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Finite Element Analysis of the Lateral Load Test on Battered Pile Group at I-10 Twin Span Bridge

INTRODUCTION

Piles are designed to transfer the applied loads into the subsurface soil. They are usually used in group with pile cap, which supports the superstructure. The design of piles is mainly based on vertical load capacity. However, design for lateral resistance is necessary for cases where considerable lateral loads are present. The lateral capacity of single piles and pile groups were investigated by field experiments, centrifuge tests, analytical methods, and numerical methods. The beam on elastic foundation theory provides a simplified analogy for the pile-soil system subjected to lateral loads. The system is idealized as a beam supported by a series of independent elastic springs that are assumed constant linear or nonlinear spring stiffnesses. The nonlinear soil spring stiffness is referred to "p-y curve," which relates the soil reaction to pile lateral deflection.

The finite element (FE) numerical analysis is a powerful method for solving complex problems especially with the huge leap in the computational power and speed of computers. Experimental studies for pile groups are expensive and can be limited, and the FE method can provide a practical, affordable, and reliable alternative to the experimental approach. The use of the FE method for the pile-soil problem allows for modeling of the several aspects of nonlinearity in the problem such as pile and soil material nonlinearity, multilayered soil, pile-soil gapping, interface friction, and pile group effect. When experimental results are limited, FE analysis can be used to extract valuable results after being verified using the available results from the experiment.

In this work, FE modeling was used to study the lateral behavior of three pile group (PG) configurations (vertical, battered, and mixed) under static and dynamic load conditions. A parametric study was conducted to evaluate the effect of pile spacing and clay soil type on the lateral behavior of PGs. FE parametric studies were also performed to develop models to evaluate p-y curves for clayey and sandy soils using hyperbolic models based on soil and pile properties.

OBJECTIVES

- Develop a 3D FE model to simulate the lateral behavior of battered pile group foundations.
- Investigate the lateral behavior of battered pile group foundations subjected to static loads as compared to vertical single and pile group foundations.
- Investigate the lateral behavior of battered pile group foundations subjected to dynamic loads due to barge impact.
- Develop p-y curves for different soil types for use in the analysis and design of battered pile group foundations subjected to lateral loads.
- Develop guidance to select parameters and p-y curves for application in FB-MultiPier, Midas, and CSIBridge/SAP2000 softwares.
- Develop rationale values of p-multipliers to incorporate the group effect in the design and analysis of battered pile group foundations subjected to lateral loads.

SCOPE

3D FE models were developed to evaluate the lateral behavior of three PG configurations (vertical, battered, and mixed) under static and dynamic lateral loading. The results of full-scale lateral load test that was conducted at M19 eastbound pier of I-10 Twin Span Bridge was used to verify the FE models. FE parametric was conducted on the PGs to investigate the effect of row/column spacing and type of clay on the performance of PGs in terms of group effect, p-multipliers, lateral displacement, contribution of axial load per pile, and lateral stiffness of PGs.

A 3D FE dynamic analysis was conducted to evaluate the effect of barge impact of different speeds on the lateral performance of the three PG configurations in terms of peak lateral displacement, peak axial reaction, peak shear force, lateral stiffness of PGs, and the contribution of piles and pier columns to the total resisting force.

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METHODOLOGY

A 3D FE analysis was used to simulate the lateral behavior of single and pile groups under static and dynamic loading. This method allows for modeling complex engineering problems, such as nonlinear material response and interaction between different geometries. Three FE models were developed for three PG configurations: vertical, battered, and mixed piles, as shown in Figure 1. The nonlinear behavior of piles was simulated using the damaged plasticity model. The clay behavior was simulated using the Anisotropic Modified Cam model and the Drucker Prager model was used to simulate sand. The full-scale lateral load test that was conducted at M19 eastbound pier foundation of the I-10 Twin Span Bridge was used to verify the FE models.

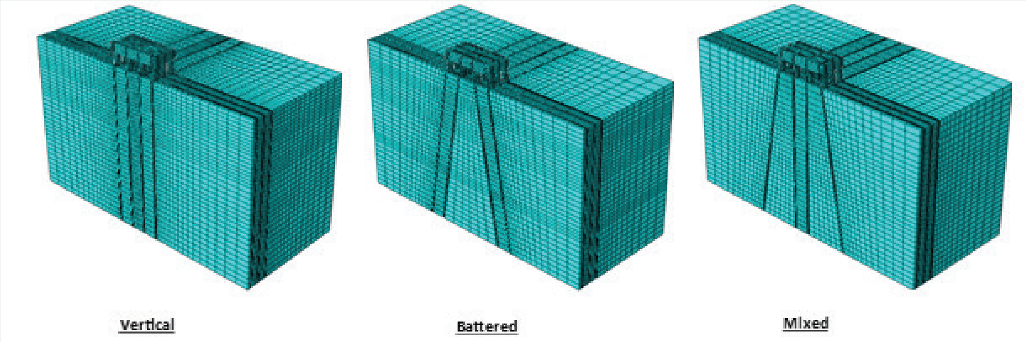

Figure 1. 3D FE models for vertical, battered and mixed pile group configurations

FE parametric studies were conducted on the three PG configurations to investigate the effect of pile spacing and clay soil type on the lateral behavior of PGs. The lateral resistance of the pile groups was investigated in terms of load-displacement, lateral stiffness, axial load, shear force, bending moment, soil resistance, and p-multipliers.

FE parametric studies were performed to develop models to evaluate p-y curves for clayey and sandy soils using hyperbolic models based on soil and pile properties. Regression analyses were performed to develop formulas for evaluating the ultimate lateral bearing capacity factor (N_p) and reference displacement of p-y curve (y_{50}) in clays. A combination of hyperbolic and power function model was developed to evaluate p-y curves in sands based on soil and pile properties.

Results of UU tests were used to develop correlations to estimate ε_{50} from soil properties (i.e., Su, PI, LI). The results of FE parametric study for p-y curves in sand were also analyzed to develop a formula to estimate coefficient of subgrade reaction (k) from soil and pile properties.

CONCLUSIONS

1. The battered pile group had the largest lateral stiffness followed by the mixed and vertical pile groups, under both static and dynamic loads.
2. The lateral load in PG rows differed in each configuration. In vertical PG, the leading row carried higher load than other rows. In battered PG, the middle rows carried higher loads than the 1st and 4th rows. In mixed PG, the percentage was higher in 1st row followed by 4th row.
3. The lateral load generated significant axial reactions in the piles. The mixed PG generated the highest percentage of axial force followed by the battered PG and then the vertical PG.
4. The vertical PG generated higher bending moment at the bottom of pile cap followed by the mixed and battered PGs under the same lateral load.
5. The battered PG had the highest p-multipliers followed by the mixed and vertical PGs. The pile row spacing had a greater influence on the p-multipliers than the column spacing.
6. FE parametric study showed that the p-multipliers is higher in stiff clays, as compared to medium stiff and soft clay.
7. The distribution of lateral force in vertical PG showed that the 1st row had slightly higher percentage compared to other rows. In battered PG, the load was distributed evenly between rows. In mixed PG, the 1st and 4th rows carried higher loads than the 2nd and 3rd rows.
8. The axial reaction results showed that only the 1st and 4th rows were axially active in the vertical PG. In battered PG, all rows were active with the 2nd and 3rd rows had higher axial force ratio than the 1st and 4th rows. In mixed PG, all rows had similar axial reaction ratio.
9. FE analysis were used to develop models to determine the three elements of the p-y curve for clays: ultimate soil resistance, pu, initial slope, and characteristic shape.

The results of UU tests were used to develop correlations to estimate the strain at 50% stress (ε_{50}) based on soil properties; and the FE parametric study were used to develop a model to estimate coefficient of subgrade reaction (k) based on soil and pile properties.

RECOMMENDATIONS

- Start using the developed p-multipliers for the battered, mixed, and vertical PGs.
- Start applying the contribution of axial force per each pile within the row/column of the PGs for inclusion in pile design.
- Start applying the results of distribution of lateral load per pile for the three PGs to calculate the contribution of lateral load for each pile for use in the lateral analysis and design of piles.
- Use the results of this study to evaluate the effect of barge speed impact on the piles' peak lateral displacement, the contribution of piles and pier columns to the total resisting force, the piles' peak shear force, the piles' peak axial force, and the axial force ratio per row.
- Implement the developed hyperbolic models for p-y curves in clay and sand in a selected pile design software, and start using them to evaluate the lateral behavior of piles driven in soils.

Start using the developed models to estimate the strain at 50% stress (ε_{50}) and coefficient of subgrade reaction, k, as an input parameter for different p-y curve models in clays and sands.