New device for measuring drilled shaft bottom sediment thickness

J. Z. Ding*[1], K. A. McIntosh[2] and R. M. Simon[1]

The sediment thickness at the bottom of a drilled shaft before the placement of concrete plays a significant role in the development of drilled shaft bearing capacity and settlement, especially for an end-bearing shaft where side shear resistance is limited and only end-bearing resistance is considered significant. Load tests have demonstrated that conscientious bottom cleaning is necessary to achieve suitable load transfer in end-bearing. Inspection and measurement of the bottom sediment thickness before concreting is challenging, expensive, and often time consuming for contractors and inspectors when direct visual inspection is not possible, as for shafts drilled through slurry or water. The Ding inspection device (DID) was developed by John Z. Ding for measuring the sediment thickness at the bottom of a drilled shaft without human access into the excavation. Laboratory model tests and field comparisons to the miniature shaft inspection device (mini-SID) have demonstrated repeatability and accuracy of sediment thickness measurements using the device.

Keywords: Drilled shaft, Sediment, Inspection, Field testing

Introduction

The total bearing capacity of a drilled shaft is directly related to the development of end-bearing and side shear resistance. The ultimate bearing capacity and allowable load of the shaft are often a function of the applied loads versus displacement limits established for the superstructure.

Currently, design engineers may adopt either allowable stress design (ASD) (O'Neill and Reese 1999) or load and resistance factor design (LRFD) for drilled shaft foundation analysis and design (Brown, Turner and Castelli 2010; Basu and Salgado 2012). In either case, considering allowable load as a function of ultimate capacity/resistance or allowable displacement versus fully mobilized displacement, designers have to establish the relationship between the capacity and the displacement characteristics of the shaft in the soil or rock.

The displacement required to fully mobilize the ultimate resistance from shaft end-bearing and side shear can be quite different (Camp, Brown and Mayne 2002; Crapps and Schmertmann 2002). In sand, the side shear component can develop 50% of ultimate capacity at a displacement of $\sim 0{\cdot}2\%$ of the shaft diameter (D) (AASHTO 1999), and may develop ultimate shear resistance in the range of 0·5–1·0% D (Bruce 1986). In contrast, the end-bearing resistance component may require a toe displacement of 2·0% D to develop 50% of its ultimate capacity (AASHTO 1999) and may require displacement in the range of 10–15% D to fully develop end-bearing resistance for bored piles or shafts in sand (Bruce 1986). For example, a 1·2-m-D shaft in sand can require up to 12·7 mm displacement to develop the ultimate side shear resistance and 178 mm to develop the ultimate end-bearing resistance. Other sources define a 'failure condition' by designating the toe displacement for ultimate end-bearing to be equal to 5% D but recognize the increase in capacity at larger displacements (O'Neill and Reese 1999). In most instances, the side shear can be assumed 100% usable within most permissible displacement criteria, but the ultimate or allowable end-bearing resistance may not develop at allowable displacements except for the situation where the shaft bears on unweathered massive bedrock (Abu-Hejleh, O'Neill, Hanneman and Atwoll 2003) and the bottom are clean.

Given the concerns of the design and construction factors affecting the development of end-bearing resistance, designers often assume that only a limited portion of the ultimate end-bearing resistance is developed within allowable foundation displacements. Even limited development of end resistance requires conscientious cleaning of the bottom of drilled shafts during construction. For example, the Florida Department of Transportation (FDOT 2013) Standard Bridge Specifications state that a minimum of 50% of the base area of each shaft should contain $<12{\cdot}7$ mm of sediment thickness at the

[1]DMY Inc., Midlothian, VA 23113, USA
[2]AMEC Foster Wheeler, Jacksonville, FL 32207, USA

*Corresponding author, email jzding@gmail.com

Published by Maney on behalf of the Institute
Received 17 November 2014; accepted 12 February 2015
DOI 10.1179/1937525515Y.0000000004

time of concrete placement, and the maximum depth of sediment or any debris at any place on the base of the shaft should be <38 mm. The implicit design assumption of this requirement is that the flowing concrete will push aside most of the remaining sediment or there will be sufficient area of contact between concrete and the base of the shaft to develop the end resistance assumed for design.

Inspection and measurement of the bottom sediment thickness for shafts constructed using the wet method of shaft excavation has proven challenging, expensive, and often time consuming for contractors and inspectors, when direct bottom observation is not possible. Even when using the dry construction method, inspectors may be reluctant to enter the shaft to the bottom to measure sediment thickness because of personnel safety concerns and the significant time required to organize confined space entry procedures.

A common method to interpret sediment thickness at the bottom of an excavated shaft is by lowering a weighted tape slowly down the hole until encountering reduced pull on the tape because of the weight resting on the top of sediment or the shaft bottom. When the weight reaches firm material, the difference between the measured depth of the shaft to the point of reduced tape pull and the bored shaft depth recorded during the drilling construction provides a rough estimate of the thickness of sediment on the shaft bottom. Currently, there are no strict guidelines on the test procedures and the required weight of the mass at the end of the tape. The accuracy of this method is subject to the experience and interpretation of the technician and the types of the soil or rock sediment encountered.

To increase the magnitude of tip resistance that can be developed at relatively small shaft movements, post-grouting was developed. Although not intended for this purpose, post-grouting has also been used as a method of pre-compressing soft sediments at the base of the shaft that should have been removed by the contractor during shaft bottom cleaning (Bruce 1986; Bruce, Nufer and Triplett 1995).

Since about the late 1990s, the shaft inspection device (SID) and later the miniature shaft inspection device (mini-SID) have been recognized as being accurate and therefore the 'gold standard' in the measurement of drilled shaft bottom sediment thickness without an inspector's entrance into the borehole. Through the quarterly graduated marks, a trained technician can 'read' the sediment thickness to an accuracy of <5 mm. The SID was developed in the early 1980s by Schmertmann and Crapps, Inc. The SID comprises a television camera sealed within a watertight jacket for inspecting both dry and wet excavations. The concept of the SID was derived from a drilled SID originally developed by Dr Jim Holden of the Australian Country Roads Board.

The SID is heavy (over 450 kg) and a large piece of equipment. It requires the extensive involvement of the drilled shaft contractor to lift and to lower it in the hole. The mini-SID was introduced around 1998 and is much lighter in weight and easier to use. However, it still requires specifically trained personnel and is a relatively time consuming test procedure. In general, it requires several field personnel and often takes ~ 1 h for a single shaft bottom inspection.

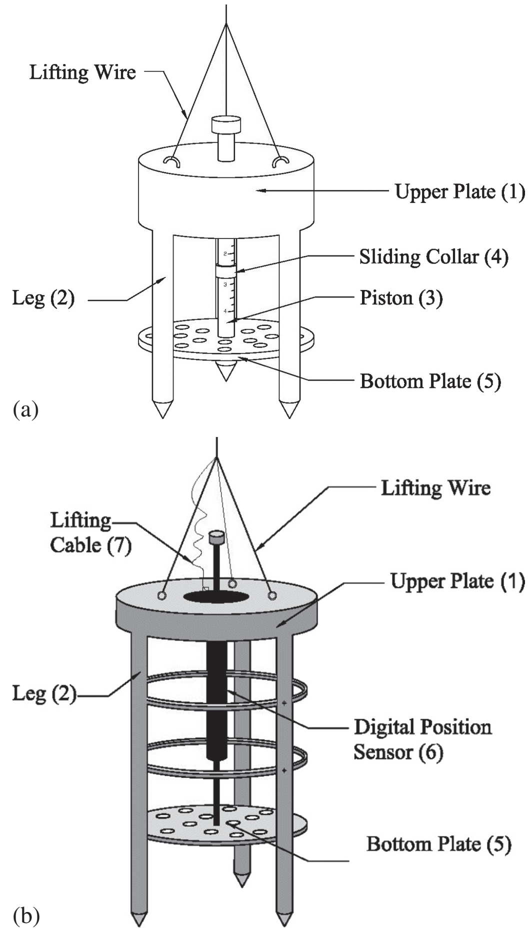

Figure 1 Ding inspection device (DID) concept, *a* mechanical measuring unit; *b* digital measuring unit

Ding inspection device (DID)

The Ding inspection device (DID) was developed by John Z. Ding to measure the sediment thickness at the bottom of a drilled shaft without human entrance into the shaft excavation. The DID was developed initially as a mechanical device as shown in Fig. 1*a*.

The mechanical device consists of an upper plate (1), three legs (2), a center piston (3), a sliding collar (4), and a bottom plate (5). The total device weighs about 8 kg. When the device is lowered to the bottom of a drilled shaft, the three 9·5-mm diameter legs penetrate the sediment under the weight of the device while the lightweight bottom plate rests on top of the sediment. The distance between penetration of the tips of the legs (2) and the penetration of the bottom plate is interpreted as the sediment thickness as measured by the sliding collar.

The DID was later upgraded as an electronic readout device with a digital position sensor (6) as shown in Fig. 1*b*. The digital DID consists of a submersible waterproof measuring unit, a digital position sensor, and a high-strength cable to carry and lower the measuring unit and to transfer the electrical signals from the digital sensor to the surface readout unit.

A digital position sensor can typically sense a submillimeter position variation. The digital DID can provide submillimeter precision of the measured sediment thickness.

The bottom plate is attached to the core of a digital sensor. It returns to the zero position with its own weight once the DID is lifted from the base of the shaft (top of the sediment) with the lifting wire. Resetting the device to zero can be confirmed with the readout unit. As the device can be reset by lifting the measuring unit out from the sediment, it is very convenient to get sediment thickness measurements at several locations on the shaft bottom.

The length of the high-strength cable can be adjusted to measure a drilled shaft $\sim$100 m deep. In general, it takes less than 10 min for a trained technician or a field engineer to complete the measurement of the sediment thickness at the bottom of a drilled shaft.

Laboratory testing

An independent laboratory verified the measurement accuracy of the digital DID by simulating the field condition of a drilled shaft bottom using two major soil conditions. Solid blocks of several measured thicknesses were used to calibrate the thickness readings of the DID on the laboratory bench. The DID readings were both repeatable and accurate at several displacement increments of the bottom plate above the plane of the leg tips resting on the bench.

The laboratory also created a model drilled shaft using a translucent PVC cylinder $\sim$38 cm in diameter and 55 cm in height. A layer of 25-mm thick commercial quick set concrete was poured at the bottom of the cylinder to represent a solid shaft bottom. Clear water filled the cylinder followed by two layers of poorly graded sand classified as SP by the Unified Soil Classification System (ASTM D2487). The thickness of the sand sediment at the bottom of the cylinder was measured at the center of the base using a manual thickness gage and using the DID after the sand had settled for periods of 15 and 30 min. The test was repeated using sandy high plasticity clay soil classified as CH. Table 1 shows the compositional and physical characteristics of the sand and clay.

It can be seen from Fig. 2 that sediment thicknesses measured using the DID agree well with those measured using a thickness gage. The laboratory test indicated that the sediment thicknesses measured by DID differ by $<1\%$ from the results using a measuring gage. The authors have also noticed that $\sim$90% of the sediments settled within 15 minutes for both sand and clay soils.

Table 1 Soil compositional and physical characteristics for the laboratory testing

	Percent passing sieve size			Atterberg limits	
Soil type	No. 4	No. 40	No. 200	LL	PI
Coarse sand	85·4	26·0	3·5		
Clay				52	24

LL: Liquid Limit; PI: Plasticity Index.

Field testing

Field comparison tests were conducted using a DID and a mini-SID for various drilled shaft sizes at project sites in Virginia and Florida, USA. The mini-SID tests were carried out by the contractor's quality control personnel. The subsurface conditions in the test shafts consisted of sandy soils underlain by slightly weathered Schist bedrock (Potomac Formation in Fairfax, VA, USA) and sandy soils underlain by highly weathered limestone (Ocala Group in Central FL, USA) (Hoffmeister 1974). In the three cases, the contractors constructed the shafts using the wet method of construction. The sediment thickness measurements were taken at the center and along the perimeter of the drilled shafts. Because the sediment thickness profile across a shaft bottom is typically uneven and the positions of the mini-SID and DID may have differed slightly on the shaft bottom, there were slight differences measured by the DID and the mini-SID. In general, the DID measured larger sediment thicknesses than the mini-SID in the field. Table 2 provides the details of the field test results.

Discussion

There are several factors that may affect the measurement accuracy using the DID. Drilled shaft contractors, design engineers, and bridge engineers from the Virginia Department of Transportation (VDOT) have questioned the systematic error from two key components of the DID device:

1. *Penetration of the three legs* into the base bearing material resulting in an increase in the measured sediment thickness.
2. *Penetration of the bottom plate* into the sediment resulting in a decrease in the measured sediment thickness.

Leg penetration

The measuring unit is supported by three legs each with a sharp tip. The weight of the DID ($\sim$8 kg) must be sufficient to push the three legs through several centimeters of sand or silt sediment to the relatively firm undisturbed bottom of the shaft. The sharp tip will theoretically also penetrate a little further into the 'firm bottom' to provide a greater inferred sediment thickness.

Based on the principle of contact mechanics, when a pointed, rigid, conical indenter contacts an elastic half-space (Fig. 3), the maximum depth of penetration can be expressed as in what follows (Sneddon 1965)

$$F = \frac{2Ed^2}{\pi(1-\nu^2)\tan\theta}$$

where
d:penetration depth;
F:penetration force;
E:elastic modulus of half-space material;
ν:Poisson's ratio of half-space material;
θ:60° (relative to the leg of the device);

Vertical bearing drilled shafts are typically designed to be socketed into sound or partially weathered bedrock

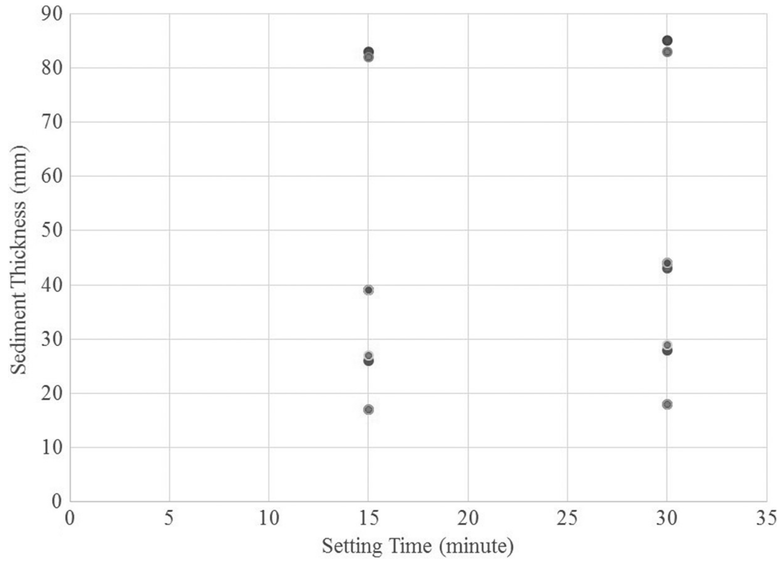

Figure 2 **Laboratory test results using Ding inspection device (DID) and a manual thickness gage Red dots: from DID; blue dots: from a measuring gage**

Table 2 **Field comparison tests**

Project location	Shaft diameter (m)	Shaft depth (m)	Bottom material	Measured sediment thickness (mm)	
				Mini-SID	DID
Fairfax, VA	1·5	22·5	Schist	12–25	19·1–25·4
Tampa, FL	1·1	12·5	Limestone	0–12	5·1–30·1
Tallahassee, FL	1·2	22·8	Limestone	12–38	33·0–99·1

Mini-SID: miniature shaft inspection device; DID: Ding inspection device.

or to bear on very dense sand or hard clay. Using a total weight of ~8 kg for the DID, Table 3 provides the estimated leg penetration for a variety of shaft bottom material types having variable elastic properties. To compare the differences, the device penetration into a medium stiff clay layer is also calculated and listed in Table 3.

The tip of the conical leg is actually a sphere of ~0·5 mm radius. Based on the principle of contact between a sphere and an elastic half-space (Fig. 4), the maximum depth of penetration can be expressed as (Hertz 1882)

$$F = \frac{4}{3} E^* R^{1/2} d^{3/2}$$

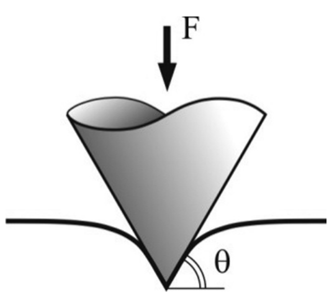

Figure 3 **Rigid conical indenter in contact with an elastic half-space**

where

$$\frac{1}{E^*} = \frac{(1 - v_1^2)}{E_1} + \frac{(1 - v_2^2)}{E_2}$$

E_1, E_2 : elastic moduli of sphere (200 GPa) and half-space material (Table 3);
v_1, v_2 : Poisson's ratios of sphere (0·3) and half-space material (Table 3);
R : radius of sphere;
d : depth of penetration;

The last column of Table 3 provides the estimated leg penetrations for a spherical tip leg.

The estimated maximum leg penetration ranges from <0·1 mm in bedrock to 1·6 mm in medium dense sand assuming the in-place soil or bedrock below the base of the shaft is moderately disturbed to hard in an undisturbed state as a result of the drilled shaft construction. Based on these calculations, the estimated magnitude of leg penetration is relatively small and meets the acceptable engineering practice where the specified limit of sediment thickness is 12·7 mm. On a rock base, where the reliance on resistance is likely to be greater, leg penetration into the rock is likely to be <0·1 mm.

Bottom plate penetration

Penetration of the bottom plate into the sediment would provide a smaller measured sediment thickness.

Table 3 Estimated DID leg penetration into various bottom materials

Shaft bottom	Elastic modulus (MPa)	Poisson's ratio	Conical tip penetration (mm)	Spherical tip penetration (mm)
Medium stiff clay	40	0.35	1.3	0.7
Hard clay	85	0.40	0.8	0.4
Medium dense sand	35	0.35	1.3	0.8
Dense sand	80	0.35	0.9	0.5
Limestone bedrock	10 000	0.25	<0.1	<0.1

DID: Ding inspection device.

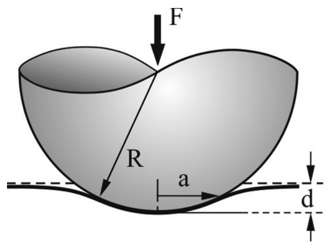

Figure 4 Rigid spherical indenter in contact with an elastic half-space

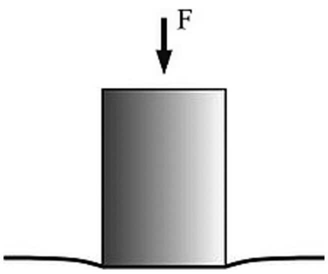

Figure 5 Contact between a rigid cylindrical indenter and an elastic half-space

The aluminum bottom plate is 6·35-mm thick and 127 mm in diameter. It has a total effective area (total plate area – the area of the holes) of 111 cm^2 and weighs $\sim$0·22 kg. Based on the principle of contact between a rigid cylindrical indenter (closed end) and an elastic half-space (Fig. 5), the penetration of the bottom plate is defined as (Sneddon 1965)

$$F = 2\alpha E d$$

where
F : normal force applied on the bottom plate (weight);
α : radius of the bottom plate;
d : plate penetration;
E : elastic modulus of the sediment beneath bottom plate;

In the extreme condition, the estimated elastic moduli of very soft clay and loose sand are <1 and 5 MPa, respectively (Bowles 1996; Callisto and Calabresi 1998), which results in a maximum estimated penetration of <0·1 mm into the sediment. The bottom plate penetration into a regular settled slough is even smaller. Therefore, the bottom plate penetration can be ignored for the purpose of sediment thickness measurement.

Conclusion

Based on the laboratory model test results and field tests comparing sediment thickness measurements to the mini-SID, the authors have reached the following conclusions:

- The DID measurements and thickness gage measurements were <0·1 mm of each other in the laboratory model testing for artificially deposited sand and clay sediments.
- The DID are in general consistent with mini-SID measurements in full-scale field tests; however, the DID measured slightly larger sediment thicknesses than the mini-SID. More field tests need to be conducted in various soil types to establish correlations between the DID and SID/mini-SID.
- The effect of the sharp tip penetration into the shaft bottom and the bottom plate penetration into the sediment are small and can be ignored in engineering practice.
- The existing DID is favorable for measuring the sediment thickness where the compositions of the slough are relatively uniform. When the slough has some gravels and cemented particles of larger diameter $\sim$75 mm, a special DID set of larger leg spacing is required.

Acknowledgements

The authors express their special thanks to Raymond Castelli of Parsons Brinkerhoff, Dan Brown and John Turner of Dan Brown and Associates, Thomas Hart of Black & Veatch, Ashton Lawler of the VDOT, Bill Ryne of LOADTEST Inc., Don Dwyer of the New York DOT, and Larry Jones and Juan Castellanos of the Florida Department of Transportation, who have provided invaluable comments in the process of developing the device. The authors also thank the engineers and laboratory technicians of Schnabel Engineering, who have provided the laboratory verification tests for the DID.

References

AASHTO. 1999. *LRFD bridge design specifications, customary U.S. units*, 2nd ed; Washington, D.C, American Association of State Highway and Transportation Officials.

Abu-Hejleh, N., O'Neill, M. W., Hanneman, D. and Atwoll, W. J. 2003. Improvement of the geotechnical axial design methodology for Colorado's drilled shafts socketed in weak rock. Report No. CDOT-DTD-R-2003-6. Denver: Colorado Department of Transportation, 192 p.

Basu, D. and Salgado, R. 2012. Load and resistance factor design of drilled shafts in sand, *Journal of Geotechnical and Geoenvironmental Engineering*, **138**, 1455–1469.

Bowles, J. E. 1996. *Foundation analysis and design*, New York, The McGraw-Hill Companies.

Brown, D. A., Turner, J. P. and Castelli, R. J. 2010. Drilled shaft: construction procedures and LRFD design methods. Publication No. FHWA NHI-1-016, Washington, D.C., Federal Highway Administration.

Bruce, D. A. 1986. Enhancing the performance of large diameter piles by grouting. Parts 1 and 2, *Ground Engineering*, May and July, respectively.

Bruce, D. A., Nufer, P. J. and Triplett, R. E. 1995. Enhancement of caisson capacity by micro-fine cement grouting – a recent case history. ASCE Special Publication 57, Verification of Geotechnical Grouting, British Geotechnical Society, London.

Callisto, L. and Calabresi, G. 1998. Mechanical behavior of natural soft clay, *Géotechnique*, **48**, (4), 495–513.

Camp, W. M., Brown, D. A. and Mayne, P. W. 2002. Construction method effects on axial drilled shaft performance, In: Proceedings of the International Deep Foundations Congress 2002, Orlando, FL, ASCE GSP 116, Vol. 1, 195–208.

Crapps, D. K. and Schmertmann, J. H. 2002. Compression top load reaching shaft bottom – theory versus tests, In: Proceedings, International Deep Foundations Congress, Orlando, FL, ASCE.

Florida Department of Transportation. 2013. Standard specifications for road and bridge construction.

Hertz, H. R. 1882. Ueber die Beruehrung elastischer Koerper (On contact between elastic bodies), in Gesammelte Werke (Collected Works). Vol. 1, Leipzig, Germany.

Hoffmeister, J. E. 1974. *Land from the sea – the geologic story of South Florida*, Coral Gables, FL, University of Miami Press.

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

Sneddon, I. N. 1965. The relation between load and penetration in the axisymmetric boussinesq problem for a punch of arbitrary profile, *International Journal of Engineering Science*, **3**, 47–57.