Performance of long drilled shafts with enlarged bases in soft soils: field load test and numerical analysis

Performance des puits forés longs avec une base élargie dans les sols molles: test de charge sur le terrain et analyse numérique

Zhe Luo, Yixiang Li
Department of Civil Engineering, University of Akron, USA, zluo@uakron.edu

Kaifu Liu
School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, China

Braja Das
College of Engineering and Computer Science, California State University, USA

ABSTRACT: In this paper, the performance of two long drilled shafts in Shanghai, China, was investigated through field load tests and numerical simulations. Both drilled shafts have a diameter of 980 mm and a length of 58.3-58.6 m. The diameters of the enlarged bases for the two drilled shafts are 1220 mm and 1300 mm, respectively. Field load tests on both drilled shafts were conducted to evaluate the load transfer characteristics, load-settlement response and the effect of enlarged base. Two numerical models based on finite element approach were prepared to simulate the load-settlement response for the drilled shafts with enlarged bases. The effect of sediment below the shaft on load-settlement curve was also modeled and investigated in the numerical analysis. The input soil parameters were estimated based on the field observations. It is shown that the numerical simulations can capture well with the field observations. The documented field load test data and the back-calculated parameters for numerical simulations can serve as a reference and basis for similar large scale drilled shaft projects.

RÉSUMÉ : Dans cet article, la performance de deux longs arbres forés à Shanghai, en Chine, a été étudiée au moyen de tests de charge sur le terrain et de simulations numériques. Les deux arbres forés ont un diamètre de 980 mm et une longueur de 58,3-58,6 m. Les diamètres des bases élargies pour les deux arbres forés sont de 1220 mm et 1300 mm, respectivement. Des essais de charge sur les deux arbres forés ont été effectués pour évaluer les caractéristiques de transfert de charge, la réponse de la charge et l'effet de l'élargissement de la base. Deux modèles numériques basés sur l'approche par éléments finis ont été préparés pour simuler la réponse de la charge-installation pour les arbres forés avec des bases élargies. L'effet du sédiment en-dessous de l'arbre sur la courbe de charge-établissement a également été modélisé et étudié dans l'analyse numérique. Les paramètres du sol d'entrée ont été estimés sur la base des observations sur le terrain. Il est démontré que les simulations numériques peuvent bien saisir les observations de terrain. Les données de test de charge de terrain documentées et les paramètres rétro-calculés pour des simulations numériques peuvent servir de référence et de base pour des projets de puits forés à grande échelle similaires.

KEYWORDS: Drilled shafts; enlarged base; load-settlement curve; numerical simulations.

1 INTRODUCTION.

Drilled shafts, also known as bored piles, have been extensively adopted as deep foundations for buildings, bridges, towers, etc. in the geotechnical engineering practice. Drilled shafts can be constructed in various types of soils and have good load-bearing performance in various combinations of external loads, such as torsion, lateral loading, uplift, compression and earthquake loading (e.g., Kulhawy 1991, O'Neill and Reese 1999, Nusairat et al. 2004, Brown et al. 2010, Fan et al. 2014). The detailed procedures for design and construction of drilled shafts are provided in a Federal Highway Administration (FHWA) report (Brown et al. 2010).

The traditional drilled shafts are straight and have a constant diameter. The bearing resistance relies on the shaft side resistance and tip resistance. For long drilled shafts in soft soils, the contribution of tip resistance to the total resistance can be negligible. There are several techniques to enhance the bearing capacity of drilled shafts: increasing the shaft length, enlarging the shaft diameter, increasing the side friction and stiffness of the shaft base by post-grouting, enlarging the surface area, enlarging the base of shafts, etc. Among those techniques, enlarging the base is considered as an effective approach to enhancing the load-bearing capacity (e.g., Cook and Whitaker 1961, Sego et al. 2003, Herrmann et al. 2013).

Although the theoretical and field research on drilled shafts with enlarged bases has been reported, the maximum length of those shafts generally ranges from 35 m to 45 m (Hu et al. 2007). For foundations subjected to large superstructure loads in deep soft soils, the design length of shafts is much longer. In this paper, the load-bearing resistance of enlarged base drilled shafts with length larger than 58 m is investigated through field load test and numerical analysis. The load test site is located in Shanghai, China. Two full-scale field load tests on enlarged base drilled shafts were conducted and the load-settlement curves were obtained.

This study further investigates the load-bearing resistance of enlarged base drilled shaft using numerical analysis. A commercial finite element code (FEM) is adopted herein and the key soil parameters were calibrated based on the field load test results. It is shown that the FEM simulation can generally capture well with the load-settlement responses that are observed in the field. The effect of sediment below the shaft is also modeled and investigated. The proper selection of the soil constitutive models and the back-calculated soil parameters can serve as a reference and alternative tool for design and analysis of similar large scale drilled shaft projects.

Table 1. Soil profile and soil parameters determined in subsurface exploration and back-calculated in numerical analysis

Soil layer	Layer thickness (m)	Water content w (%)	Unit weight γ (kN/m^3)	Void ratio e_0	Cohesion c (kPa)	Friction angle ϕ (°)	Referenced secant stiffness E_{50}^{ref} (kPa)
Miscellaneous fill	1.2	–	18.7	0.87	15	11	3200
Silty clay	1.4	34.4	18.7	0.87	15	11	4560
Silt with sand	4.3	38.5	18.6	0.86	22	20	8880
Organic clay	3.5	44.2	17.3	1.34	11	11	2040
Organic clay	4.3	48.4	16.9	1.34	10	11	1872
Clay	4.8	46.1	17.1	1.30	25	11	2088
Silt with sand	8.9	35.3	18.0	1.03	22	20	3424
Clay	15	33.8	18.2	0.94	25	10	7632
Silty clay	6.9	34.6	17.9	1.01	15	10	3744
Silty clay with sand	6	31.7	18.2	0.94	10	20	3624
Silty fine sand	33.7	25.4	18.6	0.78	14	11	9952

2 OBSERVATIONS FROM FIELD LOAD TESTS

2 .1 *Site information*

In a local project of expressway close to Fujin Road in Shanghai, China, the enlarged base drillled shafts were chosen as the foundation for a new bridge as a result of high load-bearing capacity requirement. A few full-scale field load tests were conducted to investigate the performance of long drilled shafts with enlarged bases at the site. Subsurface investigation shows that the majority of the soils at this site are soft clays. Table 1 shows the soil profile, soil layer thickness, water content, unit weight and void ratio for various layers.

The soil profile consists of the following seven types of soils: (1) a 1-m-thick miscellaneous fill at the surface; (2) a total of 8-m-thick silty clay in two layers, located at depths of 1–2 m and 44–51 m; (3) a total of 10 m of silt with sand in two layers, located at depths of 2–4 m and 21–29 m; (4) an approximately 8.5-m-thick organic clay layer between 8 and 15.5 m; (5) a total of 20 m of clay in two layers, located at depths of 15.5–20.5 m and 29.5–44.5 m; (6) silty clay with sand that is approximately 5-m-thick between 51 and 56.5 m from the ground surface; and (7) a roughly 9.5-m-thick silty fine sand, located from 56.5 m in depth to the bottom of borehole (65 m). Other soil parameters from subsurface exploration are documented in Liu et al. (2017).

2 .2 *Field load test results*

Two representative drilled shafts are selected in this study. Field load tests were then conducted to investigate the load-settlement behavior of the two drilled shafts with enlarged bases. The end-product shafts have lengths of 58.6 m and 58.3 m, respectively. The diameters for both shafts are approximately 980 mm at the end of construction. The diamters of the enlaged bases for two shafts are 1220 mm and 1300 mm, respectively. The structural parameters for these two drilled shafts are listed in Table 2. The two long drilled shafts are denoted as Shaft 1 and Shaft 2 in this study.

The twelve to fifteen load increments were applied on the shaft head until the ultimate state was reached. Each load increment was maintained until the rate of displacement of the shaft cap was less than 0.1 mm/hour. After the maximum load was reached, the load was reduced to zero in several steps. The strains during the load test were recorded by the automatic data acquisition system. Interested readers are referred to Liu et al. (2017) for the details of the load test program.

Table 2. Structural parameters for drilled shafts with enlarged bases

Parameter	*Shaft 1*	*Shaft 2*
Length (m)	58.6	58.3
Diameter (mm)	980	980
Base diameter (mm)	1220	1300
Young's modulus (GPa)	31.1	27.9
Unit weight (kN/m^3)	24.0	24.0

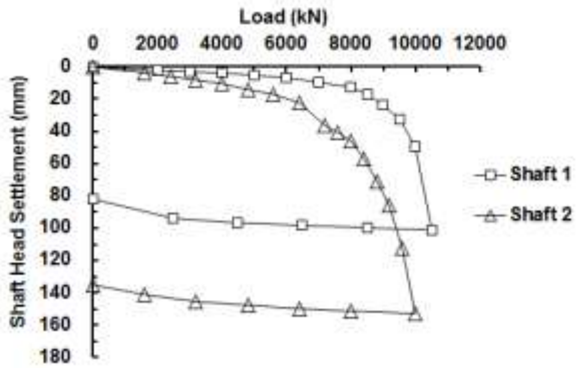

Figure 1. Load-settlement curves for the two drilled shafts with enlarged bases.

Figures 1 shows the relationship between the applied total load at the shaft head and the head settlement measured in the load tests for Shaft 1 and Shaft 2, respectively. At a limiting settlement of 25 mm, the load bearing capacity for Shaft 1 and Shaft 2 exceeds 9000 kN and 6500 kN, respectively. At the same test site, a straight drilled shaft with the comparable length and diameter were constructed and tested following the same load test procedure. The results show that the enlarged bases can effectively increase the load bearing resistance. Interested readers are referred to Liu et al. (2017) for the comparision of drilled shafts with enlarged bases and without enlarged bases.

The discrepancy of load-settlement responses between Shaft 1 and Shaft 2 can be caused by several factors such as spatial variability of soils, quality control, testing errors, setup phenomenon, etc. Considering the relative distances among borehole, Shaft 1 and Shaft 2 at the site, the spatial variability of soil property, uncertainty in soil profile and construction errors are considered to be the major factors in this study.

3 FINITE ELEMENT MODELING FOR LONG DRILLED SHAFTS WITH ENLARGED BASE

3 .1 *Numerical models*

The full-scale field load test, especially for the long drilled shafts with enlarged bases, is expensive for regular geotechnical engineering projects. In practice, engineers can benefit from and utilize their past experience if a simple design tool is available in the preliminary design phase. In this regard, numerical analysis is conducted in this study to simulate the load-settlement response observed in the field load test.

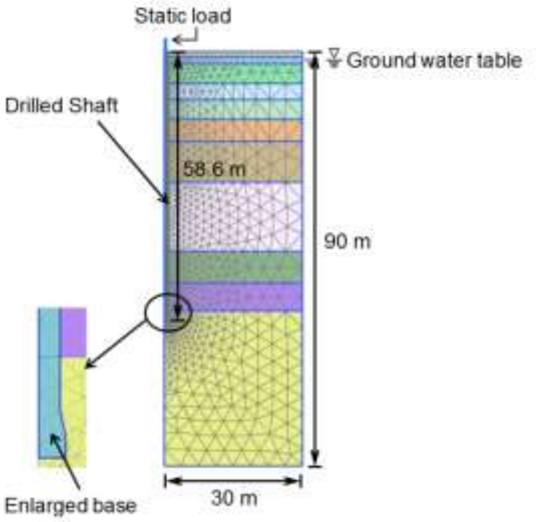

Figure 2. Finite element model for a drilled shaft with enlarged base.

The commercial finite element code PLAXIS 2D is used in this study. The 15-noded triangle element is used as the element type. The axisymmetric model for a drilled shaft with enlarged base is shown in Figure 2. The height and width of the model are set to be 90 m and 30 m to minimize the boundary effect. The bottom boundary is restrained from both horizontal and vertical movements, and the left and right-side boundaries are only restrained horizontally. A polygon with high modulus is used to represent the drilled shaft in axisymmetric model. The enlarged base is also modeled.

In FEM models, the soil profile follows the detailed eleven soil layers as shown in Table 1. The Hardening Soil (HS) model is selected to model the constitutive relationships of soft soils at site, which can more rationally capture the load-settlement response than Mohr-Coulomb model. The key soil parameters used in HS model, cohesion (*c*), internal friction (ϕ) and referenced secant stiffness (E_{50}^{ref}), are shown in Table 1. These soil parameters are not included in the report of subsurface exploration. The input parameters used in numerical analysis are then back-calculated by the research team by combining the field observations and engineering judgment.

The materials of drilled shaft are modeled using linear-elastic model. The structural parameters for the two shafts, including shaft length, shaft diameter, base diameter, modulus and unit weight, are listed in Table 2. The soil–shaft interaction was modeled by the zero-thickness interface element. The strength reduction factors for interfaces are 0.75.

The field observations show that the bottom sediment can have significant influence on the load-bearing capacity of the drilled shafts. In this field load test, it was found that the bottom sediment below Shaft 2 is larger than that below Shaft 1. In this regard, two FEM models are established and the following two simulations are performed:

1) In the first FEM model, the sediment below the shaft toe is not modelled. Considering the structural parameters for Shaft 1 and Shaft 2 are almost identical (in reference to Table1), the structural parameters for Shaft 2 is chosen in the model development. The soil profile and soil parameters follow those in Table 1.
2) In the second FEM model, the sediment below the shaft toe is modelled, as shown in Figure 3. The sediment has a thickness of 20 cm and is modelled by HS model. The parameters used for modeling the sediment are shown in Table 3. All other model parameters are the same as those in the first model.

In the numerical simulations, the load and unloading cycle follows the procedures in the field load test. The drained analysis is performed to obtain the load-settlement curve.

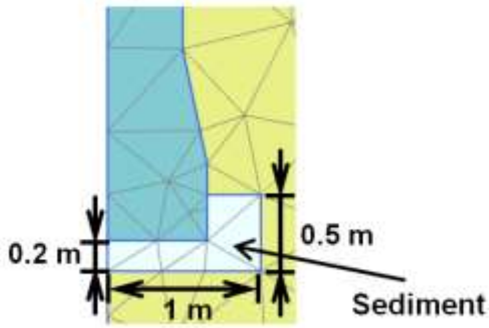

Figure 3. Illustration of sediment modelled in numerical analysis.

Table 3. Parameters for sediment in numerical analysis

Layer thickness (m)	Unit weight γ (kN/m^3)	Void ratio e_0	Cohesion *c* (kPa)	Friction angle ϕ (°)	Referenced secant stiffness E_{50}^{ref} (kPa)
0.5	17.3	1.2	11	11	3000

3 .2 *Simulation results*

The simulated load-settlement response for Shaft 1 is shown in Figure 4. For comparison purpose, the observed load-settlement curve for Shaft 1 in Figure 1 is also plotted in Figure 4. It is shown than the numerical simulation can capture the overall trend of the load-settlement behavior of this enlarged base drilled shaft: initially the settlement increases with axial load almost linearly until the ultimate state is reached. After the load approximately exceeds 9000 kN, the settlement increases significantly with the load. Following several unloading stages, the shaft head settlement rebounds back to approximately 95 mm, compared to the observed residual settlement of 82 mm.

Figure 4 also indicates that the numerical model developed for Shaft 1 yields conservative results, compared to those from field load test. For instance, at a limiting settlement of 25 mm, the loading bearing capacity for Shaft 1 is estimated to be close to 5000 kN, in contrast to 9000 kN determined by field load test, as in Figure 4. Although further refinement of the soil parameters can yield a simulated load-settlement curve that is closer to the field observation, this study intends to establish one FEM model for both drilled shafts at the same site.

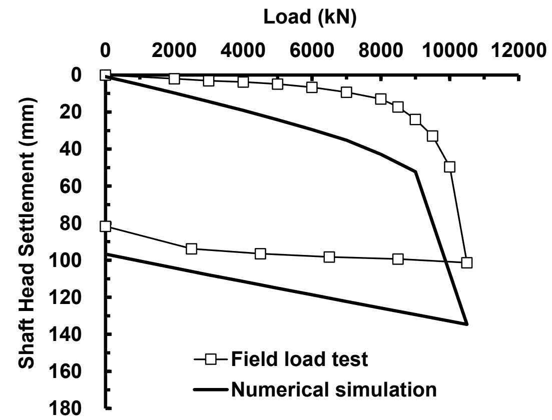

Figure 4. Comparison of load-settlement curves for between field load test and numerical simulation Shaft 1.

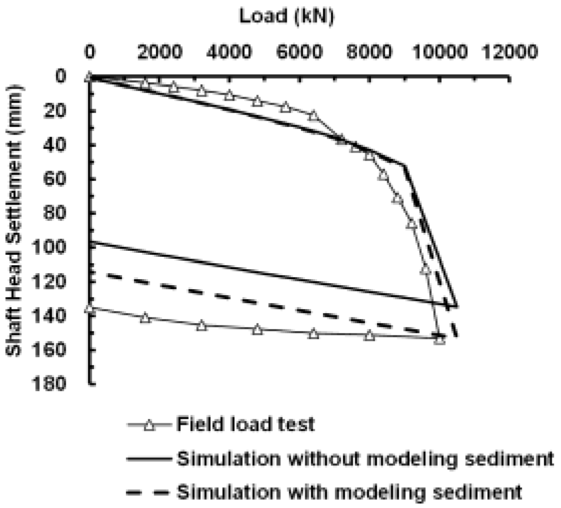

Figure 5. Comparison of load-settlement curves between field load test and numerical simulation for Shaft 2.

Similarly, Figure 5 shows the simulated load-settlement response for Shaft 2. It is noted that the load-settlement curve by "simulating without modeling sediment" is the same simulation curve in Figure 4. In comparison, the load-settlement curve by "simulating with modeling sediment" is shown to capture better with the observed load-settlement curve. As such, the effect of sediment below the shaft is modelled and illustrated in FEM.

It is also demonstrated that the numerical simulation can yield comparable results with the field load test. The numerical model considering sediment, developed for Shaft 2, yields slightly conservative results. For instance, at a limiting settlement of 25 mm, the loading bearing capacity for Shaft 2 is estimated to be approximately 5000 kN, comparing with 6500 kN determined by field load test, as in Figure 5.

The numerical analysis in this study shows that the proper selection of soil constitutive models and the back-calculated soil parameters can serve as a reference and alternative tool for design and analysis of similar large scale drilled shaft projects.

4 CONCLUSION

In this paper, the performance of long drilled shafts with enlarged bases in soft soils is explored using field load test and numerical analysis. The load-settlement curves for two drilled shafts with enlarged bases are determined from field load test. The FEM simulation using a axisymmetric model can yield results that are comparable with the field observations. The numerical analysis is considered as an effective tool to aid the geotechnical design.

5 REFERENCES

Brown D.A., Turner J. P. and Castelli R. J. 2010. Drilled shafts: construction procedures and LRFD design methods. *Federal Highway Administration*, NHI-10-016, Course NO. 132014, Washington, DC.

Cook R.W. and Whitaker T. 1961. Experiments on model pile with enlarged bases. *Geotechnique* 11 (1), 1–13

Fan H., Huang Q. and Liang R.H. 2014. Reliability analysis of piles in spatially varying soils considering multiple failure modes. *Computers and Geotechnics*, 57, 97–104.

Herrmann R.A., Löwen M., Tinteler T. and Krumm S. 2013. Research on the load-bearing behaviour of bored piles with different enlarged bases. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, 2–6 Septermber, 2013. International Society of Soil Mechanics and Geotechnical Engineering, London, 2755–2758.

Hu, Q., Zhang T. and Xie X. 2007. Experimental study on the bearing capacity of large diameter cast-in-place under-reamed pile in deep soft soils. *China Civil Engineering Journal*, 40(4), 87–91.

Kulhawy F.H. 1991. *Drilled shaft foundations. Foundation engineering handbook*, 2nd Ed., Fang HY, Ed., Van Nostrand Reinhold, New York, 537−552.

Liu K., Xie X., Luo Z., Hu Q. and Huang C. 2017. Full-scale field load testing of long drilled shafts with enlarged base constructed in marine sediment. *Marine Georesources & Geotechnology*, 35(3), 346-356.

Nusairat J., Liang R.Y., Engel R. Hanneman D., Abu-Hejleh N. and Yang, K. 2004. Drilled shaft design for sound barrier walls, Signs, and Signals. *Report* CDOT-DTD-R-2004-8, Colorado DOT, CO.

O'Neill M.W. and Reese L.C. 1999. Drilled shafts: construction procedures and design methods. Federal Highway Administration, *Report* No. IF-99-025, Washington, DC.

Sego D.C., Biggar K.W. and Wong G. 2003. Enlarged base (belled) piles for use in ice or ice-rich permafrost. *Journal of Cold Regions Engineering*, 17 (2), 68–88.