



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS

Lecture 38: Foundations on Slopes - 1

B.K. MAHESHWARI

Professor, Dept. of Earthquake Engineering, IIT Roorkee

E-mail: bk.maheshwari@eq.iitr.ac.in



ERD of Foundations - Modules

1. Introduction
2. Shallow Foundations
3. Pile Foundations
4. Well Foundations
5. SSI for Deep Foundations
6. Miscellaneous

Module - 6

Miscellaneous



Module - 6: Topics

1. Raft Foundation – Numerical Examples
2. Shallow Foundations on Slopes

Chapter 2: Foundations on Slopes

- **Background**
- **Static Bearing Capacity**
- **Seismic Bearing Capacity**
- **Codal provision**
- **Numerical Examples**

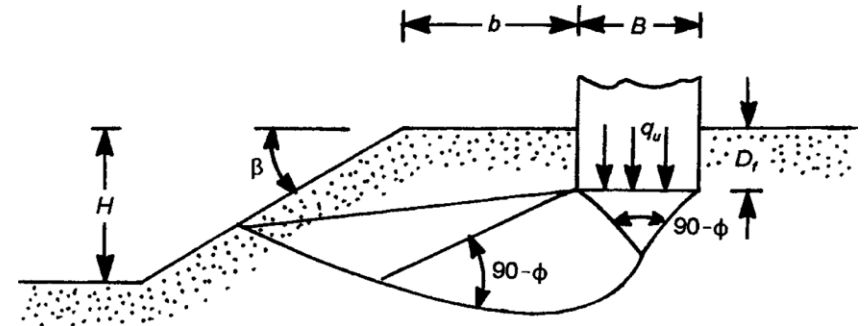
Background

- In hilly areas, most of the construction is on slopes. This requires foundations to be placed on slopes.
- Even assuming that the slope is stable, when foundations are constructed on slopes, their bearing capacity reduces.
- This reduction is mostly on account of change in the values of dimensionless bearing capacity factors which reduces significantly as the slope angle increases.
- Further, these factors reduce as seismic acceleration increases.

Static Bearing Capacity

- Meyerhof (1957)
- Hansen (1970) and Vesic (1975)
- Saran, Sud and Handa (1989)
- Gemperline (1988)
- Graham et al. (1988)

Meyerhof (1957) proposed a theoretical solution to determine the ultimate bearing capacity of a shallow foundation located on the face and top of a slope.



Nature of plastic zone under a rough continuous foundation on the face of a slope

Meyerhof (1957) - continue

The ultimate bearing capacity can be expressed as:

$$q_u = cN_c + qN_q + \frac{1}{2}\gamma BN_\gamma \quad (1a)$$

The preceding relationship can also be expressed as

$$q_u = cN_{cq} + \frac{1}{2}\gamma BN_{\gamma q} \quad (1b)$$

The factor N_{cq} depends on N_c and N_q ; and the factor $N_{\gamma q}$ depends on N_γ and N_q . Thus instead of three factors, only two bearing capacity factors are used.

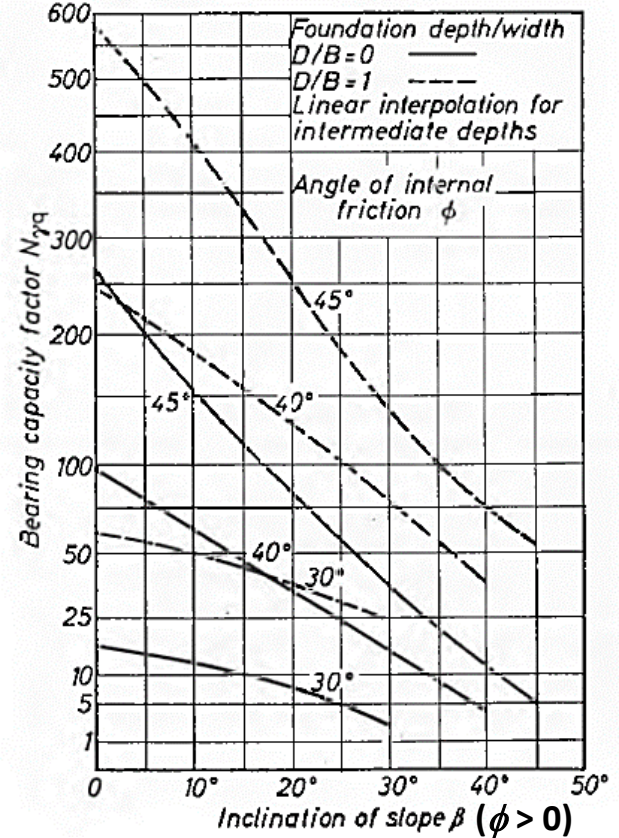
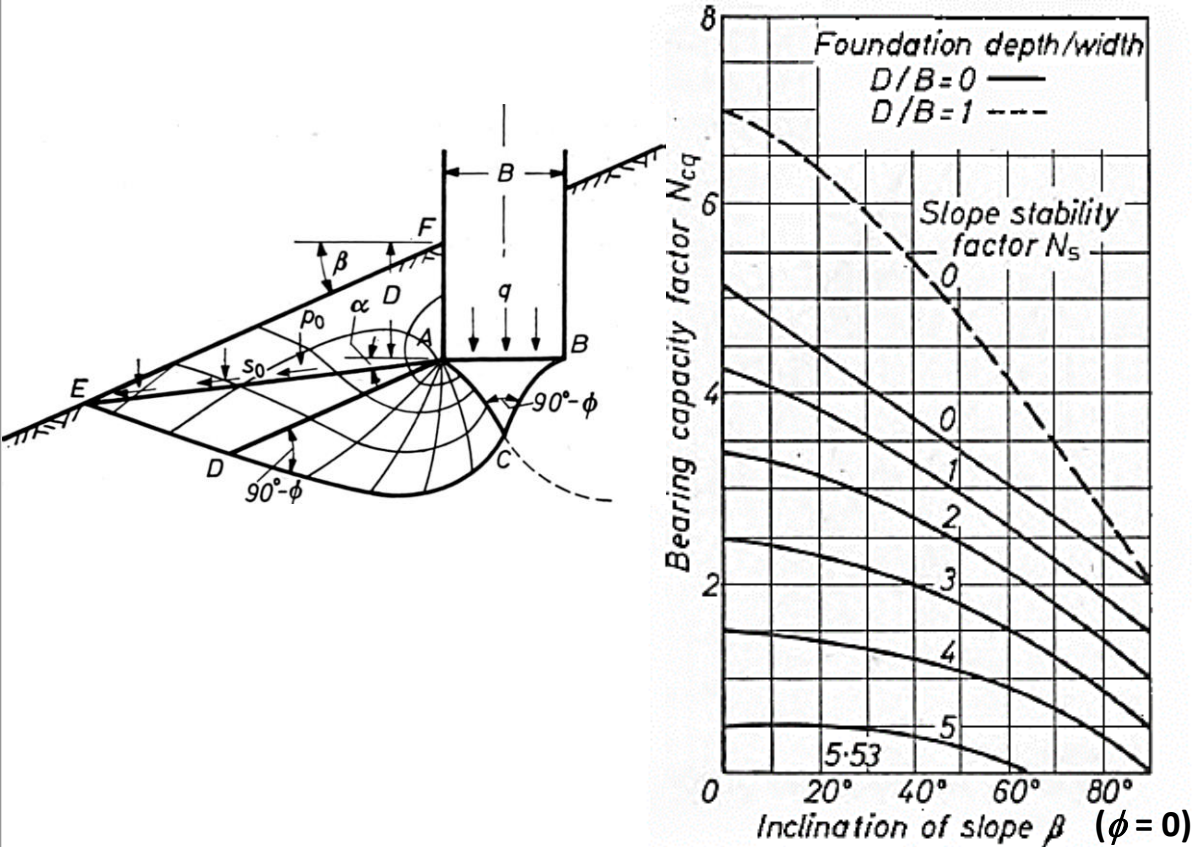
For purely cohesive soil (that is, $\phi = 0$) $q_u = cN_{cq} \quad (1c)$

For purely cohesionless soil (that is, $c = 0$) $q_u = \frac{1}{2}\gamma BN_{\gamma q} \quad (1d)$

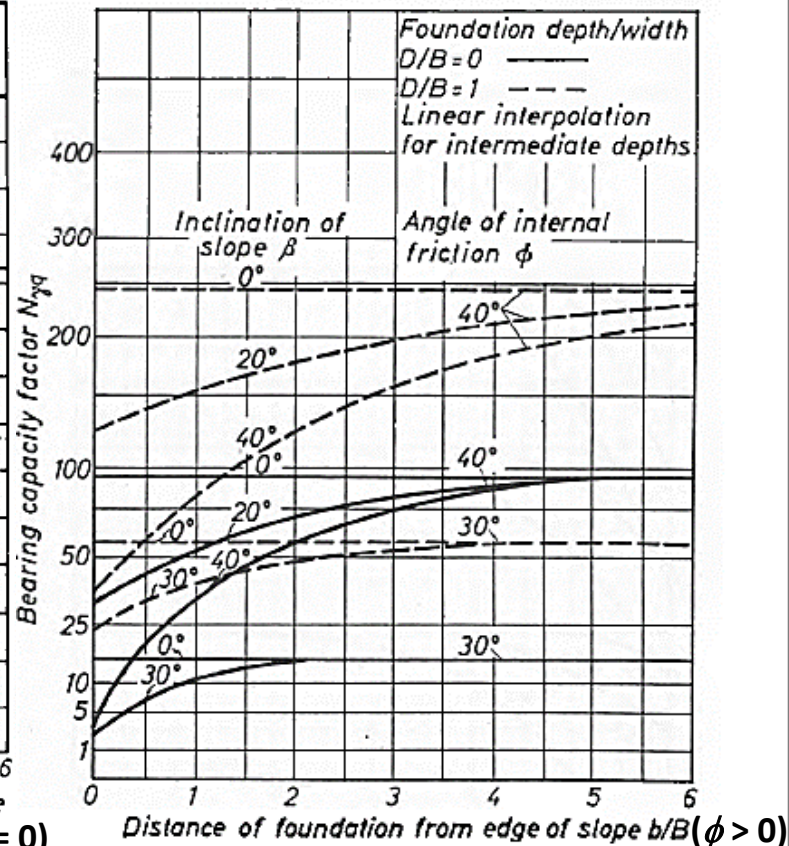
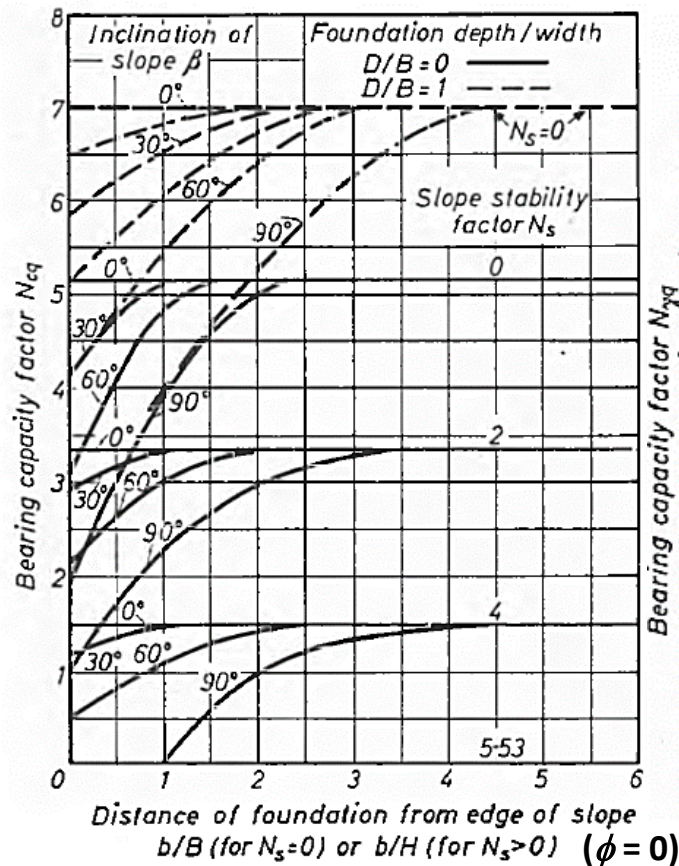
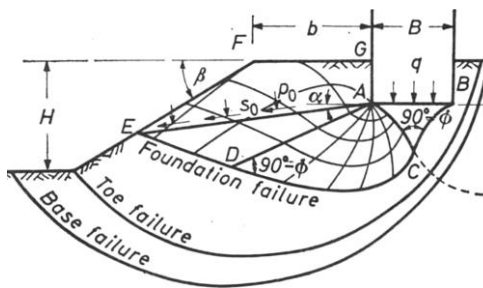
Stability Number $N_s = \frac{\gamma H}{c}$

Where, H = height of the slope, c = cohesion and γ = unit weight of soil

Bearing capacity factors for strip foundation on face of slope



Bearing capacity factors for strip foundation on top of slope



Solutions of Hansen and Vesic

Hansen (1970) proposed the following relationship for the ultimate bearing capacity of a continuous foundation at the edge of slope:

$$q_u = cN_c\lambda_{c\beta} + qN_q\lambda_{q\beta} + \frac{1}{2}\gamma BN_\gamma\lambda_{\gamma\beta} \quad (2a)$$

Where, N_c , N_q & N_γ are bearing capacity factors

$\lambda_{c\beta}$, $\lambda_{q\beta}$ & $\lambda_{\gamma\beta}$ are slope factors

$$\lambda_{c\beta} = \frac{N_q\lambda_{q\beta}-1}{N_q-1} \quad (\text{for } \phi > 0) \text{ and } \lambda_{c\beta} = 1 - \frac{2\beta}{\pi+2} \quad (\text{for } \phi = 0) \quad (2b \text{ \& } c)$$

$$\lambda_{q\beta} = \lambda_{\gamma\beta} = (1 - \tan\beta)^2 \quad (\text{for } \beta < 45^\circ) \quad (2d)$$

$$q = \gamma D_f$$

Solutions of Hansen and Vesic

For $\phi = 0$ condition, Vesic (1975) pointed out that, with the absence of weight due to the slope, the bearing capacity factor N_γ has a negative value and can be given as:

$$N_\gamma = -2\sin\beta \quad (3)$$

Thus for $\phi = 0$ condition, with $N_c = 5.14$ and $N_q = 1$, Eq. (2a) takes the form

$$q_u = c(5.14) \left(1 - \frac{2\beta}{5.14} \right) + \gamma D_f (1 - \tan\beta)^2 - \gamma B \sin\beta (1 - \tan\beta)^2$$

Or

$$q_u = (5.14 - 2\beta)c + \gamma D_f (1 - \tan\beta)^2 - \gamma B \sin\beta (1 - \tan\beta)^2$$

Solution by Limit Equilibrium and Limit Analysis

Saran, Sud, and Handa (1989) provided a solution to determine the ultimate bearing capacity of shallow continuous foundations on the top of a slope using the limit equilibrium and limit analysis approach. According to this theory, for a strip foundation

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

Where, N_c , N_q & N_γ are bearing capacity factors and the numerical values are given in the Table (next slide)

Table: Bearing Capacity Factors Based on Saran, Seed, and Handa's Analysis

Factor	β (deg)	$\frac{D_f}{B}$	$\frac{b}{B}$	Soil friction angle, ϕ (deg)						
				40	35	30	25	20	15	10
N_c	50	0	0	21.68	16.52	12.60	10.00	8.60	7.10	5.50
	40			31.80	22.44	16.64	12.80	10.04	8.00	6.25
	30			44.80	28.72	22.00	16.20	12.20	8.60	6.70
	20			63.20	41.20	28.32	20.60	15.00	11.30	8.76
	≤ 10			88.96	55.36	36.50	24.72	17.36	12.61	9.44
	50	0	1	38.80	30.40	24.20	19.70	16.42		
	40			48.00	35.40	27.42	21.52	17.28		
	30			59.64	41.07	30.92	23.60	17.36		
	20			75.12	50.00	35.16	27.72	17.36		
	≤ 10			95.20	57.25	36.69	24.72	17.36		
	50	1	0	35.97	28.11	22.38	18.38	15.66	10.00	
	40			51.16	37.95	29.42	22.75	17.32	12.16	
	30			70.59	50.37	36.20	24.72	17.36	12.16	
	20			93.79	57.20	36.20	24.72	17.36	12.16	
	≤ 10			95.20	57.20	36.20	24.72	17.36	12.16	
	50	1	1	53.65	42.47	35.00	24.72			
	40			67.98	51.61	36.69	24.72			
	30			85.38	57.25	36.69	24.72			
	≤ 20			95.20	57.25	36.69	24.72			

Table: Bearing Capacity Factors Based on Saran, Seed, and Handa's Analysis

Factor	β (deg)	$\frac{D_f}{B}$	$\frac{b}{B}$	Soil friction angle, ϕ (deg)						
				40	35	30	25	20	15	10
N_q	30	1	0	12.13	16.42	8.98	7.04	5.00	3.60	
	20			12.67	19.48	16.80	12.70	7.40	4.40	
	≤ 10			81.30	41.40	22.50	12.70	7.40	4.40	
	30	1	1	28.31	24.14	22.5				
	20			42.25	41.4	22.5				
	≤ 10			81.30	41.4	22.5				

Factor	β (deg)	$\frac{D_f}{B}$	$\frac{b}{B}$	Soil friction angle, ϕ (deg)						
				40	35	30	25	20	15	10
N_γ	30	0	0	25.37	12.41	6.14	3.20	1.26	0.70	0.10
	20			53.48	24.54	11.62	5.61	4.27	1.79	0.45
	10			101.74	43.35	19.65	9.19	4.35	1.96	0.77
	0			165.39	66.59	28.98	13.12	6.05	2.74	1.14
	30	0	1	60.06	34.03	18.95	10.33	5.45	0.00	
	20			85.98	42.49	21.93	11.42	5.89	1.35	
	10			125.32	55.15	25.86	12.26	6.05	2.74	
	0			165.39	66.59	28.89	13.12	6.05	2.74	
	30	1	0	91.87	49.43	26.39				
	25			115.65	59.12	28.80				
	20			143.77	66.00	28.89				
	≤ 15			165.39	66.59	28.89				
	30	1	1	131.34	64.37	28.89				
	25			151.37	66.59	28.89				
	≤ 20			166.39	66.59	28.89				

Empirical Relationship Based on Centrifuge Testing

Gemperline (1988) reported the results of 215 centrifuge tests on continuous foundations located at the top of a slope of cohesionless sand. Based on these 215 tests, Gemperline proposed that the ultimate bearing capacity of a continuous foundation can be expressed as: $q_u = \frac{1}{2} \gamma B N_{\gamma q}$

Empirical Relationship Based on Centrifuge Testing

Shields et al (1990) normalized the $N_{\gamma q}$ values proposed by Gemperline (1988) in the following form:

$$\frac{N_{\gamma q}}{N_{\gamma qR}} = \left[1 + 0.65 \left(\frac{D_f}{B} \right) \right] \left\{ 1 - 0.8 [1 - (1 - \tan \beta)^2] \left[\frac{2}{2 + \left(\frac{b}{B} \right)^2 \tan \beta} \right] \right\} \\ \left\{ 1 - 0.33 \left(\frac{D_f}{B} \right) \tan \beta \left[\frac{2}{2 + \left(\frac{b}{B} \right)^2 \tan \beta} \right] \right\} \quad (1a)$$

Where $N_{\gamma qR}$ = the value of $N_{\gamma q}$ for a reference continuous foundation at the surface of level ground (that is, $\frac{D_f}{B} = 0$ and $b/B = \infty$)

The magnitude of $N_{\gamma qR}$ can be given by the following relationship

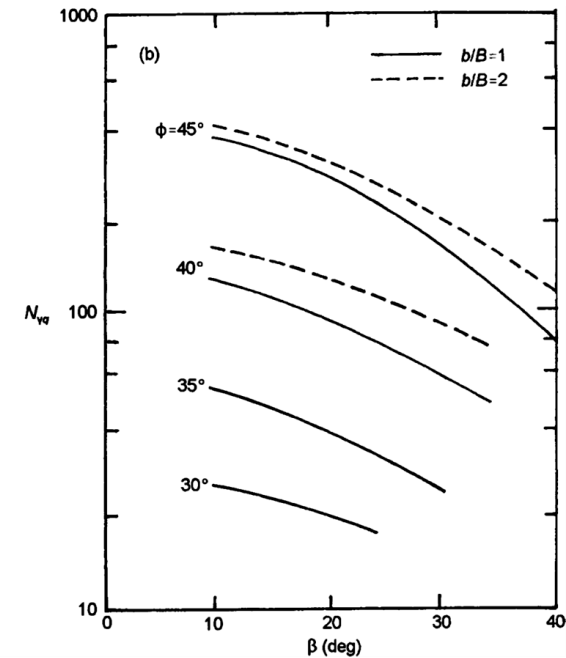
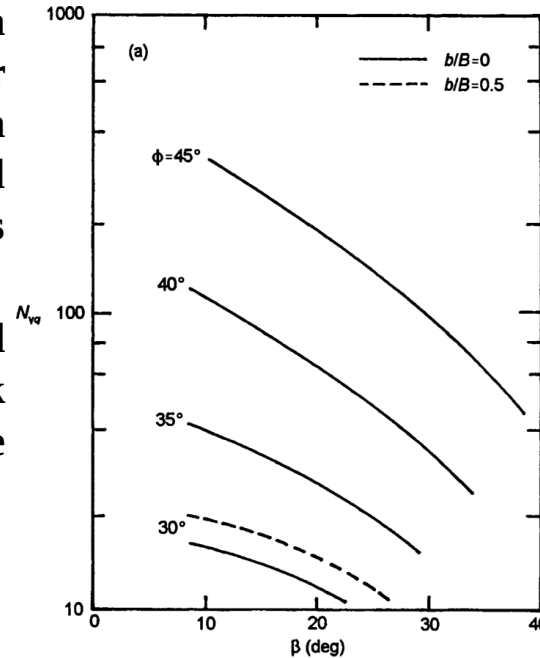
$$N_{\gamma qR} = \left(10^{0.1159\phi - 2.386} \right) \left(10^{0.34 - 0.2 \log B} \right) \quad (1b)$$

Where, ϕ is in degrees and B is in inches.

Graham et al.'s theoretical values of $N_{\gamma q}$

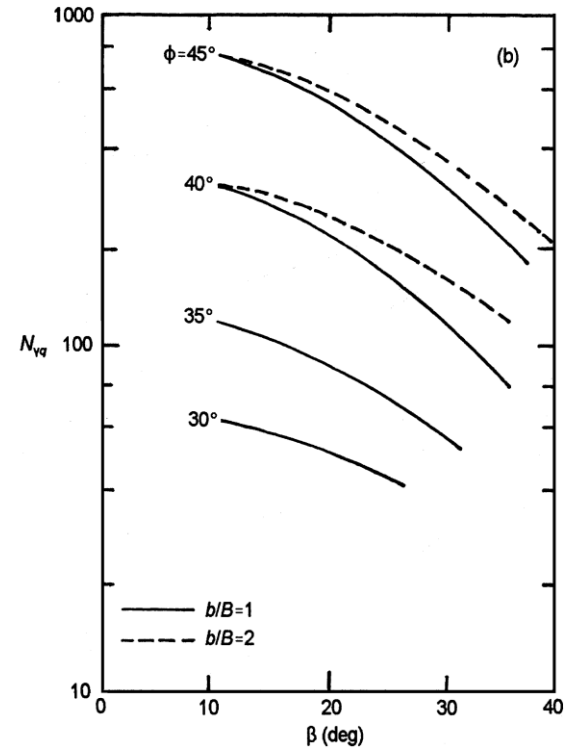
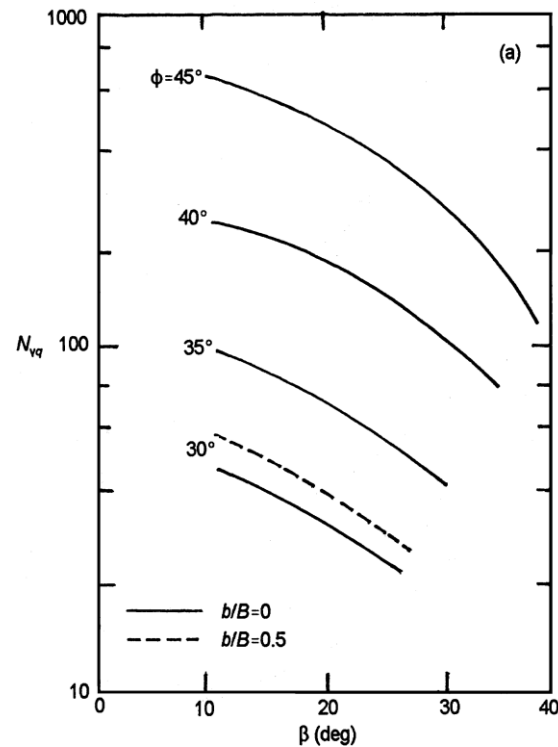
Graham et al. (1988) provided a solution for the bearing capacity factor for a shallow continuous foundation on the top of a slope in granular soil based on the method of stress characteristics.

The failure zones in the granular soil for embedment (D_f/B) and setback (b/B) assumed for this analysis are shown in Figures.



At embedment ratio ($D_f / B = 0$)

Graham et al.'s theoretical values of $N_{\gamma q}$



At embedment ratio ($D_f/B = 1$)

Reference

1. Das, B.M. (1999): **Shallow foundations: bearing capacity and settlements**, CRC Press LLC, USA.
2. Gemperline, M. C. (1988): **Centrifuge modelling of shallow foundations**, in Proc.,ASCE Spring Convention.
3. Graham, J., Andrews, M. and Shields, D. H. (1988): **Stress characteristics for shallow footings in cohesionless slopes**, Canadian Geotech. J., 25(2), 238.
4. Hansen, J. B. (1970), *A revised and extended formula for bearing capacity*, Bulletin 28, Danish Geotechnical Institute, Copenhagen.
5. Meyerhof, G. G. (1957): **The ultimate bearing capacity of foundations on slopes**. Proc. 4th Int. Conf. Soil Mech. Found. Engng, London 1, 384–386.
6. Saran, S., Sud, V. K., and Handa, S. C. (1989): **Bearing capacity of footings adjacent to slopes**, J. Geotech. Eng., ASCE, 115(4), 553.
7. Vesic, A. S. (1975), **Bearing capacity of shallow foundations**, in *Foundation Engineering Hand-book*, Winterkorn, H. F., and Fang, H. Y., Eds., Van Nostrand Reinhold Co.

Thank You

