Design of Drilled Shafts Supporting Sound Walls

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Drilled shafts are widely adopted as the foundation for sound walls. However, there has been a lack of uniformity in design and analysis methods and design criteria, in terms of factor of safety against ultimate capacity failure as well as the allowable deflection. In order to establish a uniform design methodology for the drilled shafts supporting sound walls in cohesive and cohesionless soils, respectively, a database of full-scale lateral load tests on fully instrumented drilled shafts was collected. Based on the compiled database, existing design methods and design criteria of laterally loaded drilled shafts were evaluated. Broms method and COM624P (or LPILE) are suggested as the design methods for drilled shafts supporting sound walls in both cohesive and cohesionless soils. Additionally, the corresponding design criteria, including factor of safety and permissible deflection, for both design methods are recommended. Two full-scale lateral load tests on fully instrumented drilled shafts were subsequently conducted in Colorado to further verify the design recommendation. A comprehensive geotechnical investigation program was also carried out at the two new lateral load test sites that included pressuremeter test, SPT, as well as laboratory triaxial consolidated undrained tests and direct shear tests on the soil samples taken from the lateral load test sites. The test results obtained at these two load test sites were employed to validate the recommended geotechnical design and geotechnical testing methods for the drilled shafts supporting sound walls.

Introduction

Sound walls are frequently constructed along portions of highways nearing residential areas. Due to economy and simplicity, drilled shafts have been widely used as foundations for sound walls. The primary loadings to sound wall foundations are lateral loads and moments from wind loads. The most common methods used by most of state Department of Transportation (DOT) for design of drilled shafts under lateral loads from wind loads are divided into two categories:

- Ultimate capacity based design methods to ensure adequate margin of safety (e.g., Brinch Hansen method 1961, Broms method 1964a and 1964b, Davidson et al. 1976, Bang & Shen 1989);
- Serviceability design methods to ensure that shafts lateral displacement is smaller than a predefined tolerable displacement (e.g., NAVFAC DM-7 1971, COM624P or LPILE).

Different engineers even in the same DOT use different design methods. The factor of safety (FS) and permissible deflections used with these methods are not uniform, sometimes even for the same design method. These methods are not intended to provide comparable levels of safety because they are for different purposes; if they provide comparable FS then one method will be adequate. Methods for determining pertinent soil parameters needed in both types of analysis (ultimate capacity and deflection prediction) also differ and have not been consistently evaluated for their applicability and accuracy. All these factors make the design very conservative and lack uniformity that could lead to high construction costs for these shafts.

Several past research studies were conducted to identify the appropriate design approach for sound walls. Boghrat (1990) discussed and compared four other design methods (TRR 616 method, Woodward and Gardner method, New York Department of Transportation Method, and North Carolina Method) by using hypothetical cases; however, no design recommendation was made due to the lack of full-scale field test data for verification. Helmers et al. (2000) conducted lateral load testing on model drilled shafts having diameters of 203 mm (8 inches) or 229 mm (9 inches) in partially saturated silts and clays at five sites in Virginia. A comparison between measured lateral capacities and predicted values by using Broms method (1964b) and Brinch Hansen method (1961) was performed. Based on the comparison, the use of Brinch Hansen method (1961) was recommended for the design of drilled shafts to support sound walls in partially saturated silts and clays, in which a reduction factor of 0.85 on the predicted capacity was also suggested.

It can be seen that previous studies have not been validated with prototype load test data. In this study, therefore, full-scale lateral load test data is used to identify the suitable design methods and acceptance criteria for the drilled shafts to support sound walls in cohesive and cohesionless soils, respectively. The current practice including analysis methods and acceptance criteria are critically reviewed. The correlations between SPT N values and soil parameters are reviewed and summarized in this paper. A lateral load test database on the drilled shafts supporting sound walls was collected to consist of seven full-scale field tests of fully instrumented drilled shafts in clay conducted in Ohio (Liang, 1997) and five tests in sand from open literature (Bhushan et al. 1981). Based on the selected database and soil parameters determined from Liang's SPT correlation charts (Liang, 2002), the most common design methods presented before were evaluated by comparing the predictions from these design methods with results from lateral load tests. Based on this evaluation, appropriate design methods and acceptance criteria for drilled shafts to support sound walls in cohesive soils and cohesionless soils are identified. A design approach incorporating both strength limit based design and the serviceability based analysis was recommended that ensures a more consistent design outcome with comparable margin of safety from both capacity and deflection viewpoints. Furthermore, two lateral load tests of fully instrumented drilled shafts constructed at a sand soil deposit and a clay soil deposit, respectively, near Denver, Colorado were conducted by Nusairat, et al. (2004). A comprehensive geotechnical investigation program was also carried out at the two new lateral load test sites that included pressuremeter test, SPT, as well as laboratory triaxial consolidated undrained (CU) tests and direct shear tests on the soil samples taken from the lateral load test sites. This also allowed for evaluation of the accuracy of various testing methods for determining the soil parameters for the design methods for sound walls. The overall test results were used to verify the recommended design and testing methods.

Review of Current Practices

Analysis Methods

In current practice, both allowable deflection based design methods and strength limit based design methods described in the following are used for sound wall foundation design (Nusairat et al., 2004).

Brinch Hansen method (1961) is based on earth pressure theory for c-w soils. The method is only applicable for short piles (drilled shafts), and a trial-and-error procedure is needed in the calculation to locate the point of rotation. Broms method (1964a, 1964b) is only suitable for homogeneous soils, either cohesive soils or cohesionless soils. However, it can be applied to short drilled shafts or long drilled shafts; and the shaft head can be free or restrained. In AASHTO "Guide Specifications for Structural Design of Sound Barriers, 1989", the Sheet Piling Method is suggested for the design of piles supporting sound barrier walls. The Sheet Piling Method was initially developed for sheet piles embedded in cohesionless soils. For cohesive soils, assumption of friction angle has to be made and the cohesion is assumed to be zero. Since it is rather difficult to make any rationale assumption about the equivalent friction angle, the Sheet Piling method is not used in this paper for drilled shafts embedded in clay.

NAVFAC DM-7 method (1971) is based on Reese and Matlock's (1956) non-dimensional solutions for laterally loaded piles with soil modulus assumed proportional to depth. The limitations of NAVFAC DM-7 method (1971) are that the lateral load cannot exceed about 1/3 of the ultimate lateral load capacity and only elastic lateral response can be predicted. COM624P (Wang and Reese, 1993) program based on p-y method (Reese et al., 1974 and 1975), or the equivalent commercial program, LPILE, has been widely used for decades. This method treats soil as Winkler foundation which may introduce a small amount of inaccuracy because it ignores the interactions between the discrete springs.

Design Criteria

For ultimate capacity based design methods, an appropriate FS has to be determined. In Colorado Department of Transportation (DOT) practice, 2.5 to 3 have been adopted as an overall FS (Nusairat et al., 2004). In this paper, the FS in the range of 2 to 3 will be investigated.

For service limit based design methods, the allowable deflection at ground level needs to be known for the design of drilled shafts to support sound walls. According to Colorado DOT practice (Nusairat et al., 2004), 0.25 to 0.5 inch (6.4 to 12.7 mm) of deflection at the ground line is considered to be acceptable. Most engineers cited 1 inch

(25.4 mm) at the ground under service loading conditions as a maximum, and some stated that deflections greater than 1 inch (25.4 mm) may be acceptable in some situations. Deflections at the bottom of the shafts are normally checked to ensure that it is a very low number to be nearly equal to zero. A tilting of the sound barrier walls of 0.833% was established for a big project in Colorado. This was selected based on aesthetic not structural concerns. In Ohio DOT practice, the allowable wall top deflection is 1% -1.5% of wall heights (Liang, 2002).

A relationship between the wall top deflection (Δ_w) and the shaft head deflection (Δ_p) can be derived as follow, if rigid body rotation of shaft and wall along shaft tip is assumed.

$$\Delta p = \Delta w \frac{L}{H_w+L} \qquad (1)$$

in which, Hw is the distance between wall top and ground line; and L is the length of embedded drilled shafts. Considering typical drilled shaft length of 9 to 15 feet (2.7 to 4.6 m) and wall height of 14 to 18 feet (4.3 to 5.5 m) in Colorado DOT and Ohio DOT practice, then 0.6 to 1.5 inch (15 to 38.1 mm) of permissible shaft top deflection could be calculated from Equation 1 based on Colorado DOT and Ohio DOT permissible deflections at wall top. Therefore, a range of permissible deflections at drilled shafts head (0.6", 1.0", and 1.5" or 15, 25.4, and 38.1 mm) will be investigated.

Soil Parameters Determination Methods

The soil parameters for p-y analysis and capacity based design methods could be obtained from geotechnical laboratory tests, SPT tests, and pressuremeter tests. Because the soil information given in the selected test database (to be introduced later) are basically in the form of SPT boring logs; the soil parameters in this study are determined from correlations with SPT N values for consistency. Anderson and Townsend (2001) evaluated several existing SPT correlations (such as Terzaghi, 1955) against 24 SPT test data in cohesionless soils based on p-y analyses. They concluded that little difference exists and the correlations are conservative. The SPT correlations for clay (such as Hegedus and Peterson, 1988) and aforementioned SPT correlations for sand were investigated against 21 lateral load tests in sand and 37 lateral load tests in clay by Liang (2002).

[Table 1] Correlations of SPT for Cohesive and Cohesionless Soils (After Liang, 2002)

Cohesive Soils

$SPT\text{-}N_{60}$	0 to 2	2 to 4	4 to 8	8 to 16	16 to 32	32 to 64
S_u (psi)	0 to 1.88	1.88 to 3.75	3.75 to 7.53	7.53 to 15.00	15.00 to 30.00	30.00 to 55.6
ε_{50}	> 0.02	0.02 to 0.01	0.01 to 0.007	0.007 to 0.005	0.005 to 0.004	0.004 to 0.002
k_s(lb/in^3)	< 30	30	100	500	1000	2000
γ_{sat} (pcf)	100 to 120	110 to 130	110 to 130	120 to 135	130 to 145	140 to 145

Cohesionless Soils

$SPT\text{-}N_{60}$		2 to 4	4 to 10	10 to 20	20 to 30	30 to 50	50 to 60
ϕ (°)		28-29	29-31	31-34	34-37	37-42	42-45
k_s (lb/in^3)	A. W. T	20-25	25-60	60-90	90-160	160-240	240-260
	B. W. T.	15-20	20-40	40-60	60-90	90-130	130-150
γ_{moist} (pcf)	Min.	104 to 108	108 to 112	115 to 120	120 to 125	124 to 128	128 to 130
	Max.	114 to 118	120 to 124	122 to 130	128 to 132	130 to 145	140 to 145

Note: S_u = undrained shear strength; ε_{50}= strain at 50% of maximum deviatoric principle stress; k_s = coefficient of subgrade reaction modulus; γ_{sat} = saturated density of soils; ϕ = friction angle; γ_{moist} = wet density of soils; A.W.T. = above water table; B.W.T. = below water table.

1 psi = 6.9 kPa; 1 lb/in^3 = 27.7 g/cm^3; 1 pcf = 16 kg/m^3.

The correlation study and extensive sensitivity study have led Liang (2002) to propose modified SPT correlations shown in Table 1, which could provide best match with p-y analysis results. Because the correlation suggested by Liang (2002) was intended for deriving soil parameters for COM624P (or LPILE) program, it was adopted in this study to obtain necessary soil parameters from SPT N values.

Lateral Load Test Database

There are quite a few lateral load test data available in the literature, such as Florida Department of Transportation's database compiled by the University of Florida. However, only a small part of the existing test data is related to the shaft diameter between 20 inch (508 mm) and 36 inch (914 mm) and shaft length between 6 feet (1.8 m) and 20 feet (6.1 m), which are commonly found for sound wall foundations. After examining the available test data, only 7 lateral load tests in clay were selected from load tests in Ohio (Liang, 1997), and 5 load tests in sand by Bhushan et al. (1981) was selected. To enlarge the database for drilled shaft tests in sand, drilled shafts with 42 inch (1.1 m) and 48 inch (1.2 m) diameter were also included. The undrained shear strength of cohesive soils and friction angle of cohesionless soils were determined using Liang (2002) correlation. The average weighted strength values for the entire soil layer are summarized in Table 2. The information of drilled shaft dimension and the moment arm (the distance between load points and ground level) are also included in Table 2.

Usually, lateral load tests do not reach the stage of complete soil failure; therefore, the ultimate lateral capacity is not directly available from test results. There are two kinds of failures: one is the drilled shaft structure failure, the other one is the failure of soils which is defined as the appearance of excessive deflection under very small increment of load. Kulhawy and Chen (1995) developed a hyperbolic curve fit technique to simulate the non-linear load-deflection behavior and to predict the ultimate capacity of piles (drilled shafts). The hyperbolic equation in terms of the lateral load (H) and the lateral deflection (δ) can be expressed as follows:

$$H = \frac{\delta}{a + b\delta} \qquad (2)$$

where a and b are curve fitting constants. The ultimate lateral load capacity is defined as the deflection δ become infinite large and is calculated as 1/b.

Evaluating Results and Recommendations

Ultimate Capacity Based Design Methods

For drilled shafts in cohesive soils, Fig. 1 presents the comparison of measured over predicted

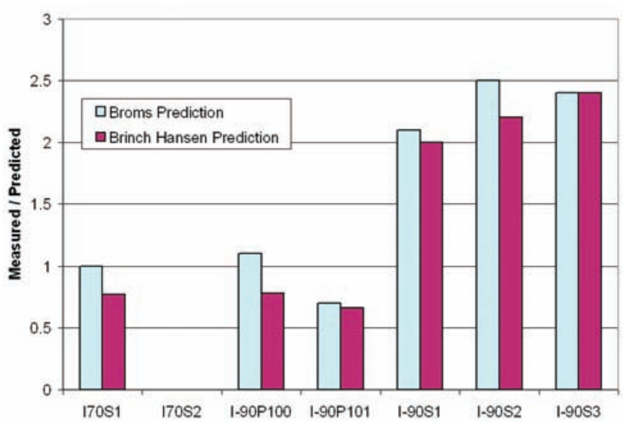
[Table 2] Selected Lateral Load Tests

Soil Type	Testing Shaft	Undrained Shear Strength (psi)	Friction Angle (degree)	Embedded Length (ft)	Moment Arm* (ft)	Diameter (inch)
Sand	Pier 1	0	39	17	0	42
	Pier 4	0	41	18	0	24
	Pier 5	0	41	18	0	36
	Pier 6	0	40	18	0	36
	Pier 7	0	40	18	0	48
Clay	I70S1	23	0	9.5	0	30
	I70S2	23	0	9.5	0	30
	I-90P100	18.7	0	10	0	36
	I-90P101	18.7	0	12	0	30
	I-90S1	22.2	0	8.7	10	30
	I-90S2	22.1	0	8.4	10	30
	I-90S3	22.6	0	12	10	30

*Moment Arm is the distance between load point and ground line.

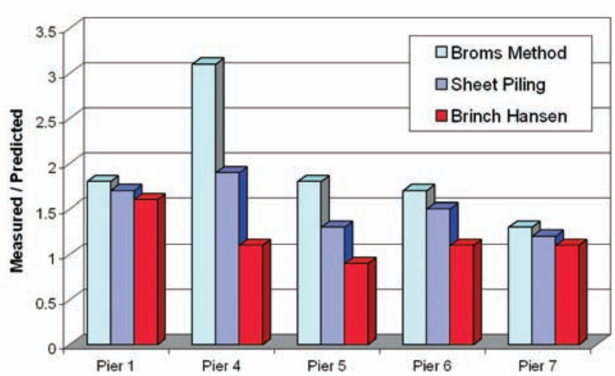
1 psi = 6.9 kPa; 1 ft = 0.305 m; 1 inch = 25.4 mm.

capacities using Broms and Brinch Hansen methods. The I70S2 test is not evaluated because the measured capacity could not be obtained. For the cases with zero feet of moment arm shown in Table 2, Broms method provides very close estimates with test results, except for one case. On the other hand, Brinch Hansen method provides aggressive and unsafe predictions in these cases. It seems that Broms method provides better prediction capability than Brinch Hansen method for these cases. For the three cases with 10 feet (3 m) moment arm shown in Table 2, Broms and Brinch Hansen method provide similar results. The ratio of the measured over the predicted capacities ranges from 2.0 to 2.5. Thus, it is found that Broms method and Brinch Hansen method provide much more conservative predictions on drilled shafts subjected to combined lateral load and moment than just lateral load. In general, Broms method provides more accurate and safer prediction than Brinch Hansen method.



[Fig. 1] Measured Over Predicted Capacities of Drilled Shafts in Clay

For drilled shafts embedded in cohesionless soils, Fig. 2 provides the comparison of measured over predicted capacities by various methods. All methods provide conservative predictions for most of the cases. Broms method provides more conservative estimates than

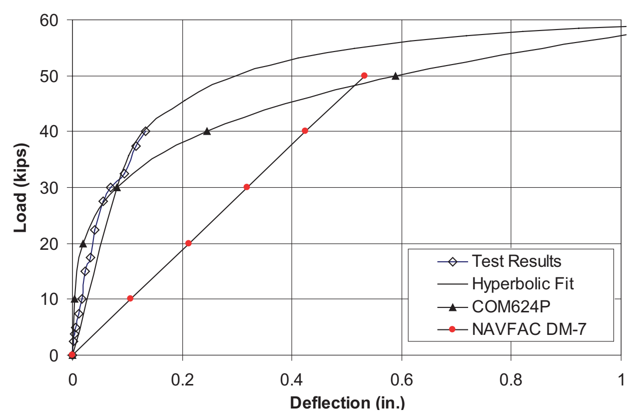


[Fig. 2] Measured Over Predicted Capacities of Drilled Shafts in Sand

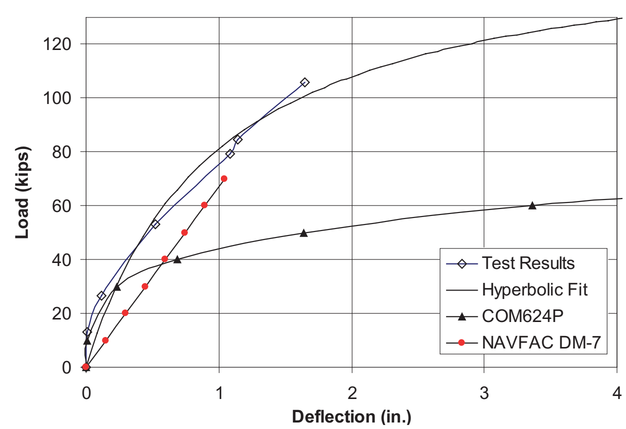
others; while Brinch Hansen method appears to provide unsafe prediction in one case. It is prudent to adopt a relative conservative method since load tests for evaluation were selected from one source. Therefore, Broms method (1964b) is suggested for estimating the ultimate capacity of drilled shafts in sand.

Service Limit Based Design Methods

The performance of COM624P (Wang and Reese, 1993) and NAVFAC DM-7 (1971) were investigated against the load test results in database. For drilled shafts in cohesive soils, comparisons among test results and analysis results of COM624P and NAVFAC DM-7 of drilled shaft I70S2 and I90S3 provide representative results as shown in Fig. 3 (a) and (b). It can be seen that NAVFAC DM-7 overpredicts deflections; while COM624P provides good agreement with measured load-deflection curves at initial portion and provides safe results in the non-linear portion.



(a) Shaft I70S2

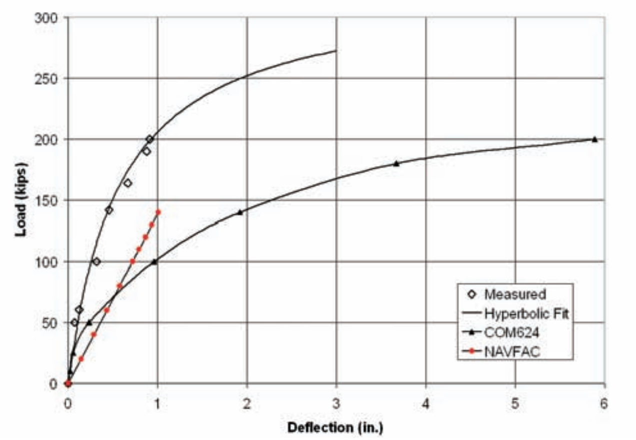


(b) Shaft I90S3

(1kip = 4.448 kN; 1 inch = 25.4 mm)

[FIG.] 3 Load-Deflection Curves at Head of Drilled Shafts

For drilled shafts in cohesionless soils, the result of Pier 5 provides typical comparisons among test results and analysis results of COM624P and NAVFAC DM-7 as shown in Fig. 4. Similar to the cases in clay, it can be seen that the NAVFAC DM-7 method provides larger deflection than measured in the initial portion; while COM624P provides good predictions in the initial portion of load-deflection curves but overpredicts deflection at high load levels.



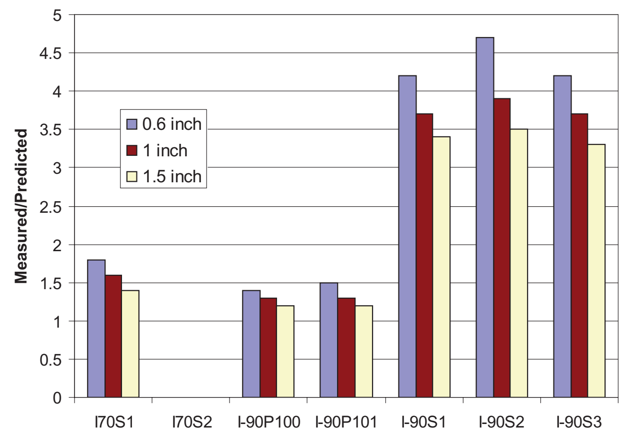
(1kip = 4.448 kN; 1 inch = 25.4 mm)

[Fig. 4] Load-deflection Curves at Head of Drilled Shaft Pier 5

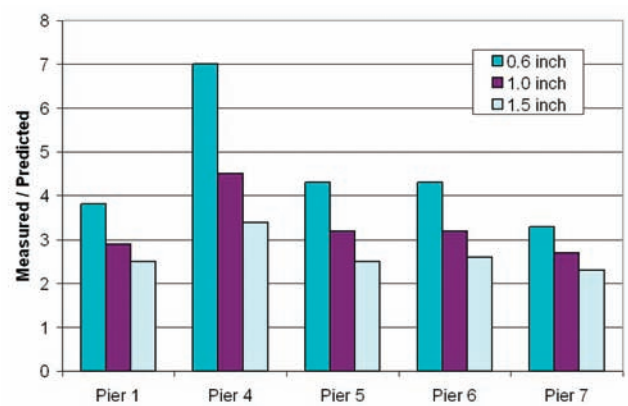
Based on above evaluation results, COM624P (or equivalent program LPILE) is recommended for the service limit based design of the drilled shafts supporting sound walls in cohesive and cohesionless soils, since NAVFAC DM-7 cannot predict the load-deflection behavior well and the prediction is linear.

Factor of Safety and Permissible Deflection

To establish a sense of linkage between the shaft deflection and shaft capacity, the normalized ratios of measured over predicted capacities using COM624P according to different permissible deflection criteria (e.g., 0.6 inch, 1 inch, and 1.5 inch or 15, 25.4, and 38.1 mm) are presented in Fig. 5(a) and (b) for drilled shafts in clay and sand, respectively. From Fig. 5(a), one can see that the normalized ratio ranges from 1.2 to 1.8, for the cases with zero moment, and from 3.3 to 4.7 for the cases with combined lateral load and moment, respectively. From Fig. 5(b), it can be seen that the factor of safety ranges from 3.3 to 7 for 0.6 inch (15 mm) permissible deflection, from 2.7 to 4.5 for 1 inch (25.4 mm) permissible deflection, and from 2.3 to 3.4 for 1.5 inch (38.1 mm) permissible deflection. All of the normalized ratios are larger than 1, which seems to suggest that all three permissible deflections are acceptable from a geotechnical capacity viewpoint.



(a) At clay sites



(b) At Sand Sites

(1 inch = 25.4 mm)

[Fig 5] Measured Over Predicted Capacities of Drilled Shafts at Various Permissible Deflections

The lateral wind loads applied to sound walls usually produce the accompanying moments. From Fig. 1, it appears that Broms method prediction is about ½ of the measured ultimate capacity for combined lateral load and moment. If a FS of two is applied to Broms method, the actual margin of safety is about 4. In considering both capacity and deflection, then a FS = 2 and allowable shaft head deflection of 1.0 inch (25.4 mm) seem to be appropriate for sound walls. It should be emphasized that this conclusion was derived from drilled shaft geotechnical response, not from structural consideration of sound walls.

Recommended Design Methodology

The design methodology for drilled shafts supporting sound walls is suggested as follows. First, Broms method and a FS of two are recommended to be used to determine the required drilled shaft length with known shaft diameter. Then, COM624P computer program (or LPILE) shall be used to check whether the deflection at drilled shaft head under the design load exceeds the permissible deflection of 1.0 inch (25.4 mm) or a deflection value designated by a structural engineer. If the deflection is less than or equal to the permissible deflection, the drilled shaft length designed by Broms method is acceptable. Otherwise, if deflection criterion controls, then COM624P computer program (or LPILE) should be run to determine the shaft length such that the design load would not result in deflection which is more than the permissible deflection.

Validation of Recommended Design Methodology

In order to validate the recommended design methodology for drilled shafts supporting sound walls, two full-scale field lateral load tests on fully instrumented drilled shafts have been conducted in Colorado (Nusairat et al., 2004). The test drilled shafts with diameter of 30 inch (762 mm) and length of 16 feet (4.9 m) were originally designed for supporting sound walls in a clay deposit and a sand deposit. A comprehensive geotechnical investigation program was also carried out at the two new lateral load test sites that included pressuremeter test (PM), SPT, as well as laboratory triaxial consolidated undrained (CU) tests and direct shear tests on the soil samples taken from the lateral load test sites (See Nusairat et al. 2004 for complete details). Pressuremeter test results were employed to indirectly estimate the soil strength values using the FHWA (1989) equation for clay site. Liang (2002) correlations were used for SPT test data interpretation. Interpreted soil strength parameters for clay and sand sites are tabulated in Tables 3 and 4, respectively.

Table 5 provides the calculated capacity and ratio of measured capacity over predicted capacity of test drilled shafts in clay and sand site using Broms method and various soil parameter determination methods. It can be seen that the soil parameters from laboratory tests (e.g. triaxial CU test or direct shear test), provide the most accurate capacities as compared with those measured for clay site. For sand site, soil parameters interpreted from Liang's (2002) SPT correlation provides the best estimate on capacity of drilled shafts.

[Table 3] Undrained Shear Strength of Colorado Clay Interpreted from Various Soil Testing Methods

Soil Layers (ft)	SPT		Lab Test	Pressuremeter
	N values	S_u (psi)	S_u (psi)	S_u (psi)
0-2.5	12	11.3	18.3	16.2
2.5-4.5	12	11.3	15	16.2
4.5-6.5	15	14	14.4	16.2
6.5-10	9	8.5	13.7	8.8
10-12.5	4	3.75	9.4	8.8
12.5-16	8	7.53	11.7	10.9

S_u = Undrained Shear Strength; 1 ft = 0.305 m; 1 psi = 6.9 kPa.

[Table 4] Cohesion and Friction Angle of Colorado Sand Interpreted from Various Soil Testing Methods

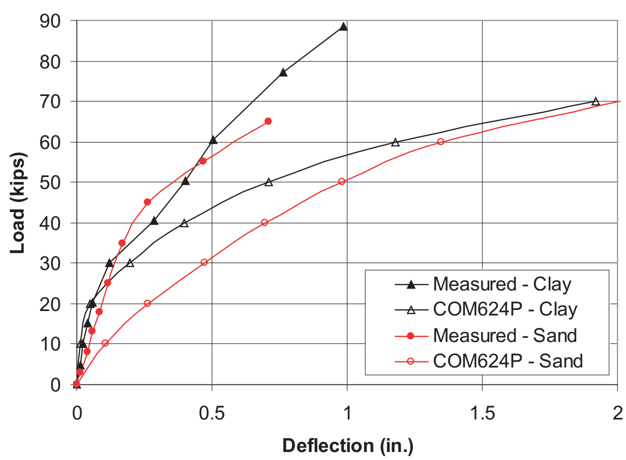
Soil Layers (ft)	Pressuremeter		SPT		Direct Shear Test	
	c' (psi)	φ' (degree)	N Values	φ (degree)	c' (psi)	φ' (degree)
0-4	9.7	34	13	36	2.3	41.1
4-6	9.7	34	8	31	2.3	41.1
6-9	5.6	28	10	33	2.3	41.1
9-15	11	27	7	29	0.7	39.5
15-15.7	11	27	7	29	0.7	39.5

c' = Drained cohesion; φ' = Drained friction angle; φ = Undrained friction angle; 1 psi = 6.9 kPa; 1ft = 0.305 m.

Table 5 Calculated Lateral Capacity of Drilled Shafts for CDOT Test Sites

Soil Parameters	Broms Method (kips)	Measured/ Predicted
Clay Site		
SPT Liang	71	1.9
Lab Test	108	1.3
PM (FHWA)	98	1.4
Sand Site		
SPT Liang	91	1.05
Direct Shear	131	0.73
PM	84	1.14
(1kip = 4.448 kN)		

Fig. 6 shows the comparison of measured and predicted load-deflection curves using soil parameters interpreted from laboratory test for clay site and SPT test for sand site. It can be seen that the predicted load-deflection curve matches the load test in clay site, especially in the initial portion of the curves. Although COM624P overpredicts the deflections for drilled shafts in sand, the prediction is still reasonable and is on the safe side.



(1 kip = 4.448 kN; 1 inch = 25.4 mm)

[FIG. 6] Load-deflection Curves at Head of Drilled Shafts Tested in Colorado

Conclusions

Various existing methods for predicting ultimate capacity and deflection of drilled shafts supporting sound walls were evaluated in this paper using data of load test database carefully selected from literature and Ohio's test results, and two new lateral load tests performed in Colorado on sandy and clayey soil sites. Methods including the Broms, COM624P, Sheet piling, Brinch Hansen, and NAVFAC DM-7 were evaluated. Based on this evaluation, a design methodology for the drilled shafts supporting sound walls is recommended. Broms method (1964a, 1964b) with a FS of two is suggested for ultimate capacity based design for drilled shafts in cohesive and cohesionless soils. The deflection at the drilled shaft head designed by Broms method should be checked to be less than a permissible deflection of 1 inch (25.4 mm) or a deflection value designated by a structural engineer, by using COM624P (or LPILE). If it exceeds permissible deflection, COM624P (or LPILE) should be used to determine the appropriate drilled shaft length.

Appropriate geotechnical test methods are recommended for obtaining relevant soil parameters for various design methods. For clay, the most appropriate soil testing method is lab test, e.g. triaxial unconfined undrained test, consolidated undrained test or direct shear test. For sand, SPT with Liang (2002) correlation provides the best soil strength interpretation. Pressuremeter test would provide reasonable soil strength interpretation as well.

The recommendations provided in this paper will result in more uniform, consistent, and cost-effective design and testing methods for the drilled shafts supporting sound walls. This uniformity ensures that fewer manhours are needed in deciding on analysis methods. Rather, engineers can focus more on the determination of high quality soil parameters for input into the analysis. This paper recommended lower FS than often used by the design engineers and geotechnical tests that will generate higher strength values than what is often assumed in the design. This will lead to significant savings in future sound wall projects. The proposed design/analysis approach for I-225 project in Colorado has been shown to reduce the required drilled shaft length by 25% compared to original Colorado DOT design approach. For a project that involves a large quantity of drilled shaft construction, or when a unique soil condition and complex loading combination exist, the lateral load test prior to final design decision could potentially offer cost saving to the project.

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