement with the experimental data. Sensitivity analyses conducted on the numerical models suggest that the consideration of boundary nonlinearity at the vicinity of soil-pile interface highly influences the response of soil-pile systems. Horizontal impedance functions of 2×2 inclined pile groups, on the other hand, show higher value of horizontal impedance functions than the corresponding vertical pile group, in line with the general understanding. Influence of pile inclination on the horizontal impedance functions of pile group is further examined through the variation of soil reactions along the pile depth. In addition, semi-empirical expressions for estimating the soil reactions, as a function of pile inclinations, are proposed.

Experimentally measured values of horizontal pile-to-pile interaction factors and single piles' horizontal impedance functions are further employed in assessing the applicability of Poulos' superposition method in computing the pile group response. Utilizing Poulos' superposition method, horizontal impedance functions of a 3×3 vertical pile group are computed. Comparisons between thus computed horizontal impedance functions and experimentally measured ones show a good agreement for low-to-intermediate loading amplitudes, signifying that Poulos' superposition method is valid under nonlinear conditions. For higher loading amplitudes, on the other hand, the pile group shows a distinct group behavior that is neither local nor global, leading to discrepancy between experimentally measured values and computed values by the Poulos' superposition method.

Although the majority of present work focuses on inertial loading conditions, simple two-dimensional linear finite element modeling is carried out for investigating the behavior of both the vertical and inclined piles under kinematic loading. Such analyses are carried out as a validation of experimental data from centrifuge tests. Through the comparison of acceleration and displacement response of the pile-cap, as well as the axial and bending strains of the piles for both the vertical and inclined pile foundations, seismic behavior of piles under kinematic loading is investigated.