881. Evaluation of tip capacity analysis model for drilled shafts in gravelly soils

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Abstract. This paper examines an analysis model for predicting the tip capacity of drilled shaft foundations under gravelly soils. Forty one static compression load test data are utilized for this purpose. Comparison of predicted and measured results demonstrates that the prediction model greatly overestimates the tip capacity of drilled shafts. Further assessment on the model reveals a greater variation in three coefficients, including the effective overburden pressure ($\overline{q}$), the overburden bearing capacity factor (N_q), and the bearing capacity modifier for soil rigidity (ζ_{qr}). These factors are modified from the back-analysis of the drilled shaft load test results. Varying effective shaft depths are considered for the back-calculation to evaluate their effects on capacity behavior. Based on the analyses, the recommended effective shaft depth for the evaluation of effective overburden pressure is limited to 15*B* (*B* = shaft diameter). The N_q and ζ_{qr} are enhanced while maintaining their basic relationship with the soil effective friction angle $\left(\overline{\phi}\right)$, in which the N_q increases and ζ_{qr} decreases as $\overline{\phi}$ increases. Specific design recommendations for the tip bearing capacity analysis of drilled shafts in gravelly soils are given for engineering practice.

Keywords: tip capacity, drilled shafts, analysis model, load test, gravelly soils, MATLAB.

Introduction

Due to its versatility, drilled shafts have been used extensively as deep foundations worldwide. An essential source of drilled shaft capacity under axial compression loading is the tip resistance. The tip resistance is generated from the bearing strength of soil beneath the pile tip. The general equation for the ultimate soil bearing capacity (q_{ult}) has been provided and improved by a number of researchers [1-3]. In recent years, the general equation [2]:

$$q_{ult} = cN_c + qN_q + 0.5\gamma BN_\gamma \tag{1}$$

in which c = soil cohesion, γ = soil unit weight, B = pile diameter, q = vertical stress at pile tip, and N_c, N_γ, N_q = bearing capacity factors, was extended to relate the model to actual field conditions. Additional modifiers that include foundation shape (*s*), depth (*d*), and rigidity (*r*) were introduced. Considering these modifiers to circular shafts, the general form of the bearing capacity equation for drained compression tip capacity is given by [3]:

$$q_{ult} = \overline{q}N_q\zeta_{qs}\zeta_{qd}\zeta_{qr} + 0.3\overline{\gamma}BN_\gamma\zeta_{\gamma r} \tag{2}$$

and the tip resistance in compression is:

$$Q_{tcp} = A_{tip} \times q_{ult} \tag{3}$$

in which ζ_{qs}, ζ_{qd}, ζ_{qr} = modifiers of N_q for foundation shape, depth, and soil rigidity, respectively, $\zeta_{\gamma r}$ = modifier of N_γ for soil rigidity, $\overline{q}$ and $\overline{\gamma}$ = effective vertical stress and soil unit weight, respectively, A_{tip} = shaft tip area, and Q_{tcp} = predicted tip resistance. The detailed values of N_γ, N_q and modifiers are presented elsewhere [4]. Recently, a re-evaluation of the tip capacity of drilled shaft was studied [5] using a large amount of field load test data in drained soils and revealed that the measured tip capacity is much less than the predicted capacity. Gravelly soils typically exhibit greater strength or stiffness than general soils. The tendency of gravels to dilate more during shearing can further provide better strength behavior. Therefore, to assess the applicability of the analysis model on drilled shafts in gravelly soils, a performance evaluation is conducted.

In this study, a database of load test case histories in gravelly soils is utilized to carry out the evaluation of the tip capacity of drilled shafts. The factors influencing the prediction of tip capacity are explored and assessed in detail. Modified factors are derived to provide a more precise prediction of tip capacity. Specific design recommendations for the tip bearing capacity analysis of drilled shafts in gravelly soils are given for practical engineering applications.

Load test data

A database is developed for this study consisting of 41 field compression load tests conducted at 23 sites. All of the selected tests were conducted on straight-sided drilled shafts with almost complete geological data. These tests are dominated by gravelly soils based on the predominant soil condition along the shaft depth and tip. The gravelly soils have particle size greater than 4.75 mm, and the content of gravels is more than 50 percents. According to the case history descriptions, the shaft construction and test performance appear to be of high quality. Consequently, these data should reflect common field situations, and the analysis results should be representative for application in practice. The basic information and properties for these cases are listed in Table 1 while the reference sources are presented in Table 2. Details can be seen elsewhere [6].

The L_1-L_2 method [7-9], which is a graphical construction method, was adopted to interpret the compression capacity from the load-displacement curve. This method employs the fact that the load-displacement curve generally can be simplified into three distinct regions: initial linear, curve transition, and final linear, as illustrated in Fig. 1. Point L_1 (elastic limit) corresponds to the load Q_{L1} and butt displacement δ_{L1} at the upper end of the initial linear region, while L_2 (failure threshold) corresponds to the load Q_{L2} and butt displacement δ_{L2} at the initiation of the final linear region. Q_{L2} is defined as the "interpreted failure load" or "interpreted capacity" because, beyond Q_{L2}, a small increase in load gives a significant increase in displacement. Chen and Fang [10] examined this method for drilled shafts and concluded that L_2 method provides reasonable results and is suitable for drilled shaft compression design. From the interpreted compression capacity, the measured tip capacity Q_{tcm} can be proportioned from the load-distribution curve along the shaft length.

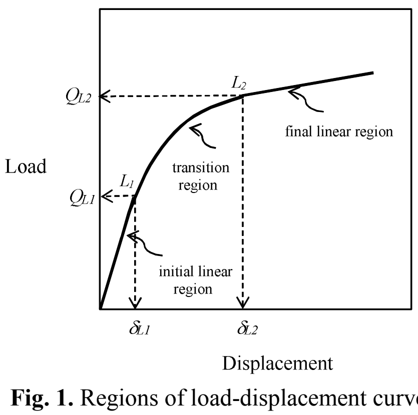

Fig. 1. Regions of load-displacement curve

Table 1. Basic information for compression tests in gravelly soils

Shaft No.	Location / Soil description	$\bar{\phi}$ [a]	γ_t [b]	$\bar{\sigma}_v$ [c]	GWT [d]	D [e]	B [f]
		(°)	(kN/m^3)	(kN/m^2)	(m)		
GC01	Taipei, Taiwan; gravel	45	20.6	135	2.5	10.4	0.60
GC02	Chin-Men, Taiwan; gravel	40	20.6	114	0.8	10.0	0.80
GC03	Hsinchu, Taiwan; gravel w / silt	45	20.5	243	7.5	16.0	1.50
GC04-1	Nantou, Taiwan; sand & gravel	45	21.0	170	6.0	10.0	1.20
GC04-2		45	21.0	170	6.0	10.0	1.20
GC05-1	Taichung, Taiwan; sandy gravel	42	21.0	225	6.0	14.8	1.50
GC05-2		42	21.0	193	6.0	12.0	1.50
GC05-3		42	21.0	224	6.0	14.7	1.50
GC06	Puerto Rico; sandy gravel	41	20.1	300	3.1	14.9	1.52
GC07	Cupertino, CA; sandy gravel	46	18.4	168	-[g]	9.1	0.76
GC08-1	Fukuoka, Japan; gravelly sand	45	17.3	206	2.0	25.0	1.20
GC08-2		45	16.3	120	0.6	17.6	1.20
GC09	Osaka, Japan; sandy gravel	37	21.0	272	1.0	23.5	1.20
GC10-1	Takasaki, Japan; sandy gravel w. boulders	41	21.0	190	3.8	13.6	1.00
GC10-2		41	21.0	188	3.8	13.4	1.00
GC10-3		41	21.0	188	3.8	13.5	1.00
GC11	Scipio, Utah; sand & gravel	43	19.6	240	-[g]	12.2	0.85
GC12	Albuquerque, NM; loose sand over dense gravel	39	18.4	182	2.4	18.5	0.91
GC13	Hsinchu, Taiwan; gravel w. silt	42	20.6	224	3.0	18.0	1.20
GC14	Taiwan; sandy gravel	45	21.0	294	1.5	25.0	1.50
GC15	Hsinchu, Taiwan; gravel w. silt	45	21.0	202	3.0	15.5	1.20
GC16-1	Taichung, Taiwan; sandy gravel	42	21.0	432	8.5	30.0	1.00
GC16-2		42	21.0	432	8.5	30.0	1.00
GC17-1	Sigurd-Salina, Utah; sand & gravel	42	21.0	206	7.0	12.2	0.61
GC17-2		41	21.0	256	-[g]	12.2	0.59
GC18-1	Belknap, Utah; sand & gravel	42	21.0	184	4.8	12.2	0.85
GC18-2		40	21.0	184	4.8	12.2	0.95
GC19-1	Belknap, Utah; sand & gravel	39	21.0	168	3.3	12.2	0.80
GC19-2		40	21.0	166	3.0	12.2	1.16
GC20-1	Black Rock, Utah; sand & gravel w. silt	40	19.6	230	-[g]	11.7	0.91
GC20-2		40	19.6	166	-[g]	8.5	0.91
GC21-1	Dusseldorf, Germany; gravelly sand & sandy gravel	40	20.5	266	-[g]	13.0	1.08
GC21-2		39	20.5	266	-[g]	13.0	0.67
GC21-3	Taoyuan, Taiwan; gravel w. sand	40	20.5	210	-[g]	10.2	0.67
GC22		47	21.6	158	4.0	10.0	0.80
GC23-1	Phoenix, AZ; silty & sandy clay over clayey gravel	42	20.4	110	-[g]	5.4	0.76
GC23-2		42	20.4	96	-[g]	4.7	0.76
GC23-3		42	20.4	100	-[g]	4.9	0.76
GC23-4		42	20.4	106	-[g]	5.2	0.76
GC23-5		42	20.4	112	-[g]	5.5	0.76
GC23-6		42	20.4	114	-[g]	5.6	0.76

a - $\bar{\phi}$ = soil effective friction angle
b - γ_t = total unit weight
c - $\bar{\sigma}_v$ = effective overburden pressure at tip
d - GWT = groundwater table
e - D = shaft depth
f - B = shaft diameter
g - GWT is not reported or below shaft tip

Table 2. Reference sources for compression load test data

Shaft No.	Reference
GC01	Yu-Ying Construction Corporation, (1999), "Report on Compression Load Test of Bored Piles for Wuku Building" Taipei, Taiwan.
GC02	Haigh-Tian Engineering, (2001), "Report on Compression Load Test of Bored Piles for Chin Men Fishing Port Office" Kimmen, Taiwan.
GC03	Tong-Fa Construction Corporation, (2000), "Report on Compression Load Test of Bored Piles for Nan Liao-Chu Tung High-Speed Road" Hsinchu, Taiwan.
GC04	Haigh-Tian Engineering, (2000), "Report on Compression Load Test of Bored Piles for Nantou Bridge" Nantou, Taiwan.
GC05	Lu Y. L. and Su P. C., (2004), "Evaluation of Pile Loading Test Results on Gravel Formations", Sino-Geotechnics, 100, Taipei, 47-54.
GC06	Farr J. S. and Aurora R. P., (1981), "Behavior of An Instrumented Pier in Gravelly Sand", Drilled Piers and Caissons, Ed. M. W. O'Neill, ASCE, New York, 53-65.
GC07	Baker C. N., Drumright E. E., Mensah F., Parikh G. and Ealy C., (1991), "Dynamic Testing to Predict Static Performance of Drilled Shafts Results of FHWA Research", Geotechnical Engineering Congress (GSP 27), 1, Ed. F. G. McLean, D. A. Campbell.
GC08	Ochiai H., Adachi S., and Matsui K., (1993), "Monitoring and Evaluation Report of Bearing Capacity of Friction Pile Based on Uncertainty of Soil Properties", Proceedings, 3rd International Conference on Case Histories in Geotechnical Engineering, 1.
GC09	Matsui T., (1993), "Case Studies on Cast-in-Place Bored Piles and Some Considerations for Design", Proceedings, 2nd International Seminar on Deep Foundations on Bored and Auger Piles, Ed. W. F. Van Impe, Ghent, 77-101.
GC10	Fujioka T. and Yamada K., (1994), "The Development of a New Pile Load Testing System", Proceedings, International Conference on Design and Construction of Deep Foundations, 2, FHWA, Orlando, 670-684.
GC11	Price R., Rollins K. M. and Keane E., (1992), "Comparison of Measured and Computed Drilled Shaft Capacities Based on Utah Load Tests", Research Record 1336, Transportation Research Board, Washington, D. C., 57-64.
GC12	Meyers B., (1992), "New Mexico Bridge on Drilled Shaft - A First", Foundation Drilling, ADSC, 31(7), 28-40.
GC13	Chung-Hua Engineering, (1995), "Report on Compression Load Test of Bored Piles for Ta-Chia Bridge", Hsinchu, Taiwan.
GC14	Diagnostic Engineering, (2002), "Report on Compression Load Test of Bored Piles for Hsi-Pin High-Speed Road", Taiwan.
GC15	Chung-Hua Engineering, (1995), "Report on Compression Load Test of Bored Piles for Ta-An Bridge", Hsinchu, Taiwan.
GC16	Lu Y. L. and Su P. C., (2005), "A Preliminary Study of Pile Construction Method and Bearing Capacity Evaluation in Gravel Formations", Sino-Geotechnics, 113, Taipei, 57-66.
GC17-GC20	Price R. M., (1993), "Evaluation of Drilled Shaft Capacity Equations Based on Utah DOT Load Tests", M. S. Thesis, Brigham Young University, Provo, 234 p.
GC21	Rollberg D., (1977), "Determination of the Bearing Capacity of Pile Driving Resistance of Piles Using Soundings", Publications of the Institute for Foundation Engineering, Soil Mechanics, Rock Mechanics and Water Ways Construction, Vol. 3 of English Edition, RWTH (University), Aachen, 227 p.
GC22	Hu S., (1993), "Distribution of *p-y* Curves of Drilled Shafts in Gravelly Cobbles", Proceedings, 5th Conference on Current Researches in Geotechnical Engineering in Taiwan, Lungmen, Taiwan, 327-334.
GC23	Beckwith G. E. and Bedenkop D. V., (1973), "An Investigation of the Load Carrying Capacity of Drilled Cast-In-Place Concrete Piles Bearing on Coarse Granular Soils and Cemented Alluvial Fan Deposits", Report AHD-RD-10-122, Arizona Highway Department, Phoenix, 314 p.

Tip capacity analysis

The predicted tip capacity, Q_{tcp} was calculated using eqns. 2 and 3, while the measured tip capacity, Q_{tcm} was proportioned from the interpreted capacity, Q_{L2}. Table 3 shows the results for the tip capacity analysis. For convenience, the table likewise shows the ranges of foundation geometry, predicted and measured tip capacities, and the capacity ratio. The data standard deviation (*SD*) and coefficient of variation (*COV*), which is the standard deviation divided by the mean are presented to observe the consistency of the results. It can be seen from these values that the database is broad. The ratio of predicted and measured tip capacities for the 41 data is in the range of 0.06 to 0.37 with a mean ratio of 0.17. This indicates that the measured results are only about 17 % of the predicted results. The *SD* and *COV* values for these data are 0.10 and 0.58, respectively. Fig. 2 presents the comparison of predicted and measured tip resistances. The regression analysis has a mean measured to predicted ratio of 0.11. These results reveal an obvious overestimation of the tip capacity in gravelly soils. Similar phenomenon was encountered by previous studies on drilled shafts [5] and pre-bored PC piles [11] in drained soils. The previous study [5] presented that the overestimation is most likely caused by the effective overburden pressure $(\overline{q})$, overburden bearing capacity factor (N_q) and other related analysis coefficients. Therefore, to provide a more reasonable prediction of the tip capacity of drilled shafts in gravelly soils, the analysis model is improved. The variability of each factor from the analysis model is determined. The factors that exhibit great variation are critically assessed and modified.

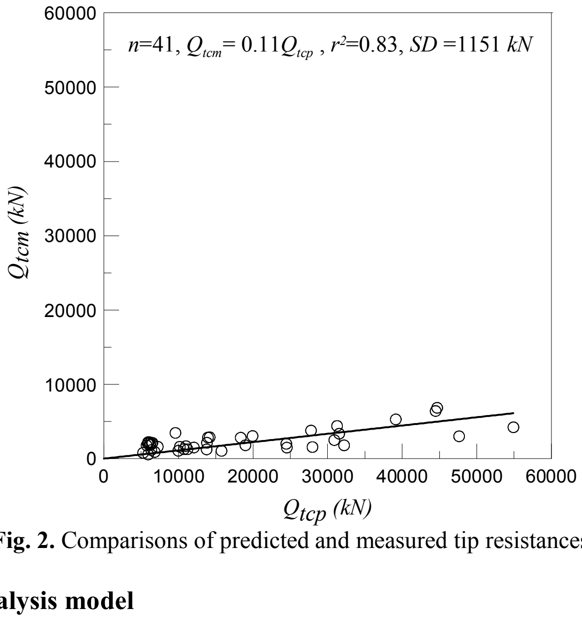

Fig. 2. Comparisons of predicted and measured tip resistances

Improvement of analysis model

Aside from the basic soil and shaft properties, the factors and modifiers of the ultimate bearing capacity equation (eqn. 2) are assessed in detail. However, based on a number of analysis in pile foundations that utilized this equation, the second term, ($0.3\overline{\gamma}BN_\gamma\zeta_{\gamma r}$) accounts for a negligibly small proportion of the overall capacity. Therefore, the analysis is focused on the parameter $\overline{q}$ and factors N_q, ζ_{qs}, ζ_{qd} and ζ_{qr}. The statistics for these coefficients based on the original values that predicted the tip resistance for the 41 drilled shaft load tests are demonstrated in Table 4 to compare their variation.

Table 3. Axial compression load test data for drilled shafts in gravelly soils

Shaft No.	Pile geometry (m)		Measured tip capacity, (L_2) Q_{tcm} (kN)	Predicted tip capacity, Q_{tcp} (kN)	Q_{tcm}/Q_{tcp}
	Depth, D	Diameter, B			
GC01	10.4	0.60	780	5260	0.15
GC02	10.0	0.80	560	5937	0.09
GC03	16.0	1.50	3012	47637	0.06
GC04-1	10.0	1.20	1998	24459	0.08
GC04-2	10.0	1.20	1490	24537	0.06
GC05-1	14.8	1.50	6413	44484	0.14
GC05-2	12.0	1.50	5280	39142	0.13
GC05-3	14.7	1.50	6842	44691	0.15
GC06	14.9	1.52	2500	30903	0.08
GC07	9.1	0.76	1600	10184	0.16
GC08-1	25.0	1.20	3780	27778	0.14
GC08-2	17.6	1.20	3045	19941	0.15
GC09	23.5	1.20	2820	18351	0.15
GC10-1	13.6	1.00	2140	13824	0.15
GC10-2	13.4	1.00	2840	13957	0.20
GC10-3	13.5	1.00	2880	14186	0.20
GC11	12.2	0.85	1245	13778	0.09
GC12	18.5	0.91	3460	9597	0.36
GC13	18.0	1.20	1795	32214	0.06
GC14	25.0	1.50	4223	54916	0.08
GC15	15.5	1.20	1561	27965	0.06
GC16-1	30.0	1.00	4400	31271	0.14
GC16-2	30.0	1.00	3360	31554	0.11
GC17-1	12.2	0.61	2052	5874	0.35
GC17-2	12.2	0.59	2242	6022	0.37
GC18-1	12.2	0.85	1280	10753	0.12
GC18-2	12.2	0.95	1260	11212	0.11
GC19-1	12.2	0.80	1600	7227	0.22
GC19-2	12.2	1.16	1044	15776	0.07
GC20-1	11.7	0.91	1500	12070	0.12
GC20-2	8.5	0.91	1060	9983	0.11
GC21-1	13.0	1.08	1800	18938	0.10
GC21-2	13.0	0.67	900	6820	0.13
GC21-3	10.2	0.67	1160	6361	0.18
GC22	10.0	0.80	1680	10999	0.15
GC23-1	5.4	0.76	1853	6228	0.30
GC23-2	4.7	0.76	1786	5733	0.31
GC23-3	4.9	0.76	2204	5933	0.37
GC23-4	5.2	0.76	2090	6183	0.34
GC23-5	5.5	0.76	1995	6425	0.31
GC23-6	5.6	0.76	2128	6517	0.33
Range	4.7-30.0	0.59-1.52	560-6842	5260-54916	0.06-0.37
Mean	13.38	1.00	2382	18187	0.17
SD	6.19	0.28	1418	13581	0.10
COV	0.46	0.28	0.60	0.75	0.58

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Table 4. Summary comparison of bearing capacity factors and modifiers

Statistics	N_q	ζ_{qs}	ζ_{qd}	ζ_{qr}	$\overline{q}$
n	41	41	41	41	41
Range	44.6-191.4	1.76-2.08	1.23-1.36	0.27-0.64	96-432
Mean	98.8	1.92	1.29	0.44	206.2
SD	35.4	0.07	0.03	0.10	103.5
COV	**0.36**	0.04	0.02	**0.23**	**0.50**

From the statistics, the parameter $\overline{q}$ and factors N_q and ζ_{qr} demonstrate relatively larger coefficients of variation of 0.50, 0.36 and 0.23, respectively. Hence, these factors are considered for the improvement analysis of the bearing capacity equation.

The large variation is very explicit from shafts with longer lengths. This manifestation reveals that the effective overburden pressure beneath the shaft tip can greatly affect the behavior of the shaft. Some research [12, 13] that focused on the study of bearing capacity explained that the tip bearing capacity of a pile in sandy soils generally increases with depth, up to a so-called critical depth. The capacity becomes constant beyond this depth. Hence, for relatively large pile depths, the analysis of effective overburden pressure can reach a maximum value at a depth of embedment known as the effective depth. In this study, varying effective depths, such as 10*B*, 15*B* and 20*B* are considered to explore the effect of shaft depth for gravelly soils and are the basis for the improvement of the factors. The calculation of the parameter $\overline{q}$ is limited to the effective depth in cases where the shaft length exceeds the effective depth. The product of the factors N_q and ζ_{qr} is back calculated from the measured tip capacity (Q_{tcm}) for the 41 field load tests to obtain their best possible combinations.

Previous studies [1, 2, 4] verified that N_q and ζ_{qr} have consistent relationship with $\overline{\phi}$, in which the N_q increases and ζ_{qr} decreases as $\overline{\phi}$ increases. The physical meaning of this principle remains the same throughout the analysis. MATLAB program is utilized to evaluate the best combination of N_q and ζ_{qr} for the given effective shaft depths because of its simplicity in designing the programming syntax. The best combinations are established based on the regression analysis and coefficient of variation for each combination.

Analysis results

The statistical summary for the combinations of N_q and ζ_{qr} for the different effective depths and the improved relationship (χ) of the predicted and measured tip capacities are shown in Table 5. The regression analysis [standard deviation (*SD*) and coefficient of determination (r^2)] are likewise indicated in the table. Results from 10*B* and 15*B* are somewhat comparable where the sum of r^2 value for N_q is a maximum at a depth of 10*B*, while the *SD* is smaller and r^2 is larger for the ratio, Q_{tcm}/Q_{tcp} in 15*B*. For more reasonable design applications, 15*B* can indicate the best possible combinations. The mean of the measured values is also very close to the predicted values (i.e., $\chi \approx 1$). Therefore, the effective depth for drilled shaft in gravelly soils can be best limited to 15*B* for the tip capacity analysis.

The correlations between N_q and $\overline{\phi}$ and ζ_{qr} and $\overline{\phi}$, for the effective depth 15*B* are shown in Figs. 3 and 4. The scatters illustrate that the modified bearing capacity coefficients still maintain their basic relationship with the soil effective friction angle, where the N_q increases and ζ_{qr}

deacreases as $\bar{\phi}$ increases. The data sets provide simplified equations for the evaluation of N_q and ζ_{qr}.

Table 5. Comparison of analysis results for different effective depths

Factor \ Effective depth	10B			15B			20B		
	SD	r^2		SD	r^2		SD	r^2	
N_q	0.30	0.70		0.38	0.68		0.43	0.60	
ζ_{qr}	0.19	0.67		0.21	0.68		0.23	0.67	
$Q_{tcm} = \chi\, Q_{tcp}$	SD	r^2	χ	SD	r^2	χ	SD	r^2	χ
	1365	0.81	1.00	1203	0.82	1.00	1389	0.79	1.01

Note: SD: standard deviation; r^2: coefficient of determination

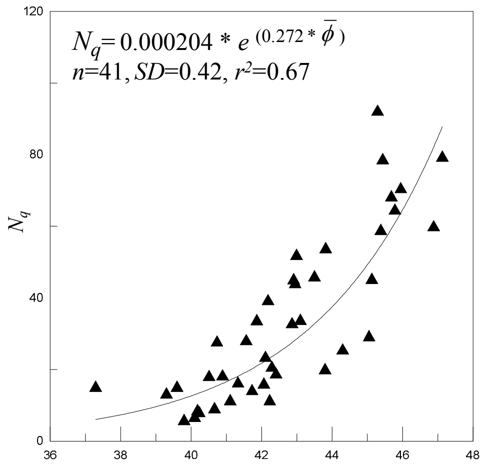

Fig. 3. Relation between N_q and $\bar{\phi}$

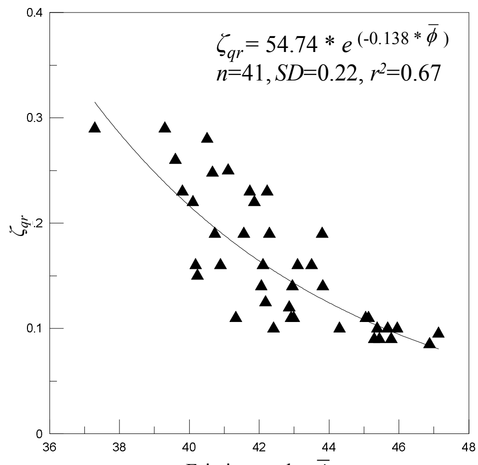

Fig. 4. Relation between ζ_{qr} and $\bar{\phi}$

The predicted $\left(Q_{tcp}\right)$ and measured $\left(Q_{tcm}\right)$ tip capacities after enhancement are demonstrated in Fig. 5 to assess the effects of the improvement. On average, the predicted tip capacities using the improved analysis model are fairly consistent with the measured capacities. Comparison of Figs. 2 and 5 clearly indicates that the predicted results are greatly enhanced. The statistical results in Fig. 5 also indicate an improved r^2. Therefore, the improved equations derived from the present study can reasonably estimate the drilled shaft tip bearing capacity in gravelly soils.

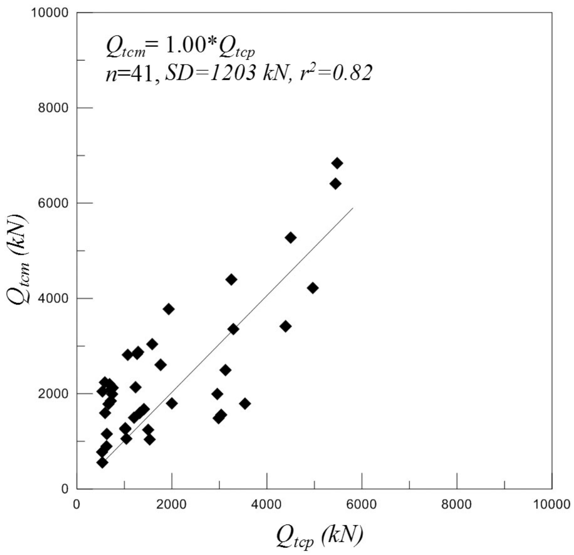

Fig. 5. Comparisons of Q_{tcm} and Q_{tcp} after improvement

Conclusions and design recommendations

The performance of an analysis model for the tip bearing capacity of drilled shafts in gravelly soils was carefully assessed. Forty one load test cases were used for the evaluation. Based on the analyses, the following conclusions are reached and conditions for the practical use of the model in engineering analysis and design are suggested:

1. Using the current analysis model, the mean ratio of the measured to predicted tip capacity is only about 0.17, indicating that the bearing capacity theory unreasonably predicts the tip capacity under tolerable design settlement.
2. The regression analysis likewise indicates a smaller ratio of the measured to predicted tip capacity of 0.11.
3. The effective overburden pressure can be limited to a shaft depth of 15B.
4. The equation for the improved rigidity modifier, ζ_{qr} is suggested as:

$$\zeta_{qr} = 54.74 \times e^{(-0.138 \times \bar{\varphi})} \tag{4}$$

5. The equation for the improved bearing capacity factor, N_q is suggested as:

$$N_q = 0.000204 \times e^{(0.272 \times \bar{\varphi})} \tag{5}$$

6. The improved analysis model greatly enhanced the predicted tip capacity of drilled shafts in gravelly soils.

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References

[1] **Hansen J. B.** A revised and extended formula for bearing capacity. Bulletin 28, Danish Geotechnical Institute, Copenhagen, 1970, p. 5-11.
[2] **Vesic A. S.** Bearing capacity of shallow foundation. Foundation Engineering Handbook, Chapter 3, Van Nostrand Reinhold, New York, 1975, p. 121-147.
[3] **Kulhawy F. H., Trautmann H. C., Beech J. F., O'Rourke T. D., McGuire W., Wood W. A., Capano C.** Transmission line structure foundations for uplift - compression loading. Report EL-2870, EPRI, Palo Alto, California, 1983.
[4] **Kulhawy F. H.** Drilled shaft foundations. Chapter 14, Foundation Engineering Handbook (2nd Ed.), Van Nostrand Reinhold, New York, 1991, p. 537-552.
[5] **Chen Y.-J., Fang Y.-C., Chu T.-H.** Evaluation of compression tip capacity for drilled shafts. Contemporary Topics in Deep Foundations. Proceedings of Selected Papers of the 2009 International Foundation Congress and Equipment Expo (GSP 185), 2009, March 15-19, Orlando, Florida.
[6] **Chu T.-H.** Evaluation of Interpretation Criteria and Capacity for Drilled Shafts in Gravelly Soils under Axial and Lateral Loading. Master Thesis, Department of Civil Engineering, Chung Yuan Christian University, Taiwan, R. O. C., 2009, (in Chinese).
[7] **Hirany A., Kulhawy F. H.** Conduct and Interpretation of Load Tests on Drilled Shaft Foundations: Detailed Guidelines. Report EL-5915(1), EPRI, Palo Alto, California, 1988.
[8] **Hirany A., Kulhawy F. H.** Interpretation of load test on drilled shafts (1): Axial compression. Foundation Engineering: Current Principles & Practices. Proceedings of the ASCE Foundation Engineering Congress (GSP22), Ed. F. H. Kulhawy, New York, 1989, p. 1132-1149.
[9] **Hirany A., Kulhawy F. H.** On the interpretation of drilled foundation load test results. Deep Foundations 2002: An International Perspective on Theory, Design, Construction and Performance. Proceedings of the International Deep Foundations Congress (GSP 116), Ed. M. W. O'Neill and F. C. Townsend, Orlando, Florida, 2002, p. 1018-1028.
[10] **Chen Y.-J., Fang Y.-C.** Critical evaluation of compression interpretation criteria for drilled shafts. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 135, No. 8, 2009, p. 1056-1069.
[11] **Marcos M. C., Chen C.-H., Chen Y.-J.** Evaluation of axial capacity of pre-bored PC piles in drained soils. Journal of Advanced Engineering, Vol. 6, No. 4, 2011, p. 321-326.
[12] **Vesic A. S.** Bearing capacity of deep foundations in sands. Highway Research Board Record, No. 39, 1963, p. 112-153.
[13] Department of the Navy, Naval Facilities Engineering Command (NAVFAC), Foundation and Earth Structure. Design Manual 7.2, 1982.