SHAFT98 - COMPUTER DESIGN PROGRAM FOR AXIALLY LOADED DRILLED SHAFTS

SUBMITTED TO

FLORIDA DEPARTMENT OF TRANSPORTATION

State Project No: 99700-3322-119
UF Project No: 49104504526
WPI No: 0510739
Contract No: B-9906

June 1998

Welcome to SHAFT98
Program for calculation of the axial capacity of a drilled shaft
Developed at the University of Florida by Kailash Krishnamurthy and P. C. Townsend for the Florida Department of Transportation

Principal Investigator: Dr. F.C. Townsend
Post-Doctorate: Dr. Kailash Krishnamurthy

Department of Civil Engineering
College of Engineering
University of Florida
Gainesville, Florida 32611-6580
Shaft98 is a Visual Basic program based upon the FHWA reports: (a) Drilled Shafts: Construction Procedure and Design Methods (1988) by L.C. Reese and M.W. O'Neill, and (b) Load Transfer for Drilled Shafts in Intermediate Geomaterials (1996) by M.W. O'Neill et al. The program calculates axial capacities and settlements for clays, sands and soft rock [unconfined compression strength ($q_u$) between 0.5 and 5.0 MPa].
### Approximate Conversions to SI Units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>When You Know</th>
<th>Multiply By</th>
<th>To Find</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LENGTH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in</td>
<td>inches</td>
<td>25.4</td>
<td>millimeters</td>
<td>mm</td>
</tr>
<tr>
<td>ft</td>
<td>feet</td>
<td>0.305</td>
<td>meters</td>
<td>m</td>
</tr>
<tr>
<td>yd</td>
<td>yards</td>
<td>0.914</td>
<td>meters</td>
<td>m</td>
</tr>
<tr>
<td>mi</td>
<td>miles</td>
<td>1.61</td>
<td>kilometers</td>
<td>km</td>
</tr>
</tbody>
</table>

| **AREA** |
| in²    | square inches | 645.2       | square millimeters | mm²   |
| ft²    | square feet   | 0.093       | square meters     | m²    |
| yd²    | square yards  | 0.836       | square meters     | m²    |
| ac     | acres         | 4.045       | hectares         | ha    |
| m²     | square miles  | 2.59        | square kilometers | km²   |

| **VOLUME** |
| fl oz  | fluid ounces  | 29.57       | milliliters     | ml    |
| gal    | gallons       | 3.785       | liters          | l     |
| ft³    | cubic feet    | 0.028       | cubic meters    | m³    |
| yd³    | cubic yards   | 0.765       | cubic meters    | m³    |

### Approximate Conversions from SI Units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>When You Know</th>
<th>Multiply By</th>
<th>To Find</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LENGTH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm</td>
<td>millimeters</td>
<td>0.039</td>
<td>inches</td>
<td>in</td>
</tr>
<tr>
<td>m</td>
<td>meters</td>
<td>3.28</td>
<td>feet</td>
<td>ft</td>
</tr>
<tr>
<td>m</td>
<td>meters</td>
<td>1.09</td>
<td>yards</td>
<td>yd</td>
</tr>
<tr>
<td>km</td>
<td>kilometers</td>
<td>0.621</td>
<td>miles</td>
<td>mi</td>
</tr>
</tbody>
</table>

| **AREA** |
| mm²    | square millimeters | 0.0016     | square inches | in²   |
| m²     | square meters     | 10.764     | square feet   | ft²   |
| m²     | square meters     | 1.195      | square yards  | yd²   |
| ha     | hectares         | 2.47       | acres         | ac    |
| km²    | square kilometers | 0.386      | square miles  | mi²   |

| **VOLUME** |
| ml     | milliliters     | 0.034       | fluid ounces  | fl oz |
| l      | liters          | 0.264       | gallons       | gal   |
| m³     | cubic meters    | 35.71       | cubic feet    | ft³   |
| m³     | cubic meters    | 1.307       | cubic yards   | yd³   |

| **MASS** |
| g      | grams           | 0.035       | ounces        | oz    |
| kg     | kilograms       | 2.202       | pounds        | lb    |
| Mg     | megagrams       | 1.103       | short tons    | (2000 lb) T |

| **TEMPERATURE (exact)** |
| °C     | °C              | 1.8(C + 32) | °F            |

| **ILLUMINATION** |
| lx      | lux             | 0.0929      | foot-candles  | fc    |
| cd/m²   | candela/m²     | 0.2919      | foot-Lamberts | fl    |

| **FORCE and PRESSURE or STRESS** |
| N      | newtons         | 0.225       | poundforce    | lbf   |
| kPa    | kilopascals    | 0.145       | poundforce per square inch | psi |

* Si is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)
DISCLAIMER

"The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Florida Department of Transportation or the U.S. Department of Transportation."

No Warranty, expressed or implied, is made by the Florida Department of Transportation as to the accuracy and the functioning of the program text or the results it produces, nor shall the fact of distribution constitute any such warranty, and no responsibility is assumed by Florida Department of Transportation in any connection therewith.

Prepared in cooperation with the State of Florida Department of Transportation and the U.S. Department of Transportation.
# Table of Contents

- **Introduction** ................................................................................. 1
- **Method of Analysis** ..................................................................... 1
  - Design for Clay........................................................................... 3
  - Design for Sand.......................................................................... 5
  - Design for Rock.......................................................................... 8
- **USER'S GUIDE** ........................................................................... 13
- **REFERENCES** ............................................................................. 24
- **APPENDIX A - Examples** .......................................................... A-1
List of Figures

Figure 1 Portions of Drilled Shaft Non-Contributory in Friction ........................................... 2
Figure 2 Trend lines for side friction and end bearing in clay ................................................. 5
Figure 3 Trend lines for side friction and end bearing in sand ............................................... 8
Figure 4 N Factors for Smooth Sockets .................................................................................. 11
Figure 5 ............................................................................................................................... 13
Figure 6 ............................................................................................................................... 14
Figure 7 ............................................................................................................................... 15
Figure 8 ............................................................................................................................... 16
Figure 9 ............................................................................................................................... 17
Figure 10 .............................................................................................................................. 18
Figure 11 ............................................................................................................................. 19
Figure 12 ............................................................................................................................. 20
Figure 13 ............................................................................................................................. 21
Figure 14 ............................................................................................................................. 22
Figure 15 ............................................................................................................................. 23
List of Tables

Table 1 Code for Soil Type .......................................................... 2
Table 2 Recommended Values for $\alpha$ for Drilled Shafts in Clay ............................... 2
Table 3 Recommended Unit End Bearing Values for Cohesion’s Soils ........................ 7
Table 4 Values of $M$ .................................................................... 11
SHAFT98 - COMPUTER DESIGN PROGRAM 
FOR 
AXIALLY LOADED DRILLED SHAFTS

Introduction

The SHAFT98 computer program is a Windows based program used to estimate the static axial capacity of drilled shafts. The methodology is based upon Federal Highway Administration reports: (a) Reese, L. and O'Neil, M. (1988) "Drilled Shafts: Construction Procedure and Design Methods", and (b) O'Neil, M.W. et al. (1996) "Load Transfer for Drilled Shafts in Intermediate Geomaterials". The former presents methods for estimating drilled shaft capacity in clays or sands, and provides settlement estimates. The latter addresses intermediate geomaterials, soft rock, $q_u$ between 0.5 and 5.0 Mpa (1.7 to 17 tsf) and SPT blow counts of 50 - 100; and provides settlement analyses. Load transfer for rock socketed shafts in Florida limestone is based upon the methodology described in; (a) FDOT Final Report " An Evaluation of Design Methods for Drilled Shafts)" (1990), which is also found (b) McVay, M.C. et al. (1992).

SHAFT98 replaces earlier versions of SHAFTUF and SHAFT93.

Method of Analysis

The axial capacity of drilled shafts can be calculated as:

$$Q_t = Q_s + Q_b$$

(Eqn 1)

where:

$Q_t$ = Ultimate shaft capacity
$Q_s$ = capacity in skin friction
$Q_b$ = Capacity in end bearing

The computations of side resistance (skin friction) and end bearing are presented in separate sections for clay, sand, and intermediate geomaterial (soft rock). Settlement calculations are also presented. These three material types (clay, sand, and soft rock) are identified as follows to be compatible with FDOT's SPT94 program.
### Table 1 Code for Soil Type

<table>
<thead>
<tr>
<th>Description</th>
<th>SHAFT98</th>
<th>SPT94</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Clay</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Clay-Silt-Sand Mixtures</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Clean Sand</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Soft Rock</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

![Diagram showing portions of drilled shaft non-contributory in friction]

**Figure 1 Portions of Drilled Shaft Non-Contributory in Friction**

### Table 2 Recommended Values for $\alpha$ for Drilled Shafts in Clay

<table>
<thead>
<tr>
<th>Location along Drilled Shaft</th>
<th>Value of $\alpha$</th>
<th>Maximum Value of fsu (tsf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From ground surface to depth of 5 ft. (1.52 m.)</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>From ground surface to length of casing</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Bottom 1 diameter of shaft or 1 stem diameter above top of bell</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>All other points along drilled shaft sides</td>
<td>0.55</td>
<td>2.75 tsf, 275 kPa</td>
</tr>
</tbody>
</table>
Design for Clay

Shear Transfer - The load transfer in side resistance for drilled shafts in clay employs the Alpha (α) method. That is, the undrained shear strength \( C_u \) of clay is found from appropriate soil tests or correlations with insitu tests and the following equation used to compute the ultimate value if unit load transfer at the depth \( z \) below the ground surface.

\[
\sigma_{u} = \alpha \ C_u
\]  
(Eqn 2)

where

\( \sigma_{u} \) = ultimate unit load transfer in side resistance at depth \( z \)
\( \alpha \) = empirical factor that varies with depth, (see Table 2 and Figure 1)
\( C_u \) = undrained shear strength at depth \( z \),

The total load \( Q_s \) in side resistance is now computed as:

\[
Q_s = \int_{z_1}^{z_2} \sigma_{u} \ dA
\]  
(Eqn 3)

where

\( dA \) = differential area of the perimeter along the side over a specific depth,
and

\( L_1 \) and \( L_2 \) = penetration of drilled shaft below ground surface between two layers.

Figure 1 illustrates the zones where \( \alpha \) is assumed to be zero. The setting of \( \alpha = 0 \) for a distance of 1 diameter above the base is from the work of Ellison et al. (1971), who showed that the downward movement of the base of the shaft can result in the development of a tensile crack in the soil near the base. Consequently, the lateral stress at the base will be reduced causing a reduction in load transfer in skin friction for this zone. In cases where a clay layer is present above the base, the program takes the arithmetic average of those \( C_u \) values between the top and the bottom of the clay layer. For a belled shaft the \( C_u \) are averaged between the top of the clay layer and to one shaft diameter above the top of the bell (if the bottom of a clay layer is below the depth of one shaft diameter above the top of the bell). However, if the top of the clay layer falls within 5 ft (1.52m) below the ground surface, the \( C_u \) average starts from the bottom of 5 ft (1.52m). The user must provide at least one \( C_u \) value for each clay layer.

End Bearing - The end bearing resistance for drilled shafts in clay is derived from the work of Skempton (1951) as follows:

\[
q_b = N_c \ C_u, \quad q_b < 40 \text{ tsf (4000 kPa)}
\]  
(Eqn 4)

where:

\( q_b \) = unit end bearing for drilled shafts in clay
\( N_c = 6.0[1 + 0.2(L/D)] \) \( N_c < 9 \)
\( C_u \) = average undrained shear strength of clay for one diameter (1.0D) below the tip.
$L =$ total embedment length of shaft  
$D =$ diameter of shaft base.

The limiting value of $q_b$ shown in equation 4 is merely the largest value of end bearing that has been measured for clays and is not a theoretical limit (Engling and Reese, 1974)

SHAFT98 interpolates or extrapolates values of Cu at depths of one base diameter of the shaft, below the base. Interpolation and extrapolation depend on the depth of Cu values input by the user. For the calculation of an average Cu value, the program takes a weighted average of all the Cu values present in above described depth range. An example with hand calculations is shown in Appendix A.

In the case where the shaft base is at the top of a clay layer, SHAFT98 takes a weighted average of Cu values between the base and one base diameter below the base.

In those rare instances where the clay at the base is soft, the value of $C_u$ may be reduced by one-third to account for local (high strain) bearing failure. Furthermore, when the base of the shaft has a diameter greater than 75 inches (1.9 m) consideration should be given to reducing $q_b$ because the settlement required to obtain the ultimate value of $q_b$ will be so great that application of safety factors in the usual range of 2 or 3 may result in excessive short term settlement. It is therefore recommended that for drilled shafts in stiff to hard clay, with $D$ exceeding 75 inches (1.9 m), that the following expressions be used to reduce $q_b$ to $q_{br}$, where $q_{br}$ is the reduced ultimate end bearing stress, to which appropriate safety factors are applied.

$$q_{br} = F_r \cdot q_b \quad \text{(Eqn 5)}$$

where:

$$F_r = \frac{2.5}{[a \cdot D_b \text{ (inches)} + 2.5 \cdot b]} \quad \text{for } F < 1.0$$

in which

$$a = 0.0071 + 0.0021 \cdot (L/D_b), \quad a < 0.015$$
$$b = 0.45 \cdot (C_{ub})^{0.5} \quad 0.5 < b < 1.5 \text{ and } C_{ub} \text{ in ksf}$$

These expressions are based upon load tests of large under-reamed drilled shafts in very stiff clay (O'Neill and Sheikh, 1985) and restrict $q_{br}$ to be the net bearing stress at a base settlement of 2.5 inches (6.35 cm). When half or more of the design load is carried in end bearing and a global factor of safety applied, the global safety factor should not be less than 2.5, unless site specific load tests deem otherwise.

**Short-Term Settlement -** The reference curves are presented in Figure 2. The marks represent the values proposed by Reese and O'Neill [FHWA (1988)] and the solid lines are the adopted curves. If the short-term settlements or differential settlements appear to be too great the applied loads can be adjusted accordingly. Normally, if the procedures for establishing ultimate loads are followed, short-term settlements should be restricted to less than one inch (2.54 cm.) when appropriate safety factors are applied.
Side friction mobilization

\[
\begin{align*}
\frac{f_r}{f_{r,\text{max}}} &= 0.593157 \times R / 0.12 & \text{for } R \leq 0.12 \\
\frac{f_r}{f_{r,\text{max}}} &= \frac{R}{(0.095155 + 0.892937 \times R)} & \text{for } R \leq 0.74 \\
\frac{f_r}{f_{r,\text{max}}} &= 0.978929 - 0.115817 \times (R - 0.74) & \text{for } R \leq 2.0 \\
\frac{f_r}{f_{r,\text{max}}} &= 0.833 & \text{for } R > 2.0 \\
\end{align*}
\]

where \( R = \frac{S}{D} \times 100 \)

For end bearing mobilization the trendline is given as:

\[
\begin{align*}
\frac{q_b}{q_{b,\text{max}}} &= 1.1823 E-4 \times R^5 - 3.7091 E-3 \times R^4 + 4.4944 E-2 \times R^3 - 0.26537 \times R^2 + 0.78436 \times R & \text{for } R \leq 6.5 \\
\frac{q_b}{q_{b,\text{max}}} &= 0.98 & \text{for } R > 6.5 \\
\end{align*}
\]

**Figure 2** Trend lines for side friction and end bearing in clay

An example is presented in Appendix A for a drilled shaft in clay.

**Design for Sand**

Side Shear resistance - The unit side resistance, as the drilled shaft is pushed downward is equal to the normal effective stress times the tangent on the interface friction angle. The normal stress at the interface of the drilled shaft and soil will be relatively low when the excavation is completed. The fluid stress from the fresh concrete will impose a normal
stress that is dependent on the characteristics of the concrete. Experiments have shown that concrete with a moderate slump (up to 6 inches, 150 mm.) acts hydrostatically over a depth of 10 to 15 ft. (3 to 4.5 m.) and there is a leveling off in the lateral stress at greater depths, probably due to arching (Bernal and Reese, 1983). Concrete with a high slump (about 9 inches, 230 mm.) acts hydrostatically to a depth of 32 ft. (10 m.). Thus, construction procedures and the concrete characteristics will probably have a strong influence on the magnitude of the lateral stress at the soil-concrete interface. Furthermore, the friction angle of the soil-concrete interface will also be affected by construction details. Consequently, a β method for calculating the unit side shear transfer is used with the following rationale:

\[ f_{sz} = K \sigma_z \tan \phi_e \]  
(Eqn 6)

\[ Q_s = \int_0^L K \sigma_z \tan \phi_e \, dA \]  
(Eqn 7)

where
- \( f_{sz} \) = ultimate unit side shear resistance in sand at depth \( z \),
- \( K \) = a parameter that combines the lateral pressure coefficient
- \( \sigma_z \) = vertical effective stress at depth \( z \)
- \( \phi_e \) = interface friction angle for soil-concrete
- \( L \) = depth of embedment for drilled shaft in sand
- \( dA \) = differential area of perimeter along sides of drilled shaft

Equations 6 and 7 can be used in computations, but simpler expressions can be developed by combining the terms for \( K \) and \( \tan \phi_e \) as \( \beta \); resulting in:

\[ f_{sz} = \beta \sigma_z \]  

\[ Q_s = \int \beta \sigma_z \, dA \]  
(Eqn 8)

\[ \beta = 1.5 - 0.135\sqrt{z} \]  
\[ 1.2 > \beta > 0.25 \]  
(Eqn 9)

where
- \( z \) = depth below ground surface, ft.

The factor \( \beta \) in equation 9 is independent of \( \phi \) (or \( N_{SP7} \)) because drilling plus stress relief produces high shearing strains in the sand at the borehole interface, and the friction angle \( \phi \) is forced toward some common critical state value. Thus, the parameter \( \beta \) varies principally with the coefficient of lateral pressure \( K \) and experimental studies have shown that this coefficient both for soil and fresh concrete exhibits some decrease with depth.

The limiting value of side resistance in equation 9 is again not a theoretical limit, but rather is merely the largest value that has been measured (Owens and Reese, 1982). Higher values can be used if justified via a load test.
End Bearing - Because of stress relief when an excavation is drilled into sand, there is a tendency for the sand to loosen slightly at the bottom of the excavation. Also there appears to be some densification of the sand beneath the base of the drilled shaft as settlement occurs. The load-settlement curves that have been obtained by experiment for the base of drilled shafts are consistent with the above concepts. The load continued to increase for some tests to a settlement of more than 15 percent of the base diameter. Such a large settlement could not be tolerated for most structures; therefore, it was decided to limit the values of end bearing for drilled shafts in granular soils to that which would occur at a downward movement of 5 percent of the base diameter.

The values of \( q_b \) are tabulated as a function of \( N_{SPT} \) (uncorrected field values) in Table 3. However, these values may have to be reduced for large diameter shafts \([D> 50 \text{ in. (1.3m)}]\), as shown by equation 10.

\[
q_{br} = 50 \times (q_b/D_b); \quad D_b \text{ in inches}
\]

or

\[
q_{be} = 1.3 \times (q_b/D_b); \quad D_b \text{ in meters} \quad \text{(Eqn 10)}
\]

<table>
<thead>
<tr>
<th>( N_{SPT} ) Values (Uncorrected)</th>
<th>Value of ( q_b ) (TSF) [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 75</td>
<td>((0.60 \times N_{SPT}) \times 60 \times N_{SPT})</td>
</tr>
<tr>
<td>above 75</td>
<td>((45) \times )</td>
</tr>
</tbody>
</table>

Table 3 suggests a limiting value of end bearing as 45 tsf (4500 kPa) at a settlement of 5 percent of the base diameter. A value of 58 tsf (5800 kPa) was measured at a settlement of 4 percent of the base diameter in Florida (Owens and Reese, 1982).

In the case where the shaft base is in sand, SHAFT98 uses the basic assumption that the soil 8D above and 3.5D below the shaft base contributes to the end bearing capacity. This assumption differs from O'Neill (1988) in which a single \( N \) value at the base characterizes the tip resistance. A weighted average in this 8D - 3.5D range is obtained via equation 11.

\[
N_{spt} = \frac{\sum N_k L_k}{\sum L_k} \quad \text{(Eqn 11)}
\]

SHAFT98 needs at least one value of SPT for each sand layer. It then calculates an area average of SPT values between the depth range of 8 shaft diameters above the base and 3.5 base diameters below the base, if no other layer except a sand layer is present in this depth range. If any other soil except sand is present in this range, then it calculates area average of SPT values between top of other layer (in other layer is present below the base), and bottom of other layer (if other layer is present above the base). If a sand layer is present above the base while the shaft is not tipped in sand, SHAFT98 asks for at least one value of SPT for each sand layer. However, SPT values are not required to calculate skin friction, but in case of editing the shaft data, this information may be required.
Immediate Settlements - The immediate settlements are computed using non-linear t-z and Q-z springs, with the shape presented in Figure 3. The equations are provided but is should be referred that there is a considerable scatter around these trend lines.

Side friction mobilization
\[
f_s/f_{s\text{max}} = -2.16*R^4 + 6.34*R^3 - 7.36*R^2 + 4.15*R \quad \text{for } R \leq 0.908333 \\
f_s/f_{s\text{max}} = 0.978112 \quad \text{for } R > 0.908333
\]

where \( R = \frac{S}{D} \times 100 \)

End bearing mobilization
\[
q_b/q_{b\text{max}} = -0.0001079* R^4 + 0.0035584* R^3 - 0.045115* R^2 + 0.34861*R
\]

![Load Transfer in Drilled Shafts Trend Lines for Sand](image)

Figure 3 Trend lines for side friction and end bearing in sand

Design for Rock

Side shear resistance - Several equations have been suggested for estimating the ultimate side friction \( f_{su} \) for drilled shafts in rock. (McVay et al. 1992). They are typically based upon unconfined compression strengths, \( q_u \) (\( \alpha \) values), or a combination of unconfined and split tensile strengths (\( 0.5\sqrt{q_u} \sqrt{q_t} \)). These correlations listed below may be entered into SHAFT98 as (Note: 1 tsf = 95.8 kPa):

\[
f_{su} = a q_u^b, \ a \text{ and } b \text{ are emperical parameters used by authors based upon their experiences}
\]

(Eqn 12)
1. Williams, et al. (1980): $f_{su} = 1.842 q_u^{0.367}$
2. Rowe and Armitage (1987): $f_{su} \text{ (tsf)} = 1.45 \sqrt{q_u}$
   for clean sockets, and $f_{su} \text{ (tsf)} = 1.94 \sqrt{q_u}$ for rough sockets;
3. Horvath and Kenney (1979): $f_{su} \text{ (tsf)} = 0.67 \sqrt{q_u}$
4. Carter and Kulhawy (1988): $f_{su} \text{ (tsf)} = 0.63\sqrt{q_u}$
5. Reynolds and Kaderabek (1980): $f_{su} \text{ (tsf)} = 0.3 (q_u)$;
6. Gupton and Logan (1984): $f_{su} \text{ (tsf)} = 0.2 (q_u)$;
7. Reese and O'Neiill (1988): $f_{su} \text{ (tsf)} = 0.15 (q_u)$;
8. Crapps (1986): $f_{su} = 0.01 \text{N (tsf)}$ or $f = -5.54 + 0.41 \text{N (tsf)}$
9. CIRIA (Hobbs and Healy, 1979)
   
<table>
<thead>
<tr>
<th>N value</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>&gt;30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{su} \text{ (tsf)}$</td>
<td>.36</td>
<td>.77</td>
<td>1.1</td>
<td>1.8</td>
<td>2.6</td>
<td>2.6</td>
</tr>
</tbody>
</table>
    
    | N Range | 10-20 | 20-50 | 50-50/3" | >50/3" |
    |---------|--------|--------|----------|--------|
    | $f_{su} \text{ (tsf)}$ | 1.5 | 2.5 | 3.8 | 5 |

An examination of these methods reveals that in the case of #5, #6 and #7, skin friction is a simple constant times $q_u$, whereas #1, #2, #3, and #4 use a power curve relationship.

End Bearing - The ultimate end bearing resistance in rock can be calculated as:

$$Q_b = q_{bu} A_b$$  \hspace{1cm} (Eqn 13)

where

- $Q_b$ = ultimate end bearing
- $q_{bu}$ = unit end bearing capacity, and
- $A_b$ = shaft base area

SHAFT98 uses the Canadian Foundation Manual method of equation 14 to estimate end bearing in rocks. However, sinkhole potential of Florida's karstic terrain, and questions concerning cleanliness of the shaft base if wet hole construction is used, have led some designers to neglect conservatively end bearing of drilled shafts in Florida (i.e., assume $q_{bt} = 0$).

$$q_{bt_{\text{max}}} = 3 \Delta K_{sp} [q_u \text{ (beneath base)}]$$  \hspace{1cm} (Eqn 14)

where:

- $\Delta = \text{depth factor} = 1 + 0.4 (L/D) < 3.4$, and
- $K_{sp} = (3 + \frac{S_d}{D}) / (10 \sqrt{1 + 300 \frac{t_d}{S_d}})$

in which:

- $s_d = \text{vertical spacing of horizontal joints beneath base}$
- $t_d = \text{thickness of these horizontal joints}$
The application of equation 14 is limited to \(0.05 < S_d / D < 2; \ t_d / D < 0.02\) and \(D > 0.3\)m. If these limiting values of \(S_d / D = 0.05\) and \(t_d / D = 0.02\) are assumed, then,

\[K_{sp} = 0.115\ \ \ \ \ \text{and}\]

\[q_{bt_{max}} = 0.346 (1 + 0.4 \ L/D) q_u \]  \hspace{1cm} (Eqn 15)

Equation 15 is programmed into SHAFT98. However, this value of \(q_{bt_{max}}\) is limited to < 2.5 \(q_u\).

Short-term settlements in rock - The short-term settlements in rock are estimated using the direct method of O'Neill et al. (1996) for rough sockets [IGM_Type = 1.0] or smooth [IGM_Type ≠ 1.0].

For side shear resistance:

1. Find the average \(E_m\) and \(f_{su}\) along the side of the rock socket.
\[E_m = \frac{\sum E_{mk} \ L_k}{\sum L_k} \ \ \ \text{where} \ E_{mk} = 115 \ q_{uk}\]

\[f_{su} = \frac{\sum f_{su} \ L_k}{\sum L_k} \ \ \ \text{where} \ f_{su} = \text{side friction from equation 12}. \ \text{Note the values selected for} \ f_{su} \ \text{depend whether the socket is considered "smooth" and failure occurs at the interface (}\alpha\text{ values)}\]

or “rough” where failure occurs through the rock \((0.5\sqrt{q_u}, \sqrt{q_r})\).

2. Calculate \(\Omega\)
\[\Omega = 1.14 \left(\frac{L}{D}\right)^{0.5} - 0.05 \left[\left(\frac{L}{D}\right)^{0.5} \ \log_{10}\left(\frac{E_c}{E_m}\right)\right] - 0.44\]

where \(E_c(1) = 57.000 \sqrt{q_{uc}}\)

3. Calculate \(\Gamma\)
\[\Gamma = 0.37 \sqrt{\left(\frac{L}{D}\right)} - 0.15 [\sqrt{\left(\frac{L}{D}\right)} - 1] \log_{10}\left(\frac{E_c}{E_m}\right) + 0.13\]

4. Find \(n\)

For “rough” sockets:
\[n = \frac{\sigma}{q_u} \ \ \ \text{where} \ \sigma = \text{normal stress of concrete} = \gamma_c Z_c M\]
Table 4 Values of M

<table>
<thead>
<tr>
<th>Socket Depth (m)</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>0.50</td>
</tr>
<tr>
<td>8</td>
<td>0.45</td>
</tr>
<tr>
<td>12</td>
<td>0.35</td>
</tr>
</tbody>
</table>

if a water table is present, then \( \sigma_n = \gamma_c (Z_c - Z_w) + \gamma_c Z_w \), where \( Z_c \) = depth to water table.

For "smooth" sockets, \( n \) is estimated from Figure 4.

![Diagram showing N Factors for Smooth Sockets]

**Figure 4 N Factors for Smooth Sockets**

5. Calculate \( \Theta_f \) and \( K_f \)

\[
\Theta_f = \frac{E_m \Omega}{\pi L T f_{sw}} W_t
\]

\[
K_f = n + \frac{(\Theta_f - n)(1-n)}{\Theta_f - 2n + 1} < 1
\]
\[ \Theta_t = \frac{E_m \Omega}{\pi L \Gamma f_{sw}} W_t \]

\[ K_t = n^+ \frac{(\Theta_t - n)(1 - n)}{\Theta_t - 2n + 1} < 1 \]

where

\[ W_t = \text{deflection at top of rock socket} \]

6. Calculate the side shear load transfer - deformation as

\[ Q_s = \pi D L \Theta_t f_{su} \quad \Theta_t < n \]
\[ Q_s = \pi D L K_t f_{su} \quad \Theta_t > n \]

For end bearing short-term settlements in rock sockets, the O'Neil et al. (1996) procedure follows as:

Find \[ Q_b = \frac{\pi D^2}{4} q_b \]

where \[ q_b = \Lambda W_t^{0.67} \], and

\[ \Lambda = 0.0134 E_m \frac{(L/D)}{(1 + L/D)} \left\{ \frac{[200(L/D)^{0.5} - \Omega][1 + (L/D)]}{\pi L \Gamma} \right\}^{0.67} \]

The total settlement \( (Q_t) \) for a rock socket would be the sum of \( Q_s + Q_b \).

An example for a rock-socketed shaft is presented in Appendix A.

In rare cases where IGM is at the ground surface the first layer should be fictitiously thin, i.e., 0.1 m.

Layered Soils

In the case of alternating layers of clay, sand, or rock, the side resistance is calculated by summing the incremental resistances for each layer. Obviously, the end bearing depends upon the layer in which the base is tipped.
Go to Start Button in Windows 95/NT, Programs, Shaft98. On Clicking Shaft98 Figure 1 pops up. Click on Main Menu. In Main Menu window, click on File, Open and then choose the appropriate input file.
Prior to inputting data, select “Units” in lower left-hand box. Enter “Groundwater location” (depth). Select “Type of Analysis” for either single or range of shaft lengths. Continuing in “Input”, enter data pertaining to shaft geometry, and soil properties. “Soil Type”

<table>
<thead>
<tr>
<th>SHAFT '98 Soil Type</th>
<th>SPT 97 Soil Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>Plastic Clay</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Clay-silt-sand mixtures</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Clean Sand</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Soft limestone</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Void</td>
</tr>
</tbody>
</table>
For SHAFT '98 "Soil Types" relating to cohesionless soils (sands) Type = 3 SPT values must be input. For cohesive soils (clays) TYPE = 1 or 2, C_u values are needed. However, these maybe obtained via: (1) direct input, (2) correlations with SPT, or (3) correlations from CPT. For intermediate geomaterials, TYPE = 4, unconfined / compression (q_u) strengths are required.

In order to do the analysis, click on Calculation, Start. Once calculation is done an information dialog box, with OK button shows up. Click the OK button for the next screen (Figure 7)

![Results window](image_url)

Figure 7

This window displays the shaft geometry, the information of soil layers, and water table. In order to view results, click on Show Results command button. In order to go back to input data or Home Screen windows click on the respective buttons. Once the Show Results button is clicked, Figure 7 looks like Figure 8.
This screen can be used to set "Factors of Safety" on skin friction and/or end bearing. The Bearing Graphics button will provide the graphics illustrated in Figure 9. To obtain the settlement data, use the "input data" button to return to the input data screen (Figure 6), and click results. From there you will be prompted for settlement.
This screen presents the bearing graph showing skin friction and tip resistance percentages. Clicking "options" (upper left) provides a menu for other screens.
This screen presents the ultimate and allowable, depending upon Factor of Safety values used, friction and end bearing values.

<table>
<thead>
<tr>
<th>Shaft Length (ft)</th>
<th>Ultimate Side Friction (Tons)</th>
<th>Ultimate End Bearing (Tons)</th>
<th>Ultimate Capacity (Tons)</th>
<th>Allowable Side Friction (Tons)</th>
<th>Allowable End Bearing (Tons)</th>
<th>Allowable Capacity (Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.28</td>
<td>2261.50</td>
<td>1366.26</td>
<td>3627.83</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 11

This screen presents the settlement graphics. Clicking the "Table" button will provide the tabular data for these curves as shown in Figure 12.
This screen presents the settlement data in tabular form. It can be obtained by clicking the Table" button upper right (See Figure 11).
This screen presents the SPT blow count graphics. It can be accessed from the Input Data screen and clicking "Results".
This screen presents the tip resistance VS displacement graphics. It can be accessed from the Input Data screen and clicking "Results".
This screen presents the friction VS displacement (t-z) graphics. It can be accessed from the Input Data screen and clicking "Results".
REFERENCES

Bernal, J.B., and Reese, L.C. "Study of the Lateral Pressure of Fresh Concrete as Related to the Design of Drilled Shafts", Research Report 308-1F, Center for Transportation Research, University of Texas, Austin, TX 1983.


Engleing, D., Reese, L.C., "Behavior of Three Instrumented Drilled Shafts under Short Term Axial Loading", Research Report 176-3, Conducted at the Center for Highway Research, University of Texas, Austin TX, for FHWA and Texas Highway Department, May 1974, 116 Pages.


APPENDIX A - Examples

CLAYS:
Example File: Clay1.dat

1. Multi Layer Clay with Casing

2. Multi Layer Clay with Casing D > 75 "

\[ c = \frac{q_e - \sigma_0}{15} \]

Clay Layer #1: \[ c = \frac{16 \times 2000 - 10 \times 100}{15} = 2066.67 \text{ psf (1.0333 tsf)} \]

Clay Layer #2: \[ c = \frac{30 \times 2000 - 30 \times 100}{15} = 3800 \text{ psf (1.90 tsf)} \]

1. **Multi Layer Clay with Casing**: Full Capacity (40 ft Shaft)

   a) Skin Friction:
   
   \[ Q_e = \pi \times 3.0 \times \left[ (20' - 6') (0.55 \times 1.033) + (20' - 3') (0.55 \times 1.9) \right] \]
   
   \[ = 9.4248 \times \left[ 7.9567 + 17.765 \right] \]
   
   \[ = 242.42 \text{ Tons} \]

   b) End Bearing:

   \[ Q_b = q_b \frac{b^2}{4}, \]

   \[ q_b = N_c C_u, \]
\[ N_e = 6.0 \times \left[ 1 + 0.2 \times \frac{40}{3} \right] = 22 > 9 \text{ (use 9)} \]

\[ Q_b = (9 \times 1.9 \text{tsf}) \frac{\pi \times 3^2}{4} = 120.87 \text{Tons} \]

c) Total Capacity = Skin Friction + End Bearing
\[ = 242.42 + 120.87 \]
\[ = 363.29 \text{Tons (ultimate)} \]

d) Calculation of Skin Friction:

![Graph showing calculation of skin friction]

\[ 1.0333 \times 0.55 = 0.568 \text{tsf} \]
\[ 1.9 \times 0.55 = 1.045 \text{tsf} \]

e) Settlement: S = (i) 0.3 " and (ii) S = 3.0 "

\[ Q_a = 242.42 T, \quad Q_b = 120.87 T, \quad Q_T = 363.24 T \]

(i)

\[ \frac{S \times 100}{D} = \frac{0.3 \times 100}{36} = 0.833 > 0.74, \quad q_{st} = 0.978929 - 0.115817(0.833 - 0.74) \times 242.42 = 234.70 \]

\[ \frac{q_{br}}{Q_b} = 1.1832E - 04 \times (0.833)^3 - 3.7091E - 03(0.833)^4 + 4.4944E - 02(0.833)^3 - 0.26537(0.833) \]
\[ 0.78436(0.833) \]
\[ = 0.4935 \times 120.87 = 59.65 T \]

\[ Q_T @ 0.3" = 234.70 + 59.65 = 294.35 T \]
(ii) \[ \frac{S \cdot 100}{D} = \frac{3.0 \cdot 100}{36} = 8.33 > 0.74, \quad q_w = 0.833 \cdot 242.42 = 201.93 \text{T} \]

\[ \frac{q_{br}}{Q_b} = 0.98 \cdot 120.87 = 118.45 \text{T} \]

\[ Q_r @ 3.0'' = 201.93 + 118.45 = 320.38 \text{ Tons} \]

2. Multi Layer Clay with Casing, but D > 75" (1.9m):
Example File: Clay2.dat

\[ \text{Casing} \]

\[ \begin{array}{c}
\text{N} = 8 \\
\gamma = 100 \text{ pcf} \\
q_c = 16 \text{ tsf}
\end{array} \]

\[ \begin{array}{c}
\text{N} = 12 \\
\gamma = 100 \text{ pcf} \\
q_c = 30 \text{ tsf}
\end{array} \]

a) Skin Friction: \[ Q_s = \pi \cdot 8.0 \cdot \left[ (20' - 6') \cdot (0.55 \cdot 1.033) + (20' - 8') \cdot (0.55 \cdot 1.9) \right] \]
\[ = 25.1327 \cdot [7.9567 + 12.5] \]
\[ = 515.14 \text{ Tons} \]

b) End Bearing: If D > 75", then \[ q_{br} = F_r, q_b \]

\[ F_r = \frac{2.5}{[a \cdot D_v \text{ (inches)} + 2.5 \cdot b]} \]

\[ a = 0.0071 + 0.0021 \left( \frac{L}{D_b} \right) \]
\[ = 0.0071 + 0.0021 \left( \frac{40'}{8'} \right) \]
\[ = 0.0176, \text{ but } a < 0.015 \]

\[ b = 0.45 \sqrt{C_u} = 0.45 \sqrt{1.9 \cdot 2.0} \quad , C_u \text{ in ksf} \]
\[ = 0.8772, \quad 0.5 < b < 1.5 \]
\[ F_r = \frac{2.5}{[0.015 (96^\circ) + 2.5 (0.8772)]} = 0.6881 \]

\[ Q_b = \frac{\pi \times 8^2}{4} (0.6881)(9 \times 1.9) = 591.48 \text{ Tons} \]
\[ Q_t = 515.14 + 591.48 = 1106.62 \text{ Tons} \]

e) Settlement: \( S = (i) 0.3^\circ \) and \( (ii) S = 3.0^\circ \)

\[ Q_s = 515.14^T, \ Q_b = 591.48^T, \ Q_t = 1106.62^T \]

(i)

\[ \frac{S}{D} \times 100 = \frac{0.3 \times 100}{96} = 0.3125 \]

\[ q_{st} = \left( \frac{100 \times S}{D} \right) \cdot \left( \frac{1}{0.095155 + 0.892937 \times \left[ \frac{100 \times S}{D} \right]} \right) \]

\[ q_{st} = (0.3125) \cdot \left( \frac{1}{0.095155 + 0.892937 \times [0.3125]} \right) \]

\[ \therefore q_{st} = 0.8325 \times 515.14 = 428.85^T \]

\[ \frac{q_{se}}{Q_s} = 1.1832E - 04 \times (0.3125)^3 - 3.7091E - 03(0.3125)^4 + 4.4944E - 02(0.3125)^3 - 0.26537(0.3125)^4 + 0.78436(0.3125)^5 \]
\[ = 0.2205 \times 591.48 = 130.44 \text{T} \]

\[ Q_{T@0.3^\circ} = 428.85 + 130.44 = 559.29 \text{Tons} \]

(ii)

\[ \frac{S}{D} \times 100 = \frac{3.0 \times 100}{96} = 3.125 \]

\[ q_{st} = 0.833, \therefore q_{st} = 0.833 \times 515.14 = 429.11^T \]

\[ \frac{q_{se}}{Q_s} = 1.1832E - 04 \times (3.125)^3 - 3.7091E - 03(3.125)^4 + 4.4944E - 02(3.125)^3 - 0.26537(3.125)^4 + 0.78436(3.125)^5 \]
\[ = 0.9127 \times 591.48 = 539.85 \text{T} \]

\[ Q_{T@3.0^\circ} = 429.11 + 539.85 = 986.96 \text{Tons} \]
SANDS:
Example file: Sand1.dat

<table>
<thead>
<tr>
<th>Depth</th>
<th>N</th>
<th>γ,pcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>100</td>
</tr>
</tbody>
</table>

1. Skin Friction:

\[
\beta = 1.5 - 0.135 \sqrt{z} \quad 0.25 < \beta \text{(tsf)} < 1.2
\]

or \(Z < 4.94\text{ft}, \beta = 1.2 \text{ tsf}, \) and \(Z > 85.73\text{ft}, \beta = 0.25\)

\[
\int_{6}^{40} \beta \sigma, dz = \int_{6}^{40} (150Z - 13.5Z^{3/2}) dZ = \frac{150Z^2}{2} - 13.5Z^{3/2} \times \frac{2}{5} \bigg|_{6}^{40} = 65,355.84 - 2,223.82 = 18,116.37 \times \frac{3\pi}{2000} = 297.50\text{T}
\]

2. End Bearing: above 8*D and below 3.5*D,

above: 40.0 - 8*D = 40.0 - 8*(3) = 16’ ;

below: 40.0 + 3.5*D = 40.0 + 3.5*(3) = 50.5’

for \(z = 16’\) \(q_b = 0.6*N = 0.6*(10) = 6\text{ tsf}\)

\(z = 20’ \quad q_b = 0.6*N = 0.6*(10) = 6\text{ tsf}\)

\(z = 25’ \quad q_b = 0.6*N = 0.6*(15) = 9\text{ tsf}\)

\(z = 60’ \quad q_b = 0.6*N = 0.6*(15) = 9\text{ tsf}\)
\[
q_b = \left[ \frac{6 \cdot (20 - 16) + 9 + 6 \cdot (25 - 20) + 9 \cdot (50.5 - 25)}{2 \cdot 50.5 - 16} \right] = 8.4348
\]

So,
\[
Q_b = 8.4348 \cdot \left[ \frac{\pi \cdot 3^2}{4} \right] = 59.622^T
\]

\[
Q_T = 297.5 + 59.62 = 357.12
\]

2. Check settlements: (a) \(S = 0.3''\) and (b) \(S = 1.44''\)

\[
R = S \cdot \frac{100}{D} = 0.3 \cdot 100 / 36 = 0.833 \quad \& \quad R = S \cdot \frac{100}{D} = 1.44 \cdot 100 / 36 = 4.00
\]

a. For \(R = 0.833\)

\[
\frac{q_{at}}{Q_s} = -2.16 \cdot R^4 + 6.34 \cdot R^3 - 7.36 \cdot R^2 + 4.15 \cdot R
\]

\[
= -2.16 \cdot (0.833)^4 + 6.34 \cdot (0.833)^3 - 7.36 \cdot (0.833)^2 + 4.15 \cdot (0.833)
\]

\[
= 0.9745
\]

\[
Q_s = 297.5 \cdot 0.9745 = 289.91^T
\]

\[
\frac{q_{bt}}{Q_b} = -0.0001079 \cdot (0.833)^4 + 0.0035584 \cdot (0.833)^3 - 0.045115 \cdot (0.833)^2 + 0.34861 \cdot (0.833)
\]

\[
= 0.2796
\]

\[
\therefore Q_b = 0.2796 \cdot 59.62 = 16.67^T
\]

b. For \(R = 4.00\)

\[
\frac{q_{at}}{Q_s} = 0.978112
\]

\[
Q_s = 297.5 \cdot 0.978112
\]

\[
= 290.99^T
\]

\[
\frac{q_{bt}}{Q_b} = -0.0001079 \cdot (4.00)^4 + 0.0035584 \cdot (4.00)^3 - 0.045115 \cdot (4.00)^2 + 0.34861 \cdot (4.00)
\]

\[
= 0.8727
\]

\[
\therefore Q_b = 0.8727 \cdot 59.62 = 52.03^T
\]
MULTILAYER- SAND-CLAY-SAND:
Example File: Sand_c.dat

<table>
<thead>
<tr>
<th>Depth</th>
<th>N</th>
<th>γ,pcf</th>
<th>C_u, tsf</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>1.90</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td>1.90</td>
</tr>
<tr>
<td>40</td>
<td>15</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>15</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

1. Skin Friction (6-20ft): \( Q_s = \frac{3\pi}{2000} \int_{6}^{20} (1.5 - 0.135\sqrt{z}) \gamma \ z \ dz \)

\[
= 0.0047 \left[ \frac{150 \cdot z^2}{2} - 13.5 \cdot z^{5/2} \cdot \frac{5}{2} \right]_{6}^{20}
\]

\[
= 0.0047 \left[ 75 \cdot (20^2 - 6^2) - 5.4 \cdot (20^{5/2} - 6^{5/2}) \right]
\]

\[
= 0.0047[27,300-9,183.6]
\]

\[
= 85.371^T
\]

2. Skin Friction (20-40ft): \( Q_s = 3\pi \left[ (40 - 20)(0.55 \cdot 1.9) \right] \)

\[
= 196.978^T
\]

3. Skin Friction (40-60ft): \( Q_s = \frac{3\pi}{2000} \int_{40}^{60} (1.5 - 0.135\sqrt{z}) \gamma \ z \ dz \)

\[
= 0.0047 \left[ \frac{150 \cdot z^2}{2} - 13.5 \cdot z^{5/2} \cdot \frac{5}{2} \right]_{40}^{60}
\]

\[
= 0.0047 \left[ 75 \cdot (60^2 - 40^2) - 5.4 \cdot (60^{5/2} - 40^{5/2}) \right]
\]

\[
= 0.0047[150,000-95,937.4]
\]

\[
= 254.764^T
\]
\[ \Sigma Q_s = 85.371 + 196.978 + 254.764 = 537.11 \text{ tons} \]

4. Tip Resistance: above 8*D and below 3.5*D,

Above: 60.0 - 8*D = 60.0 - 8*(3) = 36 ft
Below: 60.0 + 3.5*D = 60.0 + 3.5*(3) = 70.5 ft

For \( z = 40 \text{ ft} \)
\[ q_b = 0.6*N = 0.6*(15) = 9 \text{ tsf} \]

\( z = 60 \text{ ft} \)
\[ q_b = 0.6*N = 0.6*(15) = 9 \text{ tsf} \]

\( z = 75 \text{ ft} \)
\[ q_b = 0.6*N = 0.6*(15) = 9 \text{ tsf} \]

So,
\[ Q_b = \left[ \frac{\pi.3^2}{4} \right] * 9 = 63.62^T \]

Check \( q_b \) of overlaying Clay:
\[ q_b = 9*C_u = 9*1.9 = 17.1 \text{ tsf longer, \therefore stop @ 40ft.} \]

5. Settlement: (a) \( S = 0.3 \) inches

\[ R = S*100/D = 0.3*100/36 = 0.833 \]

Sand (0-20 ft): \( q_s / Q_s = -2.16*R^4 + 6.34*R^3 - 7.36*R^2 + 4.15*R \)
\[ = -2.16*(0.833)^4 + 6.34*(0.833)^3 - 7.36*(0.833)^2 + 4.15*(0.833) \]
\[ = 0.9745 \]
\[ q_s = 0.9745 * 85.371 \]
\[ = 83.197^T \]

Clay (20-40 ft): \( q_s = 0.978929 - 0.115817(R - 0.74) \)
\[ q_s = 0.978929 - 0.115817(0.833 - 0.74) * 196.978 = 190.706^T \]

Sand (40-60 ft): \( q_s = 0.9745 * 255.117 \)
\[ = 248.611^T \]
\[ q_s / Q_s = -0.0001079*(.833)^4 + 0.0035584*(.833)^3 - 0.045115*(.833)^2 + 0.34861*(.833) \]
\[ = 0.2796 \]
\[ Q_b = 0.2796 \times 63.617 = 17.787^T \]

\[ \therefore \text{When } S = 0.3 \text{ inches,} \]
\[ Q_s = 83.197 + 190.706 + 248.611 = 522.51 + Q_t = 17.787^T \]
\[ = 540.29 \text{ tons.} \]
IGM: (Sand & Limestone)
File: IGM_S.dat

Casing

\[ \gamma = 100 \text{pcf (15.708 kN/m}^3) \]
\[ N = 10 \]

LimeStone:
\[ q_u = 10 \text{ tsf (95.76 kPa, 0.96 Mpa)} \]
\[ q_c = 1 \text{ tsf (95.76 kPa, 0.096 Mpa)} \]
\[ \gamma = 135 \text{ pcf (21.2 kN/m}^3), \quad \gamma_c = 20.4 \text{ kN/m}^3 \]
\[ E_c = 57,000, \sqrt{f_y} = 57,000, \sqrt{5000 \text{ psi}} \]
\[ = 4.03E6 \text{ psi (27.77E6 kPa)} \]

Because of unit comparison problems, calculate Sand using English and Rock using SI units.

1. Skin Friction (Sand):
\[ Q_s = \frac{3.28 \times \pi}{2000} \int_{0}^{20} \left(1.5 - 0.135 \sqrt{z}\right) \gamma z \ dz \]
\[ = \frac{3.28 \times \pi}{2000} \left[ \frac{150 * z^2}{2} - 13.5 * z^{5/2} * \frac{5}{2} \right]_{0}^{20} \]
\[ = \frac{3.28 \times \pi}{2000} \left[ 75 \times (20^2 - 6.56^2) - 5.4 \times (20^{5/2} - 6.56^{5/2}) \right] \]
\[ = 0.00515[26,772.5-9064.6] \]
\[ = 91.23^1 = 91.23 \times 2000/224.809 = 811.66 \text{ kN} \]

3. Analysis of Rock resistance has 2 design methodologies:

(a) UF method: Skin Friction defined as

(1) Williams \[ f_{su} = 1.842 q_u^{0.367} \]

(2) McVay \[ f_w (tsf) = \frac{1}{2} \sqrt{q_u \sqrt{q_t}} \]

(3) User defined.

and Tip resistance is user defined, typically \[ q_b = q_u / 2. \] No settlements can be calculated using this method.

(b) O’Neill (FHWA) intermediary geo-materials method, this method is deformation based.
4. UF method (Rock): (Note: Must enter values for $q_u$ and $q_l$)

$$Q_s = \pi \ d \ L \ f_{su} = \pi \ (1m) \ (3.05m) \ (0.5 \sqrt{95.76} \sqrt{95.76}) = 1450.79 \ kN$$

$$\Sigma Q_s = 811.66 + 1450.79 = 2262.45 \ kPa$$

Assuming $q_b = \frac{1}{2} q_u : Q_l = \frac{\pi (l)^3}{4} (0.5 \times 957.6) = 376kN$

Then, $Q_s + Q_l = 2638.45kN$

5. O'Neill IGM: (Note: Must enter values for $E_c$, slump, $E_m/E_l$, $E_m$, and IGM_Type = 2)

- a. $E_m = 115 \ q_u = 115 \ (0.96 \ MPa) = 110.4 \ MPa.$

- b. $\Omega = 1.14 \left(\frac{L}{D}\right)^{1/2} - 0.05 \left(\frac{L}{D}\right)^{1/2} \ - 1 \log\left(\frac{E_c}{E_m}\right) - 0.44$

$$\Omega = 1.14(3.05)^{1/2} - 0.05(3.05^{1/2} - 1) \log\left(\frac{27.777}{110.4}\right) - 0.44 = 1.46$$

- c. $\Gamma = 0.37 \left(\frac{L}{D}\right)^{1/2} - 0.15 \left(\frac{L}{D}\right)^{1/2} - 1 \log\left(\frac{E_c}{E_m}\right) + 0.13$

$$\Gamma = 0.37(3.05)^{1/2} - 0.15(3.05^{1/2} - 1) \log\left(\frac{27.777}{110.4}\right) + 0.13 = 0.507$$

- d. $\frac{\theta}{w} = \frac{E_m \Omega}{\pi \ L \ \Gamma f_{su}}; \ f_{su} = \frac{1}{2} \sqrt{q_u \sqrt{q_l}}$

$$\frac{110.4 \times 1.46}{\pi \times 3.05 \times 0.507 \times (\frac{1}{2} \sqrt{0.96} \sqrt{0.96})} = \frac{161.18}{0.7374} = 218.586 / m$$

- e. $\Lambda = 0.0134 \ E_m \left(\frac{h}{D}\right) \left(\frac{200}{\sqrt{D} - \Omega} \left[1 + \frac{h}{D}\right]\right)^{0.67} \ \left(\frac{\pi L \Gamma}{\pi L \Gamma}\right)$

$$\Lambda = 0.0134 \ (110.4 \ MPa) \left(\frac{3.05}{4.05}\right) \left(\frac{200}{\sqrt{3.05} - 1.46} \left[1 + 3.05\right]\right)^{0.67}$$

$$= 1.141(4.7757)^{0.67}$$

$$= 3.159 \ MPa \ m^{-0.67}$$
\[ \Lambda = (1114.1 \text{ kPa}) \left( \frac{200 \left[ \sqrt{3.05} - 1.46 \right] [1 + 3.05]}{\pi \times 3050 \times 0.507} \right)^{0.67} \]

\[ = 1.1141[0.1316] \]

\[ = 146.65 \text{ kPa mm}^{0.67} \]

d. Determine \( n \) for deformation criteria Fig 36 \[
\frac{q_u}{\sigma_p} = \frac{957.6 \text{ kPa}}{100} = 9.576
\]

\[
\frac{E_n}{\sigma_n} ; \quad \sigma_n = M \gamma_c Z_c ; \quad \text{Since} \quad Z_c = 6.1 + \frac{3.05}{2} = 7.625m \quad (\text{use} \ 8m)
\]

For a slump = 175 mm, \( M(Fig 3.5) = 0.78 \)

\[
\therefore \sigma_n = 0.78 * 20.4 * 7.625 = 121.33 \text{ kPa}
\]

\[
\therefore \frac{E_n}{\sigma_n} = \frac{110,400}{121.33} = 909.9 \quad \therefore \ n \approx 0.42
\]

g. Select values of 'w' for calculating

\[
Q_i = \pi D L \theta f_{uw} + \frac{\pi D^2}{4} q_b \quad \text{for} \quad \theta < n ; \quad q_b = \Lambda w^{0.67}
\]

\[
Q_i = \pi D L k f_{uw} + \frac{\pi D^2}{4} q_b \quad \text{for} \quad \theta > n
\]

1) Let \( w = 2 \text{ mm} ; \quad \theta / w = 218.586, \)

\[
\therefore \theta = 218.586 \times 0.002m = 0.437 < n = 0.45
\]

\[
Q_i = \pi \times 1 \times 3.05 \times 0.437 \times (151.4 \text{ kPa}) + \frac{\pi \times 1^2}{4} \times 146.65 \times 2^{0.67}
\]

\[
= 634 + 182.8
\]

\[
= 816.7 \text{ kPa}
\]

2) Let \( w = 5 \text{ mm} ; \quad \theta / w = 218.586, \)

\[
\therefore \theta = 218.586 \times 0.005m = 1.093 > n = 0.45
\]

\[
k = n + \frac{(\theta - n)(1 - n)}{(\theta - 2n + 1)} = 0.45 + \frac{(1.093 - 0.45)(1 - 0.45)}{(1.093 - 2(0.45) + 1)} = 0.7706
\]
\[ Q_t = \pi \times 1 \times 3.05 \times 0.77 \times (151.4 \text{ kPa}) + \frac{\pi \times 1^2}{4} \times 146.65 \times 5^{0.67} \]

\[ = 1118 + 336.8 \]

\[ = 1455 \text{ kPa} \]

h. Now go back and calculate sand capacity using trend lines when \( w = 2 \text{mm} \) and \( 5 \text{mm} \).

1. \( R = (s*100/D); \)

\[
\text{@ 2mm } R = (0.2\text{cm}*100/100\text{cm}) = 0.2
\]

\[
\text{@ 5mm } R = (0.5\text{cm}*100/100\text{cm}) = 0.5
\]

2. \( q_a / Q_s = -2.16*R^4 + 6.34*R^3 - 7.36*R^2 + 4.15*R \)

\[
= -2.16*(0.2)^4 + 6.34*(0.2)^3 - 7.36*(0.2)^2 + 4.15*(0.2)
\]

\[
= 0.5829 \text{ for } w = 2\text{mm}
\]

\( q_s = 0.5829 \times (811.66 \text{ kN}) \)

\[ = 473.1 \text{ kN} \text{ for } 2 \text{ mm} \]

\( q_a / Q_s = -2.16*R^4 + 6.34*R^3 - 7.36*R^2 + 4.15*R \)

\[
= -2.16*(0.5)^4 + 6.34*(0.5)^3 - 7.36*(0.5)^2 + 4.15*(0.5)
\]

\[
= 0.892 \text{ for } w = 5\text{mm}
\]

3. \( q_s = 0.892 \times (811.66 \text{ kN}) \)

\[ = 724.4 \text{ kN} \text{ for } 5 \text{ mm} \]

i. Total Shaft Capacity (Sand + Rock)

1) @ 2mm \( Q_T = 473.1 \text{ kN} + 634 \text{ kN} + 182.8 \text{ kN} = 1289.9 \text{ kN} \)

2) @ 5mm \( Q_T = 724.4 \text{ kN} + 1118 \text{ kN} + 336.8 \text{ kN} = 2179.2 \text{ kN} \)
IGM: (Sand, Clay & Limestone)

File: S_C_LIMEROCK.DAT

\[ \gamma = 100 \text{pcf (15.708 kN/m}^3) \]
\[ N = 10 \]
\[ \gamma = 100 \text{pcf (15.708 kN/m}^3) \]
\[ c = 1.9 \text{tsf (181.94 kPa)} \]

Limestone:
\[ q_u = 10 \text{tsf (957.6 kPa, 0.96 Mpa)} \]
\[ q_t = 1 \text{tsf (95.76 kPa, 0.096 Mpa)} \]
\[ \gamma = 135 \text{pcf (212 kN/m}^3), \quad \gamma_c = 20.4 \text{kN/m}^3 \]
\[ E_c = 57,000, \sqrt{f_w} = 57,000, \sqrt{5000 \text{psi}} \]
\[ = 4.03E6 \text{psi (27.77E6 kPa)} \]
\[ f_w = \frac{1}{2} \sqrt{q_u \sqrt{q_t}} = 151.41 \text{kPa} \]
Smooth socket IGM_type = 2.0

1. Skin Friction (Sand):
\[ Q_s = \frac{3.28 * \pi}{2000} \int_{6.56}^{20} (1.5 - 0.135\sqrt{z}) \gamma z \, dz \]
\[ = \frac{3.28 * \pi}{2000} \left[ \frac{150 * x^2}{2} - 13.5 * z^{5/2} * \frac{5}{2} \right]_{6.56}^{20} \]
\[ = \frac{3.28 * \pi}{2000} \left[ 75 * (20^2 - 6.56^2) - 5.4 * (20^{5/2} - 6.56^{5/2}) \right] \]
\[ = 0.00515[26,772.5-9064.6] \]
\[ = 91.23^T = 91.23*2000/224.809 = 811.66 \text{kN} \]

2. Skin Friction (Clay):
\[ Q_s = \pi D L \alpha C_u = \pi (1) (3.05) (0.55*181.94) \]
\[ = 958.85 \text{ kN (107.78}^T) \]

3. Skin Friction (Rock):
(Note: UF method needs \( q_u \) and \( q_t \))
\[ Q_s = \pi D L f_w = \pi (1) (3.05) (151.41 \text{kPa}) \]
\[ = 1450.8 \text{ kN (163.075}^T) \]
4. End Bearing (Rock):

\[ Q_b = \frac{\pi}{4} d^2 q_b; \quad \text{Let} \quad q_b = 0.5 \ q_u \]
\[ = \pi *(1)*(0.25)*(0.5*957.6 \ \text{kPa}) \]
\[ = 376.05 \ \text{kN} \ (42.27^\circ) \]

5. Summary: \[ Q_T = 811.66 + 958.85 + 376.05 = 3,597.4 \ \text{kN} \ (404.36^\circ) \]

No settlement in this method.

2. FHWA IGM Calculations: (Note: Must enter values for \( E_c \), slump, \( E_m/E_t \), \( E_m \), and IGM_Type = 2)

a. \( E_m = 115 \ q_u = 115 \ (957.6 \ \text{kPa}) = 110.4 \ \text{MPa} \).

b. \( \Omega = 1.14 \left( \frac{L}{D} \right)^{1/2} - 0.05 \left( \left( \frac{L}{D} \right)^{1/2} - 1 \right) \log \left( \frac{E_c}{E_m} \right) - 0.44 \)
\[ \Omega = 1.14(3.05)^{1/2} - 0.05(3.05^{1/2} - 1)\log\left(\frac{27,777}{110.4}\right) - 0.44 = 1.46 \]

c. \( \Gamma = 0.37 \left( \frac{L}{D} \right)^{1/2} - 0.15 \left( \left( \frac{L}{D} \right)^{1/2} - 1 \right) \log \left( \frac{E_c}{E_m} \right) + 0.13 \)
\[ \Gamma = 0.37(3.05)^{1/2} - 0.15(3.05^{1/2} - 1)\log\left(\frac{27,777}{110.4}\right) + 0.13 = 0.507 \]

d. \[ \frac{\theta}{w} = \frac{E_m \Omega}{\pi \ L \ \Gamma \ f_{sw}} \; \quad f_{sw} = \frac{1}{2} \sqrt{q_u} \sqrt{q_t} \]
\[ = \frac{110.4*1.46}{\pi \ * 3.05 * 0.507 * (\frac{1}{2} * 0.151 \text{MPa})} = \frac{161.18}{0.7336} = 219.73 / \text{m} \]

e. \[ \Lambda = 0.0134 \ E_m \left( \frac{\sqrt{b}}{\sqrt{D} + 1} \right) \left\{ \frac{200 \left[ \sqrt{b} - \Omega \right] \left[ 1 + \frac{b}{D} \right]}{\pi \ L \ \Gamma} \right\}^{0.67} \]
\[ \Lambda = 0.0134 \times (110,112.5 \text{kPa})^{3.05} \left( \frac{4.05}{200} \left( \frac{\sqrt{3.05} - 1.46}{\pi \times 3050 \times 0.507} \right) \right)^{0.67} = 146.27 \text{kPa mm}^{-0.67} \]

f. Determine \( n \) for deformation criteria Fig 36
\[ \frac{q_b}{\sigma_p} = \frac{957.6 \text{kPa}}{100} = 9.576 \]

\[ \frac{E_m}{\sigma_n} \quad \sigma_n = M \gamma_c Z_c; \quad \text{Since} \quad Z_c = 6.1 + 3.05 + \frac{3.05}{2} = 10.675m \]

For a slump = 175 mm, \( M(\text{Fig}3.5) = 0.68 \)
\[ \therefore \sigma_n = 0.68 \times 20.4 \times 10.675 = 148.1 \text{kPa} \]
\[ \therefore \frac{E_m}{\sigma_n} = \frac{110,112.5}{148.1} = 743.6 \quad \therefore n \approx 0.4 < n = 0.45 \]

g. Select values of \('w'\) for calculating

\[ Q_t = \pi D L \theta f_{sw} + \frac{\pi D^2}{4} q_b \quad \text{for} \quad \theta < n; \quad q_b = \Lambda w^{0.67} \]
\[ Q_t = \pi D L k f_{sw} + \frac{\pi D^2}{4} q_b \quad \text{for} \quad \theta > n \]

1) Let \( w = 2 \text{ mm}; \quad \theta / w = 219.73 \text{ m}^{-1}, \)
\[ \therefore \theta = 219.73 \times 0.002m = 0.439 < n = 0.45 \]
\[ Q_t = \pi \times 1 \times 3.05 \times 0.439 \times (151.4 \text{ kPa}) + \frac{\pi \times 1^2}{4} \times 146.27 \times 2^{0.67} \]
\[ = 636.85 + 182.8 \]
\[ = 819.2 \text{ kPa} \]

2) Let \( w = 5 \text{ mm}; \quad \theta / w = 219.73 \text{ m}^{-1}, \)
\[ \therefore \theta = 219.73 \times 0.005m = 1.099 > n = 0.45 \]
\[ k = n + \frac{(\theta - n)(1-n)}{(\theta - 2n + 1)} = 0.45 + \frac{(1.099 - 0.45)(1 - 0.45)}{(1.099 - 2(0.45) + 1)} = 0.75 \]
\[ Q_i = \pi \cdot 1 \cdot 3.05 \cdot 0.75 \cdot (151.4 \text{ kPa}) + \frac{\pi \cdot 1^2}{4} \cdot 146.27 \cdot 5^{0.67} \]

\[ = 1084.6 + 335.9 \]

\[ = 1420.5 \text{ kPa} \]

h. Now go back and calculate sand capacity using trend lines when w = 2mm and 5mm.

1. \[ R = (s \cdot 100/D); \]

@ 2mm \[ R = (0.2 \text{cm} \cdot 100/100 \text{cm}) = 0.2 \text{, and} \]

@ 5mm \[ R = (0.5 \text{cm} \cdot 100/100 \text{cm}) = 0.5 \]

2. \[ q_{st} / Q_s = -2.16 \cdot R^4 + 6.34 \cdot R^3 - 7.36 \cdot R^2 + 4.15 \cdot R \]

\[ = -2.16 \cdot (0.2)^4 + 6.34 \cdot (0.2)^3 - 7.36 \cdot (0.2)^2 + 4.15 \cdot (0.2) \]

\[ = 0.5829 \text{ for } w = 2 \text{mm} \]

3. \[ q_s = 0.5829 \cdot (811.66 \text{ kN}) \]

\[ = 473.1 \text{ kN} \text{ for } 2 \text{ mm} \]

2. \[ q_{st} / Q_s = -2.16 \cdot R^4 + 6.34 \cdot R^3 - 7.36 \cdot R^2 + 4.15 \cdot R \]

\[ = -2.16 \cdot (0.5)^4 + 6.34 \cdot (0.5)^3 - 7.36 \cdot (0.5)^2 + 4.15 \cdot (0.5) \]

\[ = 0.892 \text{ for } w = 5 \text{mm} \]

3. \[ q_s = 0.892 \cdot (811.66 \text{ kN}) \]

\[ = 724.4 \text{ kN} \text{ for } 5 \text{ mm} \]

4. Clay: \[ R = s \cdot 100/D; \text{ @ 2 mm } R = 0.2 \text{ & 0.5 @ 5 mm } 0.12 < R < 0.74 \]

\[ q_{st} = \frac{R}{Q_s} = \frac{0.2}{0.095155 + 0.892937 \cdot R} = 0.731 \]

\[ = \frac{0.5}{0.5416} = 0.9232 \]

\[ q_s = 0.7310 \cdot 958.85 = 700.55 \text{ kN} \text{ @ 2 mm} \]

\[ q_s = 0.9232 \cdot 958.85 = 885.16 \text{ kN} \text{ @ 5 mm} \]
1. Total Shaft Capacity (Sand + Rock)

1) @ 2mm \( Q_T = 473.1 \text{ kN} + 700.5 \text{ kN} + 636.85 \text{ kN} + 182.4 = 1992.8 \text{ kN} \)

2) @ 5mm \( Q_T = 724.4 \text{ kN} + 885.16 \text{ kN} + 1084.6 \text{ kN} + 335.9 \text{ kN} = 3030.1 \text{ kN} \)

**IGM: (Sand & Limestone)** Consider “Rough” Socket:

\[
\gamma = 100 \text{ pcf (15.708 kN/m}^3) \\
N = 10
\]

Limestone:
\[
q_u = 10 \text{ tsf (957.6 kPa, 0.96 Mpa)} \\
q_s = 1 \text{ tsf (95.76 kPa, 0.096 Mpa)} \\
\gamma = 135 \text{ pcf (21.2 kN/m}^3), \quad \gamma_e = 20.4 \text{ kN/m}^3
\]

\[
E_c = 57,000 \sqrt{f_y} = 57,000 \sqrt{5000 \text{ psi}} = 4.03E6 \text{ psi (27.77E6 kPa)}
\]

\[
f_{su} = \frac{1}{2} \left( q_u + q_s \right) = 151.41 \text{ kPa}
\]

1. From Previous Example,

a) Skin Friction (Sand): \( Q_s = \frac{3.28 * \pi}{2000} \int_0^{20} \left( 1.5 - 0.135 \sqrt{z} \right) \gamma z \text{ dz} \)

\[
= \frac{3.28 * \pi}{2000} \left[ \frac{150 * z^2}{2} - 13.5 * z^{5/2} * \frac{5}{2} \right]_0^{20}
\]

\[
= \frac{3.28 * \pi}{2000} \left[ 75 * (20^2 - 6.56^2) - 5.4 * (20^{5/2} - 6.56^{5/2}) \right] = 0.00515[26,772.5-9064.6] = 91.23 \text{ kN}
\]

2. O’Neill (FHWA) Rock - Rough Socket: (Note: Must enter values for \( E_c \), slump, \( E_m/E_l \), \( E_m \), and IGM_Type = 1.0)

a) If “Rough” \( n = \sigma_n / q_u \)
\[ \sigma_n = M \gamma_c Z_c; \quad \text{Since} \quad Z_c = 6.1 + \frac{3.05}{2} = 7.625 m \quad (\text{use} \ 8m) \]

For a slump = 175 mm, \( M(\text{Fig} \ 3.5) = 0.78 \)

\[ : \sigma_n = 0.78 \times 20.4 \times 7.625 = 121.33 \ kPa \]

b) \( n = \frac{\sigma_n}{q_u} = \frac{121.33}{95.76} = 0.13 \)

c) \[
Q_t = \pi D L \theta f_{sw} + \frac{\pi D^2}{4} q_b \quad \text{for} \quad \theta < n; \quad q_b = \Lambda w^{0.67} \\
Q_t = \pi D L k f_{sw} + \frac{\pi D^2}{4} q_b \quad \text{for} \quad \theta > n
\]

d) \( \theta / w = 218.586 \ m^{-1} \)

e) Let \( w = 2 \ mm; \quad : \theta = 218.586 \times 0.002m = 0.437 > n = 0.13 \)

\[ k = n + \frac{(\theta - n)(1 - n)}{(\theta - 2n + 1)} = 0.13 + \frac{(0.437 - 0.13)(1 - 0.13)}{(0.437 - 2(0.13) + 1)} = 0.356 \]

\[ Q_t = \pi \times 1 \times 3.05 \times 0.356 \times (151.4 \ kPa) + \frac{\pi \times 1^2}{4} \times 146.65 \times 2^{0.67} \]

\[ = 516.48 + 182.83 \]

\[ = 699.3 \ kPa \]

f) Calculate sand capacity using trend lines when \( w = 2 \ mm \)

1. \( R = (s \times 100/D); \ @ 2 \ mm \ R = (0.2 \ cm \times 100/100 \ cm) = 0.2 \)

2. \( q_{st} / Q_s = -2.16 \times R^4 + 6.34 \times R^3 - 7.36 \times R^2 + 4.15 \times R \)

\[ = -2.16 \times (0.2)^4 + 6.34 \times (0.2)^3 - 7.36 \times (0.2)^2 + 4.15 \times (0.2) \]

\[ = 0.5829 \ \text{for} \ w = 2 \ mm \]

3. \( q_s = 0.5829 \times (811.66 \ kN) \)

\[ = 473.1 \ kN \ \text{for} \ 2 \ mm \]

g) \( \Sigma Q = 473.1 + 516.48 + 182.83 = 1172.4 \)