CHAPTER 6 - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

The objective of this report is to study the effect of structural anomalies in a drilled shaft on its capacity, to produce guidelines for assessing the importance of anomalies on the drilled shaft capacity in different soils, and to prioritize anomalies the remediation effort.

The study included: 1) conducting a comprehensive literature search of drilled shafts with anomalies; 2) developing the finite element code, PSI-VA, for use in this study; and 3) evaluating the effect of factors such as anomaly location and sizes, soil types, and concrete strength on shaft capacity.

The anomalies (or anomaly or imperfection) were caused mainly by the deficiencies in construction quality control that resulted in the creation of a void or voids with or without earth filling, as reported by DiMaggio (2008), Haramy (2006), and Mullins, etc., (2005). These anomalies can be located by various geophysical and tomographic techniques (Haramy, 2006; Haramy, et al., 2007). Once located, the subsequent tasks would include the assessment of its effect on the drilled shaft capacity, which is dictated by its structural and geotechnical capacities and also the design of a corrective measure. This study focuses on the anomaly effect on the drilled shaft capacity. A comprehensive finite element analysis program was carried to assess the effect of concentric anomalies. The study covers 1-m and 2-m diameter drilled shafts in clayey soils including soft, medium, stiff, very stiff, and extremely stiff clays and the medium, dense, and very dense sands. The study can be expanded to cover the effect of nonconcentric anomalies under both axial and lateral loads, static and/or dynamic, expected to more dramatically affect the drilled shaft capacity.

6.2 FINDINGS AND CONCLUSIONS

The comprehensive finite element analysis program provides the following major conclusions: anomalies will affect axial structural capacity; drilled shaft capacity is affected by the size and location of anomalies and the strength of the surrounding soils; and concentric anomalies can drastically decrease the structural capacity of a drilled shaft even under axial load, depending on the location of anomalies.

Finite element analyses were also performed to validate the PSI computer code for predicting the measured performance of drilled shafts and also to compare the PSI predictions to the analysis results using other computer codes. Findings confirmed that excellent agreements were achieved between the PSI results and the measured shaft-load test results under vertical or lateral load CDOT (Jamal Nusairat, et al., 2004), Brinkgreve (2004), and UC Berkeley (Wang, et al., 2004). Excellent agreements were also achieved between the PSI results and the analysis results using PLAXIS 2D, PLAXIS 3D, ABAQUS, ANASYS, and LS-DYNA by the authors cited in the article. These comparisons validate **PSI code** as an effective code for use in assessing drilled shaft performance under vertical and/or lateral loads. Based on the PSI code, PSI-VA was developed specifically for the evaluation of the anomaly effect on drilled shaft capacity.

PSI-VA was then used in the finite element analysis for the evaluation of the effect of anomalies on drilled shaft capacities. Analysis and findings of 1-m and 2-m in diameter drilled shafts in clayey soils including soft, medium, stiff, very stiff, and extremely stiff clays and medium, dense, and very dense sands are summarized as follows:

- Structural capacity reduction of drilled shafts depends on concentricity of anomalies. Nonconcentric anomalies result in much more severe structural capacity reduction.
- When the structural capacity is smaller than the geotechnical capacity over some length of a drilled shaft, the structural capacity curve intersects the shaft-load transfer curve. In this case the anomalies located at a depth shallower than the depth of such intersection will result in drilled shaft capacity reduction, which is controlled by the reduced structural capacity. Below such depth, however, the anomaly will not affect the drilled shaft capacity.
- When structural capacity is larger than geotechnical capacity, the shaft-load transfer curve lies to the left of structural capacity curve; and the drilled shaft experiences smaller loads than that associated with the structural capacity. Thus, structural anomalies do not affect the drilled capacity; and the geotechnical capacity controls its design.
- When the structural capacity curve lies to the left of geotechnical capacity curve, the drilled shaft capacity is affected by the anomalies located at any depth; and the structural capacity controls the design.
- Analysis results show that nonconcentric anomalies drastically compromise the structural capacity because of the bending moment, and nonconcentric anomalies are much more critical.
- The strength of soils surrounding drilled shafts influences the drilled shaft capacity and performance. Thus, the effects of soil types and strengths on load transfer must be investigated.
- It is critical to locate a anomaly(s) and assess its effects on the drilled shaft capacity.
- Because of the potentially strong negative effect of anomalies on drilled shaft capacity, it is of paramount importance to monitor the drilled shaft construction QA/QC, including maintaining a proper rebar spacing-aggregate size ratio and a proper concrete slump (or fluidity) to avoid anomalies in regions outside the reinforcing cage. Once detected, it must be eradicated by grouting.

6.3 RECOMMENDATIONS FOR REMEDIATION

The following are the recommendations for the remediation guidelines:

- A proper construction quality monitoring program including sonic wave survey; tomographic imaging; and temperature, moisture, and density measurements are recommended for all critical drilled shafts.
- Once anomalies are located, the voids must be filled with concrete grout.
- If prioritization is necessary in fixing the anomalies, the shallow, nonconcentric anomalies must receive first attention because of higher load and more drastic effect of anomalies.

- The effects of soil types and strengths must be properly assessed from the shaft-load transfer curve and the structural-capacity curve to assess the critical nature of a anomaly(s).

6.4 FUTURE STUDY

The following extensions would have completed the comprehensive study on the effect of anomalies on drilled shaft capacity:

- Install strain gages (or load cells) at a proper depth increment to measure load transferred; and, if possible, install settlements at different depths to provide t-z curves for assessing the load transfer. These gages and load cells could have been used to monitor the drilled shaft performance and safety during its lifetime.
- Extend the study to cover the effect of nonconcentric anomalies on vertical drilled shaft capacity.
- Extend the study to cover the effect of anomaly on the lateral load carrying capacity of a drilled shaft.
- Extend the study to cover the transient loads, like wind and seismic loads.
- Complete the development of a computer code for the design of drilled shafts under static and transient loads. This code could be named PSI-VLT for vertical, lateral, and torsional loads. It could be developed into a comprehensive program to be used in drilled shaft design.