Axial Capacity of Drilled Shafts in Shale

This Design Guide has been developed to provide geotechnical and structural engineers with alternative procedures for estimating improved geotechnical axial capacity of drilled shafts in shale.

The Department has experienced many projects in the past where conventional sampling and testing methods for shale has resulted in the material being poorly characterized with weak compressive strengths. In addition, estimating the nominal side and tip resistance of drilled shafts in shale using conventional formulas for rock or intermediate geomaterials has also often resulted in conservative capacities. Poor characterization and estimation of geotechnical resistance often translates into drilled shafts that have an excessively large diameter and/or embedment into the shale resulting in increased foundation costs. As such, the Department has conducted a research project with the University of Illinois at Urbana-Champaign (UIUC) to evaluate sampling and testing procedures for shales in Illinois as well as methods for estimating side and tip resistance of drilled shafts. The results of this study and alternative procedure for field testing and estimating the side and tip resistance of drilled shafts in weak shales having an unconfined compressive strength ranging from 10 to 100 ksf is summarized below. Reference is made to research report FHWA-ICT-13-017, "Improvement for Determining the Axial Capacity of Drilled Shafts in Shale in Illinois", for further detailed information regarding these alternative procedures.

Geotechnical Axial Resistance of Drilled Shafts in Shale:

The factored resistance of drilled shafts in shale, R_R, should be determined considering the combined side and tip resistances using the following formulas:

$R_R = \phi R_n = \phi_{qs} R_s + \phi_{qp} R_p$

R_s = nominal shaft side resistance

= $q_s A_s$

R_p = nominal shaft tip resistance

= $q_p A_p$

ϕ_{qs} = geotechnical resistance factor for side resistance

= 0.5 for Strength Limit State

= 1.0 for Service and Extreme Limit State

ϕ_{qp} = geotechnical resistance factor for tip resistance

= 0.5 for Strength Limit State

= 1.0 for Service and Extreme Limit State

A_s = area of shaft side surface (ft^2)

q_s = unit side resistance (ksf)

= $0.30\, q_u \leq 30$

A_p = area of shaft tip (ft^2)

q_p = unit tip resistance (ksf)

= $2.5\, q_u\, d_c$

d_c = Vesic's depth correction factor

= $1.0 + 0.4(k)$

k $= \frac{L}{D}$ for $\frac{L}{D} \leq 1$

$= \tan^{-1}\left(\frac{L}{D}\right)$ for $\frac{L}{D} > 1$ (radians)

L = embedment depth in shale (in.)

D = shaft diameter (in.)

q_u = unconfined compressive strength of shale (ksf)

It is recommended that the q_u value used to calculate tip resistance reflect the weighted average within a depth of 2 shaft diameters below the tip elevation. Also, it is permissible to assume that the full length of drilled shaft embedded in shale contributes to the development of side resistance.

<u>Settlement Analysis:</u>

The Service Limit State "settlement", or axial displacement of the drilled shaft that occurs as the side and tip resistance is mobilized, should be determined. The estimated displacement should be reported along with the geotechnical axial resistance so that the structural designer can select a drilled shaft depth that provides sufficient factored axial capacity and results in a tolerable service settlement for the structure being designed. The following relationships should be used in evaluating the axial load-deformation response for side and tip resistance.

q-z = unit tip resistance load-displacement response (k/in.)

$$= \frac{3.2\, q_u\, d_c\, D\, \pi}{4\left(\frac{\delta}{D} + \frac{1.3}{100}\right)}$$

δ = tip movement (in.)

t-z = unit side resistance load-displacement response (k/in.)

$= \frac{R_s}{0.007\ D}$ for $\Delta \leq 0.007\ D$

$= 0$ for $\Delta > 0.007\ D$

Δ = settlement for a given layer (in.)

Variables not described above are defined in the previous section for estimating the factored geotechnical axial resistance of the drilled shaft. Please note that the t-z relationship is bilinear in that the stiffness and side resistance plateau at a settlement value of approximately 0.7% of the shaft diameter.

Unconfined Compressive Strength of Shale

Research indicates that conducting unconfined compression strength tests on cored shale specimens often results in under prediction of the compressive strength of the material due to premature failure along joints and fissures as well as damage caused by coring and transportation. As such, it is recommended that laboratory testing be used to determine the compressive strength of shales consist of triaxial testing on undrained specimens with the confining pressures equal to the overburden stress at the elevation of the shale specimen. Alternatively, UIUC has developed a Modified Standard Penetration Test (MSPT) for evaluating in situ shale strength.

A MSPT is conducted in accordance with conventional SPT (AASHTO T 206) protocol except as follows:

1. The SPT split spoon sampler penetration is determined after every 10 blows of the hammer to a maximum of 100 blows. To determine the sampler penetration, field personnel must identify a reference point on the hammer or drill rods, and another which is stationary, between which a “measured rod length” can be obtained at each increment of 10 hammer blows. This is illustrated in Figure 1 in which case “L” is the measured rod length between reference points with the top of the drill casing serves as the stationary reference point. The penetration distance is taken as the measured rod length at each increment of 10 hammer blows subtracted from the initial measured rod length at 0 blows. If the penetration is not changing substantially after the initial 40 blows, the number of blows per measurement may

be increased to 20 to accelerate the test and any missed increments shall be obtained by interpolation.

Figure 1. Measured rod length example for MSPT test.

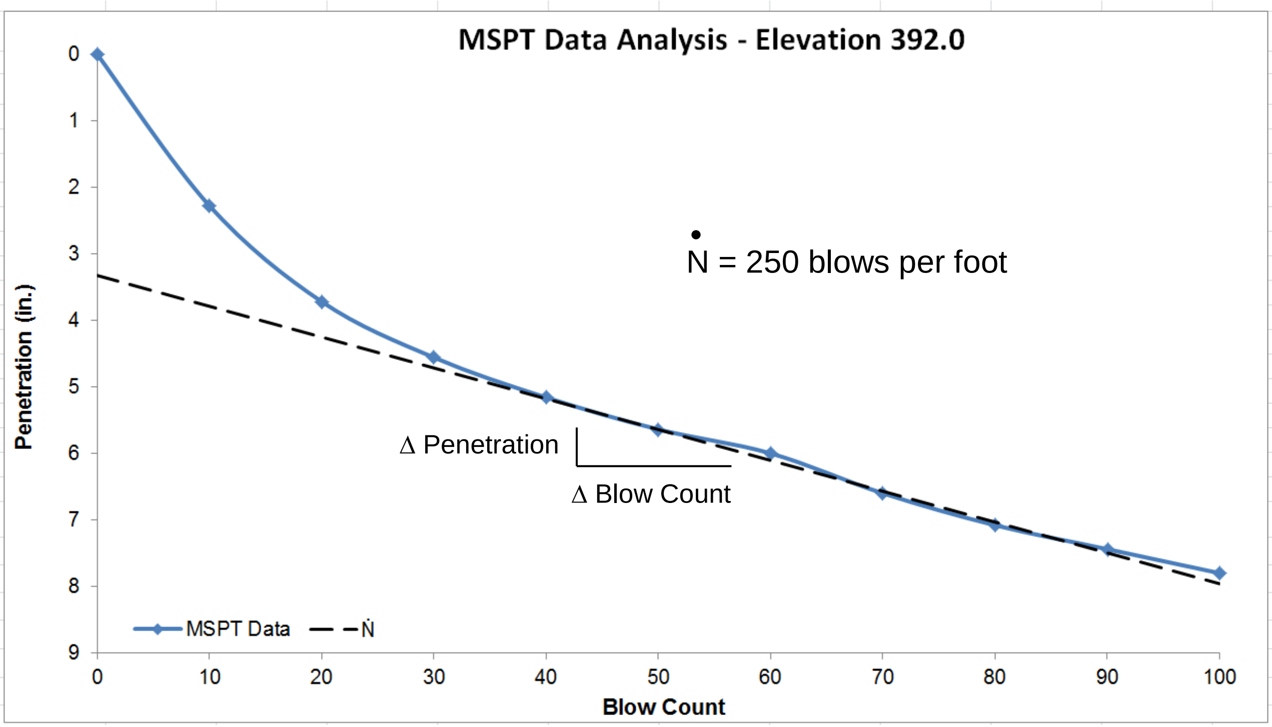
2. The penetration depth versus MSPT blow count is then plotted to determine a penetration rate, **Ṅ**. **Ṅ** represents the inverse value of the slope of the portion of the graph that is linear. Figure 2 provides example MSPT data and the corresponding plot used to determine **Ṅ**. In Figure 2, "X" reflects MSPT data that was used in the example to depict the linear portion of the graph for calculation of **Ṅ.** The initial part of the graph is often nonlinear due to disturbance, loose material in the boring, and reduced confining pressure and is neglected in determining **Ṅ**. The portion of the data that may be neglected in determining **Ṅ** will vary depending upon the scenario and data collected and requires use of engineering judgment. A minimum of five points shall be used to determine the slope and they should be the ones which create the lowest standard deviation.

3. The unconfined compressive strength of the shale can then be estimated using the following formula:

q_u = 0.096 $\dot{\mathbf{N}}$ (ksf)

$\dot{\mathbf{N}}$ = MSPT penetration rate (bpf)

Elevation:		392.00	
Blow Counts		Measured Rod Length (in.)	Penetration (in.)
0		39.36	0
10		37.08	2.28
20		35.64	3.72
30		34.8	4.56
40	X	34.2	5.16
50	X	33.72	5.64
60		33.36	6
70	X	32.76	6.6
80	X	32.28	7.08
90	X	31.92	7.44
100		31.56	7.8



$$\dot{\mathbf{N}} = \frac{\Delta \text{ Blow Count}}{\Delta \text{ Penetration}}$$

Figure 2. Example MSPT data and plot to determine $\dot{\mathbf{N}}$.

It is recommended that the MSPT test be performed at 2'-6" intervals to a depth that is approximately twice the shaft diameter below the anticipated drilled shaft tip elevation. Data for penetrations that exceed the barrel length of the split-barrel sampler should be disregarded as this data will reflect potentially erroneous driving resistance due to the sampler being full.

MSPT field and analysis data should be recorded on form BBS 139. Excel spreadsheets have been developed as companion tools to the Design Guide to assist designers with use of this alternative design procedure for drilled shafts in shale as well as interpretation of the MSPT data for completing form BBS 139. These spreadsheets are available within the Bridges and Structures division/office heading of the "IDOT Forms Section" found on the on the IDOT internet site.