Modified Standard Penetration Test for Drilled Shaft Design in Weak Rocks

Timothy D. Stark, James H. Long, & Ahmed Baghdady
University of Illinois at Urbana-Champaign

OTEC 2015
Columbus, Ohio
October 28, 2015
Illinois Shales
SPT in Weak Rock

- 18 inches
- 100 blows << 18 inches
Outline

- Drilled Shaft Design in Weak Rock
- Laboratory $q_u$ Measurement
- Field $q_u$ Measurement
Side Resistance

- Linear Function

\[ f_s = 0.3 \times q_u \leq 30 \text{ ksf} \]
Tip Resistance

- Accounts for
  - Tip displacement
  - Embedment depth in weak rock

\[ q_t = \frac{3.2 \times \delta / D}{\delta / D + 1.3} \times q_u \times d_c \leq 2.5 \times q_u \times d_c \]

where
- \( q_t \) = tip resistance, ksf
- \( q_u \) = unconfined compressive strength, ksf
- \( \delta / D \) = ratio of tip movement to tip diameter, in percent
- \( d_c \) = Vesic’s depth correction factor = 1.0 + 0.4 * k, dimensionless
- \( k = \begin{cases} L / D & L / D \leq 1 \\ \tan^{-1}(L / D) & L / D > 1 \end{cases} \)
- \( L = \) embedment depth in weak rock, in.

Stark, Long, and Baghdady (2015)
Outline

• Drilled Shaft Design
• Laboratory $q_u$ Measurement
• Field $q_u$ Measurement
Shale Coring
Shale Cores

Stark, Long, and Baghdady (2015)
Shale Trimming Equipment

Stark, Long, and Baghdady (2015)
New Triaxial Compression Test Equipment

Stark, Long, and Baghdady (2015)
Triaxial Compression Testing

[Image: A triaxial compression test setup with a sample being tested.]

Stark, Long, and Baghdady (2015)
Laboratory and in Situ Tests: Effect of Confining Pressure in Triaxial Compression Tests

Stark, Long, and Baghdady (2015)
Outline

- Drilled Shaft Design
- Laboratory $q_u$ Measurement
- Field $q_u$ Measurement
SPT = ?
SPT in Weak Rock

- 18 inches
- 100 blows \(<\) 18 inches
Initial and Secondary Slopes

Typical MSPT penetration and blowcount relationship for Illinois shale

- Initial Slope
- Secondary or Linear Slope

Stark, Long, and Baghdady (2015)
Penetration Rate

\[ \dot{N} = \frac{1}{\frac{\Delta (\text{Penetration Depth})}{\Delta (\text{MSPT Blowcounts})}} \]

Stark, Long, and Baghdady (2015)
MSPT Datasheet

Stark, Long, and O souli (2014)
## MSPT Datasheet

### Drilled Shaft Axial Capacity --- Shale

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MSPT Summary

- Provide estimate of UCS
- Reduce laboratory testing

\[ q_u (\text{ksf}) = 0.036 \times \left( \frac{N}{1.12} \right) \]
**Subsurface Investigation Locations**

**IDOT Drilled Sites**
- IL 23 over Otter Creek, LaSalle (Streator)
- IL 23 over Short Point Creek, Livingston
- US 24 over the Lamoine River, Brown
- Flora, Clay County
- IL 89 over the Illinois River, Spring Valley
- IL 133 over Embarrass River

**Wang Engineering Drilled Sites**
- FAI 80 over Aux Sable Creek, Grundy
- IL 5 over IL 84, Rock Island
- FAU 6265 Illinois River Bridge Replacement, La Salle
- I-55 over Des Plaines River

**Bulldog Drilled Sites**
- CH-9 @ I-74, Galesburg
- Fulton and Tazwell Counties

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Stark, Long, and Osouli (2014)
Penetration Rate v. UCS Relationship

\[ q_u (\text{ksf}) = 0.077 \times \hat{N}^{1.12} \]

Stark, Long, and Baghdady (2015)
Summary of MSPT Method

\[ q_u (\text{ksf}) = 0.036 \times \left( \sqrt{N} \right)^{1.12} \]

\[ q_t = \frac{3.2 \times \delta/D}{\delta/D + 1.3} q_u \leq 2.5 q_u d_c \]

\[ f_s = 0.3 \times q_u \]

Stark, Long, and Baghdady (2015)
O-Cell Test

Stark, Long, and Baghdady (2015)
O-Cell Test

Stark, Long, and Baghdady (2015)
Non-Invasive MSPT
Non-Invasive MSPT

Stark, Long, and Baghdady (2015)
No Measurement MSPT
Non-Invasive MSPT

Stark, Long, and Baghdady (2015)
\[ q_u \text{ (ksf)} = 0.077 \times \left( \frac{\dot{N}}{N} \right) \]

\[ q_t = \frac{3.2 \times \delta/D}{\delta/D + 1.3} \times q_u \times d_c \leq 2.5 \times q_u \times d_c \]

\[ f_s = 0.3 \times q_u \]
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"High Value"

State departments of transportation are committed to using research and innovation to meet the challenge of delivering more efficient and safer transportation systems. The projects on these pages, funded primarily through national programs, are a few among many that exemplify the high return on transportation research investments. The State Planning and Research (SPR) Program, as the nation’s cornerstone state transportation research program, provides federal aid funding to the states to address top concerns and identify solutions at the state level.

The bridge and structure projects highlighted here are examples of state DOTs providing “Transportation Excellence through Research.” The projects were compiled from the 2014 High Value Research solicitation carried out by the Value of Research Task Force, part of the American Association of State Highway and Transportation Officials Research Advisory Committee.

Guidelines for Better Culvert Repair, Rehabilitation and Replacement
Minnesota

Culverts under our roadways are critical channels for water and wildlife. Over time, however, culvert deterioration due to erosion, corrosion, freeze-thaw cycles and loading can damage the roadway above, even to the point of collapse. Fortunately, a wide range of effective repair, rehabilitation and replacement techniques have been developed in recent years to cost-effectively address culvert deterioration.

Researchers worked with the Minnesota Department of Transportation to review published literature and existing techniques from other state transportation departments, Minnesota cities and counties, and contractors. The information was then organized into illustrated, easy-to-use Best-Practices Guidelines for repair of culvert repairs ranging from 24 inches to 72 inches in diameter.

The Guidelines explain such techniques as cured-in-place pipe lining (CIPP), sliplining, centrifugally cast concrete lining, spall repair and joint repair. Model specifications, special provisions and standard detail drawings make the Guidelines immediately ready for practice. MnDOT implementation efforts include a webinar and training sessions to support district offices in use of the Guidelines.

Integrating Aesthetics and Engineering
Texas

When it came time to replace the 100-year-old West Seventh Street Bridge linking Fort Worth’s downtown and cultural district, results from a series of TxDOT research projects were put to work. The innovative bridge design incorporated several low-cost rapid-construction techniques. The beams and deck, plus all 12 of the identical 300-ton arches, were pre-cast on a nearby site and lifted into place over the Clear Fork Trinity River.

Opened to traffic in 2013, the architecturally stunning bridge features a network of stainless steel hangers tying the graceful arches to the deck and separating pedestrians and bicyclists from traffic on 1/2-foot travel ways along both sides of the bridge. Construction took only four months, compared to a typical 12-month bridge replacement using traditional methods.

Stark, Long, and Osouli (2014)
Using Carbon Fiber Reinforcement (CFR) to Reduce Bridge Repair Costs

Louisiana

Louisiana implemented existing technology using carbon fiber and inorganic polymer coating for repairing the pile cap of an end bent on the Morganza Floodway Bridge. The concrete tee beam had widespread spalling at the girder bearing extending to the bearing plates. This damaged concrete was removed and the cleaned surface was covered with epoxy concrete to patch the damaged areas. All bearing plate locations were strengthened to prevent delamination by confining it with high modulus carbon composite wrapping and then coating it with an inorganic polymer that provides UV protection and prevents mold and mildew growth. The carbon fiber composite has complete chemical adhesion with the pile cap and its high modulus fibers will not allow the material to separate from concrete.

The overall cost was 67% less than the cost of providing an external reinforcement retrofit, 93% less than the cost of replacing the pile cap, and 96% less than the cost of using vacuum assisted resin transfer molding cap repair. The project clearly demonstrates the significant cost savings that can be realized from effective implementation of existing composites technology for repairing and rehabilitating damaged components.


Infrared Testing Detects Drilled Shaft Defects

Washington

Supporting columns for highway structures are often constructed of concrete poured into drilled shafts. Assessing the final integrity and strength of these underground concrete columns is an important quality assurance step in bridge construction. Thirty years ago this assessment consisted primarily of monitoring the properties of the delivered concrete mix and testing the strength of hardened cylinders cast above ground from the same mix. Recent trends in quality assurance, however, also include post-construction, non-destructive testing of the underground concrete column made possible by steel access tubes attached to the nearby cage into which the wet concrete is poured. One group of such methods makes use of sonic sensors lowered into the access tubes at various depths to measure the structural soundness of the cured concrete.

Recognizing the limitations and relatively high costs of sonic and other state-of-the-art quality assurance methods to inspect subsurface concrete columns, the Washington State Department of Transportation explored a relatively new testing method called thermal integrity profiling (TIP). In this 18-month study WSDOT conducted TIP testing on eleven drilled shafts at eight sites throughout the state, with various shaft sizes and several concrete mix designs. Thermal sensors installed in the access tubes measured the temperatures generated by the curing concrete, providing an overall assessment of the concrete shaft based on the presence or absence of intact, heat-producing concrete. TIP testing provides details of shaft integrity, including effective shaft size (diameter and length), anomaly detection inside and outside the reinforcement cage, cage alignment and proper hydration of the concrete. The ability to detect concrete volumes outside the reinforcing cage is perhaps the strongest feature of the TIP method as compared with sonic testing.

WSDOT is implementing the TIP test method on select bridge projects with multiple drilled shafts and has submitted the TIP technology for consideration by the Federal Highway Administration for its Every Day Counts Initiative that recognizes proven but underutilized innovations.

Low-Cost Test Leads to Savings in Drilled Shaft Construction

Illinois

Over the last eight years the Illinois Department of Transportation has spent about $13 million per year on foundation piling, while at the same time period, use of drilled shafts increased from less than $1 million per year to almost $14 million. This project studied drilled shafts founded in weak Illinois shale (<100 ksf) and developed a new in situ testing procedure as well as a corresponding design theory to reduce testing costs and shaft length (and thus construction expense).

Eight bridge sites have been evaluated using the Modified Standard Penetration Test (MSPT), which was identified as the most consistent and low-cost way to characterize the in-situ strength. A correlation was developed to relate the MSPT to the unconfined compressive strength which allowed design methods to be evaluated and resistance factors developed. Drilled shafts at two sites were load tested with an Osterberg Cell (O-cell) to validate the proposed testing and design procedure.

The new testing and design method is expected to reduce shaft depth by about 20 percent. With about 40 percent of shafts being founded in shale and typically one-third of the shaft expense due to rock, the expected annual savings is at least $400,000 per year.

https://apps.illinois.edu/projects/getfile.asp?id=3088

Thermal sensors in underground tubes measure the strength of poured concrete columns.

Stark, Long, and Osouli (2014)
“High Value”

- “Top Ten” High Value Projects
- TRB Research Poster Session

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Stark, Long, and Osouli (2014)
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**Bulldog Drilled Sites**
- CH-9 @ I-74, Galesburg

Stark, Long, and Baghdady (2015)
Modified SPT Log

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Stark, Long, and Baghdady (2015)