Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

Special Issue

EVALUATION OF END BEARING CAPACITY OF DRILLED SHAFTS IN SAND BY NUMERICAL AND SPT-BASED METHODS

I. Shooshpasha[1]*, M. Kharun[2], A. Hasanzadeh[1]

[1]Department of Civil Engineering, BabolNoshirvani University of Technology, Babol, Iran

[2]Department of Architecture&Civil Engineering, RUDN University, Moscow, Russia

Published online: 24 November 2017

ABSTRACT

Drilled shafts are a common type of pile foundations which are often used as foundations for buildings, bridges and other structures. The end bearing capacity of drilled shafts, which plays an important role in their design particularly in sandy soils, has traditionally been estimated using empirical or semi-empirical methods. With advances in computing power, it is now possible to conduct more realistic analyses. In this paper, at first, the end bearing capacity of drilled shafts in sandy soils is analyzed numerically and validated with the results of pile load test. Then, the numerical results are compared with the results of Standard Penetration Test (SPT)-based methods. The comparison indicated that there is a satisfactory agreement between the results of numerical method proposed in this paper and the results achieved by SPT-based methods.

1. INTRODUCTION

Pile foundations are usually applied to support different structures built on loose or soft soils, where shallow foundations would undergo excessive settlements or have low bearing capacity. Drilled shafts are a common type of pile foundations which are broadly described as

Author Correspondence, e-mail: shooshpasha@nit.ac.ir

doi: http://dx.doi.org/10.4314/jfas.v9i7s.27

cylindrical, deep, cast-in-place concrete foundations poured in and formed by a bored excavation. Drilled shaft is a versatile foundation system that has many advantages in comparison with other types of pile foundations. For example, construction of drilled shafts generates less noise and vibration. Therefore, they are well suited to use in urban areas. In many cases, a large diameter drilled shaft can replace a group of piles which in turn eliminates the need for a pile cap. Due to the flexural strength of a large diameter column of reinforced concrete, drilled shafts have enjoyed increased use for highway bridges in seismically active areas. Furthermore, drilled shafts may be used as foundations for other applications such as retaining walls, sound walls or high mast lighting where a simple support for overturning loads is the primary function of the foundation [1].

Pile foundation design, due to the complexity of the interaction mechanism between soil and pile, is still considered as one of the most difficult tasks in geotechnical engineering [2]. Bearing capacity is considered to be one of the significant factors that govern the design of pile foundations [3]. Determination of axial capacity of piles has been a challenging problem since the beginning of the geotechnical engineering profession. The bearing capacity of piles is governed both by its structural strength and the supporting soil properties. Obviously, the smaller of the two values should be used for the design. Generally, the pile capacity based on soil properties governs the design except probably in timber piles [4].The capacity of drilled shafts comes mainly from skin friction and end bearing. The skin friction develops between the shaft concrete and the surrounding soil. The skin friction is transmitted to the soil along the length of drilled shaft. However, the end bearing is analogous to shallow foundation bearing capacity with a very large depth of footing [5]. The end bearing capacity is transmitted to the base of drilled shaft. Particularly in sandy soils, the end bearing capacity can have an important role in the design of drilled shafts. In some projects, drilled shafts are designed primarily based on the magnitude of the end bearing capacity [6]. The end bearing capacity of drilled shafts can be estimated by static analysis, dynamic analysis, dynamic testing, in-situ testing and pile load test. Various investigations have been conducted for determination of the end bearing capacity of piles [7-14].

In recent years, application of Standard Penetration Test (SPT) as one of in-situ testing techniques has increased for pile design and analysis. Specially, the pile load capacity in sandy soils has often been estimated based on SPT results. On the other hand, acceptance of numerical analyses in geotechnical problems is growing. In this study, a numerical method is proposed for determination of end bearing capacity of drilled shafts in sand. To investigate the base load-settlement behavior of drilled shaft in sandy soils, the numerical prediction results are compared with the results of pile load test. Then, for performing a case study, this numerical method is applied for a region in north of Iran. Finally, the obtained numerical results are compared with the results estimated by SPT-based methods.

2. NUMERICAL MODELING

Recently, finite element calculations are more and more used in the design of foundations. Numerical modeling in the present paper was performed by the Plaxis program which is a two-dimensional (2-D) finiteelement computer program. Plaxis is available commercially to analyze deformation and stability of various geotechnical problems. The program can be used in plane strain as well as in axisymmetric modeling. In this study, a numerical methodology is presented to model and simulate the end bearing capacity of drilled shafts in sandy soils. The Mohr-Coulomb elasto-plastic model has been applied in the modeling. Since cylindrical types of drilled shafts with constant circular cross section have been routinely adopted in practice and the axial end bearing capacity of these drilled shafts has symmetry about the vertical axis, the axisymmetric option is used for this three dimensional problem. Moreover, the axisymmetric option decreases the number of elements in the solution procedure. In Fig. 1, the hollow space on the top left side shows the location of the drilled shaft.

The side and bottom boundaries are located far enough from the drilled shaft so that the effects of boundaries on the response of drilled shaft would be negligible. The side boundaries are restricted in the horizontal direction and the bottom boundary is restricted in both horizontal and vertical directions. A fine finite mesh was used with 15-node triangular elements for modeling. In this numerical procedure, pile tip is given the vertical downward displacement for determination of the end bearing capacity (Fig. 2 (a)). As expected, stresses around the drilled shaft start to increase during this downward displacement. This increase in stress would be higher for the pile tip (Fig. 2 (b)). The increase in stress for pile tip is registered and, as a result, the end bearing capacity of drilled shafts can be obtained.

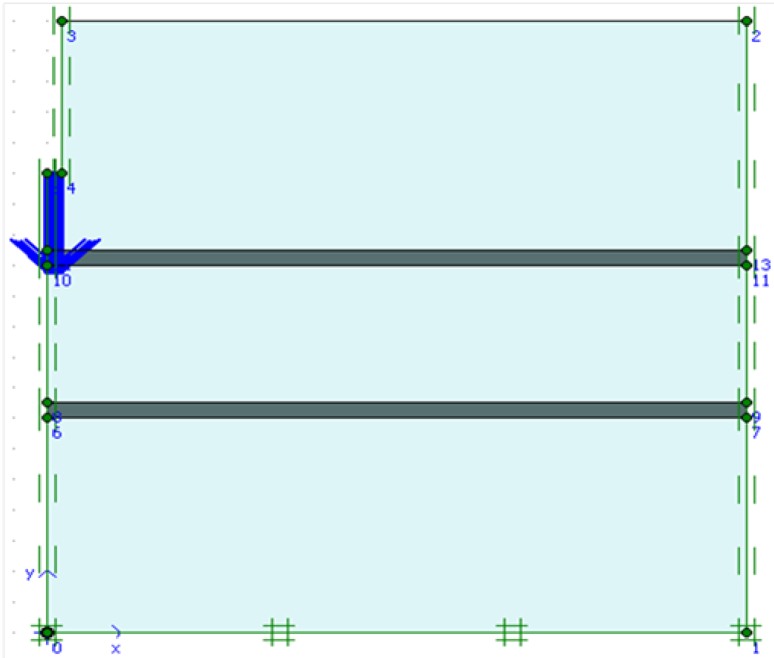
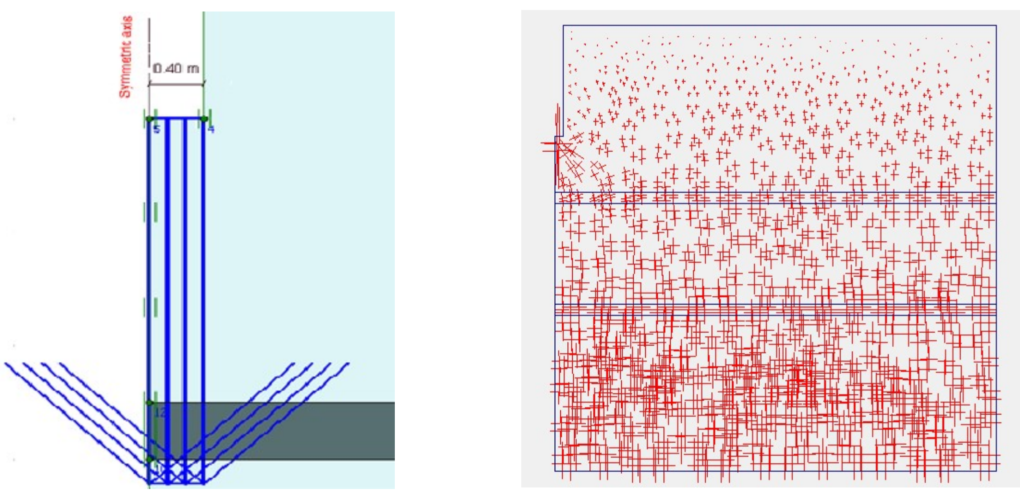


Fig.1. Numerical modeling of a drilled shaft



(a) (b)

Fig.2. (a) Close-up view of the tip of drilled shaft (b) Stress distribution

3. VALIDATION

Owing to uncertainties in geotechnical parameters, construction factors and other variables, the capacity of a drilled shaft often needs to be verified using a load test [15]. Pile loading test results provide reliable data for engineers that enable them to confirm and refine appropriate soil strength, stiffness and compressibility characteristics [16]. Therefore, in order to evaluate the validity and performance of the proposed finite element analysis of pile base load-settlement response in sand, a load test on a drilled shaft is modeled by this numerical method and analyzed. For this purpose, a pile load test performed by the Georgia Institute of Technology [17] is selected. The test site had a layer of residual, silty fine sand extending down to 19.5 m, underlain by partially weathered rock and then sound bedrock. A series of laboratory tests were performed on soil samples for determination of basic soil properties. Grain size distribution analysis showed that soil is consisted of approximately 70% sand, with the clay content of only about 8%. Moreover, the Atterberg limits testing showed that almost all of the soils were non-plastic. Table 1 depicts basic soil properties.

Table 1. Basic soil properties at Georgia Tech. site [17]

Layer number	**Depth (m)**	**Friction angle (°)**	**Coefficient of lateral earth pressure at rest**
1	0-1.82	34	0.44
2	1.82-3.93	34	0.44
3	3.93–5.93	37	0.40
4	5.93–7.93	33	0.46
5	7.93–9.93	32	0.47
6	9.93–11.93	32	0.47
7	11.93–13.93	36	0.41
8	13.93–14.93	38	0.38
9	14.93–16.76	36	0.41
10	16.76–18.28	36	0.41

The diameter of drilled shaft was 76 cm and had a length of 16.8 m. In the present study, this pile load test was modeled by the proposed numerical method. The base load-settlement curves of pile load test [17] and the modeled one were plotted together in Fig. 3. The comparison demonstrates a good agreement between the results.

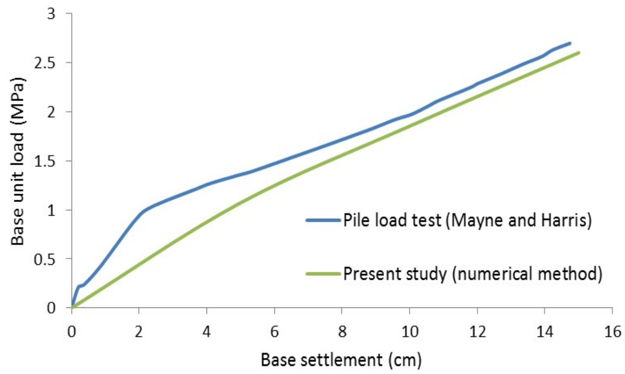


Fig.3. Comparison between base load-settlement curves obtained by pile load test and the present study

4. DETERMINATION OF THE END BEARING CAPACITY OF DRILLED SHAFTS (CASE STUDY)

By performing a 20 m borehole in a region in Babolsar city, north of Iran, the soil stratigraphy has been recognized. Table 2 shows soil stratigraphy in which N, G_s and γ are number of SPT blows, specific gravity and unit weight of soil, respectively. These parameters are obtained based on the results of laboratory and field tests. As observed, the soil consists of poorly-graded sand (SP) according to Unified Soil Classification System (USCS), except two 0.5-m layers that are of clay with low (CL) and high (CH) plasticity. The numerical modeling of a drilled shaft with an embedment depth of 5 m and a diameter of 80 cm in this site (in Babolsar city) was previously shown (Fig. 1). In the numerical modeling, soil properties were assigned based on soil stratigraphy. The side boundaries, located at a horizontal distance of 20 m from the drilled shaft axis, are restricted in the horizontal direction and the bottom boundary, located at a vertical distance of 15 m from the end of the drilled shaft, is restricted in both horizontal and vertical directions. Pile tip is given the vertical downward displacement as was shown in Fig. 2.

Fig. 4 depicts the drilled shaft tip behavior in this site. As observed in Fig. 4, with increase in the downward displacement at the pile tip, the generated stresses at the pile tip also increase and no peak point is observed in stress-settlement curve. Thus, it is essential to select a criterion for determining the ultimate end bearing capacity from the numerically obtained base load-settlement curve.To assess the end bearing capacity of drilled shafts, researchers have suggested that the fully mobilized end bearing is the capacity that can be developed at a given displacement of pile tip. Reese and Wright [18] and O'Neill and Reese[19] proposed that the required displacement for full mobilization of end bearing capacity is 5% D, where D is the shaft diameter. This value, based on Fleming et al. [20] suggestion is 5–10% D. According to Coduto[21], and White and Bolton[22] recommendations, the required pile tip displacement is 10% D. Moreover, the suggested value by Tomlinson [23] is 10–20% D. It should be noted that pile design based on selecting a pile tip displacement of more than 10% D may not satisfy the required serviceability condition of a structure. Hence, in this study, it is assumed that the end bearing capacity is mobilized at a tip displacement of 10% D. Therefore, for this drilled shaft, the end bearing capacity at the tip displacement of 8 cm is registered which is 836 kPa (Fig. 4).

Table 2. Exploratory boring log

Depth (m)	**Soil classification**	**Graphic log**	**N**	**G_S**	**γ (gr/cm^3)**
1.0	SP		11	2.81	1.83
2.0	SP		13	2.81	1.89
3.0					
3.5	SP		15	2.79	1.88
4.0					
5.0	SP		18	2.76	1.93
6.0					
7.0					
7.5	CL		10	2.72	1.75
8.0					
9.0					
10.0	SP		25	2.81	1.98
11.0					
12.0					
12.5	CH		12	2.36	1.75
13.0					
14.0					
15.0					
16.0					
17.0					
17.5	SP		36	2.75	2.11
18.0					
19.0					
20.0	SP		40	2.75	2.12

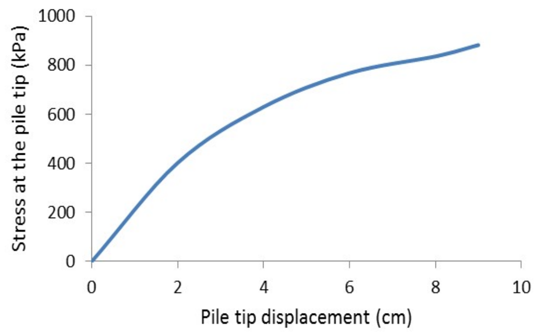


Fig.4. Tip stress versus tip displacement for a drilled shaft
(embedment depth = 5 m, diameter = 80 cm)

5. EFFECT OF DRILLED SHAFT EMBEDMENT DEPTH

By conducting a series of numerical analyses for drilled shafts with different embedment depths of 5, 10 and 15 m, the effect of embedment depth on the end bearing capacity of drilled shafts is investigated. The selected shaft diameter (D) in these analyses is a constant value of 80 cm. The results of analyses show that the end bearing capacity values of drilled shafts with embedment depths of 5, 10 and 15m are 836, 1205 and 1463 kPa, respectively (Fig. 5). As observed, for a drilled shaft with diameter of 80 cm, by increasing the embedment depth from 5 to 10 m, the amount of increase in the end bearing capacity is 44% but by increasing the embedment depth from 10 to 15 m, the rate of increase in the end bearing capacity is only 21%. Similar results were obtained for drilled shafts with constant diameters of 40 and 60 cm and different embedment depths of 5, 10 and 15 m that can be observed in Fig. 5. It can be concluded that with increase in the pile embedment depth for a constant pile diameter, the end bearing capacity also increases but with a smaller rate.

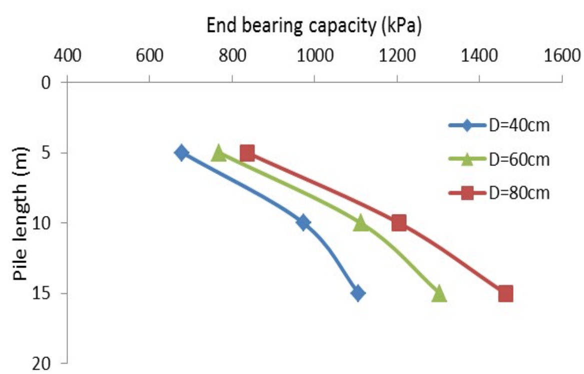


Fig.5. Variation of the end bearing capacity of drilled shafts with embedment depth

6. EFFECT OF DRILLED SHAFT DIAMETER

In order to investigate the influence of drilled shaft diameter on the end bearing capacity, some numerical analyses were carried out for drilled shafts with constant embedment depths (L) of 5, 10 and 15 m and different diameters of 40, 60 and 80 cm. Fig. 6 shows the variations of the stresses at the drilled shaft tip versus drilled shaft diameter.

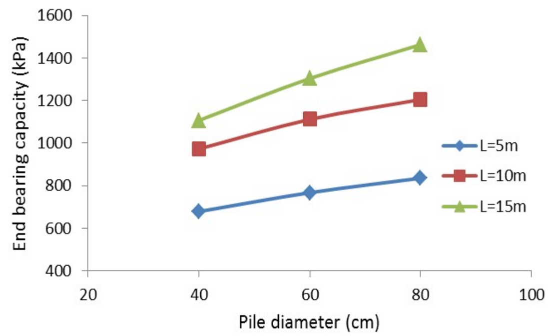


Fig. 6. Variation of the end bearing capacity of drilled shafts with diameter

It is observed that the end bearing capacity for a 5-m drilled shaft with diameter of 40 cm is 679 kPa, while this value is 768 kPa for a drilled shaft with diameter of 60 cm and, as calculated previously, the end bearing capacity for a drilled shaft with diameter of 80 cm is 836 kPa. In other words, by increasing the pile diameter from 40 to 60 cm, the amount of increase in the end bearing capacity is 13% but by increasing the pile diameter from 60 to 80 cm, the amount of increase in the end bearing capacity is only 8%. Hence, for a constant embedment depth, increase of pile diameter leads to an increase in the end bearing capacity. However, the end bearing capacity increases with a decreasing rate. Similar curves were obtained for drilled shafts with constant embedment depths of 10 and 15 m and different diameters of 40, 60 and 80 cm.

7. COMPARISON OF END BEARING CAPACITY OF DRILLED SHAFTS

Table 3 shows end bearing capacity values for different drilled shafts obtained by numerical method.

As expected, A1 has the lowest and C3 has the highest value of end bearing capacity. It is observed that the end bearing capacity of B2 (D = 60 cm, L = 10 m) is a little more than the end bearing capacity of A3 (D = 40 cm, L = 15 m). It shows that with increase in pile diameter from 40 to 60 cm, the influence of pile diameter on the end bearing capacity is more than the effect of pile length but this trend is not observed with increase in pile diameter from 60 to 80 cm, so that the end bearing capacity of B3 (D = 60 cm, L = 15 m) is more than C2 (D = 80 cm, L = 10 m). Therefore, the effect of length on the value of the end bearing capacity of these piles is more significant.

Table 3. End bearing capacity values of drilled shafts

Drilled shaft	Diameter (cm)	Embedment depth (m)	End bearing capacity (kPa)
A1	40	5	679
A2	40	10	973
A3	40	15	1107
B1	60	5	768
B2	60	10	1112
B3	60	15	1304
C1	80	5	836
C2	80	10	1205
C3	80	15	1463

8. DETERMINATION OF END BEARING CAPACITY OF DRILLED SHAFTS BY SPT-BASED METHODS

The SPT is one of the most common in-situ tests used to determine geotechnical engineering properties of subsurface soil. The blows required to drive the split-barrel sampler a distance of 300 mm, after an initial penetration of 150 mm, is referred to as the SPT N-value. This procedure has been accepted internationally with only slight modifications. SPT N-value has been used for designing structural foundations and other earth structures, particularly, for the bearing capacity of piles so that determination of pile capacity by SPT is one of the earliest applications of this test [24]. The end bearing capacity of drilled shafts in sandy soils is often evaluated using SPT results achieved at the site where drilled shafts will be constructed. Table 4 presents some common SPT-based methods for estimation of end bearing capacity of drilled shafts. It should be noted that in the following Table, N is average of standard penetration number values around drilled shaft base. In addition, the parameters D and L are diameter and embedment depth of drilled shafts, respectively.

Table 4: Some SPT- based methods for estimation of end bearing capacity of drilled shafts

Method	End bearing capacity (Q_p)
Meyerhof [25]	$Q_p\ (MPa) = kN_b(\frac{L}{D}) \leq mN_b$ N_b: average of N between 10D above and 5D below pile base k=0.012, m=0.12
Reese and Wright [18]	Q_p (kPa) =65N
Decourt [26]	Q_p (kPa) = 150N
O'Neill and Reese [19]	$Q_p\ (kPa) = \frac{L}{10}57.5N \leq \frac{L}{10}2900$:for L≤10m Q_p (kPa) = 57.5N ≤ 2900 :for L>10m

Table 5 shows comparison of the end bearing capacity values obtained from proposed numerical method and the ones estimated by SPT-based methods for different drilled shafts:

Table 5: Comparison of end bearing capacity values (kPa) between proposed numerical and SPT-based methods

Drilledshaft \ Method	Meyerhof	Reese and Wright	Decourt	O'Neill and Reese	Numerical (this study)
A1	1710	931	2148	411	679
A2	2100	1018	2349	901	973
A3	1440	1560	3600	1380	1107
B1	1340	931	2148	411	768
B2	1950	1018	2349	901	1112
B3	2916	1560	3600	1380	1304
C1	1005	931	2148	411	836
C2	1860	1018	2349	901	1205
C3	2490	1560	3600	1380	1463

The results show that, for this site, the end bearing capacity values estimated by Reese and Wright [18] method are approximately close to the ones obtained by the proposed numerical method. Howover, O'Neill and Reese [19] method underestimates, and Meyerhof [25] and Decourt [26] methods overestimate the end bearing capacity values of drilled shafts.

9. CONCLUSION

In the present study, a numerical modeling procedure was applied to analyze the end bearing capacity of drilled shafts in sandy soils. The elasto-plastic Mohr–Coulomb model was used in the procedure. A comparison between numerical and measured results of pile load test showed that compatibility between results was acceptable. Numerical analyses were carried out on drilled shafts with different diameters and embedment depths. The results showed that with increase in the embedment depth or diameter of drilled shafts, the end bearing capacity increases with a decreasing rate. Moreover, comparison between the results of proposed numerical and some common SPT-based methods indicated that there is a satisfactory agreement between the results of this numerical method and ones estimated by Reese and Wright method[18].

6. REFERENCES

[1] Brown D.A., Turner J.P. and Castelli R.J. Drilled Shafts: Construction Procedures and LFRD Design Methods. Report No. FHWA NHI-10-016, Federal Highway Administration, USA, 2010.

[2] Ai Z.Y. and Cheng Y.C. Analysis of Vertically Loaded Piles in Multilayered Transversely Isotropic Soils by BEM. Engineering Analysis with Boundary Elements, 2013, 37(2): 327-335.

[3] Alkroosh I. and Nikraz H. Predicting Axial Capacity of Driven Piles in Cohesive Soils Using Intelligent Computing. Engineering Applications of Artificial Intelligence, 2012, 25 (3): 618-627.

[4] Kameswara Rao N.S.V. Foundation Design: Theory and Practice. 1st Edition, John Wiley and Sons, USA, 2011.

[5] Gunaratne M. The Foundation Engineering Handbook. Taylor and Francis, London, UK, 2006.

[6] Winterkorn H.F. and Fang H.Y. Foundation Engineering Handbook, Van Nostrand Reinhold Company Inc., New York, USA, 1975.

[7] Dung N.T., Chung S.G., Kim S.R. and Chung J.G. Comparative Study Between Design Methods and Pile Load Tests for Bearing Capacity of Driven PHC Piles in the Nakdong River Delta. Journal of the Korean Geotechnical Society, 2007, 23(3): 61-75.

[8] Ishihara K. Recent Advances in Pile Testing and Diaphragm Wall Construction in Japan. Geotechnical Engineering Journal of the SEAGS and AGSSEA, 2010, 41(3): 1-43.

[9] Dung N.T., Chung S.G., Kim S.R. and Beak S.H. Applicability of the SPT-based Methods for Estimating Toe Bearing Capacity of Driven PHC Piles in the Thick Deltaic Deposits. KSCE Journal of Civil Engineering, 2011, 15(6): 1023-1031.

[10] Veiskarami M.,Eslami A. and Kumar J. End-Bearing Capacity of Driven Piles in Sand Using the Stress Characteristics Method: Analysis and Implementation. Canadian Geotechnical Journal, 2011, 48(10): 1570-1586.

[11] Manandhar S. and Yasufuku N. Analytical Model for the End-bearing Capacity of Tapered Piles Using Cavity Expansion Theory. Advances in Civil Engineering, 2012: 1-9.

[12] Yu F. and Yang J. Base Capacity of Open-ended Steel Pipe Piles in Sand. Journal of Geotechnical and Geoenvironmental Engineering, 2012, 138(9): 1116-1128.

[13] Singh G. and Walia B.S. Prediction Model for Skin Friction and Tip Bearing Capacity of Bored Piles by FEM. International Journal of Advanced Structures and Geotechnical Engineering, 2013, 2(4): 161-168.

[14] Han F., Salgado R., Prezzi M. and Lim J. Shaft and Base Resistance of Non-Displacement Piles in Sand. Computers and Geotechnics, 2017, 83: 184-197.

[15] Chen Y.J. and Fang Y.C. Critical Evaluation of Compression Interpretation Criteria for Drilled Shafts. Journal of Geotechnical and Geoenvironmental Engineering, 2009, 135(8): 1056-1069.

[16] Abdrabbo F.M. and Gaaver K.E. Undrained Behavior of Auger Cast-in-place Piles in Multilayered Soil. Alexandria Engineering Journal, 2013, 52(2): 187-195.

[17] Mayne P.W. and Harris D.E. Axial Load-displacement Behavior of Drilled Shaft Foundations in Piedmont Residuum. FHWA Reference No. 41-30-2175, Georgia Tech. Research Corporation, USA, 1993.

[18] Reese L.C. and Wright S.J. Construction Procedure and Design for Axial Loading, Drilled Shaft Manual. HDV–22, Implementation Package 77–21, Vol. 1, Implementation Division, US Department of Transportation, McLean, USA, 1977.

[19] O'Neill M.W. and Reese L.C. Drilled Shafts: Construction Procedures and Design Methods. Report No. FHWA-IF-99-025, Federal Highway Administration, USA, 1999.

[20] Fleming W.G.K., Weltman A.J., Randolph M.F. and Elson W.K. Piling Engineering. Wiley, New York, USA, 1985.

[21] Coduto D.P. Foundation Design: Principles and Practices. 2nd Edition, Prentice-Hall Inc., New Jersey, USA, 2001.

[22] White D.J. and Bolton M.D. Comparing CPT and Pile Base Resistance in Sand. Geotechnical Engineering, 2005, 158(1): 3-14.

[23] Tomlinson M.J. Pile Design and Construction Practice. 4th Edition, E and FN SPON, London, UK, 1994.

[24] Shooshpasha I., HasanzadehA. and Taghavi A. Prediction of the Axial Bearing Capacity of Piles by SPT-based and Numerical Design Methods. International Journal of GEOMATE, 2013, 4(2): 560-564.

[25] Meyerhof G.G. Bearing Capacity and Settlement of Pile Foundations. ASCE, Journal of the Geotechnical Engineering Division, 1976, 102(3): 195-228.

[26] Decourt L. Prediction of the Bearing Capacity of Piles Based Exclusively on N Values of the SPT. In: Proceedings of the 2nd European symposium, vol 1: Standard Penetration Test, Amsterdam, Netherland, 1982: 29–34.

How to cite this article:
Shooshpasha I, Kharun M, Hasanzadeh A. Evaluation of end bearing capacity of drilled shafts in sand by numerical and spt-based methods. J. Fundam. Appl. Sci., 2017, *9(7S), 282-295.*