

THE BEARING CAPACITY EQUATION

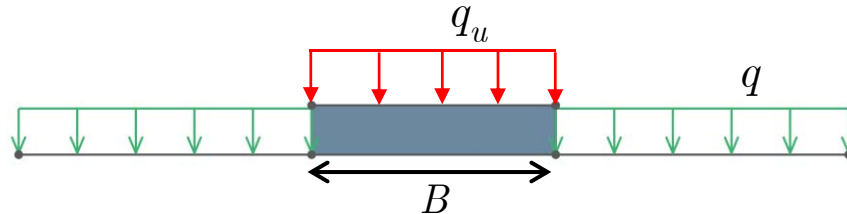
- why don't I get the same result with OPTUM?

KRISTIAN KRABBENHOFT

Optum Computational Engineering

Outline

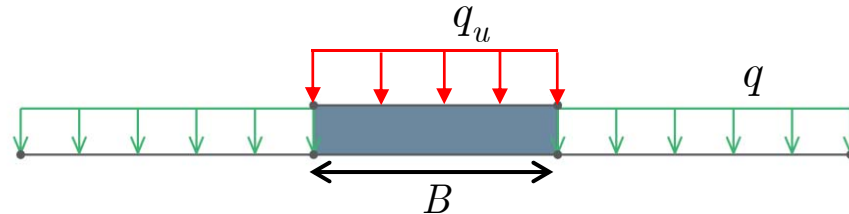
- + Bearing capacity factor N_γ
- + Superposition principle
- + Inclined loading
- + Eccentricity
- + Shape – 2D to 3D



The bearing capacity equation:

$$q_u = cN_c + qN_q + \frac{1}{2}\gamma BN_\gamma$$

where N_c , N_q , N_γ = bearing capacity factors – functions of ϕ



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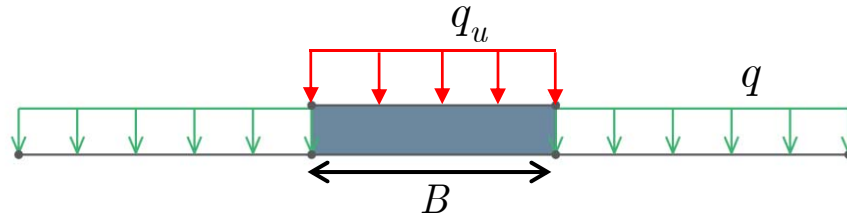
where N_c , N_q , N_γ = bearing capacity factors – functions of ϕ

Undrained:

$$q_u = (2 + \pi)s_u + q$$

Drained:

$$q_u = qN_q + \frac{1}{2}\gamma BN_\gamma$$



The bearing capacity equation:

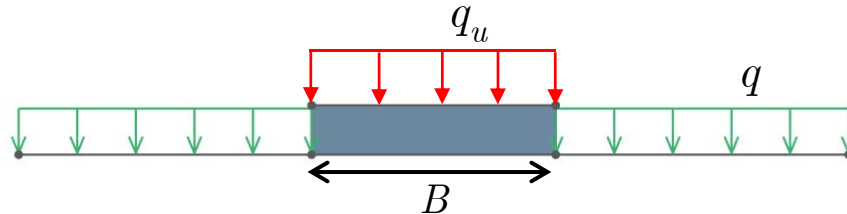
$$q_u = cN_c + qN_q + \frac{1}{2}\gamma BN_\gamma$$

where

$$N_q = \exp(\pi \tan \phi) \tan^2(45^\circ + \frac{1}{2}\phi)$$

$$N_c = (N_q - 1) \cot \phi$$

$$N_\gamma = 2(N_q - 1) \tan \phi$$



The bearing capacity equation:

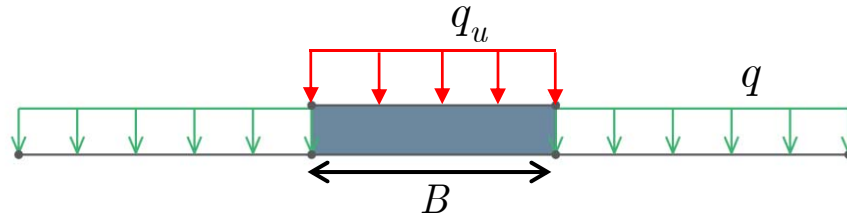
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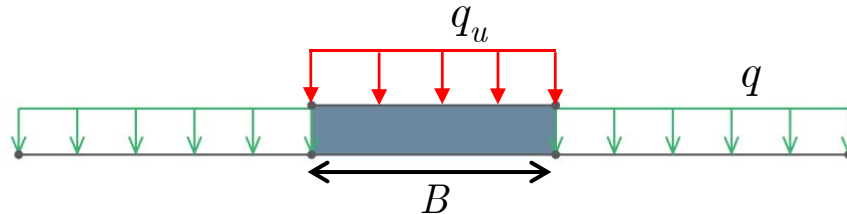
where

$$N_q = \exp(\pi \tan \phi) \tan^2(45^\circ + \frac{1}{2}\phi)$$

$$N_c = (N_q - 1) \cot \phi$$

$$N_\gamma = 2(N_q - 1) \tan \phi \quad (\text{EC7})$$

$$= 1.5(N_q - 1) \tan \phi \quad (\text{Brinch Hansen})$$



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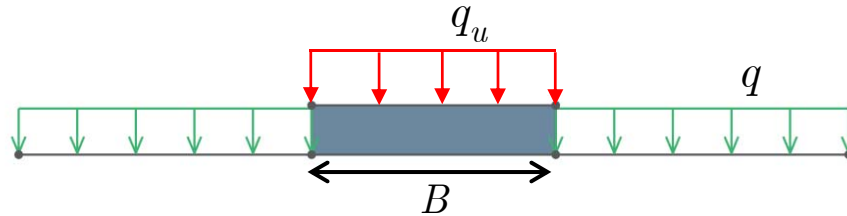
$$N_\gamma = 2(N_q - 1) \tan \phi \quad (\text{EC7})$$

$$= 1.5(N_q - 1) \tan \phi \quad (\text{Brinch Hansen})$$

$$= (N_q - 1) \tan(1.4\phi) \quad (\text{Meyerhof})$$

⋮

BEARING CAPACITY EQUATION



Weightless soil:

$$q_u = cN_c + qN_q$$

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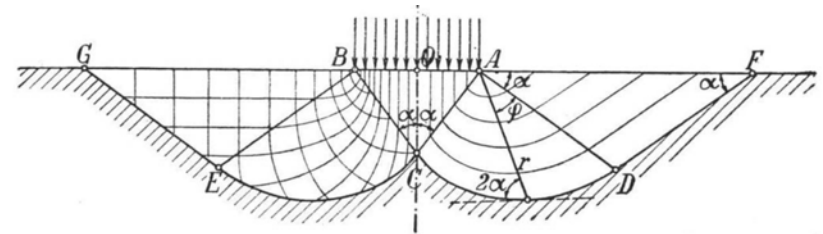
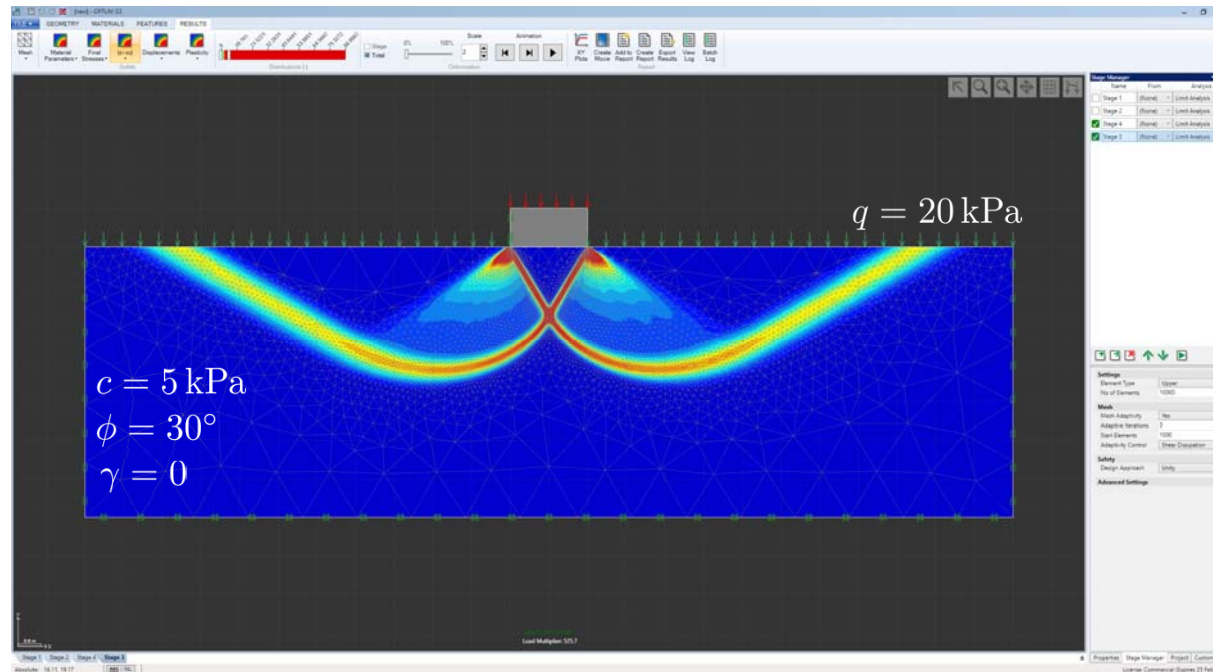


Figure 1.

This solution is exact (Prandtl 1921, Reissner 1924)

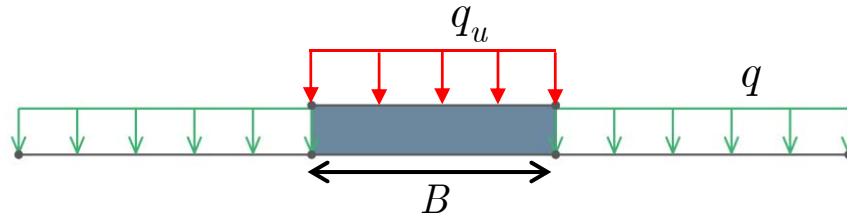
OPTUM G2



10,000 elements (LB/UB) + 3 adaptive iterations (sol time \approx 20 sec):

$q_u \text{ (kN/m}^2\text{)}$				
LB	UB	(LB+UB)/2	Exact	Error (%)
509.5	525.7	517.6	518.7	-0.2%

BEARING CAPACITY EQUATION



Weightless soil:

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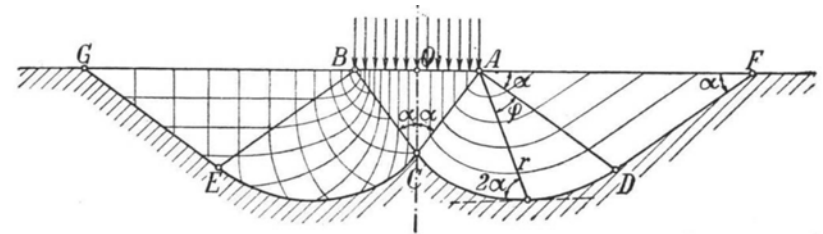
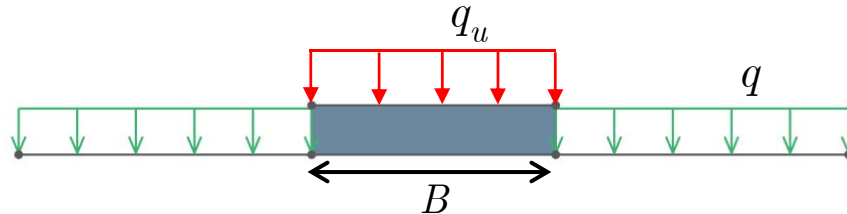


Figure 1.

This solution is exact (Prandtl 1921, Reissner 1924)



Ponderable soil – superposition:

$$q_u = cN_c + qN_q + \frac{1}{2}\gamma BN_\gamma$$

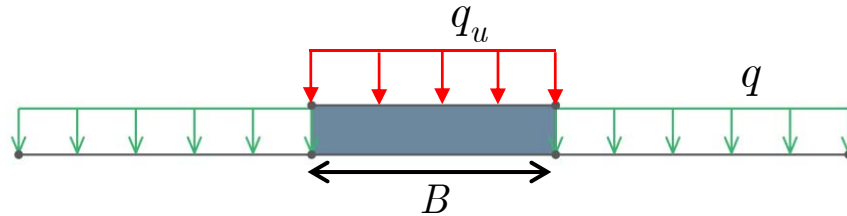
where

$$N_q = \exp(\pi \tan \phi) \tan^2(45^\circ + \frac{1}{2}\phi)$$

$$N_c = (N_q - 1) \cot \phi$$

$$N_\gamma = ?$$

This solution is conservative – provided that N_γ is exact



Exact N_γ – zero cohesion + zero surcharge:

$$q_u = \frac{1}{2}\gamma B N_\gamma$$

or

$$N_\gamma = \frac{2q_u}{\gamma B}$$

100 year search for exact N_γ

60 N_γ expressions (Diaz-Segura 2013)



NOTE

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Assessment of the range of variation of N_γ from 60 estimation methods for footings on sand

Edgar Giovanni Diaz-Segura

E.G. Diaz-Segura. Pontificia Universidad Católica de Valparaíso, Av. Brasil 2147, Piso 4, Valparaíso 2362804, Chile.
E-mail for correspondence: edgar.diaz@ucv.cl.

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60 N_γ expressions (Diaz-Segura 2013)

Table 1. Expressions for the estimation of the N_γ factor.

Author	Expression
Terzaghi (1943); fitted expression; limit equilibrium	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 3.0 \right] \tan(1.34\phi)$
Taylor (1948); limit equilibrium	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right)$
Caquot and Kérisel (1953); fitted from Ukritchon et al. (2003); method of characteristics	$N_\gamma = \left[1.413 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1.794 \right] \tan(1.27\phi)$
Biares et al. (1961); equilibrium limit	$N_\gamma = 1.8 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan \phi$
Feda (1961); empirical	$N_\gamma = 0.01 \exp(\phi/4)$ (for $\phi < 35^\circ$; ϕ in degrees)
Meyerhof (1963); semi-empirical based on limit equilibrium	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan(1.4\phi)$
Hu (1964); fitted expression; equilibrium limit	$N_\gamma = \left[1.901 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 0.27 \right] \tan(1.285\phi)$
Krizek (1965); empirical	$N_\gamma = \frac{6\phi}{40 - \phi}$ (for $\phi < 35^\circ$; ϕ in degrees)
Booker (1969); method of characteristics	$N_\gamma = 0.1045 \exp(9.6\phi)$
Hansen and Christensen (1969); fitted expression; method of characteristics	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan(1.33\phi)$
Muhs and Weiss (1969); (Eurocode 7); semi-empirical expression	$N_\gamma = 2 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan \phi$
Abdul-Baki and Beik (1970); fitted expression; limit equilibrium	$N_\gamma = \left[1.752 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 0.186 \right] \tan(1.32\phi)$
Brinch-Hansen (1970); semi-empirical based on Lundgren-Mortensen (1953) failure mechanics	$N_\gamma = 1.5 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan \phi$
Davis and Booker (1971); fitted expression; limit equilibrium	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 2.33 \right] \tan(1.316\phi)$
Chummar (1972); fitted expression; semi-empirical	$N_\gamma = \left[7.12 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 65.5 \right] \tan(0.27\phi)$
Vesic (1973); approximation based on Caquot and Kérisel (1953) analysis using the method of characteristics	$N_\gamma = 2 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1 \right] \tan \phi$
Chen (1975); upper bound limit analysis	$N_\gamma = 2 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1 \right] \tan \phi \tan\left(\frac{\pi}{4} + \frac{\phi}{5}\right)$
Chen (1978); fitted from mechanics two values; upper bound limit analysis	$N_\gamma = \left[1.45 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 0.754 \right] \tan(1.41\phi)$
Salençon et al. (1976); fitted expression; limit equilibrium	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1.0 \right] \tan(1.405\phi)$
Steenfelt (1977); empirical fitting from N_γ values obtained from Lundgren and Mortensen (1953)	$N_\gamma = \left[0.08705 + 0.3231 \sin(2\phi) - 0.04836 \sin^2(2\phi) \right] \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(1.5\pi \tan \phi) - 1 \right]$
Craig and Pariti (1978); fitted expression; limit equilibrium	$N_\gamma = \left[2.22 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 0.222 \right] \tan \phi$
Spangler and Handy (1982); approximation from Terzaghi's Mechanism	$N_\gamma = 1.1 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan(1.3\phi)$
Ingra and Baecher (1983); statistical analysis of footing load test data	$N_\gamma = \exp(0.173\phi - 1.646)$ (ϕ in degrees)

BEARING CAPACITY EQUATION

60 N_γ expressions (Diaz-Segura 2013)

Table 1 (continued).

Author	Expression
Simone and Restaino (1984); fitted expression; method of characteristics	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan(1.341\phi)$
Hettler and Gudehus (1988); empirical	$N_\gamma = \exp[5.71(\tan \phi)^{1.13}] - 1.0$
Saran and Agarwal (1991); fitted expression; limit equilibrium	$N_\gamma = \exp\left(\frac{0.757}{\ln \phi} + 15.286\phi - 3.452\right)$
Bolton and Lau (1993); method of characteristics	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1 \right] \tan(1.5\phi)$
Bolton and Lau (1993); fitted expression from original values; method of characteristics	$N_\gamma = \left[1.274 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 3.736 \right] \tan(1.367\phi)$
Kumbhojkar (1993); fitted expression; numerical solution by graphical method	$N_\gamma = \left[1.2 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1.324 \right] \tan(1.417\phi)$
Zadroga (1994); empirical expression	$N_\gamma = 0.657 \exp(0.141\phi) \quad (\phi \text{ in degrees})$
Manoharan and Dasgupta (1995); fitted expression; finite element nonassociated flow rule	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 3.464 \right] \tan(1.279\phi)$
Bowles (1996); fitted expression from K_{pr} values; limit equilibrium	$N_\gamma = \frac{\tan \phi}{2} \left(\frac{K_{pr}}{\cos^2 \phi} - 1 \right) \quad K_{pr} = \exp\left(1.708 + 3.287\phi - \frac{0.34}{\ln \phi}\right)$
Frydman and Burd (1997); fitted expression; finite difference analysis	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1.0 \right] \tan(1.4\phi)$
Michalowski (1997); upper bound limit analysis	$N_\gamma = \exp(0.66 + 5.11 \tan \phi) \tan \phi$
Paolucci and Pecker (1997); fitted expression; upper bound limit analysis	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1.0 \right] \tan(1.71\phi)$
Danish standard DS415 (Danish Standards Association 1998); empirical fitting from N_γ values obtained from Lundgren and Mortensen (1953)	$N_\gamma = \frac{1}{4} \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1.0 \right] \cos \phi^{1.5}$
Soubra (1999); fitted expression; upper bound limit analysis	$N_\gamma = \left[1.374 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 0.162 \right] \tan(1.343\phi)$
Coduto (2001); approximation from Terzaghi's Mechanism	$N_\gamma = \frac{2 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1 \right] \tan \phi}{1 + 0.4 \sin(4.0\phi)}$
Perkins and Madson (2000); upper-bound analysis based on Chen (1975)	$N_\gamma = \frac{1}{2} \tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \left[\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(1.5\pi \tan \phi) - 1 \right] + \frac{\sin \phi \cos \phi}{(1 + 8 \sin^2 \phi)(1 - \sin \phi)} \left[\left(\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) - \frac{\cot \phi}{3} \right) \exp(1.5\pi \tan \phi) + \tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \frac{\cot \phi}{3} + 1 \right]$
Poulos et al. (2001); solution based on Davis and Booker (1971)	$N_\gamma = 0.1054 \exp(9.6\phi)$
Ueno et al. (2001); fitted expression; method of characteristics	$N_\gamma = \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) - 1.0 \right] \tan(1.461\phi)$
Wang et al. (2001); fitted expression for mechanics one; upper bound limit analysis	$N_\gamma = 1.2 \left[\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 4.6 \right] \tan(1.436\phi)$
Wang et al. (2001); fitted expression for mechanics two; upper bound limit analysis	$N_\gamma = \left[1.234 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 4.151 \right] \tan(1.394\phi)$
Zhu et al. (2001); case 1; limit equilibrium	$N_\gamma = \left[2 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \exp(\pi \tan \phi) + 1 \right] (\tan \phi)^{1.55}$

BEARING CAPACITY EQUATION

60 N_γ expressions (Diaz-Segura 2013)

Table 1 (concluded).

Author	Expression
Zhu et al. (2001); case 2; limit equilibrium	$N_\gamma = \left[2 \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) + 1 \right] \tan(1.07\phi)$
Cassidy and Housley (2002); fitted expression; method of characteristics	$N_\gamma = \left[0.85 \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 3.884 \right] \tan(1.716\phi)$
Dewaikar and Mohapatra (2003); fitted expression; limit equilibrium — Terzaghi's mechanism	$N_\gamma = \left[1.626 \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) + 2.019 \right] \tan(1.373\phi)$
Kumar (2003); fitted expression; method of characteristics	$N_\gamma = \left[0.96 \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) + 0.508 \right] \tan(1.352\phi)$
Kumar (2003); fitted expression; upper bound analysis — both sides failure mechanism	$N_\gamma = \left[1.379 \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 0.461 \right] \tan(1.337\phi)$
Ukritchon et al. (2003); fitted expression from mean values; lower and upper bound analysis	$N_\gamma = \left[1.279 \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 3.057 \right] \tan(1.219\phi)$
Hijaj et al. (2005); lower and upper bound analysis	$N_\gamma = \exp \left\{ \frac{\pi}{6} (1 + 3\pi \tan \phi) \right\} (\tan \phi)^{2.95}$
Martin (2005); fitted expression method of characteristics	$N_\gamma = \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 1.0 \right] \tan(1.338\phi)$
Smith (2005); method of characteristics	$N_\gamma = 1.75 \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(0.75\pi + \phi) \tan \phi - 1.0 \right] \tan \phi$
Kumar and Kouzer (2007); fitted expression; upper bound limit analysis	$N_\gamma = \left[1.012 \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 0.226 \right] \tan(1.426\phi)$
Lyamin et al. (2007); lower and upper bound analysis	$N_\gamma = \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 0.6 \right] \tan(1.33\phi)$
Kumar and Khatri (2008); fitted expression; lower bound finite elements and linear programming	$N_\gamma = \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 1.0 \right] \tan(1.264\phi)$
Salgado (2008); approximation expression from N_γ values of Martin (2005) and Lyamin et al. (2007)	$N_\gamma = \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 1.0 \right] \tan(1.32\phi)$
Yang and Yang (2008); fitted expression; upper bound limit analysis	$N_\gamma = \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) + 1.0 \right] \tan(1.396\phi)$
Jahanandish et al. (2010); fitted expression; zero extension lines method	$N_\gamma = \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) + 1.0 \right] \tan(1.5\phi)$
Kumar and Khatri (2011); fitted expression; lower bound with finite element and linear programming	$N_\gamma = \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right) \exp(\pi \tan \phi) - 5.115 \right] \tan(1.577\phi)$



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21 Giugno 2005

Exact bearing capacity calculations using the method of characteristics

Dr C.M. Martin
Department of Engineering Science
University of Oxford

http://www2.eng.ox.ac.uk/civil/people/cmm/download/iacmag05_cmm.ppt

Exact bearing capacity calculations using the method of characteristics

C.M. Martin

Department of Engineering Science, University of Oxford

Keywords: bearing capacity, shallow foundation, cohesive-frictional, limit analysis

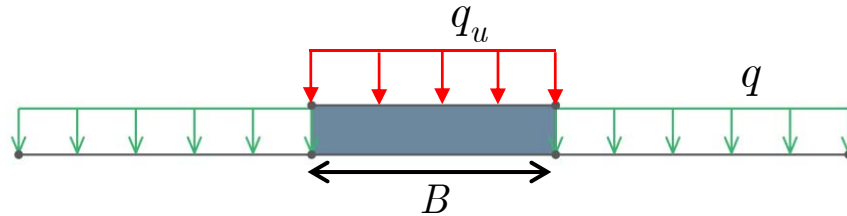
ABSTRACT: This paper discusses the use of the method of characteristics (commonly referred to as the slip-line method) to solve the classic geotechnical bearing capacity problem of a vertically loaded, rigid strip footing resting on a cohesive-frictional halfspace. It would appear that, contrary to popular belief, the method of characteristics can be used to establish the exact plastic collapse load for any combination of the parameters c , ϕ , γ , B and q – including the infamous ' N_γ problem'. This applies to footings of arbitrary roughness, though only the extreme cases (smooth and fully rough) are considered in detail here.

http://www2.eng.ox.ac.uk/civil/people/cmm/download/iacmag05_cmm.pdf

N_γ ($\delta = \phi$) by common formulae: error [%]

ϕ [°]	Meyerhof (1963)	Hansen (1970)	Vesić (1975)	Eurocode (1996)	Poulos et al. (2001)
5	-38.5	-34.3	296.3	-12.4	114.9
10	-15.3	-10.2	182.6	19.8	30.0
15	-4.4	0.1	124.1	33.4	10.1
20	1.1	3.8	89.7	38.4	5.9
25	4.2	4.1	67.6	38.8	7.1
30	6.2	2.1	51.8	36.2	8.9
35	7.8	-1.6	39.3	31.2	7.7
40	9.5	-7.0	27.9	23.9	0.3
45	12.2	-14.3	16.0	14.3	-15.3

BEARING CAPACITY EQUATION



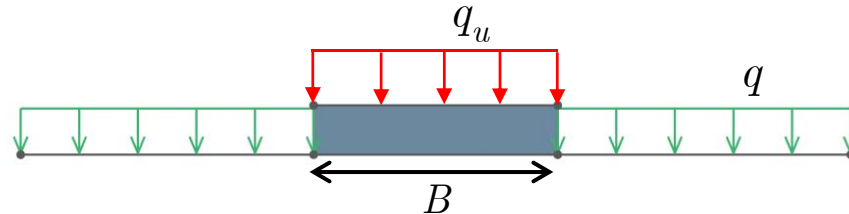
Exact N_γ – zero cohesion + zero surcharge:

$$q_u = \frac{1}{2}\gamma B N_\gamma$$

or

$$N_\gamma = \frac{2q_u}{\gamma B}$$

Exact N_γ determined by CM Martin in 2005 using method of characteristics



Exact N_γ – zero cohesion + zero surcharge:

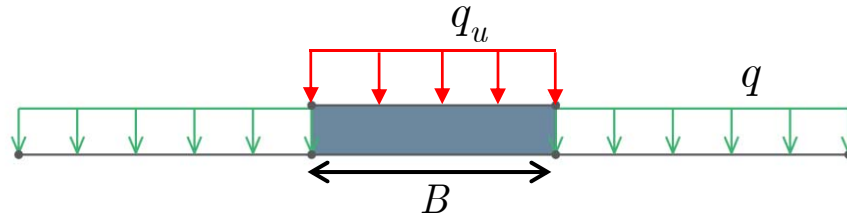
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Analytical expression not available, but still exact



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Exact N_γ determined by CM Martin in 2005 using method of characteristics

Analytical expression not available, but still exact

Good approximation:

$$N_\gamma = (N_q - 1) \tan(1.34\phi)$$

BEARING CAPACITY EQUATION

Good approximation:

$$N_\gamma = (N_q - 1) \tan(1.34\phi)$$

ϕ (°)	Exact	Approximate	N_γ error (%)
15	1.1814	1.0763	-8.9
20	2.8389	2.7274	-3.9
25	6.4913	6.3952	-1.5
30	14.754	14.705	-0.33
35	34.476	34.512	+0.11
40	85.566	85.716	+0.18
45	234.21	234.71	+0.21

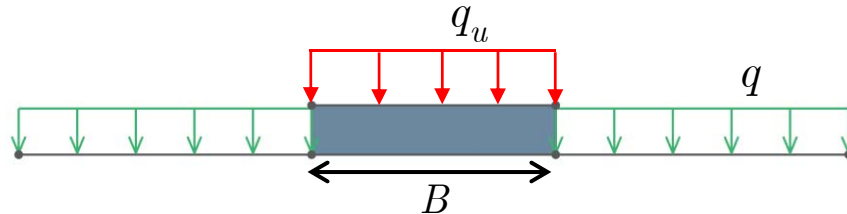
BEARING CAPACITY EQUATION

Good approximation:

$$N_\gamma = (N_q - 1) \tan(1.34\phi)$$

ϕ (°)	Exact	Approximate	ϕ error (°)
15	1.1814	1.0763	-0.52
20	2.8389	2.7274	-0.25
25	6.4913	6.3952	-0.10
30	14.754	14.705	-0.02
35	34.476	34.512	+0.005
40	85.566	85.716	+0.008
45	234.21	234.71	+0.009

BEARING CAPACITY EQUATION



Final equation:

$$q_u = cN_c + qN_q + \frac{1}{2}\gamma BN_\gamma$$

where

$$N_q = \exp(\pi \tan \phi) \tan^2(45^\circ + \frac{1}{2}\phi)$$

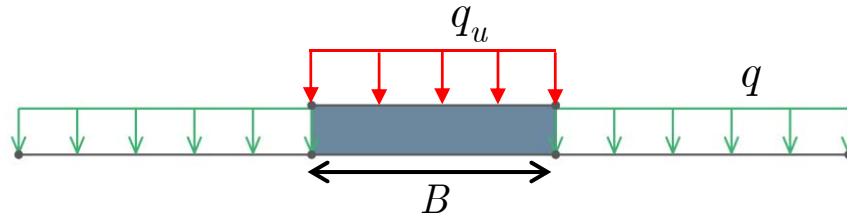
$$N_c = (N_q - 1) \cot \phi$$

$$N_\gamma = (N_q - 1) \tan(1.34\phi)$$

This solution is conservative¹

¹To within the approximation of N_γ

BEARING CAPACITY EQUATION



Final equation:

$$q_u = cN_c + qN_q + \frac{1}{2}\gamma BN_\gamma$$

where

$$N_q = \exp(\pi \tan \phi) \tan^2(45^\circ + \frac{1}{2}\phi)$$

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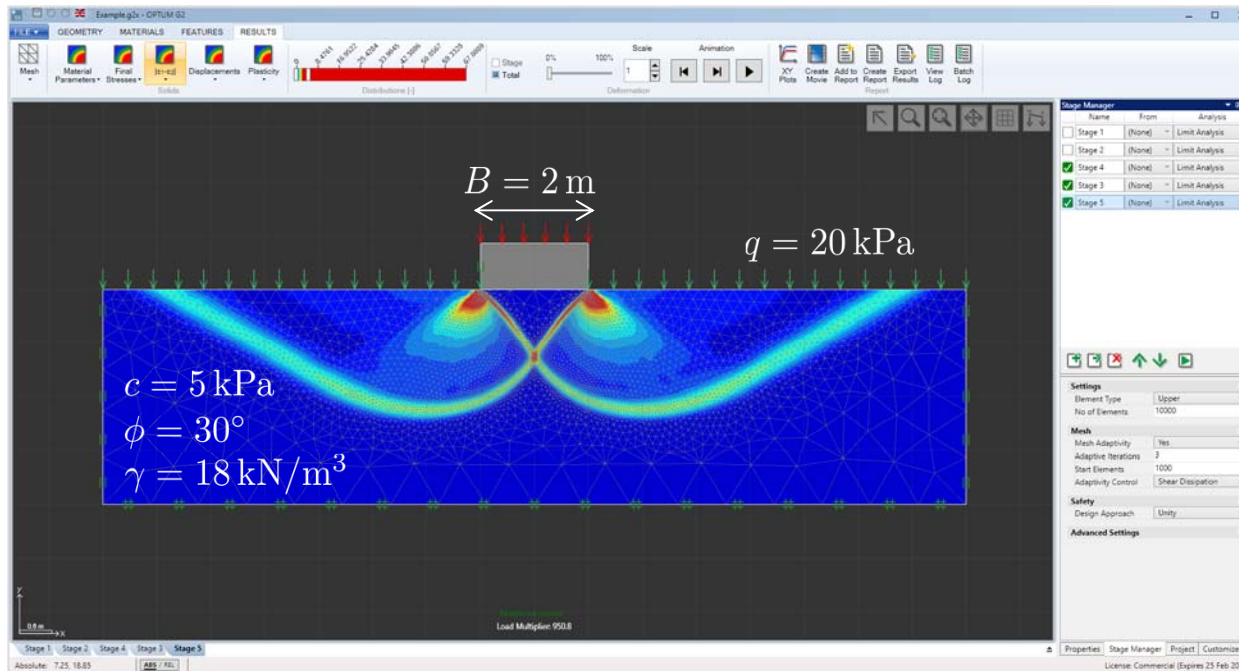
$$N_\gamma = (N_q - 1) \tan(1.34\phi)$$

This solution is conservative¹

General solution: numerical analysis

¹To within the approximation of N_γ

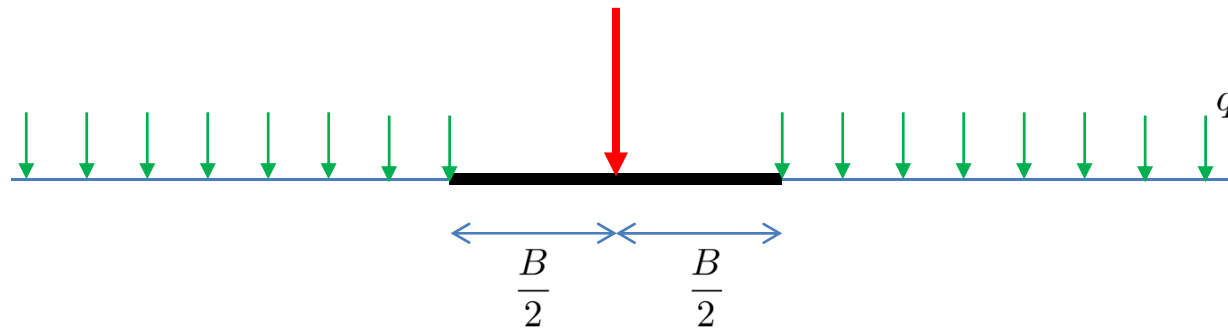
OPTUM G2



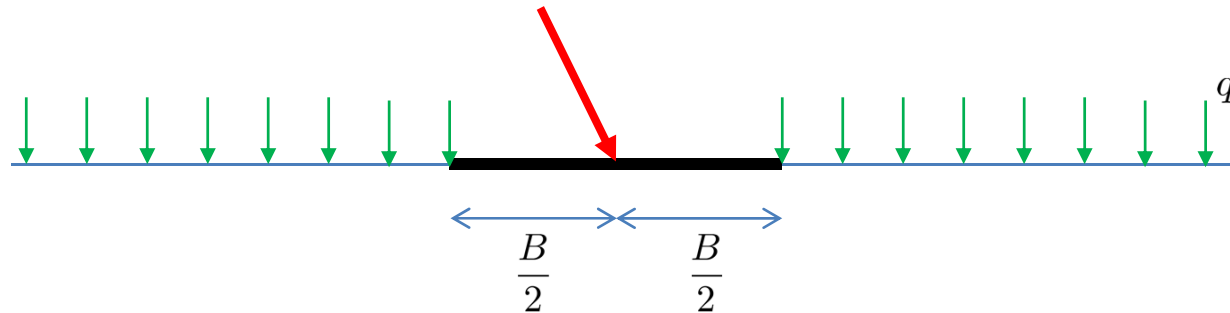
10,000 elements (LB/UB) + 3 adaptive iterations (sol time \approx 20 sec):

$q_u \text{ (kN/m}^2\text{)}$				
LB	UB	$(LB+UB)/2$	BCE	Dev. (%)
915.4	950.8	933.1	783.4	+16%

Inclined load

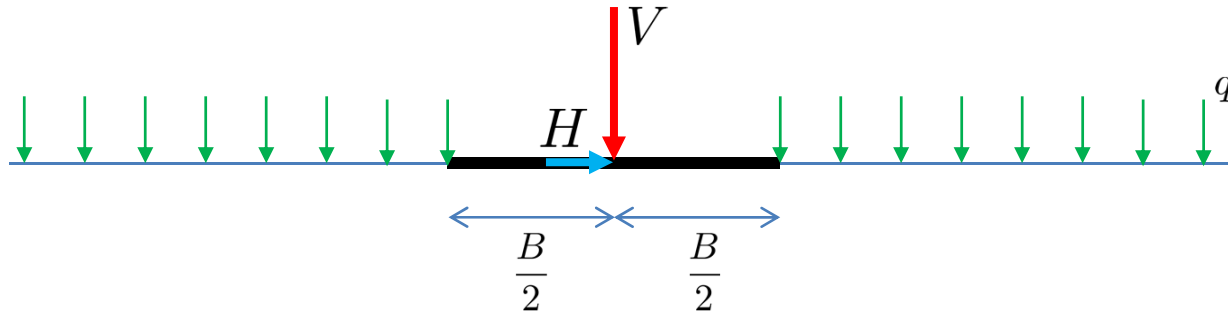


Inclined load



BEARING CAPACITY EQUATION

Inclined load



Modified equation:

$$\frac{V_u}{B} = cN_c i_c + qN_q i_q + \frac{1}{2}\gamma B N_\gamma i_\gamma$$

where (EC7, strip)

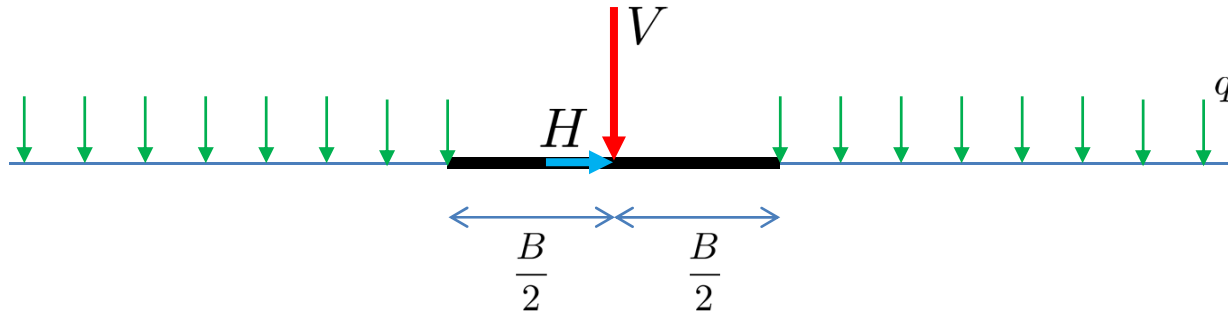
$$i_q = \left(1 - \frac{H}{V + Bc/\tan \phi}\right)^2$$

$$i_c = i_q - \frac{1 - i_q}{N_c \tan \phi}$$

$$i_\gamma = \left(1 - \frac{H}{V + Bc/\tan \phi}\right)^3$$

BEARING CAPACITY EQUATION

Inclined load



Surface foundation, $c = 0$:

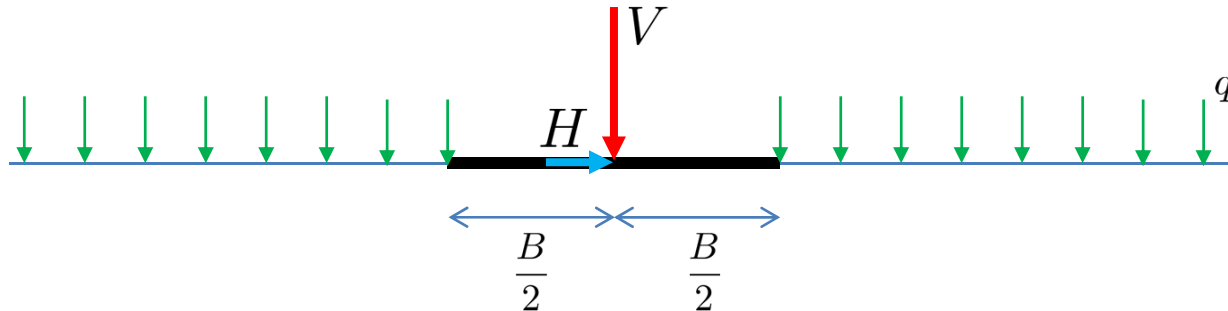
$$\frac{V_u}{B} = \frac{1}{2} \gamma B N_\gamma i_\gamma$$

where

$$i_\gamma = \left(1 - \frac{H}{V}\right)^3 \quad (\text{EC7})$$

BEARING CAPACITY EQUATION

Inclined load



Surface foundation, $c = 0$:

$$\frac{V_u}{B} = \frac{1}{2} \gamma B N_\gamma i_\gamma$$

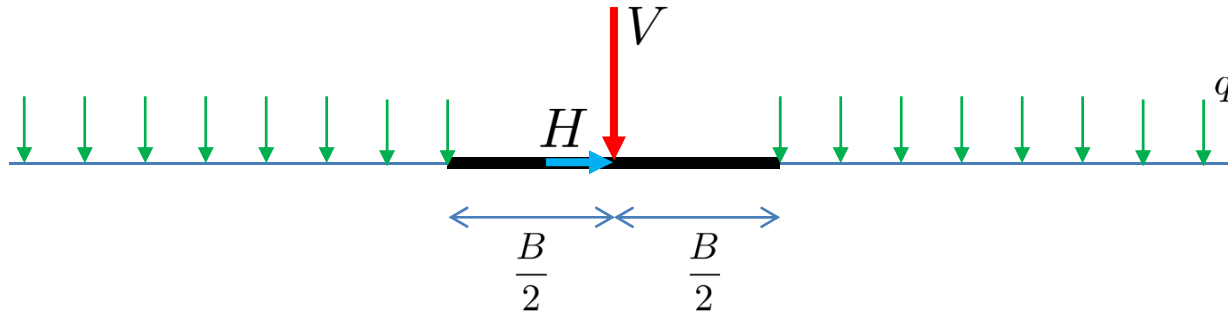
where

$$i_\gamma = \left(1 - \frac{H}{V}\right)^3 \quad (\text{EC7})$$

$$i_\gamma = \left(1 - \frac{0.7H}{V}\right)^5 \quad (\text{DNV})$$

BEARING CAPACITY EQUATION

Inclined load



Surface foundation, $c = 0$:

$$\frac{V_u}{B} = \frac{1}{2} \gamma B N_\gamma i_\gamma$$

where

$$i_\gamma = \left(1 - \frac{H}{V}\right)^3 \quad (\text{EC7})$$

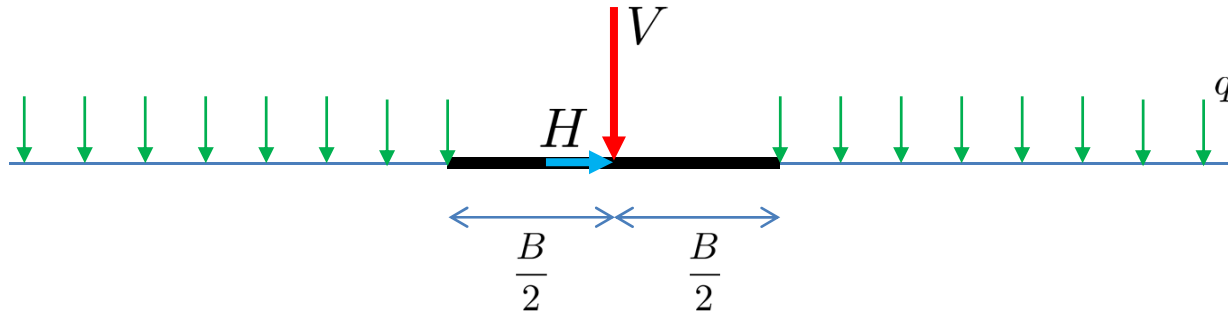
$$i_\gamma = \left(1 - \frac{0.7H}{V}\right)^5 \quad (\text{DNV})$$

However:

$$i_\gamma > 0 \quad \text{for} \quad H = V \tan \phi \quad (\text{sliding})$$

BEARING CAPACITY EQUATION

Inclined load



Surface foundation, $c = 0$:

$$\frac{V_u}{B} = \frac{1}{2} \gamma B N_\gamma i_\gamma$$

where

$$i_\gamma = \left(1 - \frac{H}{V}\right)^3 \quad (\text{EC7})$$

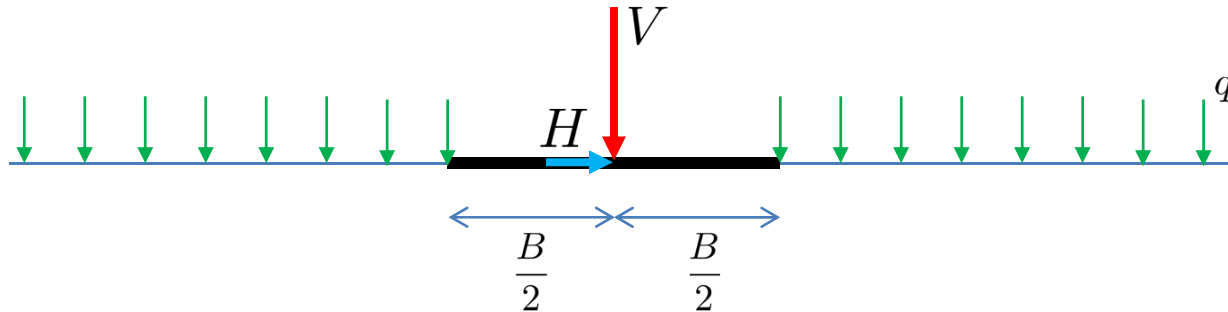
$$i_\gamma = \left(1 - \frac{0.7H}{V}\right)^5 \quad (\text{DNV})$$

Alternative:

$$i_\gamma = 1 - \left(\frac{H}{V \tan \phi}\right)^m, \quad m = \frac{40.6 \tan \phi}{20.7 - 8.8 \tan \phi}$$

BEARING CAPACITY EQUATION

Inclined load

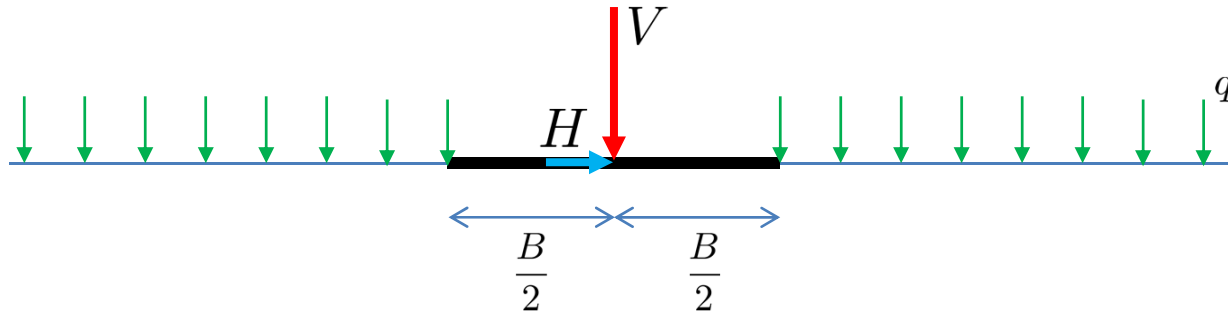


VH diagram:

$$\frac{V_u}{B} = \frac{1}{2} \gamma B N_\gamma \left[1 - \left(\frac{H}{V \tan \phi} \right)^m \right]$$

BEARING CAPACITY EQUATION

Inclined load



VH diagram:

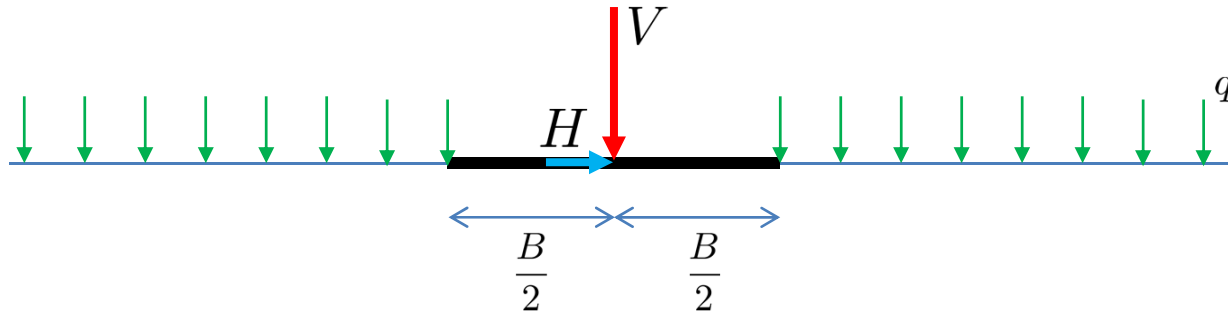
$$\frac{V_u}{B} = \frac{1}{2} \gamma B N_\gamma \left[1 - \left(\frac{H}{V \tan \phi} \right)^m \right]$$

or:

$$H = \left[1 - \left(\frac{V}{\frac{1}{2} \gamma B^2 N_\gamma} \right)^{\frac{1}{m}} \right] V \tan \phi$$

BEARING CAPACITY EQUATION

Inclined load



VH diagram:

$$\frac{V_u}{B} = \frac{1}{2} \gamma B N_\gamma \left[1 - \left(\frac{H}{V \tan \phi} \right)^m \right]$$

or:

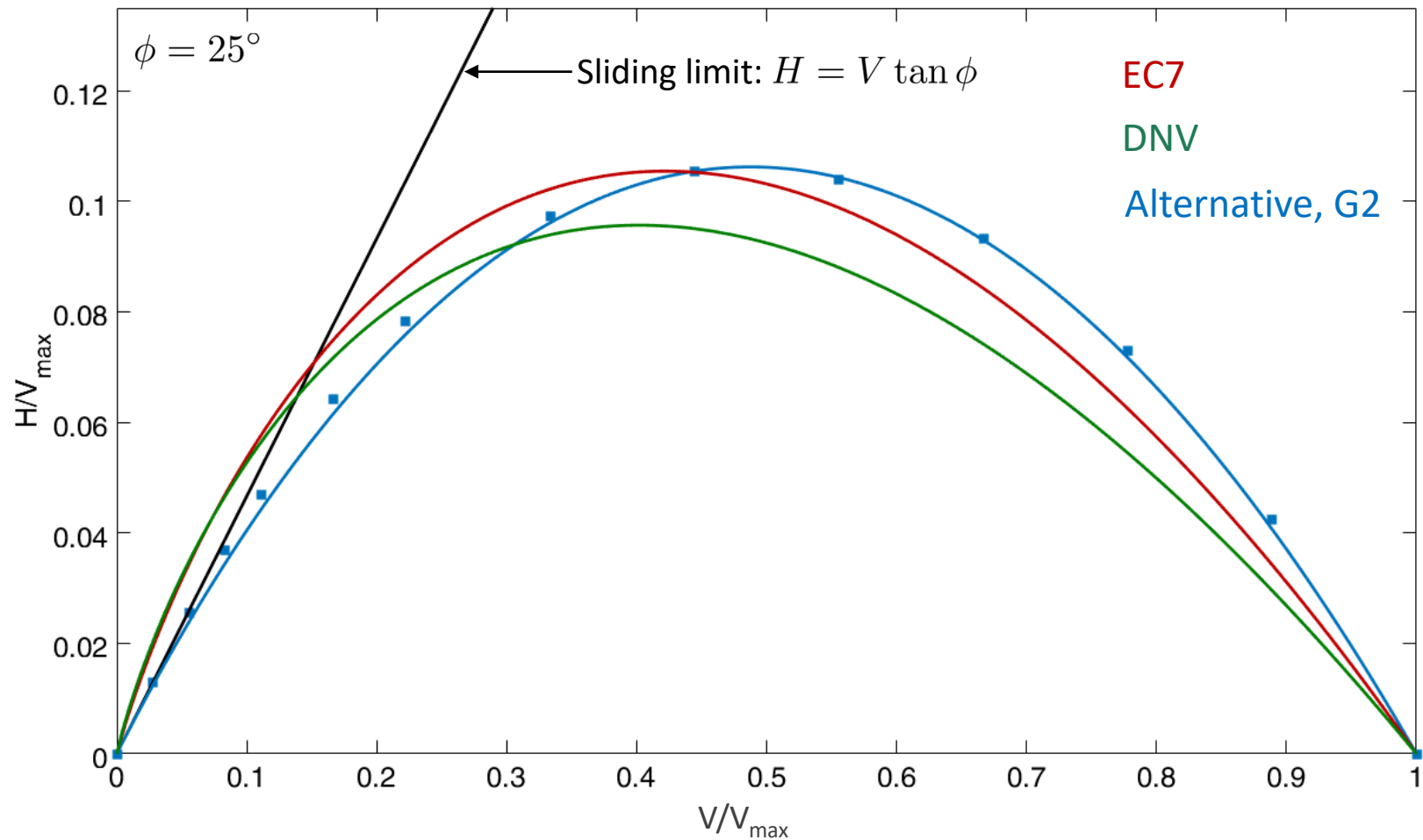
$$\frac{H}{V_{\max}} = \left[1 - \left(\frac{V}{V_{\max}} \right)^{\frac{1}{m}} \right] \frac{V}{V_{\max}} \tan \phi$$

where

$$V_{\max} = \frac{1}{2} \gamma B N_\gamma$$

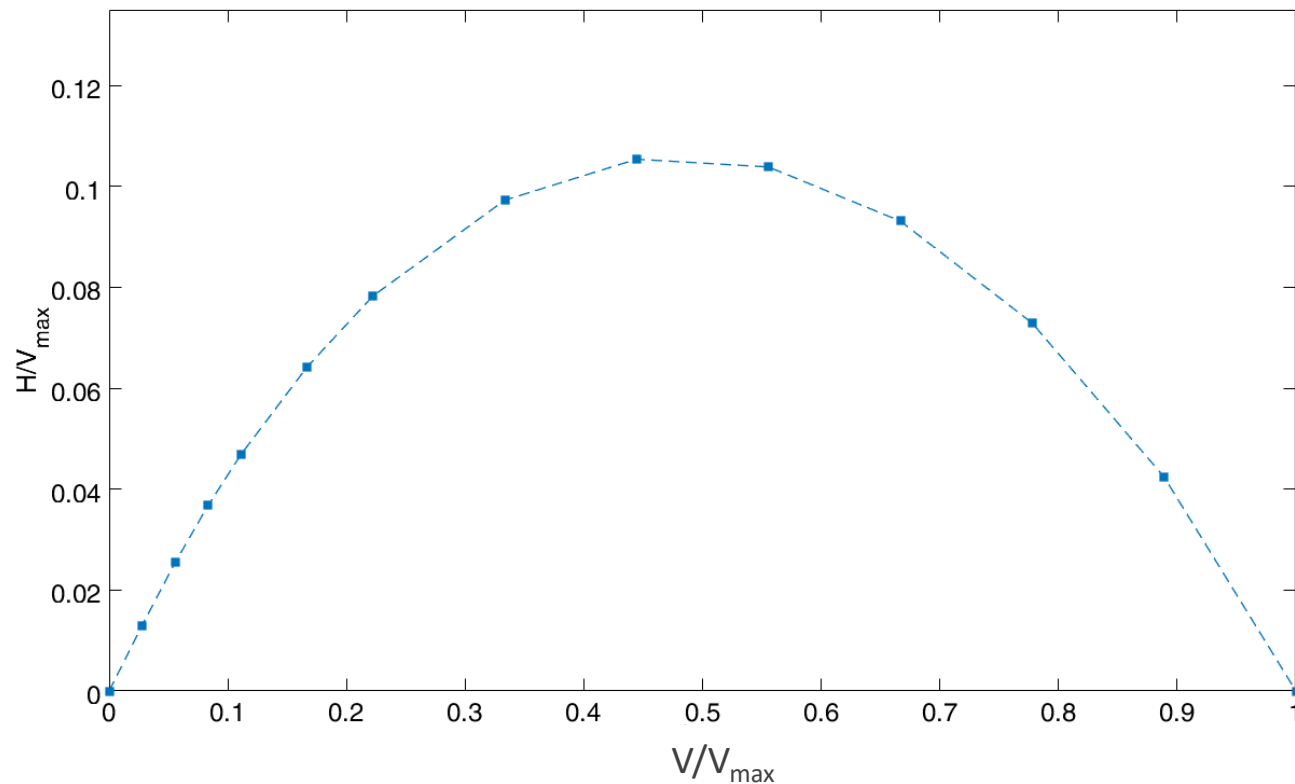
BEARING CAPACITY EQUATION

Inclined load



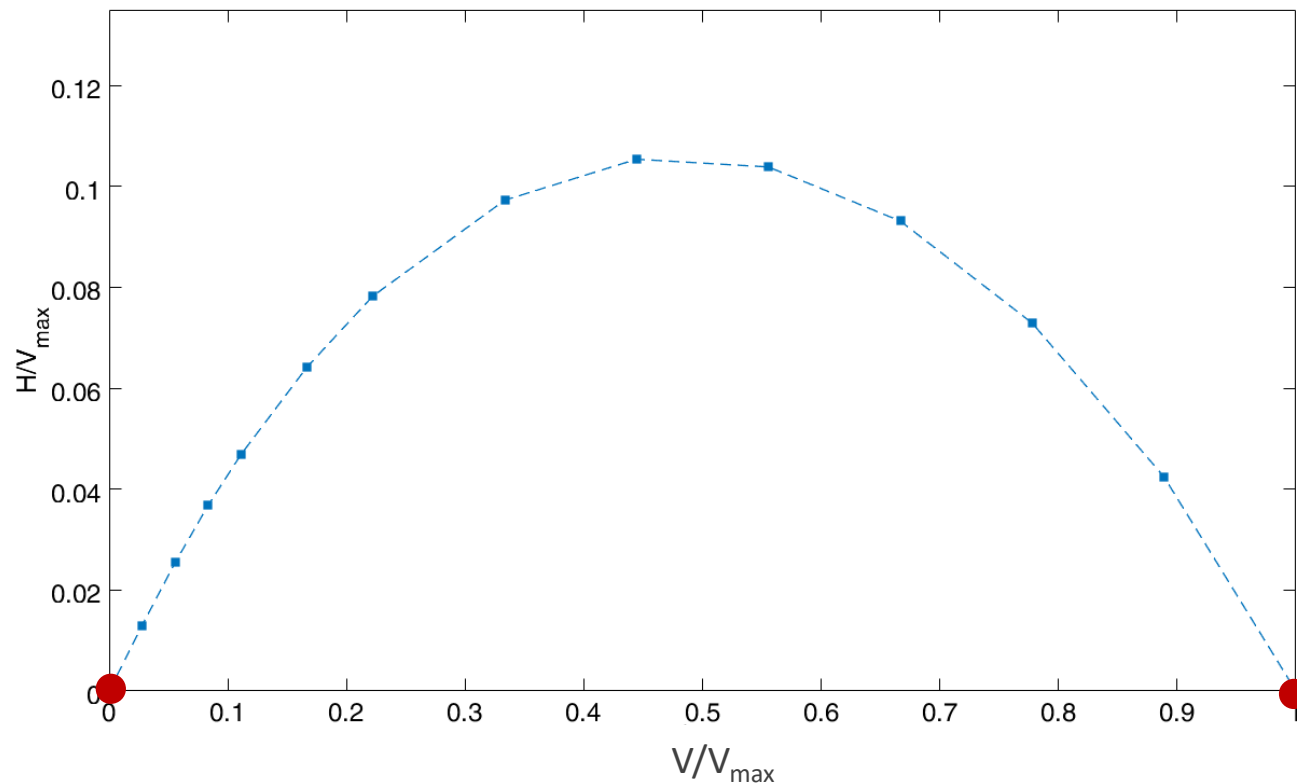
VH diagrams using Limit Analysis

1. Determine V_{\min} and V_{\max}



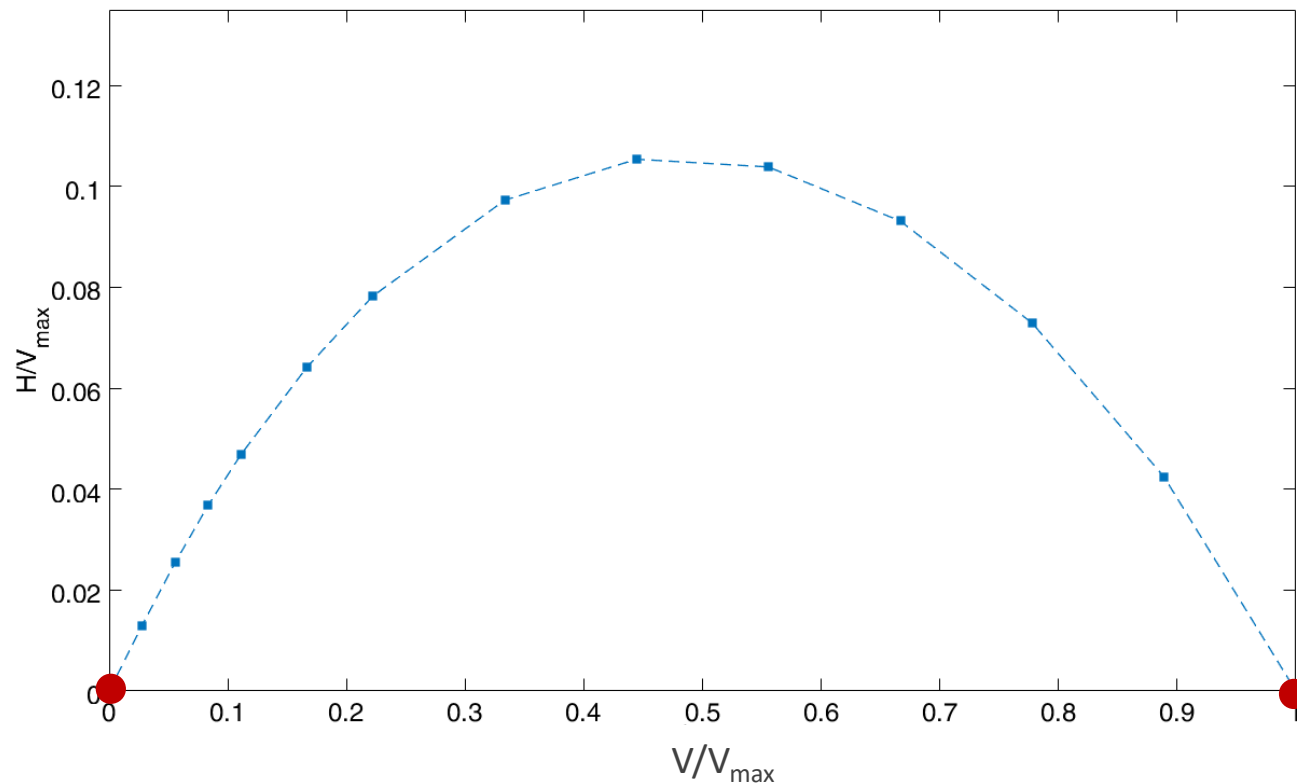
VH diagrams using Limit Analysis

1. Determine V_{\min} and V_{\max}



VH diagrams using Limit Analysis

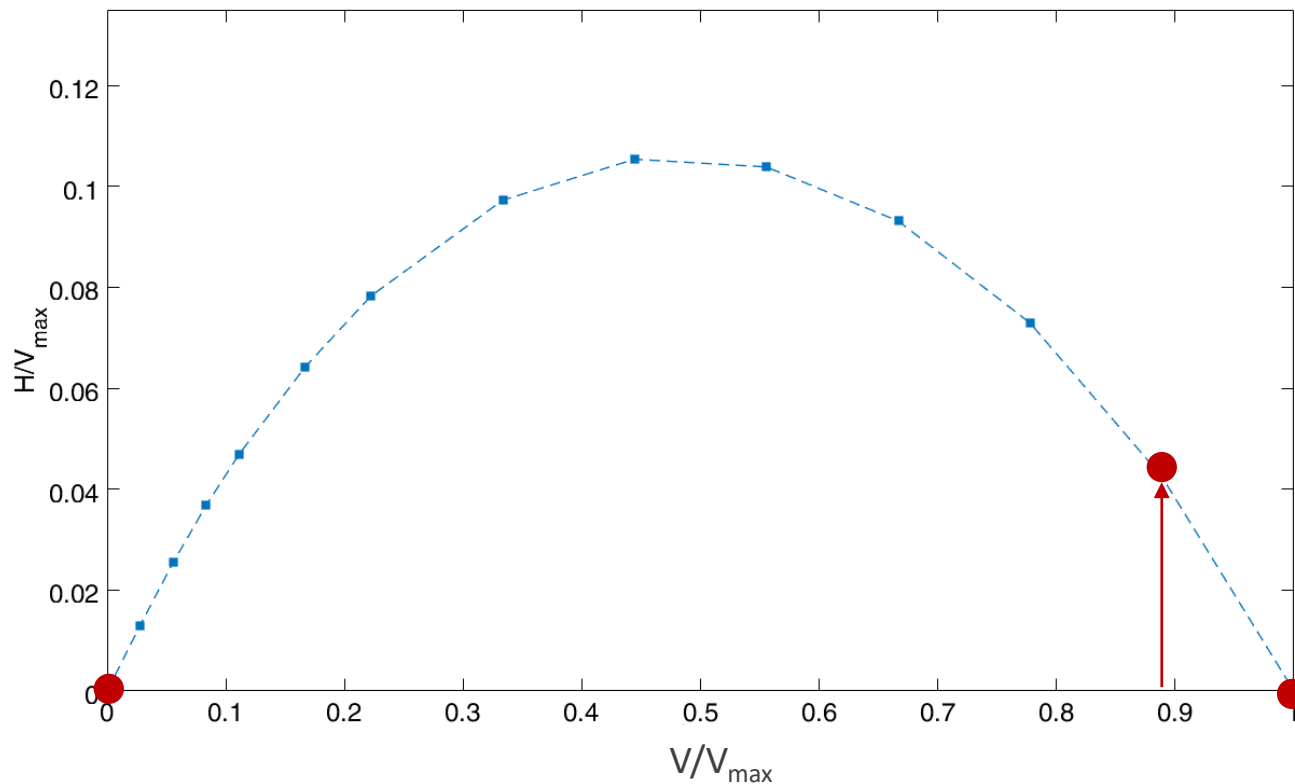
1. Determine V_{\min} and V_{\max}
2. Determine H for fixed V in between V_{\min} and V_{\max}



BEARING CAPACITY EQUATION

VH diagrams using Limit Analysis

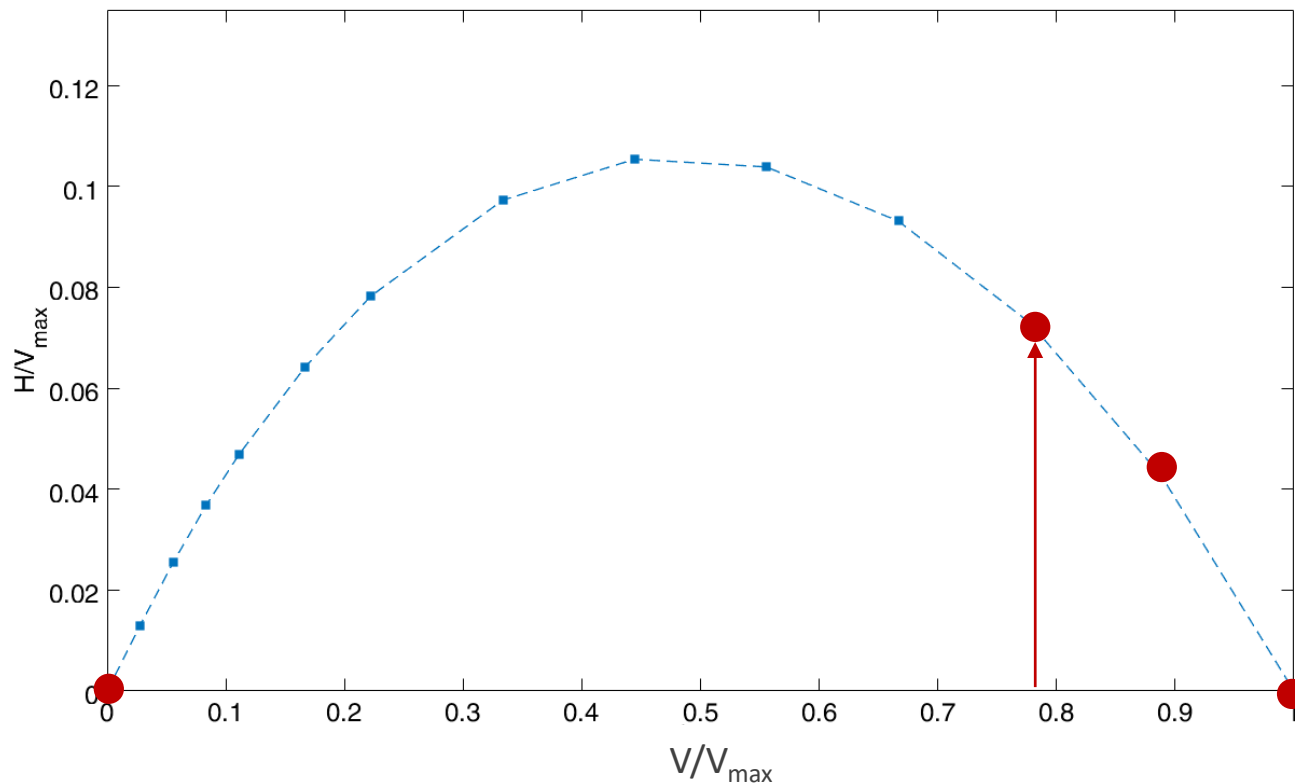
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BEARING CAPACITY EQUATION

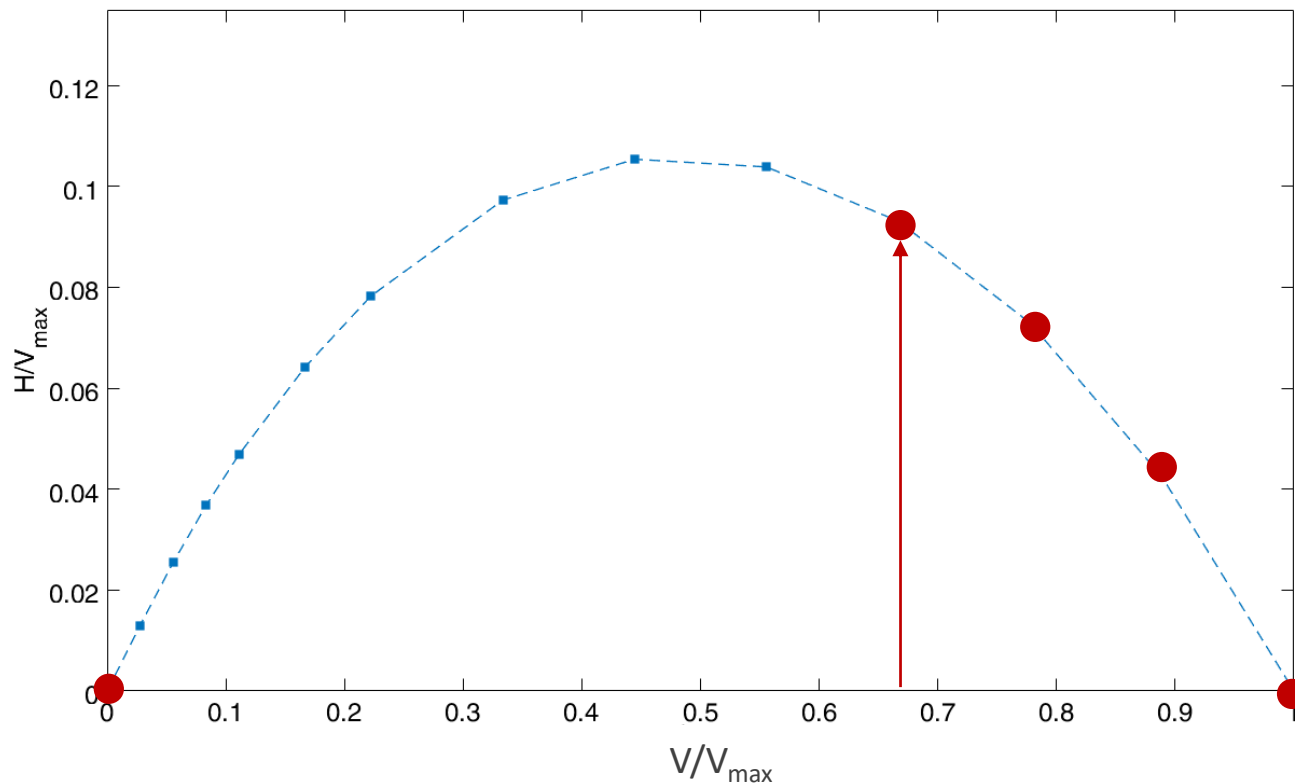
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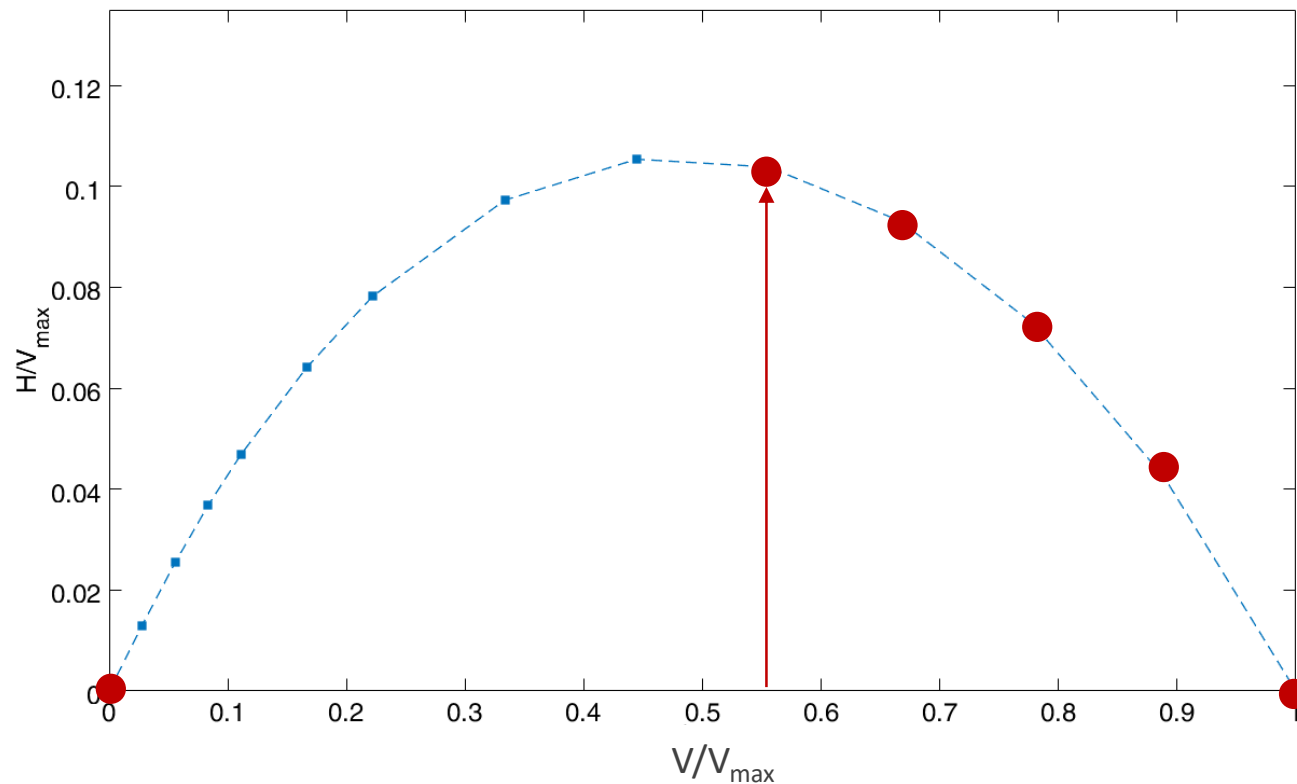
VH diagrams using Limit Analysis

1. Determine V_{\min} and V_{\max}
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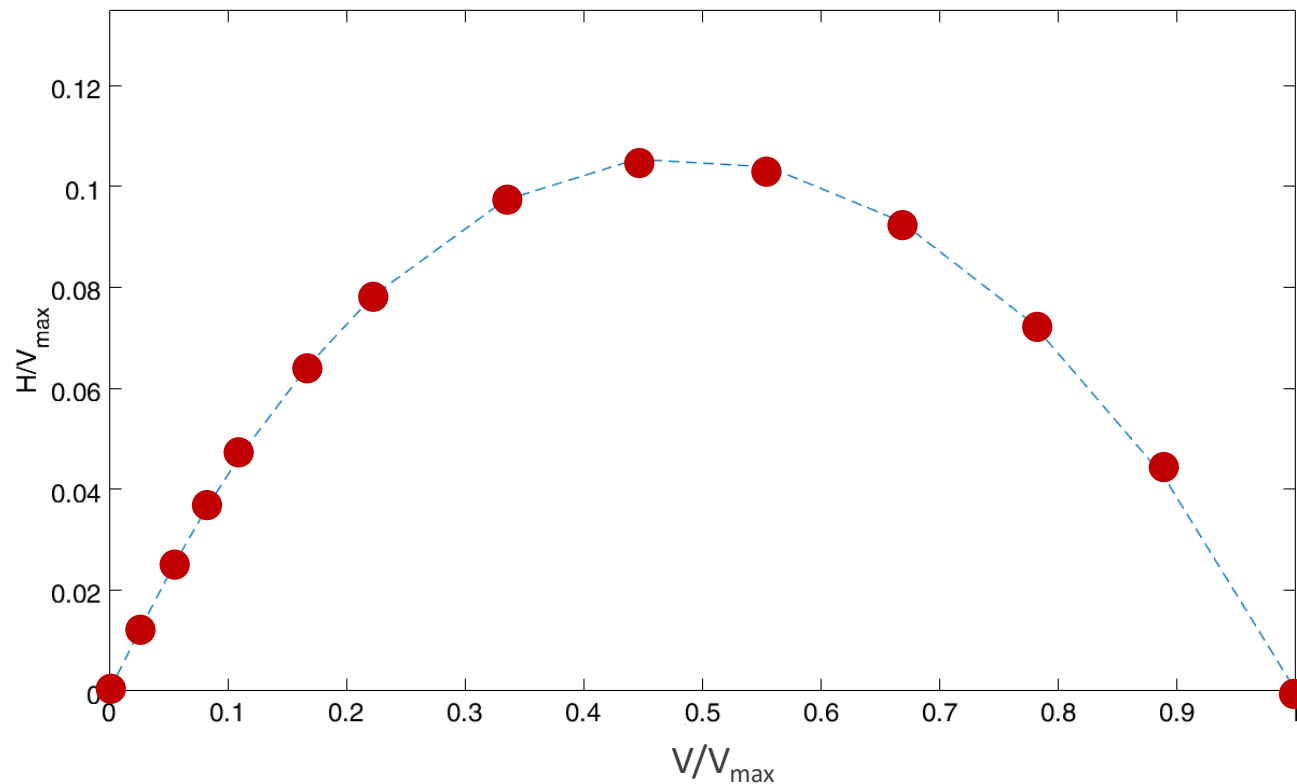
VH diagrams using Limit Analysis

1. Determine V_{\min} and V_{\max}
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VH diagrams using Limit Analysis

1. Determine V_{\min} and V_{\max}
2. Determine H for fixed V in between V_{\min} and V_{\max}



VH diagrams using Limit Analysis

YouTube channel page for Optum Computational Engineering. The page displays a banner image of a construction site with a large geodesic dome structure. Below the banner, the channel name "Optum Computational Engineering" is shown with 281 subscribers. The "HOME" tab is selected. A video titled "Why Choose Optum" is featured. Below this, a row of video thumbnails is displayed, with the thumbnail "OPTUMG2 VIA MATLAB" highlighted by a red box. The "OPTUM G2" playlist is also visible.

Optum Computational Engineering
281 subscribers

Why Choose Optum
Optum Computational Engineering · 3.5K views · 2 years ago
Next Generation Design Software for Engineers

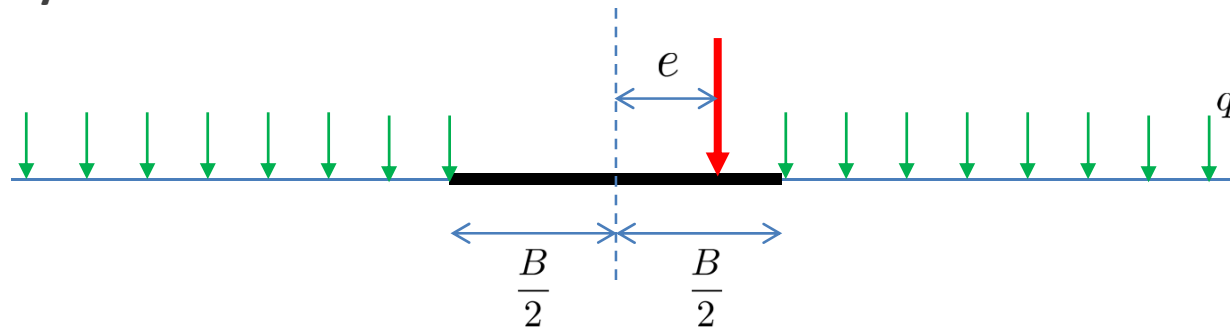
OPTUM G2 ▶ PLAY ALL

- OPTUM G2 - the basics
Optum Computational Engineering · 850 views · 5 months ago
- OPTUM G2 Slope Stability - Factor of Safety
Optum Computational Engineering · 5K views · 5 years ago
- OPTUM G2 Shallow foundation - Upper and low...
Optum Computational Engineering · 1.3K views · 5 years ago
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Optum Computational Engineering · 5.1K views · 7 months ago
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Optum Computational Engineering · 915K views · 1 month ago
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Eccentricity



Eccentricity

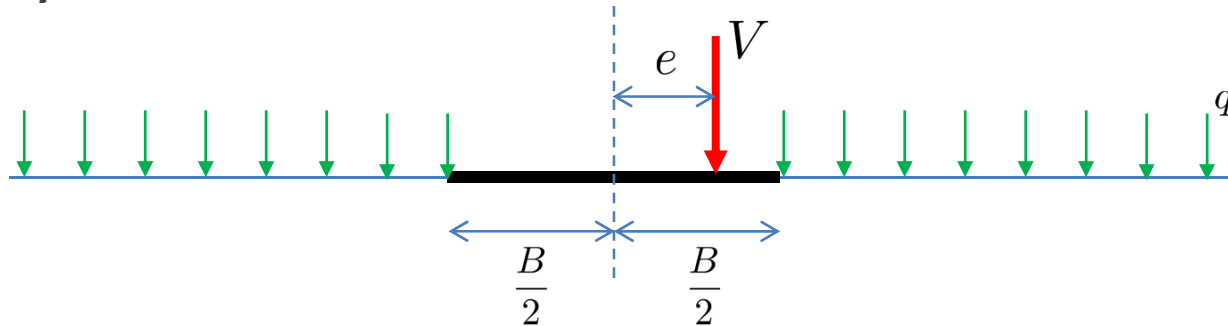


Eccentricity



BEARING CAPACITY EQUATION

Eccentricity



Modified equation:

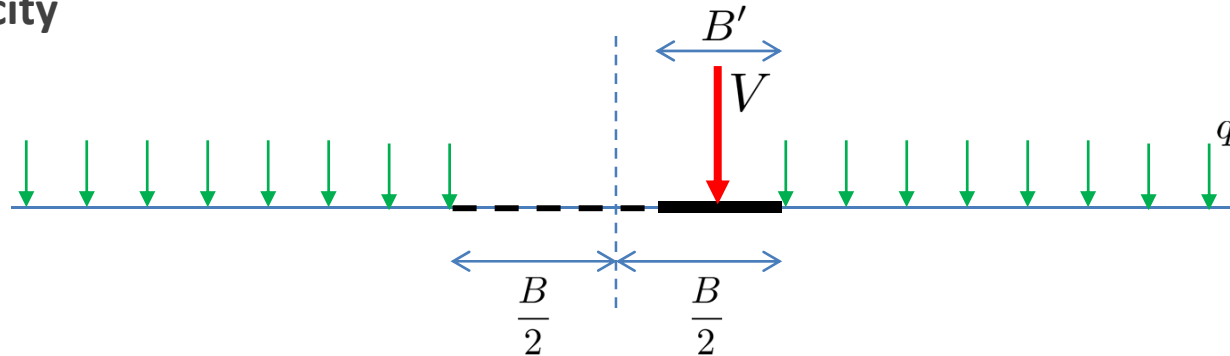
$$\frac{V_u}{B'} = cN_c i_c + qN_q i_q + \frac{1}{2}\gamma B' N_\gamma i_\gamma$$

where

$$B' = B - 2e$$

BEARING CAPACITY EQUATION

Eccentricity



Modified equation:

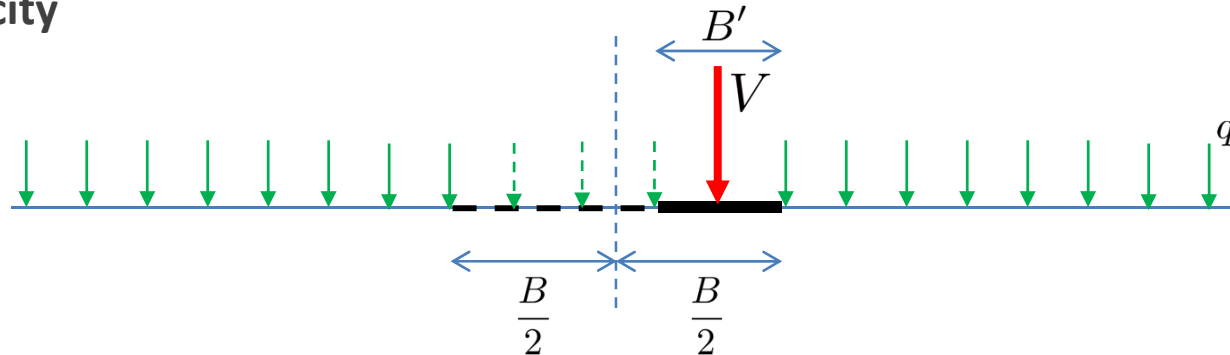
$$\frac{V_u}{B'} = cN_c i_c + qN_q i_q + \frac{1}{2}\gamma B' N_\gamma i_\gamma$$

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BEARING CAPACITY EQUATION

Eccentricity



Modified equation:

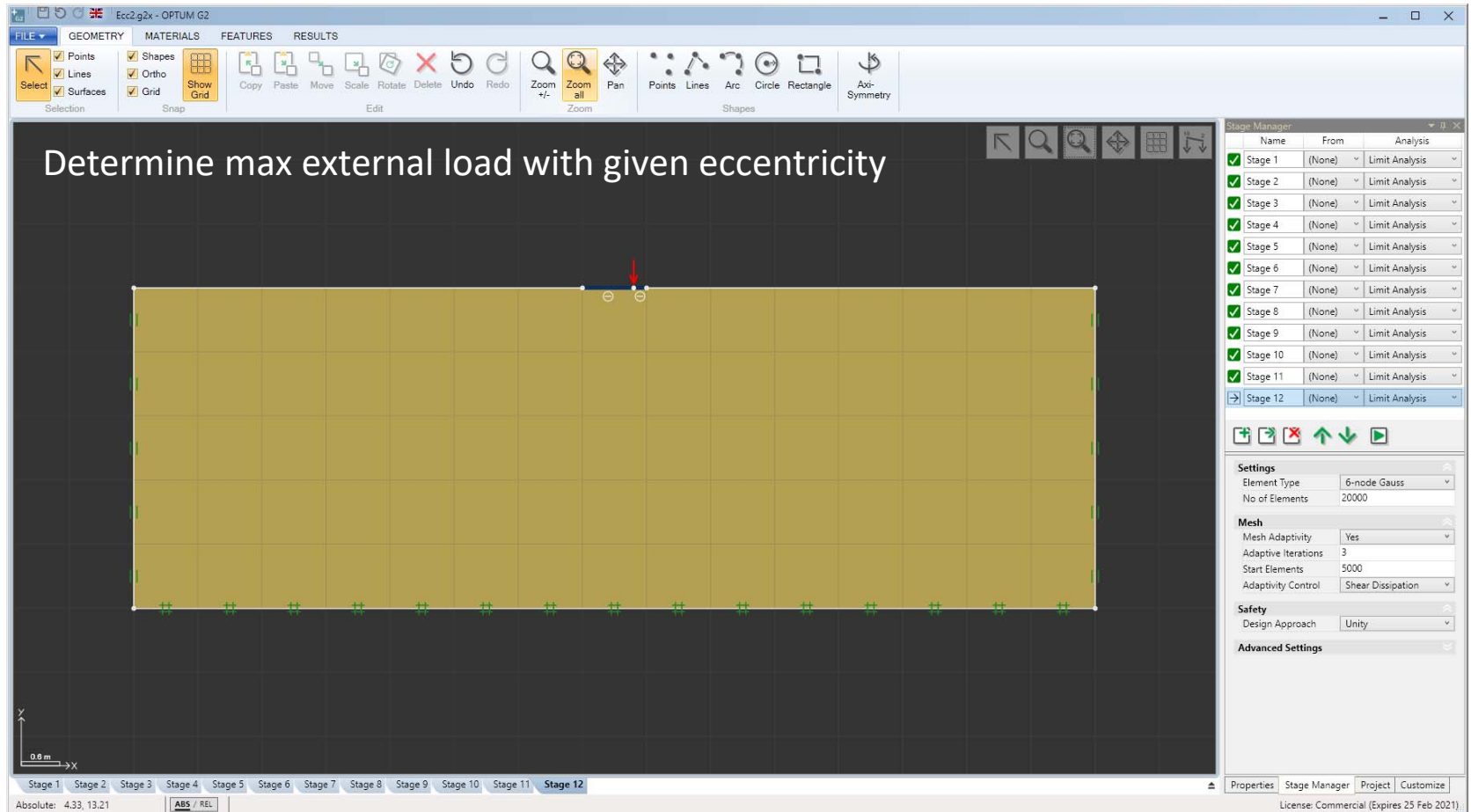
$$\frac{V_u}{B'} = cN_c i_c + qN_q i_q + \frac{1}{2}\gamma B' N_\gamma i_\gamma$$

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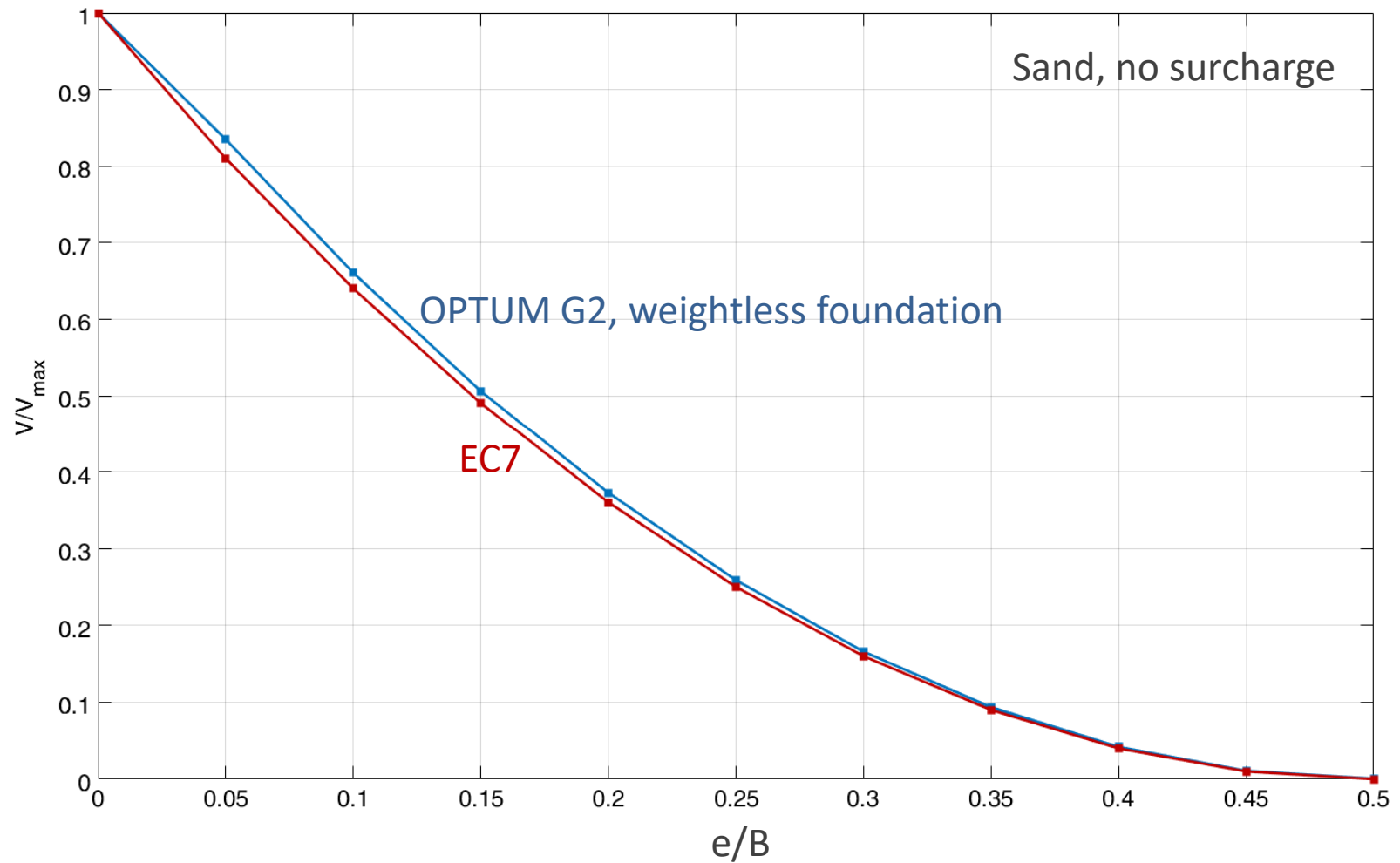
BEARING CAPACITY EQUATION

Eccentricity



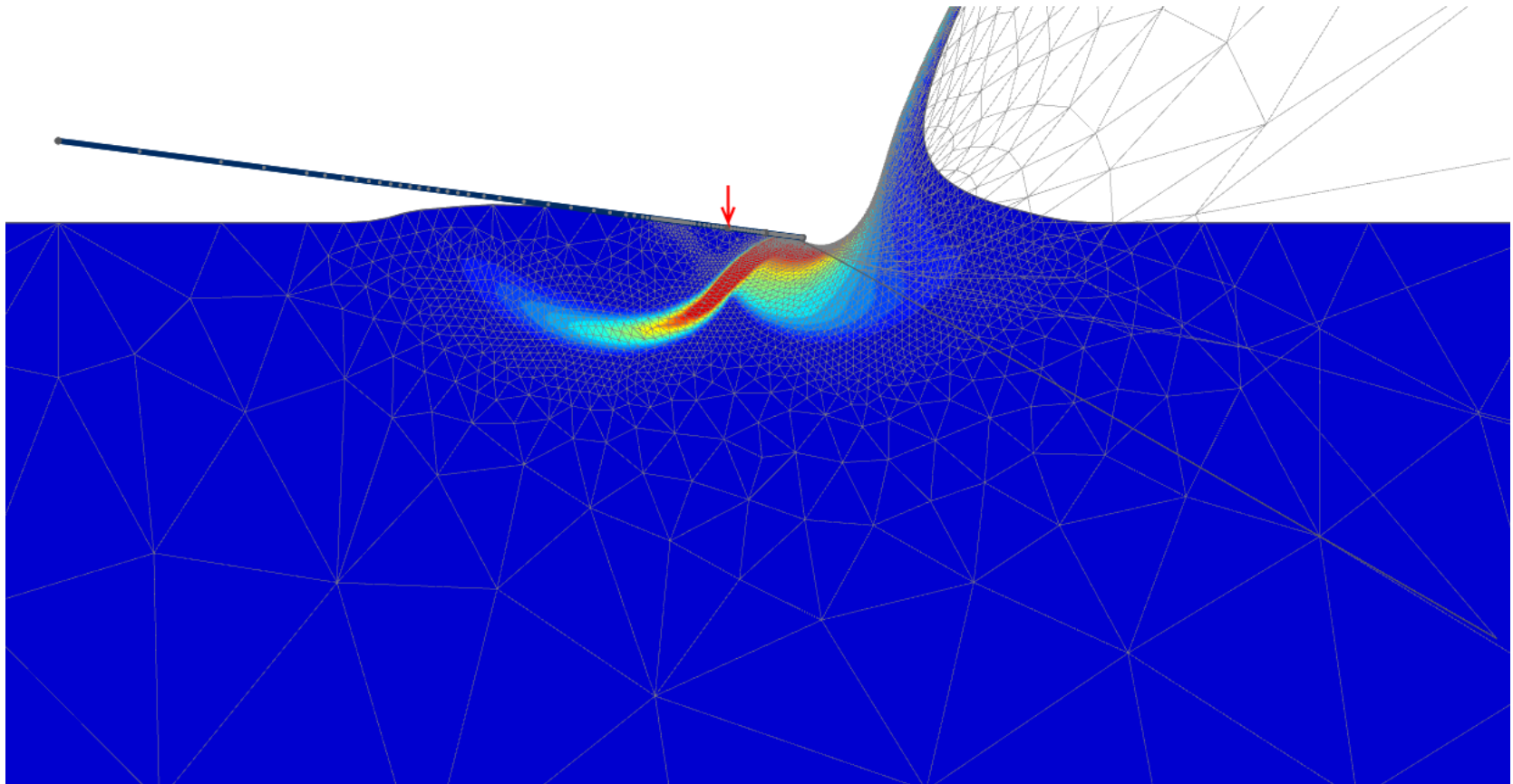
BEARING CAPACITY EQUATION

Eccentricity



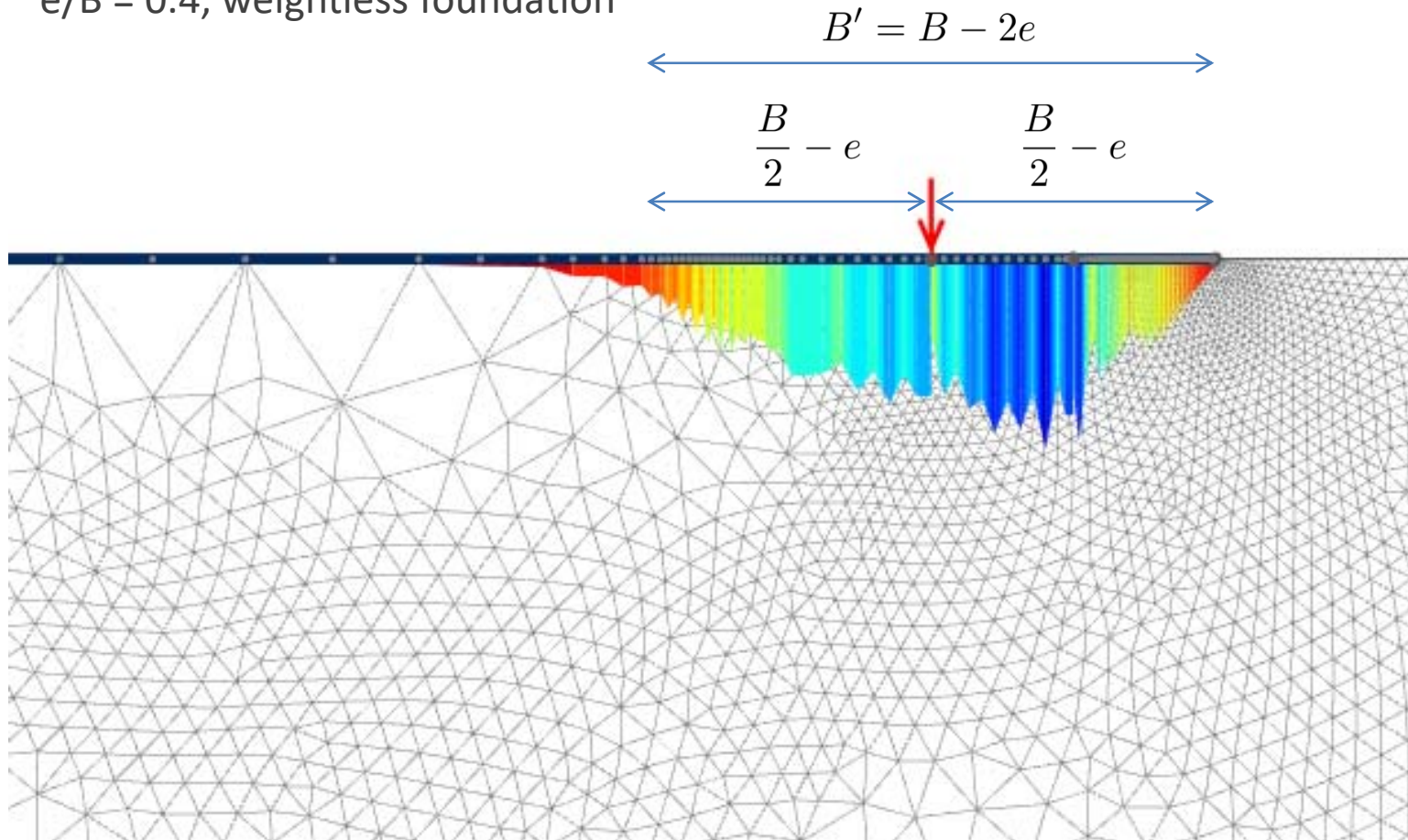
Eccentricity

$e/B = 0.4$, weightless foundation



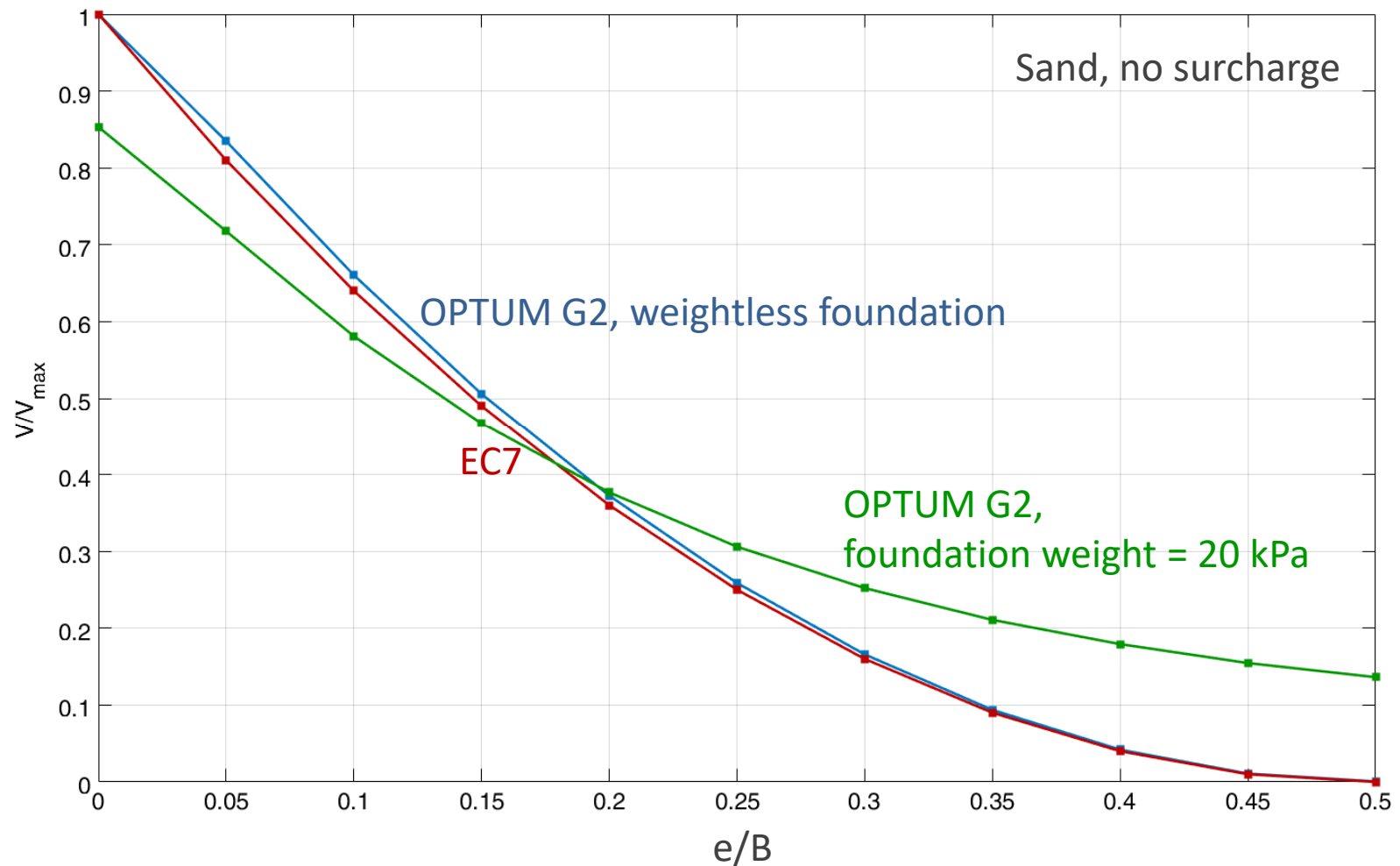
Eccentricity

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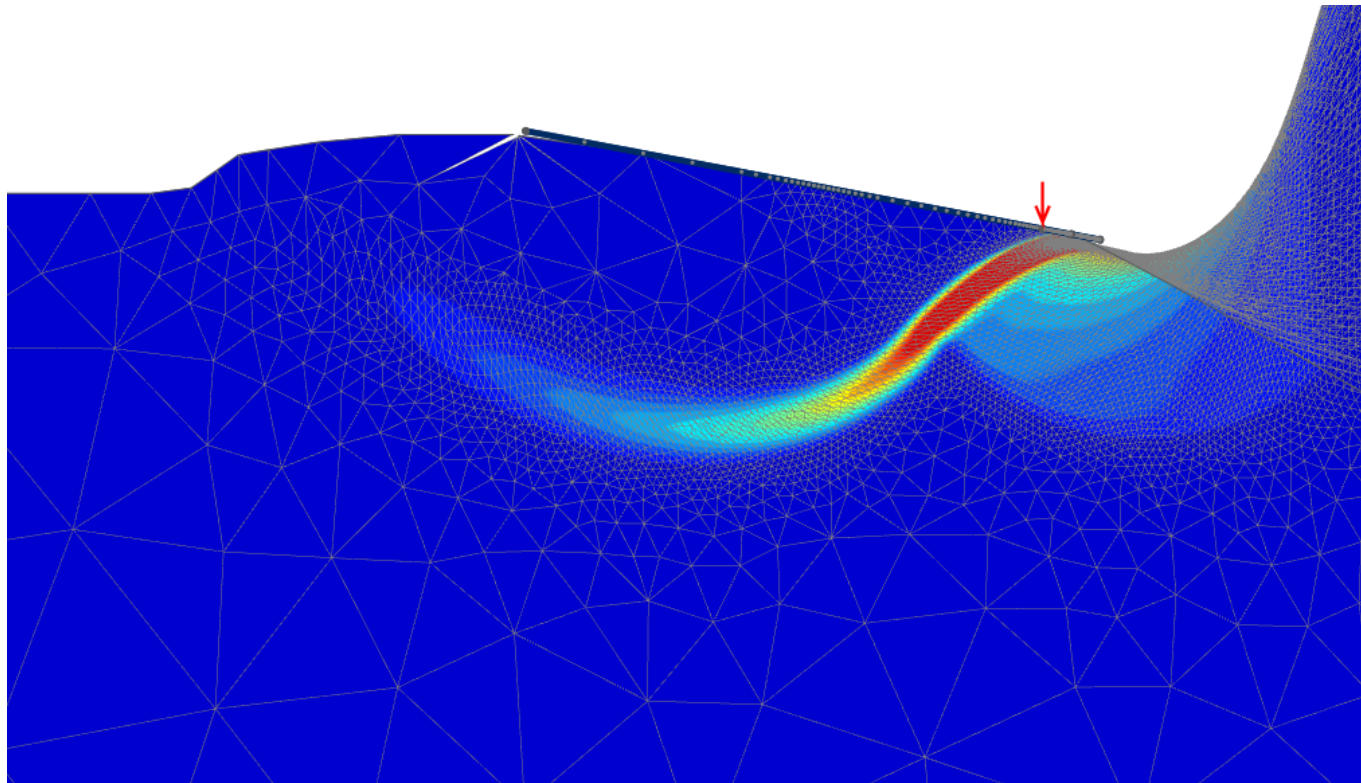
BEARING CAPACITY EQUATION

Eccentricity



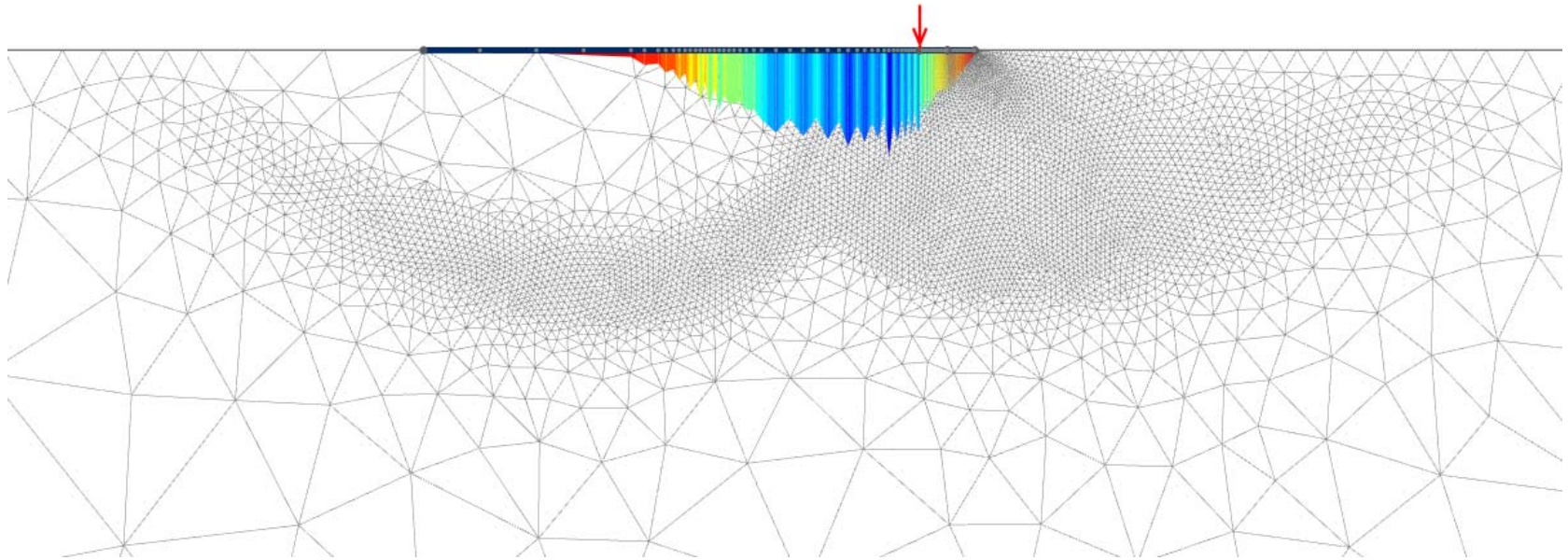
Eccentricity

$e/B = 0.4$, foundation weight = 20 kPa



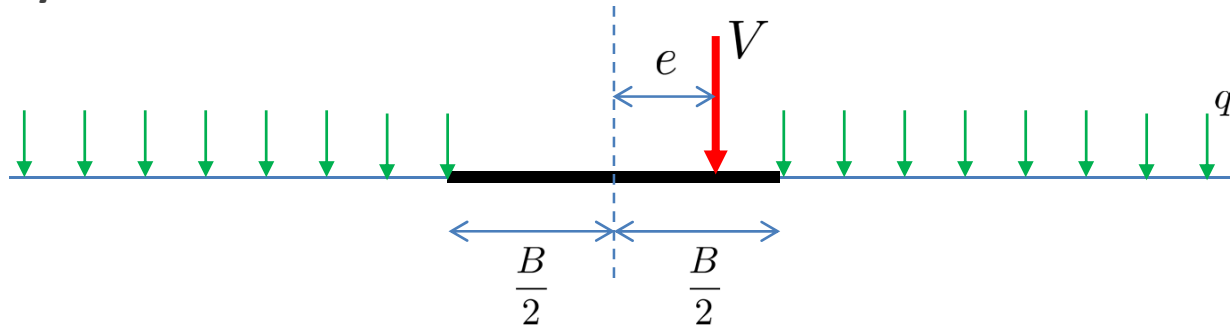
Eccentricity

$e/B = 0.4$, foundation weight = 20 kPa



BEARING CAPACITY EQUATION

Eccentricity



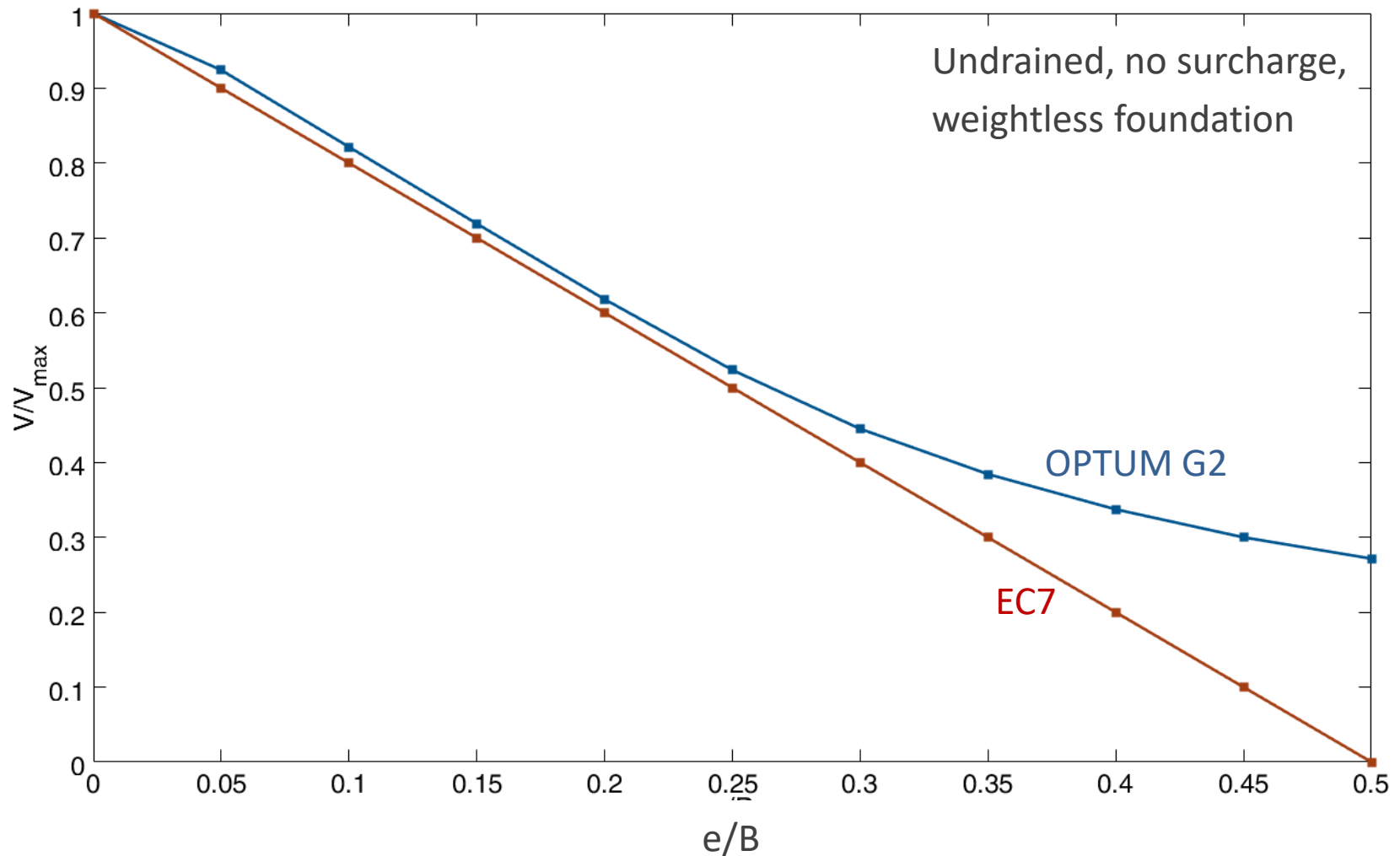
Undrained, no surcharge:

$$\frac{V_u}{B'} = (2 + \pi)s_u$$

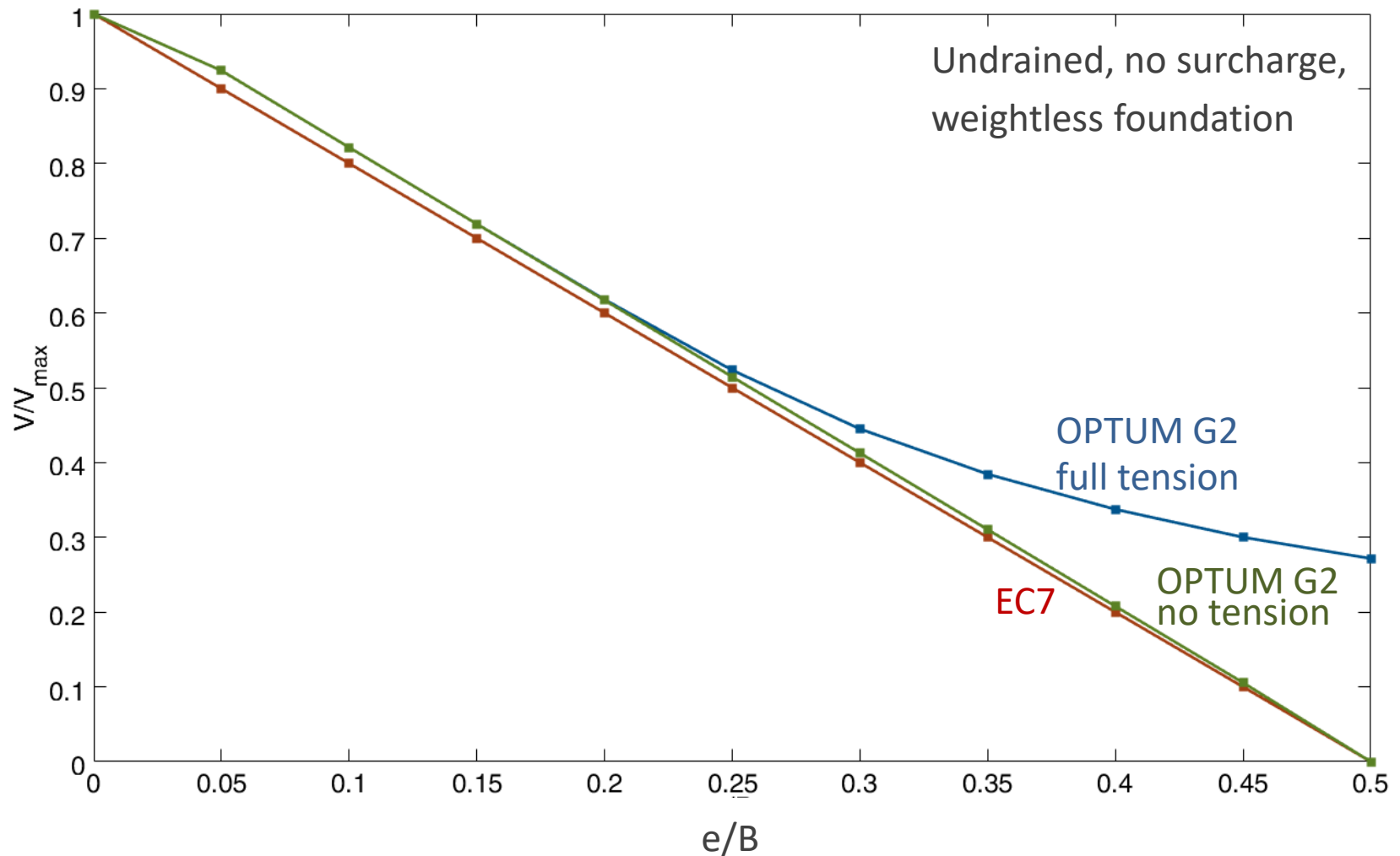
where

$$B' = B - 2e$$

Eccentricity

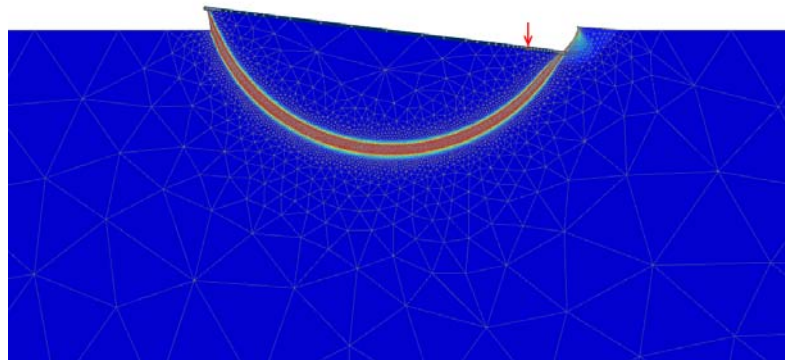


Eccentricity

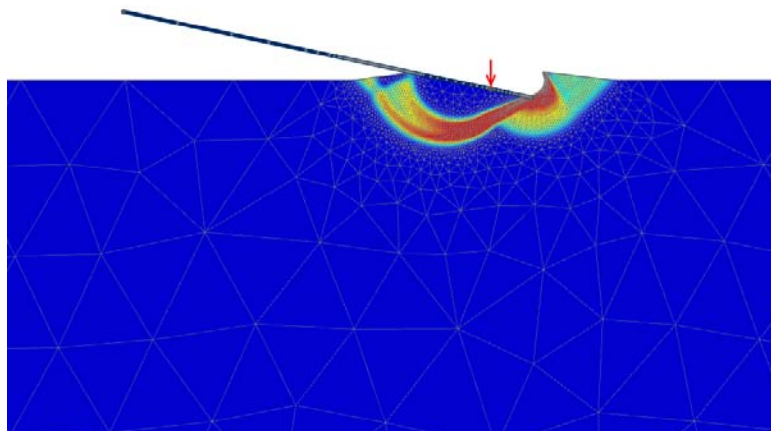


Eccentricity

$$e/B = 0.4$$



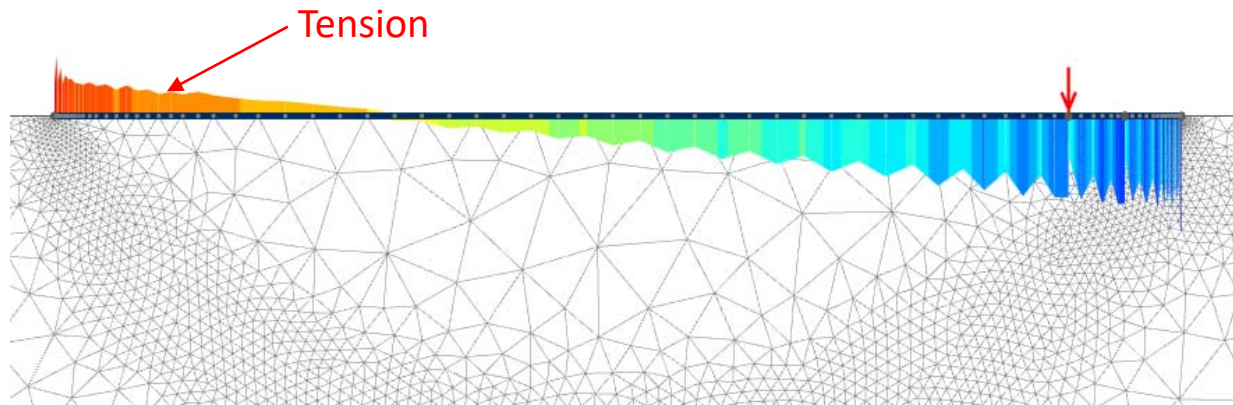
Full tension at interface



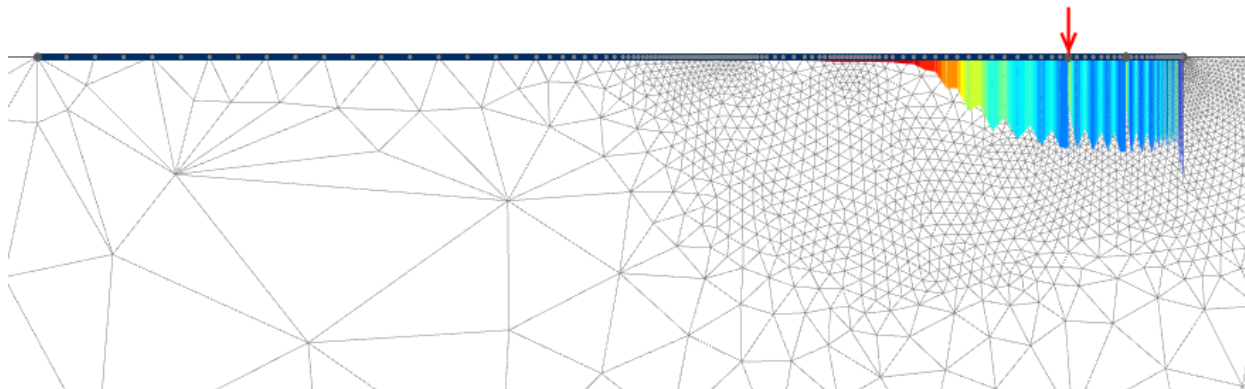
No tension at interface (tension cut-off)

Eccentricity

$$e/B = 0.4$$



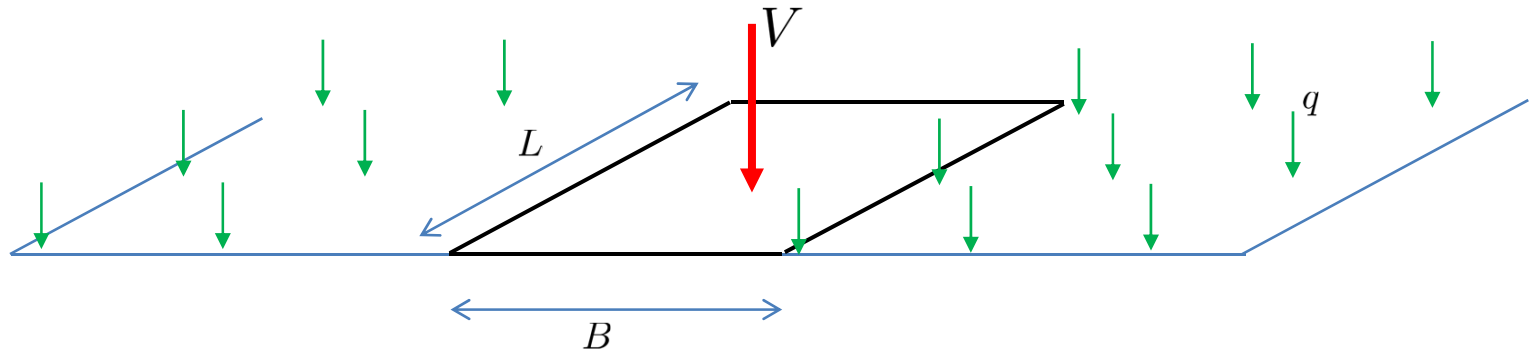
Full tension at interface



No tension at interface (tension cut-off)

BEARING CAPACITY EQUATION

Shape



Modified equation:

$$\frac{V_u}{A} = cN_c i_c s_c + qN_q i_q s_q + \frac{1}{2}\gamma B N_\gamma i_\gamma s_\gamma$$

where (EC7)

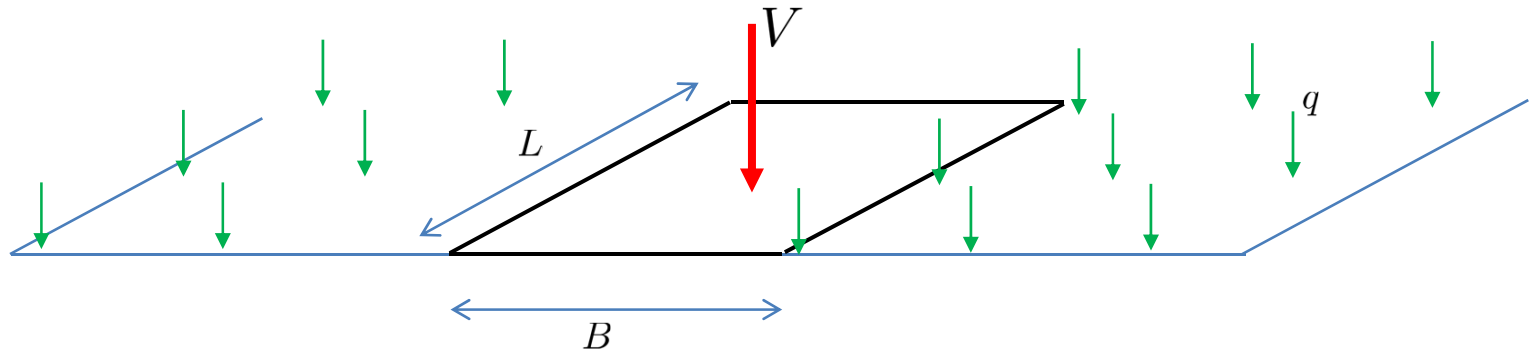
$$s_q = 1 + \frac{B'}{L'} \sin \phi$$

$$s_c = \frac{s_q N_q - 1}{N_q - 1}$$

$$s_\gamma = 1 - 0.3 \frac{B'}{L'}$$

BEARING CAPACITY EQUATION

Shape



Modified equation:

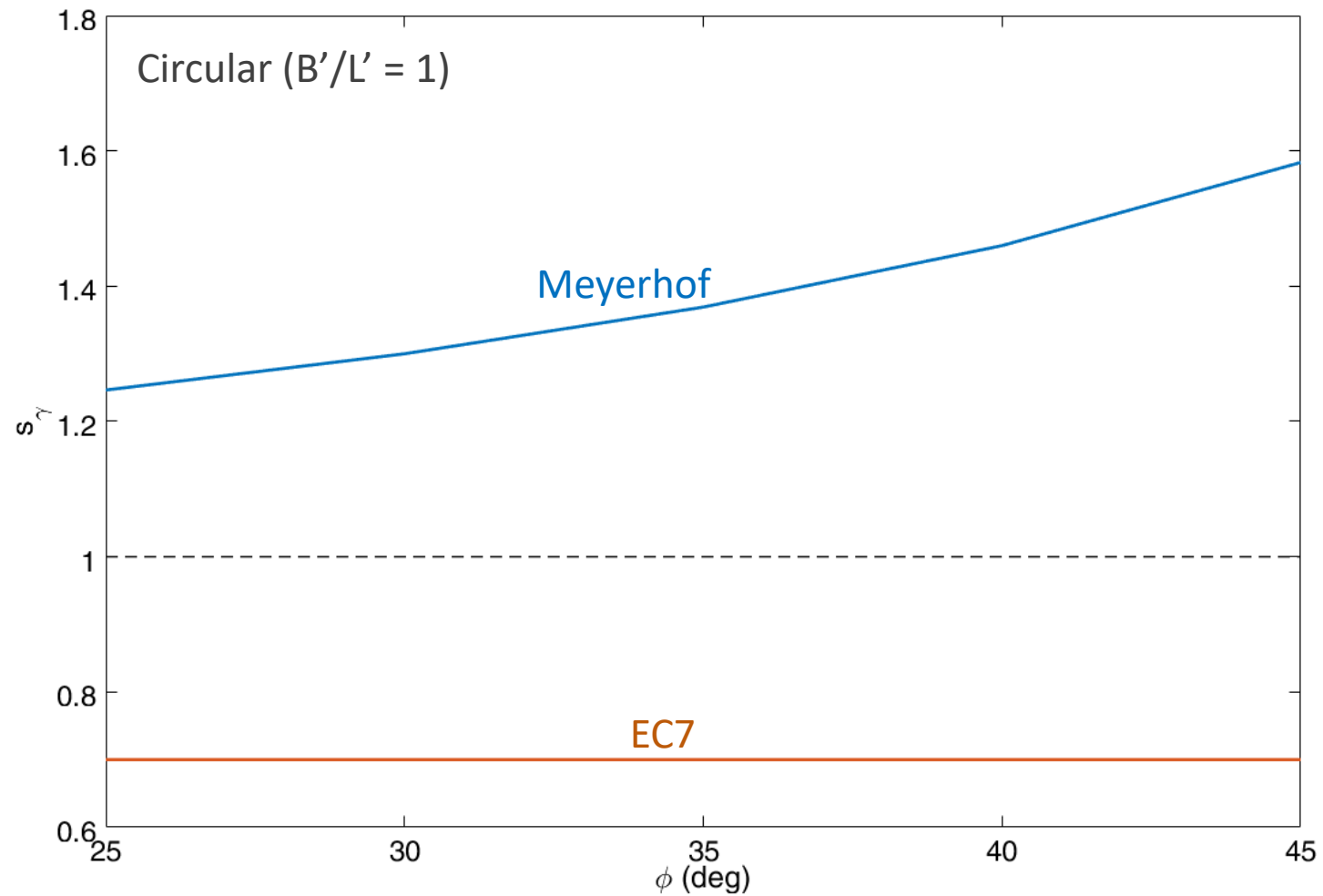
$$\frac{V_u}{A} = cN_c i_c s_c + qN_q i_q s_q + \frac{1}{2} \gamma B N_\gamma i_\gamma s_\gamma$$

Two families of shape factors:

EC7: $s_\gamma = 1 - 0.3 \frac{B'}{L'}$: independent of ϕ and always ≤ 1

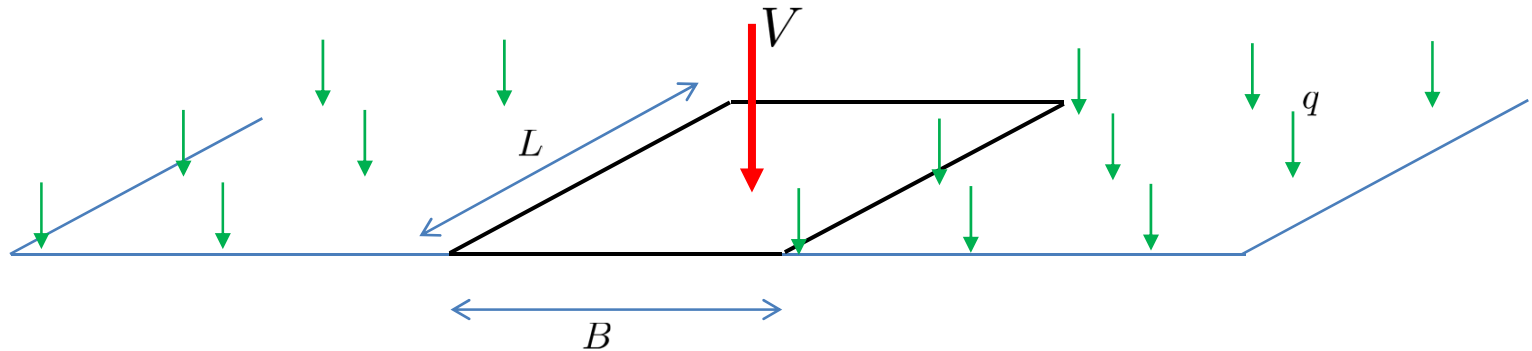
Meyerhof: $s_\gamma = 1 + 0.1 \tan^2(45 + \frac{1}{2}\phi)$: dependent on ϕ and always ≥ 1

Shape



BEARING CAPACITY EQUATION

Shape



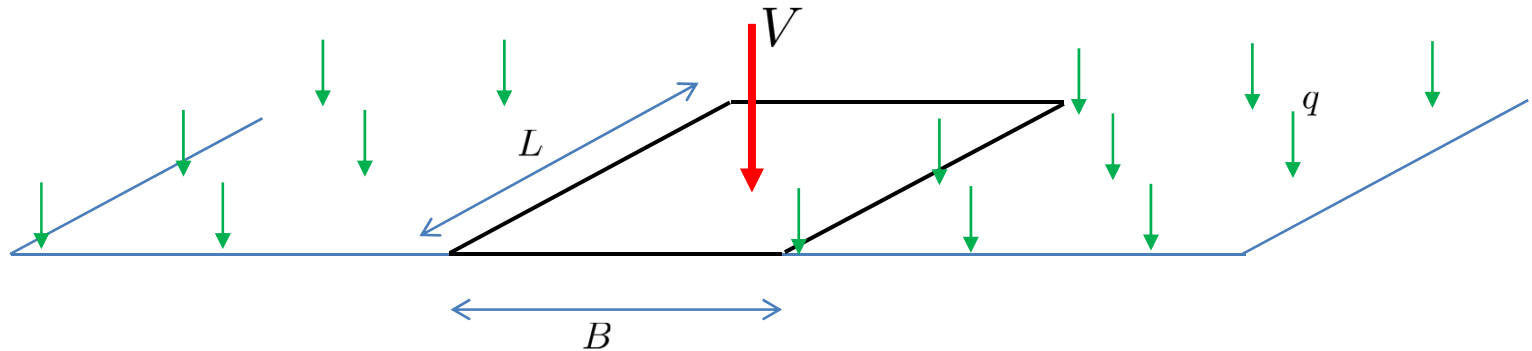
Two families of shape factors:

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BEARING CAPACITY EQUATION

Shape



Two families of shape factors:

EC7: $s_\gamma = 1 - 0.3 \frac{B'}{L'}$: independent of ϕ and always ≤ 1

Meyerhof: $s_\gamma = 1 + 0.1 \tan^2(45 + \frac{1}{2}\phi)$: dependent on ϕ and always ≥ 1

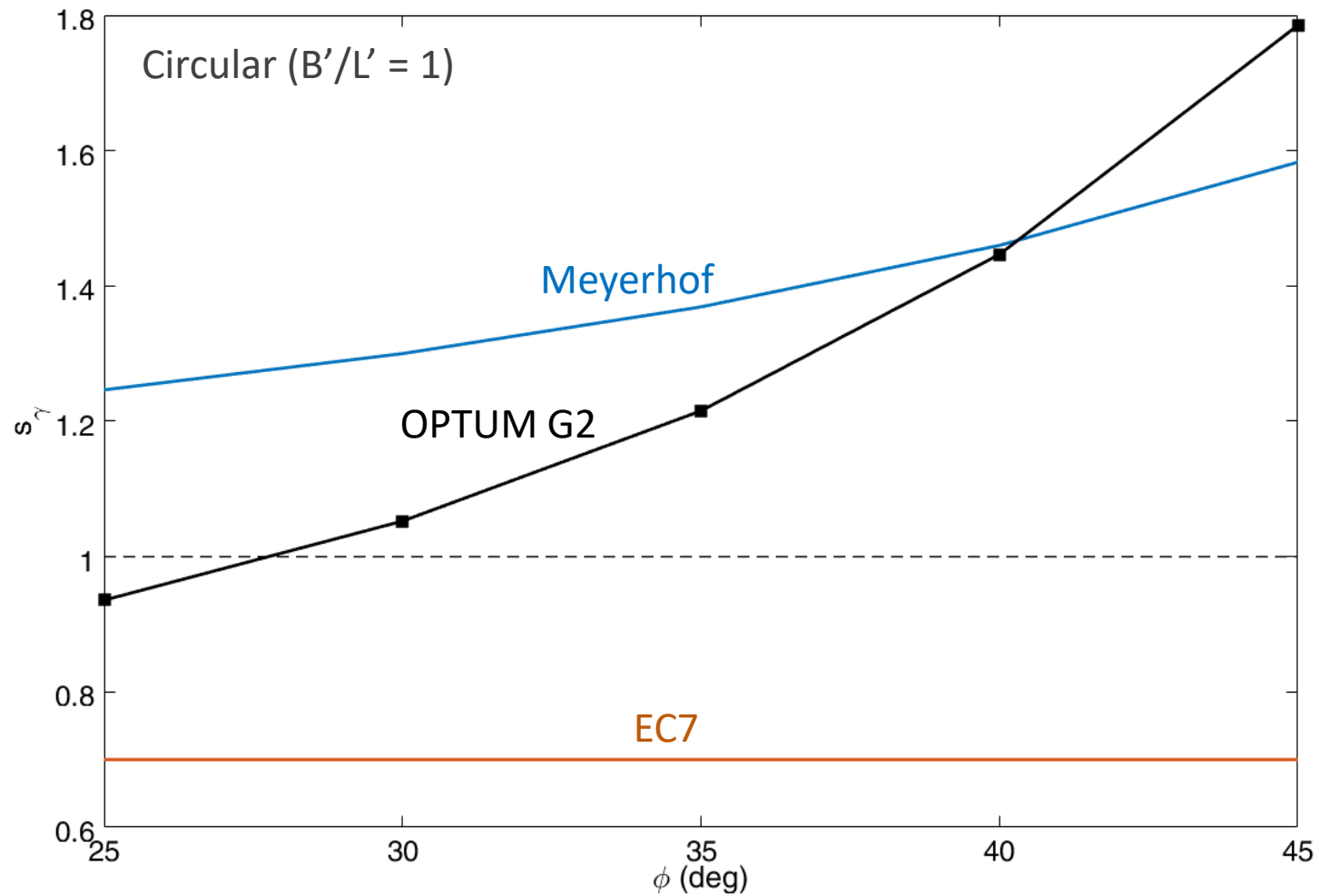
Who is right? –Only one way to find out: OPTUM G2

$$q_u = \frac{1}{2} \gamma B N_\gamma i_\gamma s_\gamma$$

Strip: plane strain ($s_\gamma = 1$)
Circular: axisymmetric

$\rightarrow s_\gamma = \frac{q_{u,circular}}{q_{u,strip}}$

Shape



BEARING CAPACITY EQUATION

Shape

Hold on: N_γ should be calculated on the basis of the *plane strain angle*

That is why $s_\gamma = 0.7$ – both shape *and* stress states not corresponding to plane strain

BEARING CAPACITY EQUATION

Shape

Hold on: N_γ should be calculated on the basis of the *plane strain angle*

That is why $s_\gamma = 0.7$ – both shape *and* stress states not corresponding to plane strain

Assume:

$$\phi_{ps} = 1.12\phi_{tr}$$

and

$$q_{u,\text{strip}} = \frac{1}{2}\gamma B N_\gamma(\phi_{ps})$$

$$q_{u,\text{circular}} = \text{calculate on the basis of } \phi_{tr}$$

BEARING CAPACITY EQUATION

Shape

Hold on: N_γ should be calculated on the basis of the *plane strain angle*

That is why $s_\gamma = 0.7$ – both shape *and* stress states not corresponding to plane strain

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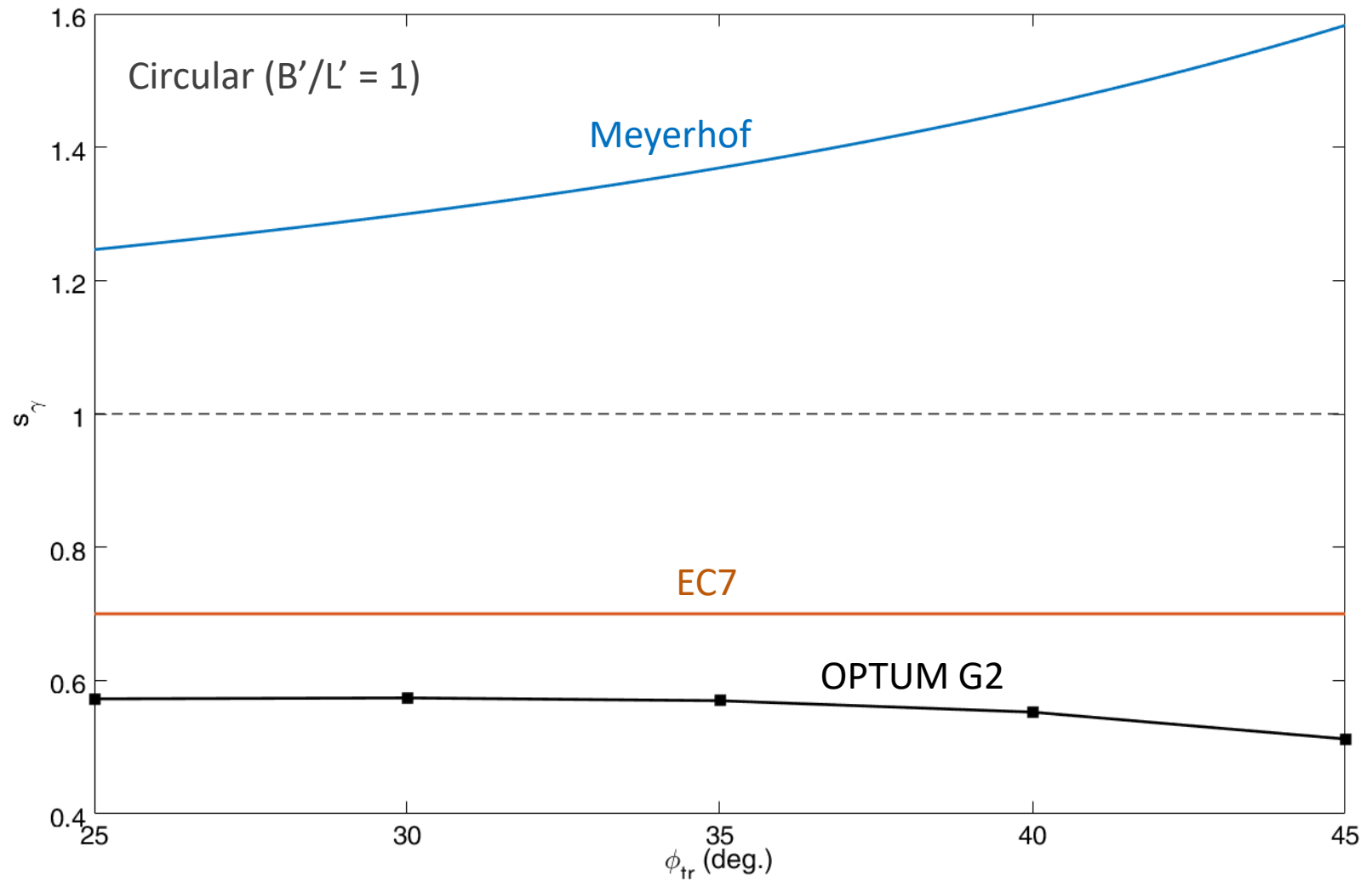
$$q_{u,\text{strip}} = \frac{1}{2}\gamma BN_\gamma(\phi_{ps})$$

$$q_{u,\text{circular}} = \text{calculate on the basis of } \phi_{tr}$$

Shape factor:

$$s_\gamma = \frac{q_{u,\text{circular}}}{q_{u,\text{strip}}}$$

Shape



BEARING CAPACITY EQUATION

Shape

Hold on: N_γ should be calculated on the basis of the *plane strain angle*

That is why $s_\gamma = 0.7$ – both shape *and* stress states not corresponding to plane strain

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$$q_{u,strip} = \frac{1}{2}\gamma BN_\gamma(\phi_{ps})$$

$$q_{u,circular} = \text{calculate on the basis of } \phi_{tr}$$

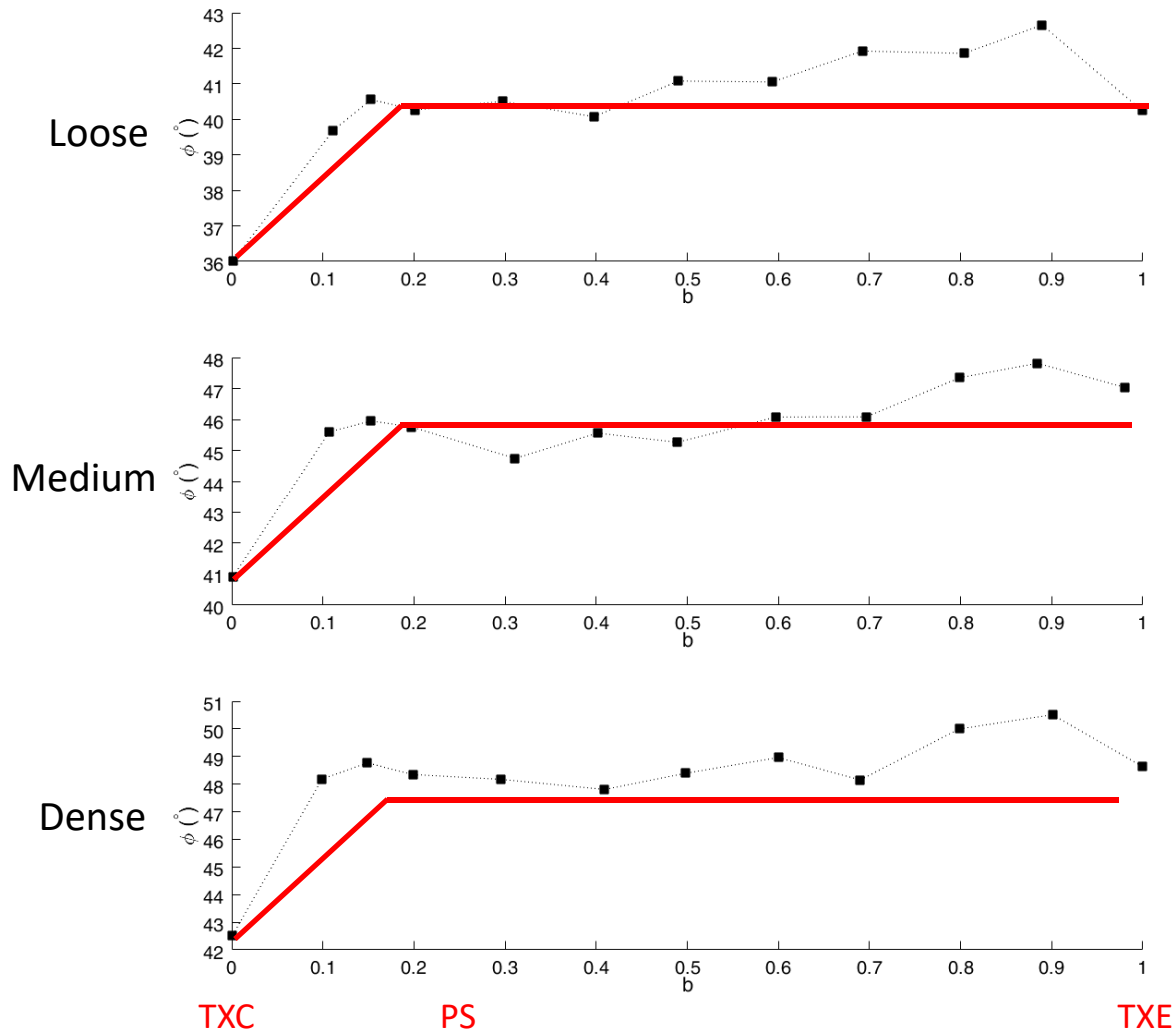
Shape factor:

$$s_\gamma = \frac{q_{u,circular}}{q_{u,strip}}$$

However: not in triaxial compression everywhere for a circular foundation

BEARING CAPACITY EQUATION

FASD



Matched in TXC and:

$$\phi_{ps} = 1.12\phi_{tc}$$

(Kulhawy & Mayne 1990)

Old Danish:

$$\phi_{ps} = 1.1\phi_{tc}$$

New Danish:

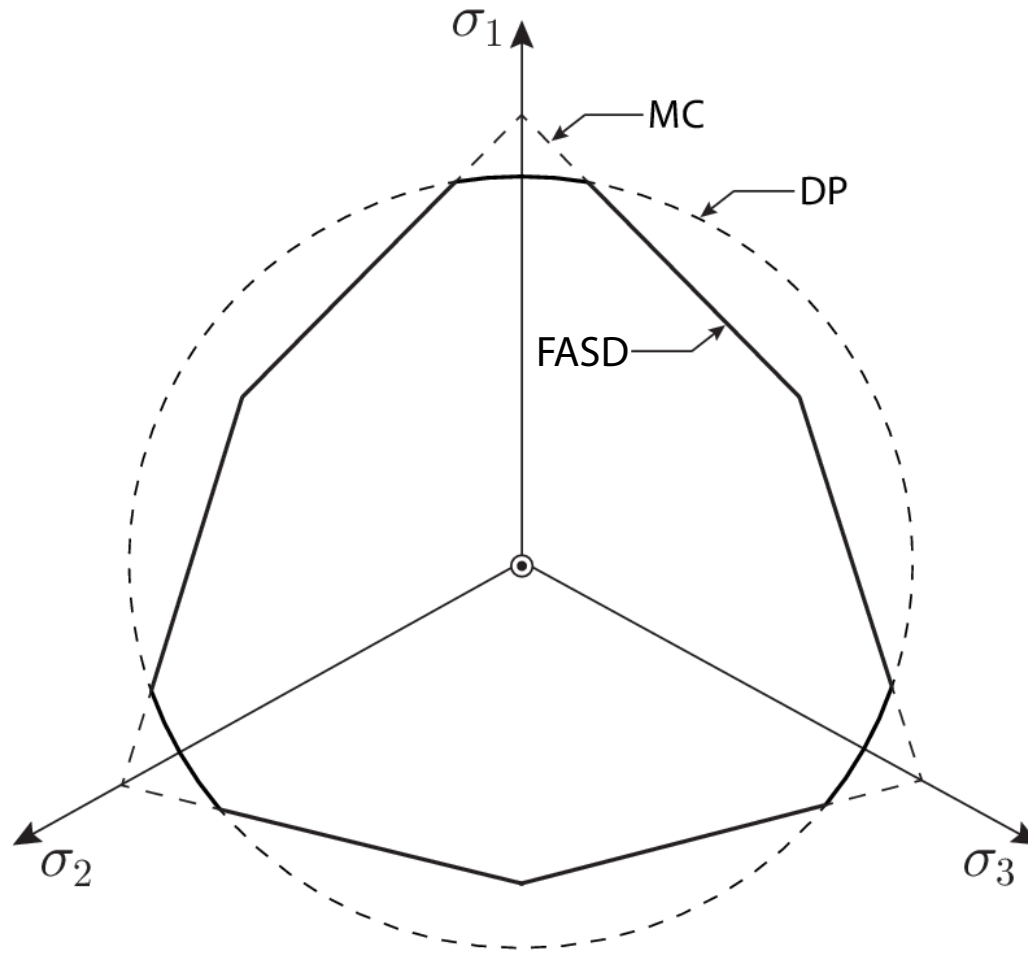
$$\phi_{ps} = (1 + 0.1I_D)\phi_{tc}$$

Stakemann (1976):

$$\phi_{ps} = (1 + 0.163I_D)\phi_{tc}$$

BEARING CAPACITY EQUATION

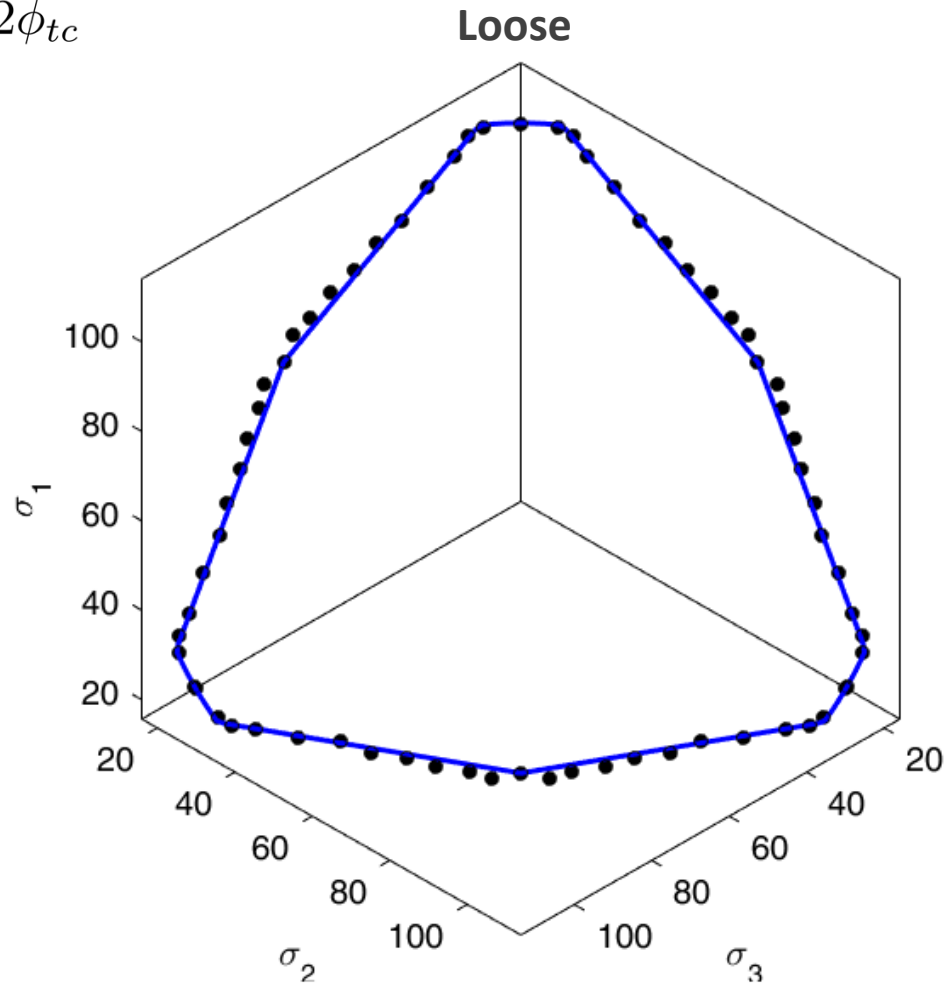
FASD Sand



BEARING CAPACITY EQUATION

FASD

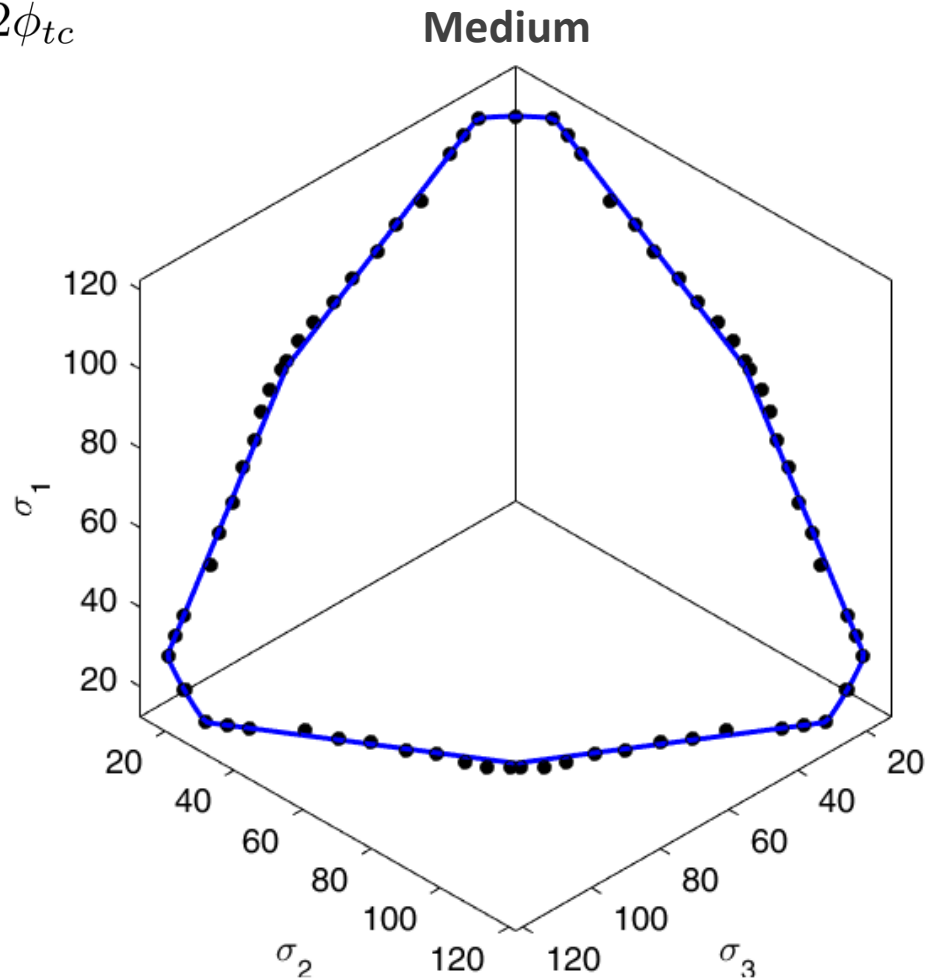
$$\phi_{ps} = 1.12\phi_{tc}$$



BEARING CAPACITY EQUATION

FASD

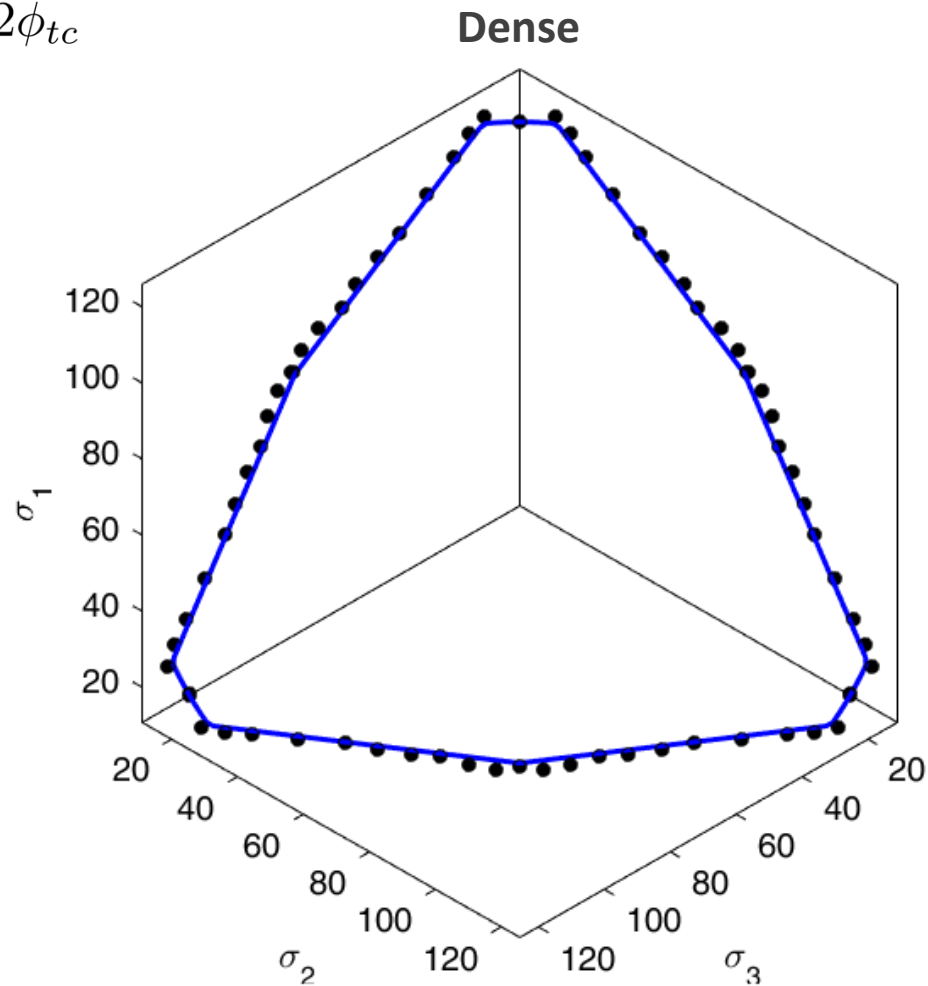
$$\phi_{ps} = 1.12\phi_{tc}$$



BEARING CAPACITY EQUATION

FASD

$$\phi_{ps} = 1.12\phi_{tc}$$



BEARING CAPACITY EQUATION

FASD

The screenshot shows the YouTube channel page for 'Optum Computational Engineering'. The channel name is in the top left, and the URL is 'youtube.com/channel/UCOVnpxMTk2o5X9y86167Ow'. The search bar contains 'optum computational engineering'. The page is organized into sections: HOME, VIDEOS, PLAYLISTS, CHANNELS, DISCUSSION, and ABOUT. The VIDEOS section is active, showing a grid of video thumbnails. The first row includes 'Introduction to OPTUM G3', 'Introduction to OPTUM G3', 'Example 1 Circular Foundations', 'Example 2 Combined Loading of Shallow...', 'Setting up 3D model in OPTUM G3 using Matlab...', and 'G2/G3 VERIFICATION'. The second row includes 'OPTUM CS in 60 seconds', 'Yield Line Calculation for concrete slab', 'OPTUM CS beta demo', and 'Reinforcement in OPTUM CS'. The third row, titled 'Webinars', includes 'Consistent undrained modelling of clays in OPTUM G3', 'How to choose the right friction angle in 3D' (highlighted with a red box), 'Introduction to OPTUM G3', 'Retaining walls in OPTUM G2', 'OPTUM G2 Slope Stability', and '3D analysis in offshore geotechnics'.

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optum computational engineering

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Introduction to OPTUM G3
w. Prof Kristian Krabbenhoft 56:20

Introduction to OPTUM G3
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353 views • 3 months ago

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Optum Computational Engine...
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OPTUM CS & MP ▶ PLAY ALL

Calculate Ultimate Load in second 1:10

OPTUM CS in 60 seconds
Optum Computational Engine...
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Optum Computational Engine...
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OPTUM CS beta demo
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177 views • 4 months ago

Reinforcement in OPTUM CS
Optum Computational Engine...
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Opt+um^{CS} 0:52

Webinars ▶ PLAY ALL

Opt+um^{CE} WEBINAR

Consistent undrained modelling of clays in OPTUM G3
w. Prof Kristian Krabbenhoft 1:00:51

Consistent undrained modelling of clays in OPTUM...
Optum Computational Engine...
19 views • 5 days ago

Opt+um^{CE} WEBINAR

Choosing the right friction angle in 3D
w. Prof Kristian Krabbenhoft 44:10

How to choose the right friction angle in 3D
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Opt+um^{CE} WEBINAR

Introduction to OPTUM G3
w. Prof Kristian Krabbenhoft 56:20

Introduction to OPTUM G3
Optum Computational Engine...
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Opt+um^{CE} WEBINAR

Retaining walls in OPTUM G2
w. Prof Kristian Krabbenhoft 59:17

Retaining Walls in OPTUM G2
Optum Computational Engine...
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Opt+um^{CE} WEBINAR

Slope Stability in OPTUM G2
w. Prof Kristian Krabbenhoft 1:00:32

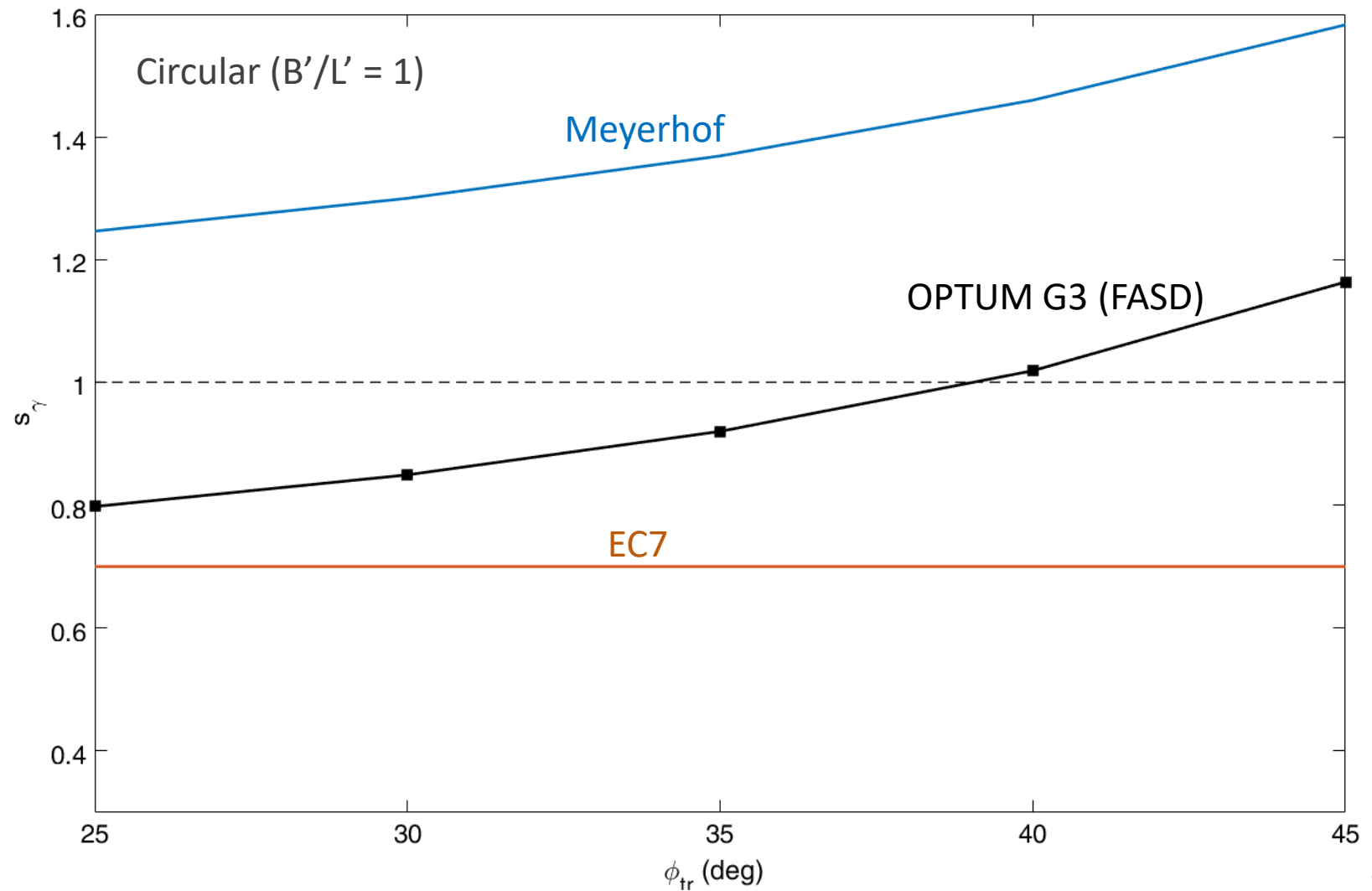
OPTUM G2 Slope Stability
Optum Computational Engine...
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Opt+um^{CE} WEBINAR

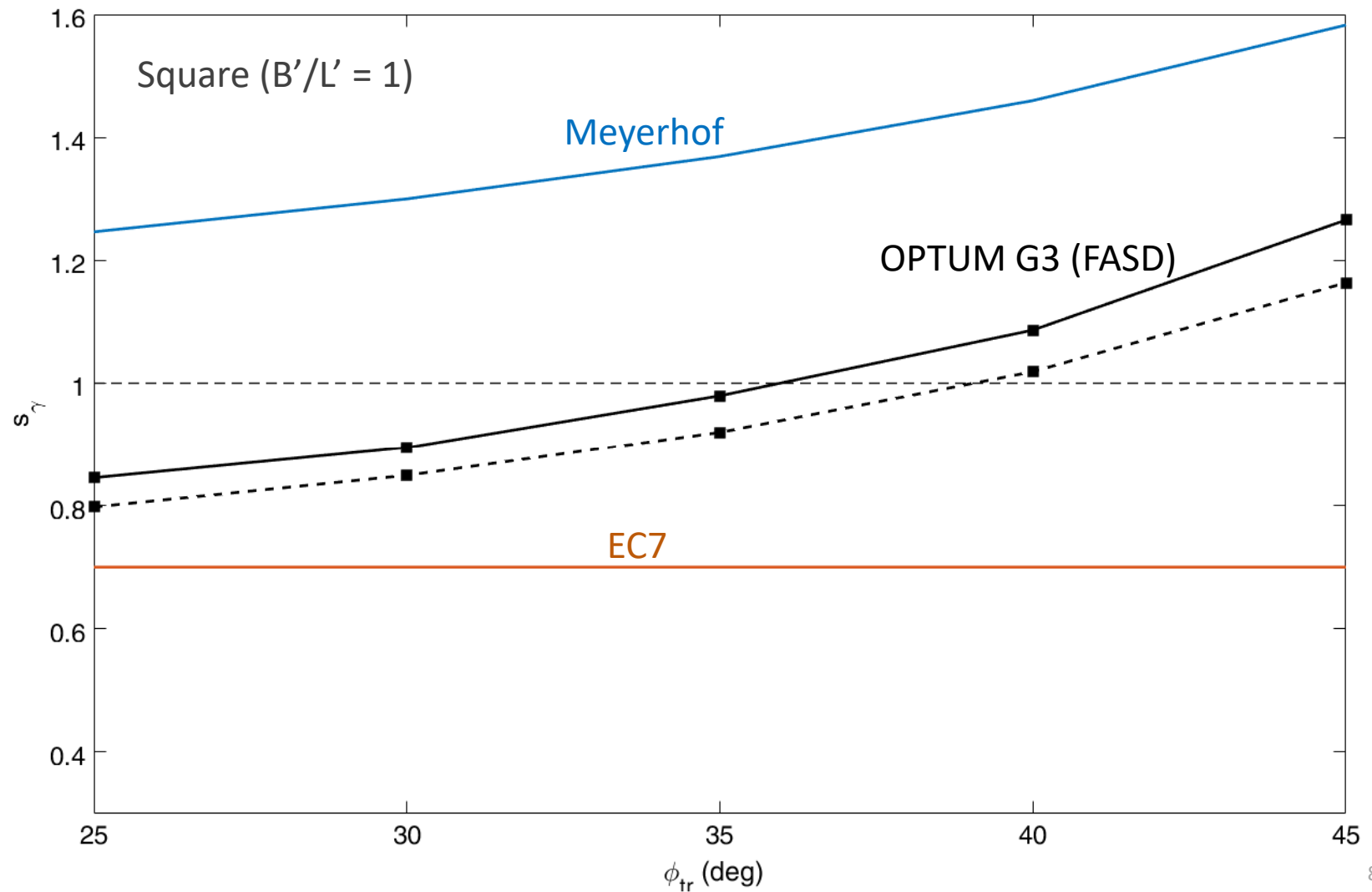
3D analysis in offshore geotechnics
w. guest speaker Christian Lindholm 53:48

3D analysis in offshore geotechnics
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Shape

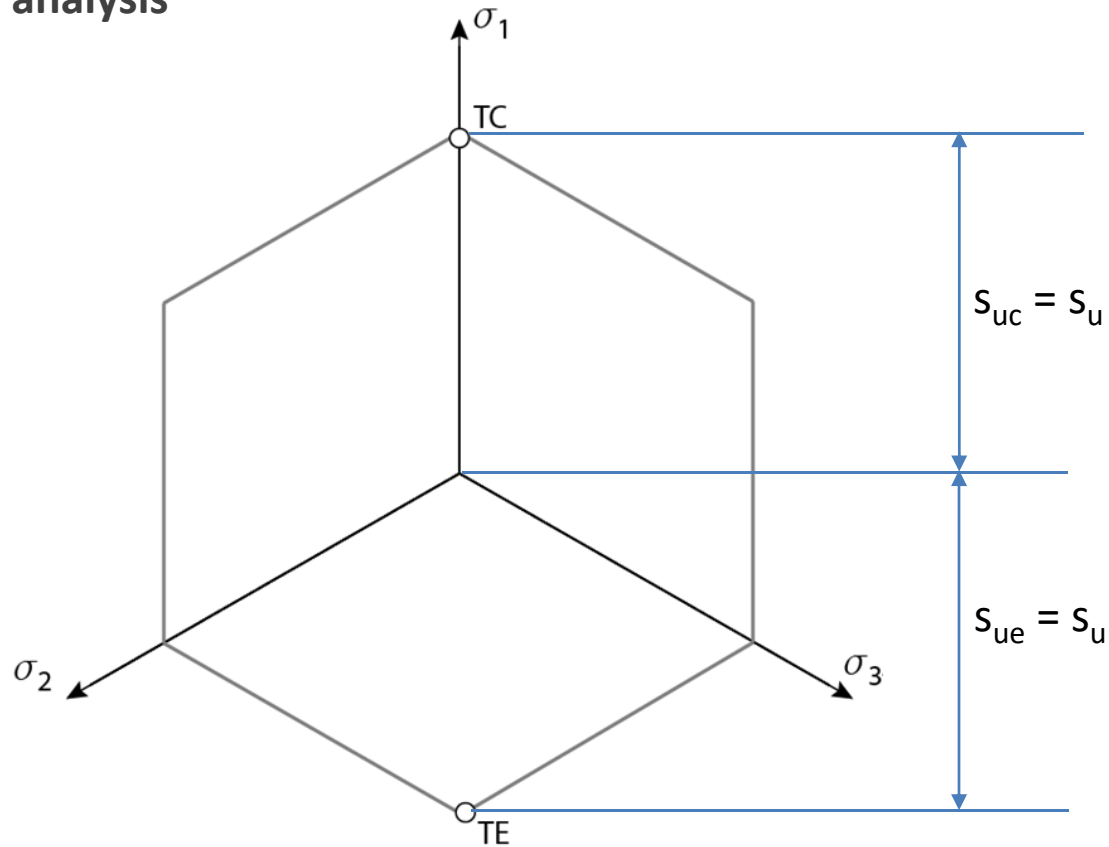


Shape



Shape

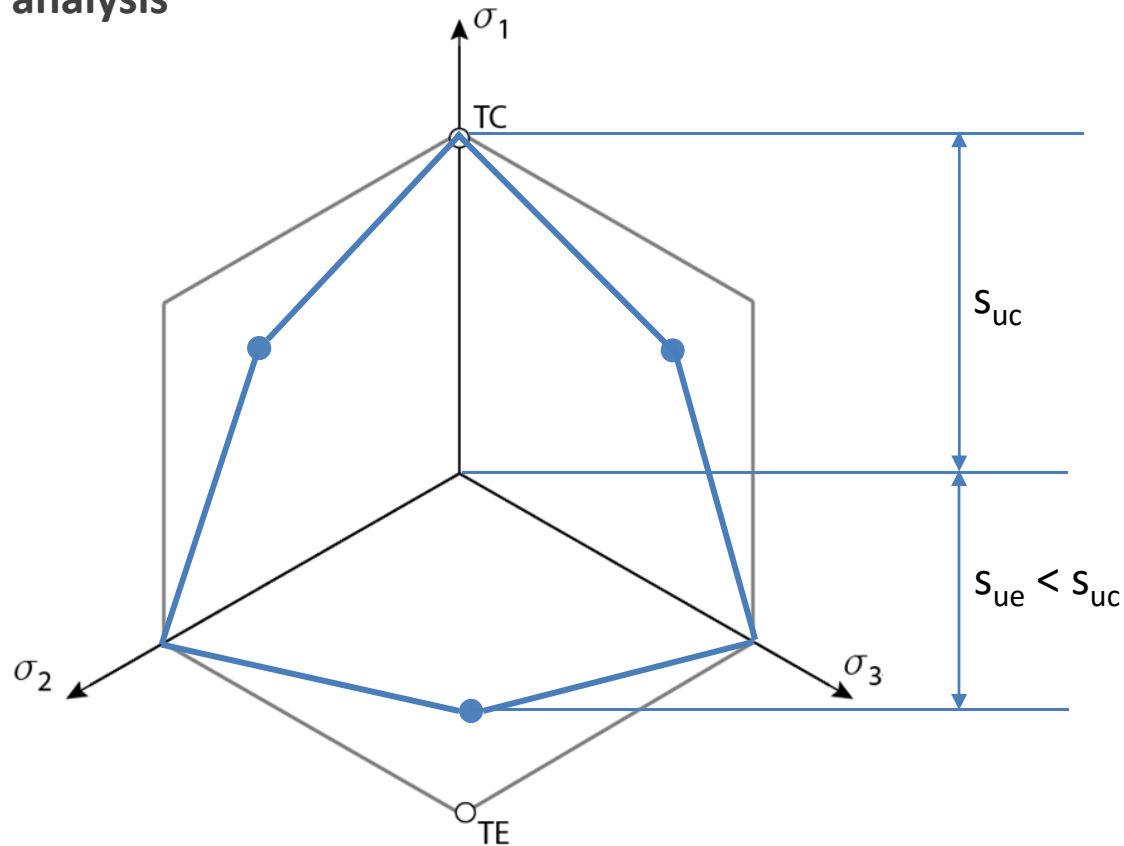
Undrained analysis



Tresca

Shape

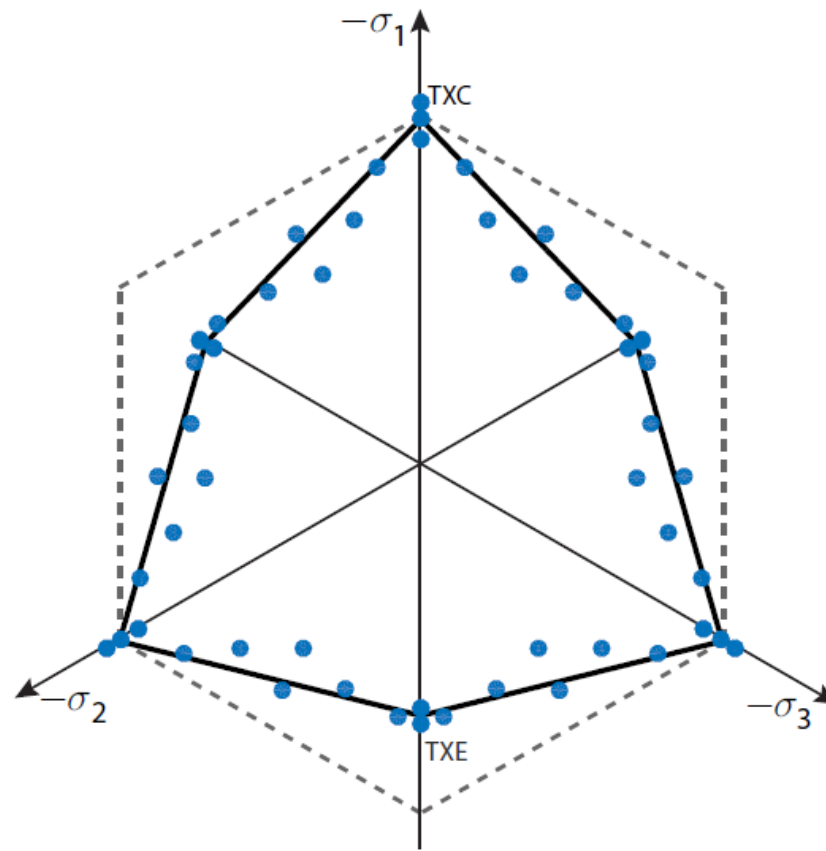
Undrained analysis



Generalized Tresca (s_{uc}, s_{ue})

Yield surface

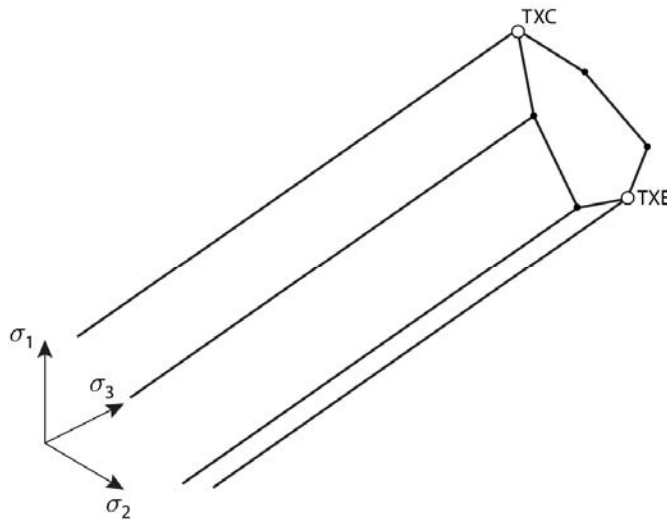
Undrained true triaxial tests on NC Edgar Plastic Kaolinite (Lade 1990)




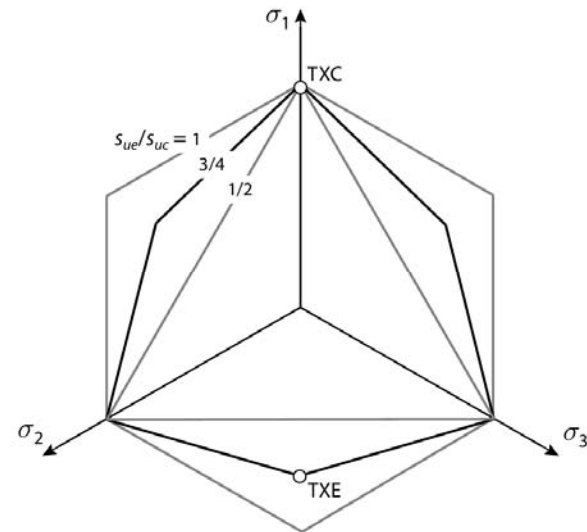
$$s_{ue}/s_{uc} = 0.7$$


Generalized Tresca

$$F_u = \sigma_1 - \sigma_3 + (s_{ue}/s_{uc} - 1)(\sigma_1 - \sigma_2) - 2s_{uc}$$



Material		>>
Name	Tresca Basic	
Material Model	Tresca	▼
Color	 click to change	
Reducible Strength	Yes	▼
Strength		>>
Option	Standard	▼
s_u (kPa)	100	



Material		>>
Name	Tresca Basic	
Material Model	Tresca	▼
Color	 click to change	
Reducible Strength	Yes	▼
Strength		>>
Option	Generalized	▼
s_{uc} (kPa)	30	
s_{ue} (kPa)	20	

BEARING CAPACITY EQUATION

Generalized Tresca + AUS

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HOME VIDEOS PLAYLISTS CHANNELS DISCUSSION ABOUT

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PLAY ALL

OptumCE WEBINAR
Consistent undrained modelling of clays in OPTUM G3
w. Prof Kristian Krabbenhoft 1:00:57

OptumCE WEBINAR
Choosing the right friction angle in 3D
w. Prof Kristian Krabbenhoft 44:10

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How to choose the right friction angle in 3D
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Introduction to OPTUM G3
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Retaining Walls in OPTUM G2
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OPTUM G2 Slope Stability
Optum Computational Engine...
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3D analysis in offshore geotechnics
Optum Computational Engine...
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Conclusions

- + The bearing capacity equation is pretty good
- + However issues with:
 - N_γ (exact solution has been available for the last 15 years)
 - Superposition (well known + conservative)
 - Inclined loading (sliding)
 - Eccentricity – requires some attention to detail (upcoming webinar)
 - Plane strain → 3D: reconsideration of soil model (MC → FASD, Tresca → GT/AUS)
 - Proper modelling of embedment rather than via surcharge
 - All the other well-known limitations – layered soils, increase of strength with depth, effects of torsion (upcoming webinar), etc

BEARING CAPACITY EQUATION

Exact N_c and N_q are universally accepted, so why not exact N_γ ?

- + Martin's solution is not exact
- + Numerical solutions don't qualify as exact
- + The concept of exactness is meaningless
- + It's complicated, there are so many approximations
- + What about the flow rule, large deformations, softening, etc?
- + There are more important problems (e.g. cure for cancer)
- + The drained case is never critical, hence N_γ is not relevant
- + q -term always dominates, hence N_γ is not important
- + Our N_γ is based on experiments (carried out in the 1950s or 60s)
- + Long standing practice will be disrupted

BEARING CAPACITY EQUATION

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BEARING CAPACITY EQUATION

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- + Long standing practice will be disrupted

There now remains the much more challenging problem of purging spurious N_γ values from the geotechnical literature

Ukritchon, B., Whittle, A. J. & Klangvijit, C. (2004). Response to discussion of 'Calculations of bearing capacity factor N_γ using numerical limit analyses' by Martin, C. M. (2004). J. Geotech. Geoenviron. Engng. Div., ASCE, 130, No. 10, 1107–1108.