COMMENTS ABOUT THE BENEFITS OF FINITE ELEMENT MODELING FOR: SOIL STRUCTURE INTERACTION ANALYSIS OF DEEP FOUNDATIONS

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İSTANBUL
January 2010

CONCLUSIONS

A three dimensional finite element continuum model was developed for the lateral response of drilled shafts. The developed model included most of the parameters that influence the lateral response of shafts. The model was used to analyze single shafts, group shafts, and the results were compared to less refined models and experimental results.

Based on the results obtained in this dissertation, the following conclusions can be made:

1.1 Finite Element Optimization

- The effective volume of soil that needs to be included in the finite element model depends on the exclusion or inclusion of soil selfweight deformations within the lateral load analysis. For the models that do not include the soil selfweight, the volume of soil that needs to be included within the model should not be less than 2.5D from the shaft surface. For the models where the soil selfweight are included in the analysis, the volume of the soil that needs to be included within the model depends on the thickness of the soil layer and the angle of friction of the soil.
- Use of four solid elements per quadrant is sufficient to define the radial spread of the shaft-soil cross section. The use of finite elements with the size equal to 2.5 percent of the depth of the shaft is sufficient define the longitudinal meshing for slender shafts with depth to diameter ratios higher than 8. For ratios lower than 8, finite element with sizes 5 percent of the shaft depth is sufficient. The division of the lateral extension of the soil by finite elements with sizes 10-15 percent of the amount of soil extension from shaft surface is sufficient.

- **The use of reduced integration linear elements for the shaft, full integration linear elements for the soil, and infinite elements for the boundary soil region gave good results and is recommended for three-dimensional FE analysis. Quadratic elements tend to cause convergence problems and instability and therefore are not recommended when modeling soil-shaft surface interaction. The use of infinite elements for soil at model boundaries rather than boundary conditions is an efficient technique to model soil continuity.**

1.2 Lateral Response of Drilled Shaft

- **Neglecting surface friction at the interface overestimates shaft displacements and moments. The effect of friction on shaft response was also dependent on the depth to diameter ratio of the shaft and support conditions at the bottom of the shaft.**
- **For shafts with depth to diameter ratios of 8 or higher, the average reduction in displacement due to an interface static friction constant of 0.2 is 3 percent, for 0.5 is 6 percent, and for 0.9 is 8 percent. The average reduction in moment due to an interface friction coefficient of 0.2 is 1.5 percent, for 0.5 is 3 percent, and for 0.9 is 4.5 percent. The shaft support conditions influence the effect of interface friction for shafts with depth to diameter ratios below 8. For shafts fixed at the bottom, the effect of friction on the shaft response due to lateral loads was less pronounced compared to that of shafts normally supported by rigid surface.**
- **Including the effects of Poisson’s ratio in the analysis increased the shaft response to lateral loading. The inclusion of Poisson’s ratio of 0.2 has increased the maximum shaft displacement by 7 percent, and the maximum moment by 1 percent. The inclusion of Poisson’s ratio of 0.4 increased the**

maximum shaft displacement by 11 percent and the maximum moment by 2 percent.

- **Including soil weight in the analysis increases the stiffness of the shaft-soil system. The maximum shaft displacement was reduced by 25 percent and the maximum moment was reduced by 6 percent. The analysis showed that for every 10pcf of increase in unit weight of cohesionless soils, the displacement of the shaft was reduced by about 2 percent and the maximum moment by about 0.5 percent.**
- **The conditions of the soil in close proximity to the shaft surface had a major impact on the shaft response. As a result of the analysis it was found that the amount of the extension of weak soil zone around the shaft as well as the amount of strength reduction within this zone highly influences the lateral capacity of the shaft, which has to be taken into account in design. This phenomenon can be analyzed efficiently with the FE modeling.**
- **Depth of soil up to 5 shaft diameters below the ground surface is the most effective depth of soil in determining the lateral response and load capacity of a drilled shaft. In addition, this zone is more susceptible to surface separation due to cyclic loads making it a critical parameter. Loss of soil support in this region had a major impact on shaft capacity for slender shafts ($Z > 5$). Loss of soil support that extends 2.5 shaft diameters below the ground surface increases the maximum shaft displacement by 73 percent and the maximum moment by 42 percent.**
- **Shaft support conditions at the bottom start to influence the shaft response for shafts with depth to diameter ratios below 10 ($Z < 5$). For depth to diameter ratio of 10, the ratio of the moment developed at the support to maximum moment was about 13 percent. This percentage increases as the**

shaft depth decreases. For shaft depth to diameter ratio of 8, the maximum displacement and the maximum moment vary by 15 percent and 5 percent for fixed support and normal support respectively. The support condition at the bottom of shaft needs to be accurately modeled.

- The approximate length of fixity predicted by the developed FE model was about 15 percent to 20 percent lower than the length of fixity estimated by less refined methods used in design practices. This indicates that the less refined methods overestimate the shaft maximum moments and maximum displacements.

1.3 Group Shafts

- As expected, the center-to-center spacing of the shafts influences the stiffness of the shaft group. As the spacing is decreased, the lateral support from the soil is reduced, thus increasing shaft displacements, and moments.
- Group coefficients were obtained for the effect of shaft spacing on the maximum shaft displacements. These coefficients are defined as the ratio of the group displacement to that of a single shaft. Group shaft analysis showed that, for practical shaft spacing (3D to 4D), the increase in group-displacement was about 50 to 60 percent.
- Support moments are observed for shafts in close proximity (for center-to-center spacing of 3D).

1.4 Comparisons with Existing Models

- Finite element modeling with soil continuum predicted lower displacement and moments compared to the spring model and the LPILE.

- **Comparison of the Type-1 FE model and the spring model confirmed the effect of shear coupling on lateral soil resistance. It was found that including shear coupling as an addition to individual spring stiffness decreased the displacements by 5 percent and the moments by 3 percent.**
- **Comparison of Type-2 FE model with the Type-1 FE model has shown the effect of soil confinement on the stiffness of the shaft. The FE model showed that including the soil weight reduced the displacements by about 25 percent and reduced the moments by 5 percent.**
- **Effectiveness of the shaft depth in resisting lateral loads depends on the relative stiffness of the shaft and the soil, as well as the depth of the shaft. The maximum depth coefficient Z_{max} beyond which the extension of the shaft has no effect on lateral loads resistance is found to be: Z_{max} =5. This conclusion confirms Matlock and Reese (1962) criteria for long shafts beyond which extension in depth has no effect on lateral load resistance of the shaft.**

1.5 Suggestions for Further Research

- **FE modeling is an effective approach to deep-foundation modeling. However, further field verification is needed to compare and calibrate the FE model in order to generate design-based guidelines.**
- **There is a need to establish design charts for lateral load design of drilled shafts. To this end, further analytical studies regarding the influence of the stiffness parameters of soil and shaft to lateral response of the shaft are needed.**
- **There is a need to study multi-layered soil profiles and cohesive soils.**

- **There is a need to study the shaft and soil response under the action of dynamic and other time dependent loads.**
- **Soil strength reduction associated with drilling operations is shown to have an important effect on lateral response of the shaft. Further in-depth investigation is needed to fully evaluate the associated effects on design capacity of a shaft under lateral loads.**

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