PennDOT e-Notification
Bureau of Business Solutions and Services
Highway/Engineering Applications Division

pennsylvania
DEPARTMENT OF TRANSPORTATION

ABLRFD
No. 018
December 1, 2014

Bearing Resistance of Spread Footing on Two Sand Layers

An issue has been discovered in ABLRFD (LRFD Abutment and Retaining Wall Analysis and Design) v1.13.0.1 and earlier versions that may result in an overestimated soil bearing resistance for a spread footing on two sand layers (Soil Category 4) specifically for Soil Conditions 6 and 7. The program does not properly account for the contribution of the second soil layer to the overall bearing resistance for these soil conditions.

For **Soil Category 4, Soil Condition 6** (Dense Sand layer over Loose Sand layer):

ABLRFD incorrectly calculates the bearing resistance of soil layer 2 (q_{ult2}).

Currently, ABLRFD uses the following equation to calculate the bearing resistance of soil layer 2 (q_{ult2}):

$$\gamma'_1 = \gamma_{isat1} - \gamma_w$$

If L' ≤ 5*B' the following equation is used to calculate bearing

$$q_{ult2} = q_{ult1} + \left(1 + \frac{B'}{L'}\right)\gamma'_1 (H_1)^2 \left(1 + \frac{2D_f}{H_1}\right)\frac{K_s \tan(\phi_{if1})}{B'} - \gamma'_1 H_1 \quad \text{(Das 11.46)}$$

If L' >5*B' then the following equation is used instead

$$q_{ult2} = q_{ult1} + \gamma'_1 (H_1)^2 \left(1 + \frac{2D_f}{H_1}\right)\frac{K_s \tan(\phi_{if1})}{B'} - \gamma'_1 H_1 \quad \text{(Das 11.44)}$$

Then if $q_{ult1} > q_{ult2}$

$q_{ult} = q_{ult2}$

If $q_{ult1} \leq q_{ult2}$

$q_{ult} = q_{ult1}$

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ABLRFD mistakenly takes the final bearing resistance (q_{ult}) as the maximum bearing resistance of the two layers (q_{ult1} and q_{ult2}) when the final bearing resistance (q_{ult}) should be the minimum of q_{ult1} and q_{ult2} equations above.

However, it has been determined that the equations listed above as 11.46 and 11.44 are being used incorrectly. These equations should be used to calculate the ultimate overall bearing resistance of the soil (q_{ult}), not q_{ult2}. The bearing resistance for soil layer 2 (q_{ult2}) must be calculated as a single soil layer, and then used in the calculation for q_{ult}. The correct calculations are shown below:

The following equation is used to calculate q_{ult2}.

$$\phi_f = \phi_{if2}$$

$$\gamma_m = \gamma_{im2}$$

$$\gamma_{sat} = \gamma_{isat2}$$

The γ_2, $N\gamma_2$, $S\gamma_2$, $i\gamma_2$, N_{q2}, S_{q2} and i_q are computed following procedures in Section 3.4.1.4.2.1.

$$q_{ult2} = 0.5\gamma_2 B' N_{\gamma 2} s_{\gamma 2} i_{\gamma 2} + \gamma_{1f} D_{f2} N_{q2} s_{q2} i_{q2} \qquad \text{(DAS 11.48)}$$

If L' >5*B' then the following equation is used to calculate bearing resistance

$$q_{ult} = q_{ult2} + \gamma_1'(H_1)^2\left(1+\frac{2D_f}{H_1}\right)\frac{K_s \tan(\phi_{if1})}{B'} - \gamma_1' H_1 \leq q_{ult1} \qquad \text{(DAS 11.44)}$$

If L' ≤ 5*B' the following equation is used to calculate bearing resistance

$$q_{ult} = q_{ult2} + \left(1+\frac{B'}{L'}\right)\gamma_1'(H_1)^2\left(1+\frac{2D_f}{H_1}\right)\frac{K_s \tan(\phi_{if1})}{B'} - \gamma_1' H_1 \leq q_{ult1} \qquad \text{(DAS 11.46)}$$

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For **Soil Category 4, Soil Condition 7** (Loose Sand layer over Dense Sand layer):

Currently, ABLRFD uses the following equation to calculate q_{ult2} for Soil Condition 7.

$$q_{ult2} = 0.5\gamma_2 B' N_{\gamma 2} s_{\gamma 2} i_{\gamma 2} + \gamma_2 D_{f2} N_{q2} s_{q2} i_{q2}$$

This equation does not correctly account for the overburden from soil layer 1.

The equation should be:

$$q_{ult2} = 0.5\gamma_2 B' N_{\gamma 2} s_{\gamma 2} i_{\gamma 2} + \gamma_{1f} D_{f1} N_{q2} s_{q2} i_{q2}$$

This equation is derived from DAS equation 11.55 except the unit weight of the top layer is used to determine the overburden.

The **DAS** references in the equations above refer to *Das, B. M., Principals of Geotechnical Engineering 3rd edition, PWS Publishing, Boston, MA, 1994.*

These corrections will be made in the next release of ABLRFD. Until then, hand calculations may be required to verify the bearing resistance for a spread footing on for Soil Category 4 with Soil Conditions 6 and 7. Attached are revised ABLRFD User Manual pages showing the corrected methodology for Soil Conditions 6 and 7.

Please direct any questions concerning the above to:

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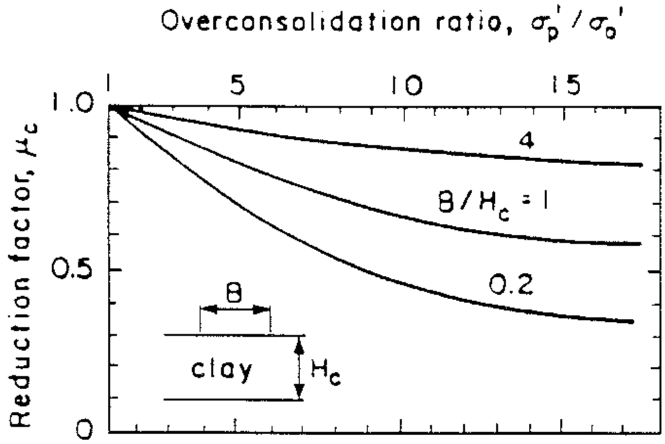
Attachment



A10.6.2.4.3-3

Figure 3.4.1.3.2-2 Consolidation Settlement Reduction Factor

$$S_{c1} = S_{c1}\mu_c$$

If the total settlement is less than zero, the program will provide a secondary calculation for total settlement which combines the elastic and secondary settlement values for the total settlement.

$$S_{t1} = S_e + S_c + S_s$$

$$S_{t2} = S_e + S_s$$

3.4.1.3.3 Secondary Settlement of Clays (and C-φ Soils)

The secondary settlement is calculated using the same sublayers as for the consolidation settlement. The secondary settlement (Ss) is equal to the sum of the secondary settlement (Ss_i) for each sublayer. This settlement starts at the end of primary consolidation settlement.

$$Ss = \sum_{i=1}^{nsub} Ss_i$$

The secondary settlement is a function of the: coefficient of secondary compression (C_α); the time interval (t_2, t_1) for which the settlement is being computed; and, the thickness of the sub-layer. The Coefficient of Secondary Compression used by the program is based on the Strain definition:

$$Ss_i = \Delta h\left[C_\alpha \log \frac{t_2}{t_1}\right]$$

3.4.1.3.4 Allowable Settlement

The acceptable total settlement is set by the program to a default value of 1 inch. The user may override this value (See the SOI and RCK commands in Chapter 5). However, a warning message is still issued if the total settlement exceeds the program default value of allowable settlement.

3.4.1.4 Bearing Capacity Check

The bearing capacity check consists of comparing the factored bearing resistance of the soil (or rock) foundation to the factored applied loads at the bottom of footing level. The check is evaluated for all applicable limit states / stages / load cases. The applied pressure due to the factored applied loads depends on several factors and is described in Section 3.4.1.4.3.

3.4.1.4.1 Bearing Capacity of Rock Foundations

The user is responsible for specifying the bearing capacity of rock foundations. The capacity is specified using the RCK command in Chapter 5.

3.4.1.4.2 Bearing Capacity of Clay and Sand Foundations

The bearing capacity of soft soils is not computed. The definition of a soft soil can be found in Section 3.4.1.3 (discussion of settlement).

The factored bearing capacity of the soil is the lesser value of ϕq_{ult} and [(0.7)(0.85)(f'_c)]. For multi-layer soils, q_{ult} is typically calculated using properties based on a “weighted average” of the soil layers, except when a multi-layer capacity is used.

The effective footing width and length values are used in the bearing capacity calculations as defined in A10.6.1.3

The depth to the ground water level from the bottom of the footing (Z_w) is used in the bearing capacity calculations and is based on the back water level entered on the AT1, AT2, AWB, or RWL command cards. This value will be zero when the water level is above the bottom of the footing.

The program classifies all soil into one of 4 Soil Classifications. Three of the soil classifications contain 3 Soil Conditions. The table on the following page lists the categories and conditions for soil typing.

Table 3.4.1.4.2-1 Soil Categories and Conditions

Soil Category	Soil Condition	Number of Layers	Clay ϕ_f=0 & c=0 & S_u>0	Sand 20<ϕ_f<60 & c=0 & S_u=0	Mixed ϕ_f>0 & c>0 & S_u=0	Condition	Description *
1	1	1	Clay, Sand, or Mixed Layer			One layer of clay, sand, or mixed	Single Layer
2	2	2	Two Layers			$c_1 < c_2$	Weak Clay over Strong Clay
	3	2	Two Layers			$c_1 > c_2$	Strong Clay over Weak Clay
	9	2	One Layer		One Layer	One Layer Clay One Layer Mixed	Mixed Soil with Clay - Undrained
3	4	2	One Top Layer	One Bottom Layer	One Top Layer	$D > H_1$	Clay or Mixed Soil over Sand
			One Bottom Layer	One Top Layer	One Bottom Layer	$D > H_1$	Sand over Clay or Mixed Soil ($\phi_{f1} < 25^{O}$ or $\phi_{f1} > 50^{O}$)
					Two Layers	$D > H_1$	Mixed Soil over Mixed Soil
	5	2	One Top Layer	One Bottom Layer	One Top Layer	$D \leq H_1$	Clay or Mixed Soil over Sand
			One Bottom Layer	One Top Layer	One Bottom Layer	$D \leq H_1$	Sand over Clay or Mixed Soil ($\phi_{f1} < 25^{O}$ or $\phi_{f1} > 50^{O}$)
					Two Layers	$D \leq H_1$	Mixed Soil over Mixed Soil
	8	2	One Bottom Layer	One Top Layer	One Bottom Layer	Top Layer Sand over a Bottom Layer of Clay or Mixed Soil	Sand over Clay or Mixed Soil ($25^{O} \leq \phi_{f1} \leq 50^{O}$)
4	6	2		Two Layers		$H_1 < 2B'$ & $\phi_{f1} > \phi_{f2}$	Dense Sand over Loose Sand
	7	2		Two Layers		$H_1 < 2B'$ & $\phi_{f1} < \phi_{f2}$	Loose Sand over Dense Sand
	10	2		Two Layers		$H_1 \geq 2B'$	Two Sand Layers

* To better clarify the calculations, the categories will be sub-divided into Soil Conditions below. The calculations are displayed in reverse order meaning the main bearing equation is listed first, then all secondary equations used to determine the main equation are listed after.

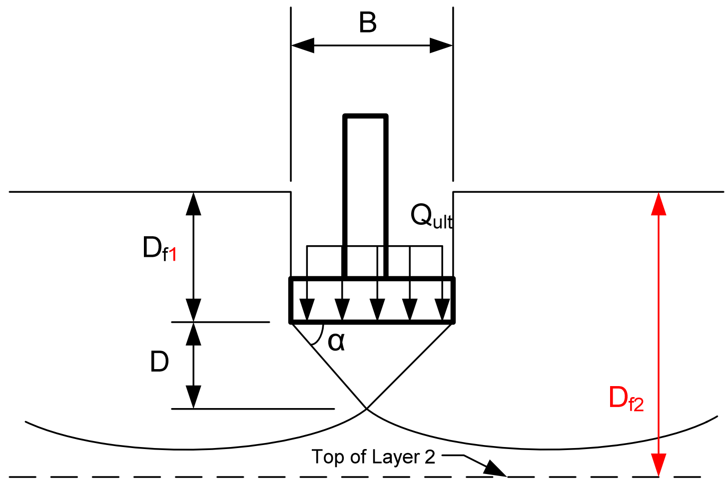


Figure 3.4.1.4.2-1 D_f definition (from Bowles Second Edition Figure 4-3)

Category Independent Calculations

The following shows calculations for values generally used by most Categories and Soil Conditions

Bearing Resistance = $q_{ult} * \phi$, where ϕ is the strength reduction factor applied to bearing resistance

$D = 0.5B' \tan\left(45 + \frac{\phi_f}{2}\right)$ Effective Shear Depth D10.6.3.1.2gP-6

$\phi_f = \tan^{-1}\left(\frac{H_1 \tan\phi_{if1} + (D - H_1)\tan\phi_{if2}}{D}\right)$ Average Soil Friction Angle for multiple Layers (Bowles Section 4-8, Fourth Edition)

$N_q = e^{\pi \tan(\phi_f)} \tan^2\left(45 + \frac{\phi_f}{2}\right)$ DC10.6.3.1.2a-1

$B' = B - 2e_B$ If e_B or e_L are < 0 then; $e_B = |-e_B|$ and $e_L = |-e_L|$ A10.6.1.3-1

$L' = L - 2e_L$ Note: L' = L since e_L is always 0 A10.6.1.3-2

3.4.1.4.2.1 Category 1 - Soil Condition 1: Single Soil Layer

For bearing resistance the equations used are shown below.

$q_{ult} = cN_c s_c i_c + 0.5\gamma B' N_\gamma s_\gamma i_\gamma + \gamma D_f N_q s_q i_q$ D10.6.3.1.2aP-2

Input for Condition 1 - Single Layer

$\gamma_m = \gamma_{im}$

$\gamma_{sat} = \gamma_{isat}$

$\phi_f = \phi_{if}$

$c = c_i$

$D_f = D_{f1}$

Calculation of Gamma (γ)

$$\gamma' = \gamma_{sat} - \gamma_w$$

If Z_w is ≤ 0

$$\gamma = \gamma'$$ D10.6.3.1.2gP-3,7

If $0 < Z_w < B'$ and $\phi_f < 37^O$

$$\gamma = \gamma' + \frac{Z_w}{B'}(\gamma_m - \gamma')$$ D10.6.3.1.2gP-2

Where γ_m is the moist unit weight of soil

If $Z_w \geq B'$ and $\phi_f < 37^O$ and $Z_w \geq D$

$$\gamma = \gamma_m$$ D10.6.3.1.2gP-1,4

If $0 < Z_w < B'$ and $\phi_f \geq 37^O$ and $Z_w < D$

$$\gamma = (2D - Z_w)\frac{Z_w \gamma_m}{D^2} + \frac{\gamma'}{D^2}(D - Z_w)^2$$ D10.6.3.1.2gP-5

Calculation of N_c, N_q, and N_γ

If Footing on or near slope

$N_c = N_{cq}$ A10.6.3.1.2c

$N_\gamma = N_{\gamma q}$ A10.6.3.1.2c

$N_q = 0.0$ A10.6.3.1.2c

If Footing NOT on or near slope

$$N_q = e^{\pi \tan(\phi_f)} \tan^2\left(45^O + \frac{\phi_f}{2}\right)$$ DC10.6.3.1.2a-1

$$N_\gamma = 2(N_q + 1)\tan(\phi_f)$$ DC10.6.3.1.2a-4

If $\phi_f \neq 0$

$$N_c = (N_q - 1)\cot(\phi_f)$$ DC10.6.3.1.2a-2

If $\phi_f = 0$

$$N_c = 5.14$$ DC10.6.3.1.2a-3

Calculation of s_c, s_q, and s_γ

If L > 5B

s_c, s_q, and s_γ = 1.0

If L ≤ 5B

If c = 0

s_c = 1

If c ≠ 0

$$s_c = 1 + \frac{B' N_q}{L' N_c}$$ Table A10.6.3.1.2a-2

$$s_q = 1 + \frac{B'}{L'}\tan(\phi_f)$$ Table A10.6.3.1.2a-2

$$s_\gamma = 1 - 0.4\frac{B'}{L'}$$ Table A10.6.3.1.2a-2

Calculation of i_c, i_q, and i_γ

If $H_u = 0.0$

i_c, i_q, and $i_\gamma = 1$

If $H_u \neq 0.0$

$$\theta = \tan^{-1}\left(\frac{V_u}{H_u}\right)$$

$$n = \frac{2+\frac{L'}{B'}}{1+\frac{L'}{B'}}\cos^2(\theta) + \frac{2+\frac{B'}{L'}}{1+\frac{B'}{L'}}\sin^2(\theta) \qquad \text{D10.6.3.1.2a-9}$$

$\varepsilon = 0.001$ degrees Angle tolerance

$$i_q = \left[1 - \frac{H_u}{V_u + B'L'c\cot(\phi_f + \varepsilon)}\right]^n \qquad \text{D10.6.3.1.2a-7}$$

$$i_\gamma = \left[1 - \frac{H_u}{V_u + B'L'c\cot(\phi_f + \varepsilon)}\right]^{n+1} \qquad \text{D10.6.3.1.2a-8}$$

If $\phi_f = 0$

$$i_c = 1 - \frac{nH_u}{B'L'cN_c} \qquad \text{D10.6.3.1.2a-5}$$

If $\phi_f \neq 0$ and $c = 0$

$i_c = 0.0$

If $\phi_f \neq 0$ and $c \neq 0$

$$i_c = i_q - \frac{1-i_q}{N_c\tan(\phi_f)} \qquad \text{D10.6.3.1.2a-6}$$

3.4.1.4.2.2 Category 2 - Two Clay layers or Undrained Two Layer Mixed Soil

Equation for bearing resistance

$$q_{ult} = c_{i1} N_m + \gamma D_f$$ D10.6.3.1.2e-4P (Eq 3.4.1.4.2.2-1)

Equations needed for N_m (both equations use these values)

$$\kappa = \frac{c_{i2}}{c_{i1}}$$

If $\kappa < 0.6$, the soil is undesirable and the program will stop with an error.

$$\beta_m = \frac{B'L'}{2(B'+L')H_1}$$ A10.6.3.1.2e-3

The average ϕ_f

$$\phi_f = \tan^{-1}\left(\frac{H_1 \tan\phi_{if1} + (D - H_1)\tan\phi_{if2}}{D}\right)$$ (Bowles Section 4-8)

N_c ,N_q and N_γ are computed using equations from Category 1

The average moist soil γ_m

$$\gamma_m = \frac{H_1 \gamma_{im1} + (D - H_1)\gamma_{im2}}{D}$$

The average saturated soil γ_{sat}

$$\gamma_{sat} = \frac{H_1 \gamma_{isat1} + (D - H_1)\gamma_{isat2}}{D}$$

γ is computed using equations from Category 1

s_c is computed using equations from Category 1

<u>Category 2: Soil Condition 2 - Weaker clay over stronger clay - Undrained</u>

Soil Correction Factor for use in Equation 3.4.1.4.2.2-1

$$N_m = \frac{\kappa N_c (N_c + \beta_m - 1)\left[(\kappa + 1)N_c^2 + (1 + \kappa\beta_m)N_c + \beta_m - 1\right]}{\left[\kappa(\kappa + 1)N_c + \kappa + \beta_m - 1\right]\left[(N_c + \beta_m)N_c + \beta_m - 1\right] - (\kappa N_c + \beta_m - 1)(N_c + 1)} \quad \text{(Eq 3.4.1.4.2.2-2)}$$

(Winterkorn and Fang 3.37)

<u>Category 2: Soil Condition 3 - Stronger clay over weaker clay - Undrained</u>

Soil Correction Factor for use in Equation 3.4.1.4.2.2-1

$$N_m = \frac{1}{\beta_m} + \kappa s_c N_c$$

A10.6.3.1.2e-1 (Eq 3.4.1.4.2.2-3)

<u>If $N_m \geq s_c N_c$</u>

$$N_m = s_c N_c$$

A10.6.3.1.2e-1

<u>Category 2: Soil Condition 9 - Mixed Soil with Clay - Undrained</u>

<u>When $c_1 \leq c_2$</u>

Use Equation 3.4.1.4.2.2-2 for N_m

<u>When $c_1 > c_2$</u>

Use Equation 3.4.1.4.2.2-3 for N_m

3.4.1.4.2.3 Category 3 – Sand over Clay or Mixed Soil / Clay or Mixed Soil over Sand

Category three uses 3 conditions to determine the bearing pressure: Conditions 4, 5 and 8.

<u>Category 3: Soil Condition 4 - Clay or Mixed Soil over Sand / Sand over Clay or Mixed Soil - D > H1</u>

The Sand over Clay or Mixed condition will only occur when the ϕ_{if1} is between 20^O and 25^O or greater than 50^O. A Mixed soil over Mixed soil case may also occur for this condition.

The following values are used in the Single layer equation. The values of the soil properties are averaged.

The Maximum Depth that bearing is effective to

$$D = \frac{B'}{2} \tan\left(45 + \frac{\phi_{if1}}{2}\right)$$

Three Conditions Control ΔH

$H_1 > D$, $\Delta h = 0$

$H_1 + H_2 > D$, $\Delta h = D - H_1$

$H_1 + H_2 \leq D$, $\Delta h = H_2$

The average cohesion value is calculated

$$c = \frac{c_{i1} H_1 + c_{i2} (\Delta h)}{H_1 + \Delta h}$$ (Bowles Section 4-8)

The average ϕ_f

$$\phi_f = \tan^{-1}\left(\frac{H_1 \tan \phi_{if1} + (\Delta h) \tan \phi_{if2}}{H_1 + \Delta h} \right)$$ (Bowles Section 4-8)

The average moist soil γ_m

$$\gamma_m = \frac{H_1 \gamma_{im1} + \Delta h \gamma_{im2}}{H_1 + \Delta h}$$

The average saturated soil γ_{sat}

$$\gamma_{sat} = \frac{H_1 \gamma_{isat1} + \Delta h \gamma_{isat2}}{H_1 + \Delta h}$$

$D_f = D_{f1}$

Compute Bearing Resistance following procedure for Soil Condition 1

Category 3: Soil Condition 5 - Clay or Mixed Soil over Sand / Sand over Clay or Mixed Soil - D $\leq$ H1

The Sand over Clay or Mixed condition will only occur when the ϕ_{if1} is between 20^{O} and 25^{O} or greater than 50^{O}. A Mixed soil over Mixed soil case may also occur for this condition.

The following values are used in the Single layer equation. The values of the soil properties for use in the single layer equation are shown below. These values are used to calculate q_{ult} for the first layer

$c = c_{i1}$

$\phi_f = \phi_{if1}$

$\gamma_m = \gamma_{im1}$

$\gamma_{sat} = \gamma_{isat1}$

$D_f = D_{f1}$

Compute bearing resistance "q_{ult1}" following procedure for Soil Condition 1

The following values are used in the Single layer equation. The values of the soil properties for use in the single layer equation are shown below. These values are used to calculate q_{ult} for the second layer

$$c = 0.67 i c_2 \qquad \text{A10.6.3.1.2b-1}$$

$$\phi_f = \tan^{-1}(0.67\phi_{if2}) \qquad \text{A10.6.3.1.2b-2}$$

$$\gamma_m = \gamma_{im2}$$

$$\gamma_{sat} = \gamma_{isat2}$$

$D_f = D_{f2}$

Compute bearing resistance "q_{ult2} " following procedure for Soil Condition 1

Then the critical Height is calculated

$$H_{crit} = \frac{3B'\ln\left(\frac{q_{ult1}}{q_{ult2}}\right)}{2\left(1+\frac{B'}{L'}\right)} \qquad \text{A10.6.3.1.2d-1}$$

If $H_1 > H_{crit}$ Then

$$q_{ult} = q_{ult1}$$

If $H_1 \leq H_{crit}$ Then q_{ult} is calculated using the equation below

$$K = \frac{1 - \sin^2 \phi_{if1}}{1 + \sin^2 \phi_{if1}} \qquad \text{A10.6.3.1.2f-2}$$

$$q_{ult} = \left[q_{ult2} + \left(\frac{1}{K}\right)c_1 \tan(\phi_{if1} + \varepsilon)\right] e^{2\left(1+\frac{B'}{L'}\right)K\tan(\phi_{if1})\frac{H_1}{B'}} - \frac{1}{K}c_1 \tan(\phi_{if1} + \varepsilon)$$

$$where \qquad \text{A10.6.3.1.2f-1}$$

$$\varepsilon = 0.01$$

If $q_{ult} > q_{ult1}$

$$q_{ult} = q_{ult1}$$

Category 3: Soil Condition 8 - Sand over Clay or Mixed Soil – $20 \leq \phi_{if1} \leq 50$

The following values are used in the Single layer equation. The values of the soil properties for use in the single layer equation are shown below. Then the q_{ult} for layer one is calculated based on the following values

$c = c_{i1}$

$\phi_f = \phi_{if1}$

$\gamma_m = \gamma_{im1}$

$\gamma_{sat} = \gamma_{isat1}$

$D_f = D_{f1}$

Compute bearing resistance "q_{ult1}" following procedure for Soil Condition 1

These values are used to calculate q_{ult} for the second layer

$c = 0.67c_{i2}$

$\phi_f = \tan^{-1}(0.67\phi_{if2})$

$\gamma_m = \gamma_{im2}$

$\gamma_{sat} = \gamma_{isat2}$

$D_f = D_{f2}$

Compute bearing resistance "q_{ult2}" following procedure for Soil Condition 1

Then the q_{ult} is calculated using the equation shown below

$$q_{ult,eq4} = q_{ult2}\ e^{0.67\left(1+\frac{B'}{L'}\right)\frac{H_1}{B'}} \quad \text{AC10.6.3.1.2f-1}$$

Then the critical Height is calculated

$$H_{crit} = \frac{3B'\ln\left(\frac{q_{ult1}}{q_{utl2}}\right)}{2\left(1+\frac{B'}{L'}\right)} \quad \text{A10.6.3.1.2d-1}$$

If $H_1 > H_{crit}$ or $q_{ult,eq4} > q_{ult1}$ Then

$$q_{ult} = q_{ult1}$$

Otherwise

$$q_{ult} = q_{ult,ex4}$$

3.4.1.4.2.4 Category 4 - Loose over Dense Sand or Dense over Loose Sand

Category four uses 3 conditions to determine the bearing pressure. Condition 6 and 7 are used when the effective depth of bearing reaches the second layer of soil. Condition 10 is reserved for when the effective depth of bearing does not reach the second layer

The following values are used in the Single layer equation. The values of the soil properties for use in the single layer equation are shown below. These values are used to calculate q_{ult} for the first layer

$c = c_{i1}$

$\phi_f = \phi_{if1}$

$\gamma_m = \gamma_{im1}$

$\gamma_{sat} = \gamma_{isat1}$

$D_f = D_{f1}$

Compute bearing resistance "q_{ult1}" following procedure for Soil Condition 1

Retain γ_1 from q_{ult1} for use in q_{ult2}

$\gamma_{1f} = \gamma_1$

If H_1 >= 2B'

Category 4: Soil Condition 10 - Two Sand Layers where $H_1 \geq$ 2B'

Then $q_{ult} = q_{ult1}$

If H_1 < 2B'

Then compare ϕ_{if1} to ϕ_{if2} to determine if **Soil Condition 6 or 7** controls

Category 4: Soil Condition 7 – Loose over Dense Sand where H_1 < 2B' and ($\phi_{f1} < \phi_{f2}$)

The following equation is used to calculate q_{ult2}.

$\phi_f = \phi_{if2}$

$\gamma_m = \gamma_{im2}$

$\gamma_{sat} = \gamma_{isat2}$

The γ_2, $N\gamma_2$, $S\gamma_2$, $i\gamma_2$, N_{q2}, S_{q2} and i_{q2} are computed following procedures in Section 3.4.1.4.2.1.

$$q_{ult2} = 0.5\gamma_2 B' N_{\gamma 2} s_{\gamma 2} i_{\gamma 2} + \gamma_{1f} D_{f1} N_{q2} s_{q2} i_{q2}$$

This equation is derived from DAS equation 11.55 except the unit weight of the top layer is used to determine the overburden.

The following equation is used to calculate q_{ult}.

$$q_{ult} = q_{ult1} + (q_{ult2} - q_{ult1})\left(1 - \frac{H_1}{2B'}\right)^2 \qquad \text{(DAS 11.54)}$$

<u>Category 4: Soil Condition 6 - Dense over Loose Sand where $H_1 < 2B'$ and ($\phi_{f1} \geq \phi_{f2}$)</u>

The following equations are used in the q_{ult} calculation

$$N_{q1} = e^{\pi \tan(\phi_{if1})} \tan^2\left(45 + \frac{\phi_{if1}}{2}\right) \qquad \text{DC10.6.3.1.2a-1}$$

$$N_{\gamma 1} = 2(N_{q1} + 1)\tan(\phi_{if1}) \qquad \text{DC10.6.3.1.2a-4}$$

$$N_{q2} = e^{\pi \tan(\phi_{if2})} \tan^2\left(45 + \frac{\phi_{if2}}{2}\right) \qquad \text{DC10.6.3.1.2a-1}$$

$$N_{\gamma 2} = 2(N_{q2} + 1)\tan(\phi_{if2}) \qquad \text{DC10.6.3.1.2a-4}$$

$\gamma'_1 = \gamma_{isat1} - \gamma_w$

$\gamma'_2 = \gamma_{isat2} - \gamma_w$

The following chart is used to determine K_s . The chart is from *Principals of Geotechnical Engineering by Braja M. Das, Third Edition*

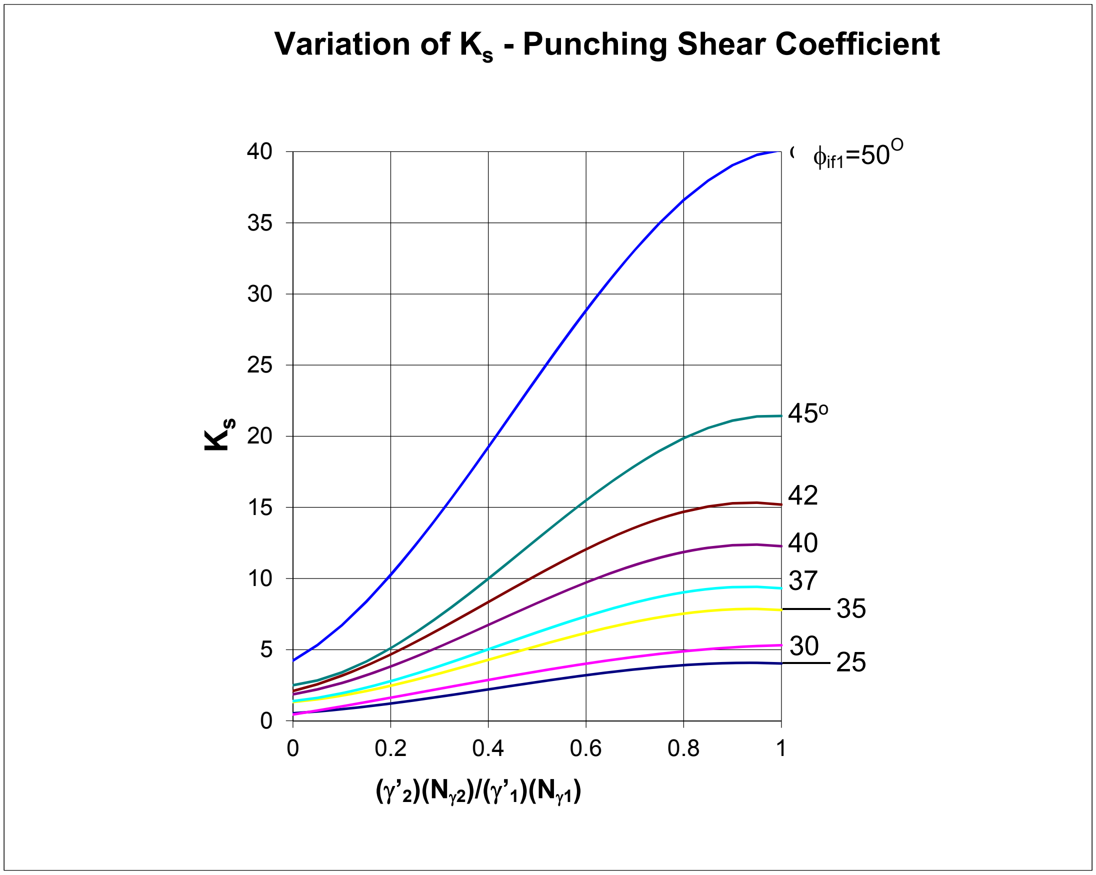


Figure 3.4.1.4.2.4-1 Punching Shear Coefficient Graph (K_s)

Then the bearing equation is determined by looking at the L'/B'

The following equation is used to calculate q_{ult2}.

$\phi_f = \phi_{if2}$

$\gamma_m = \gamma_{im2}$

$\gamma_{sat} = \gamma_{isat2}$

The γ_2, $N\gamma_2$, $S\gamma_2$, $i\gamma_2$, N_{q2}, S_{q2} and i_q are computed following procedures in Section 3.4.1.4.2.1.

$$q_{ult2} = 0.5\gamma_2 B' N_{\gamma 2} s_{\gamma 2} i_{\gamma 2} + \gamma_{1f} D_{f2} N_{q2} s_{q2} i_{q2} \qquad \textbf{(DAS 11.48)}$$

If L' >5*B' then the following equation is used **to calculate bearing resistance**

$$q_{ult} = q_{ult2} + \gamma_1'(H_1)^2\left(1+\frac{2D_f}{H_1}\right)\frac{K_s \tan(\phi_{if1})}{B'} - \gamma_1' H_1 \leq q_{ult1} \qquad \text{(DAS 11.44)}$$

If L' ≤ 5*B' the following equation is used to calculate bearing **resistance**

$$q_{ult} = q_{ult2} + \left(1+\frac{B'}{L'}\right)\gamma_1'(H_1)^2\left(1+\frac{2D_f}{H_1}\right)\frac{K_s \tan(\phi_{if1})}{B'} - \gamma_1' H_1 \leq q_{ult1} \qquad \text{(DAS 11.46)}$$