



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS

Lecture 39: Foundations on Slopes - 2

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ERD of Foundations - Modules

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

Module - 6

Miscellaneous

Module - 6: Chapters

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



Chapter 2: Foundations on Slopes

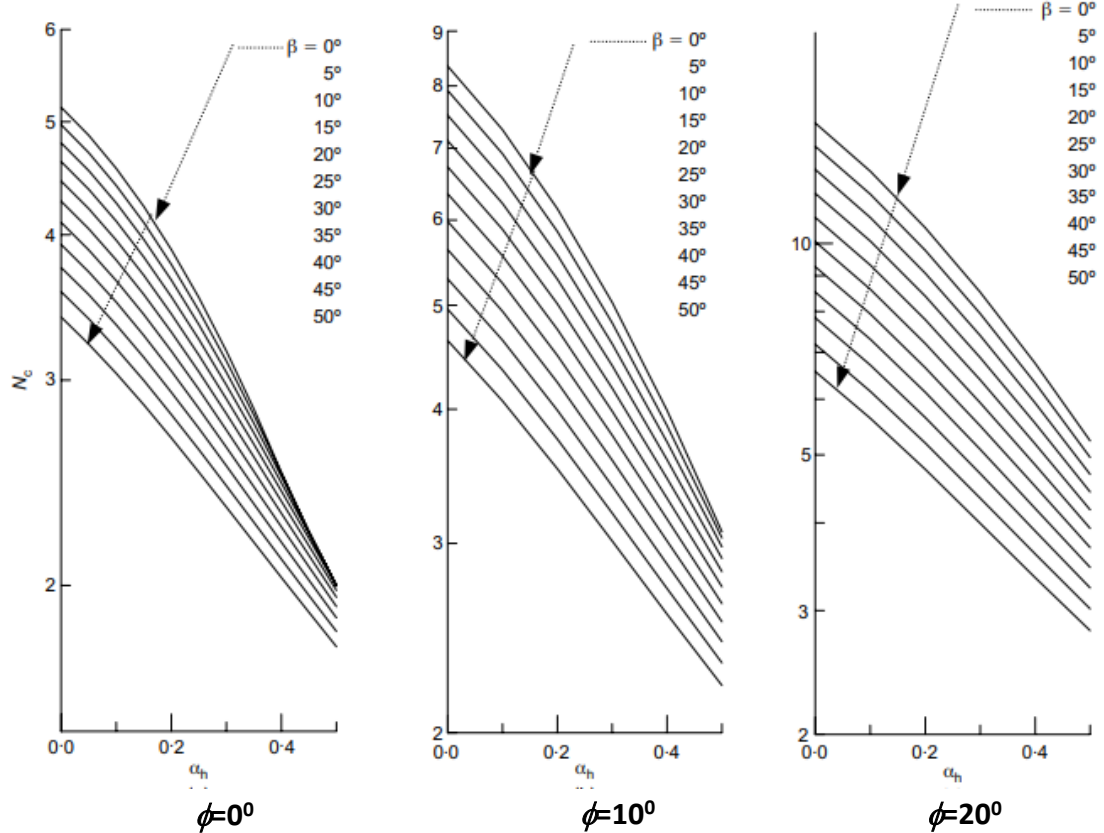
- **Background**
- **Static Bearing Capacity**
- **Seismic Bearing Capacity**
- **Codal provision**
- **Numerical Examples**

Seismic Bearing Capacity

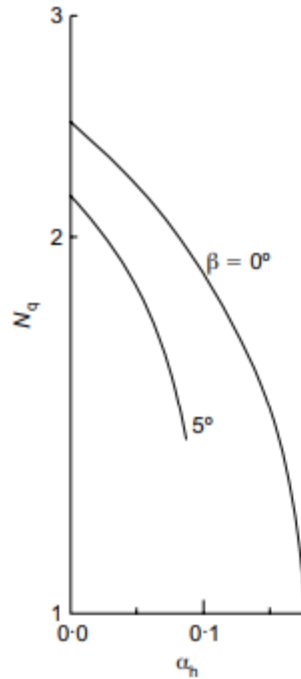
- **Kumar and Rao (2003)**
- **Chakraborty and Kumar (2015)**

Kumar and Rao (2003)

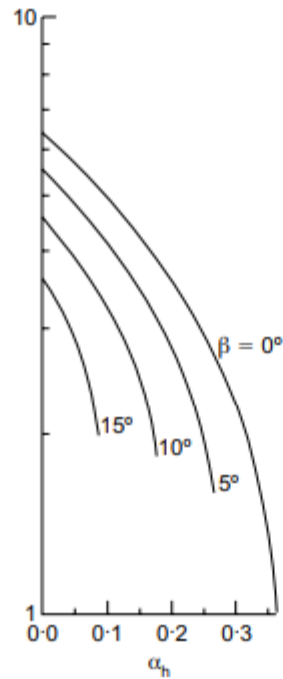
Kumar and Rao (2003) studied bearing capacity of footing on of the slopes. They found, an increase in the magnitude of α_h brings an appreciable reduction in all the bearing capacity factors. The magnitudes of the bearing capacity factors decrease further with increases in ground inclination.



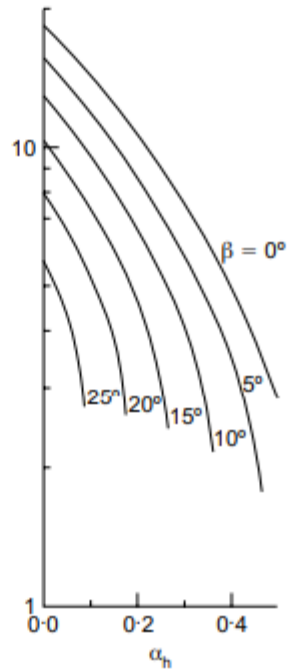
Kumar and Rao (2003) - Continue



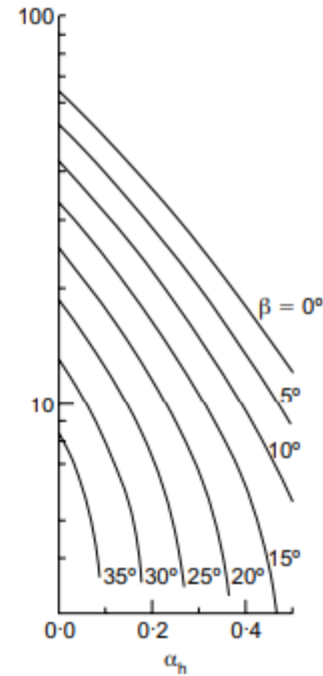
$\phi = 10^\circ$



$\phi = 20^\circ$



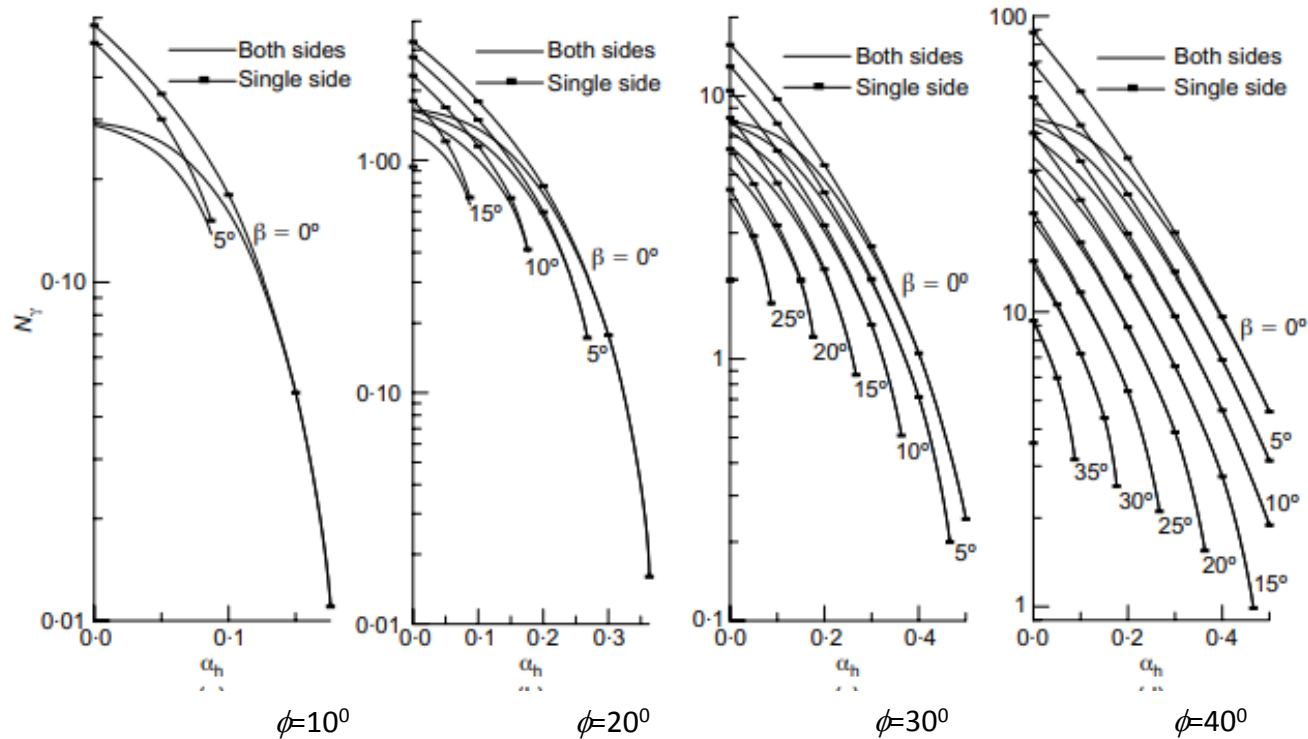
$\phi = 30^\circ$



$\phi = 40^\circ$

(c = Constant)

Kumar and Rao (2003) - Continue



Seismic Bearing Capacity

Terzaghi (1943)'s standard bearing capacity expression:

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

N_c , N_q and N_γ with α_h for different values of ϕ and β are taken from previous Figures

Chakraborty and Kumar (2015)

Earlier Kumar and Rao (2003) has given seismic bearing capacity factors for the footing on the of the slope using the method of stress characteristics.

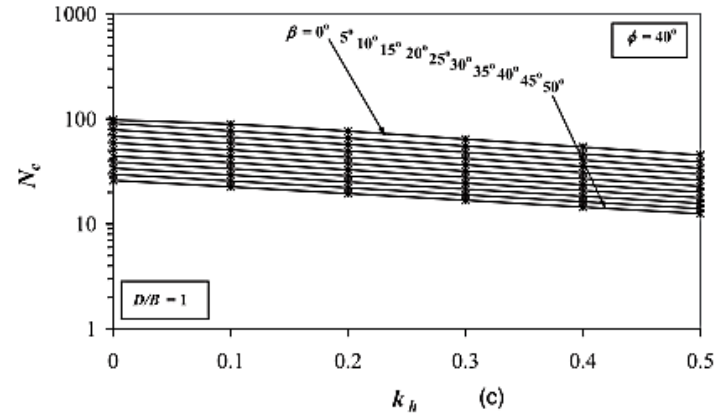
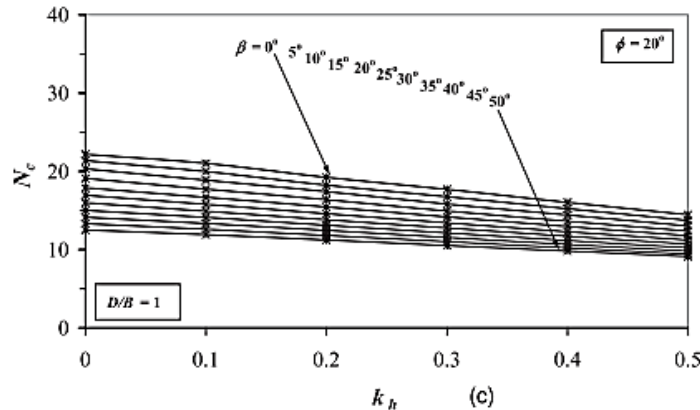
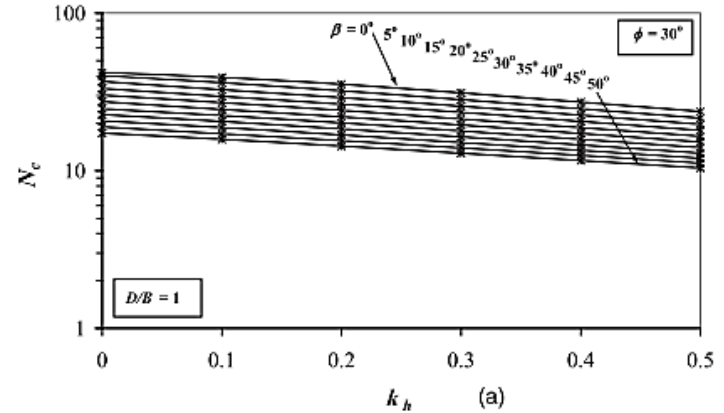
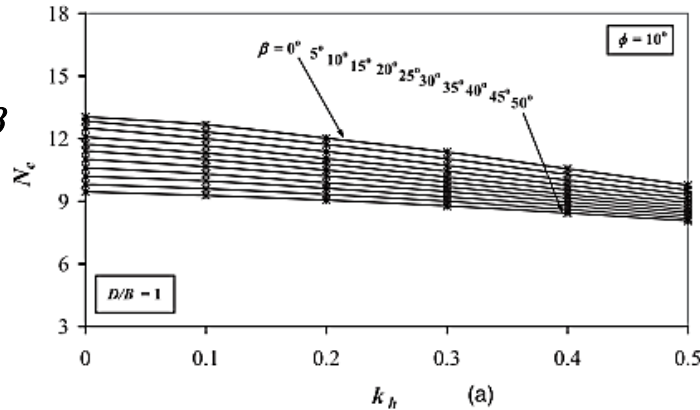
Later, Chakraborty and Kumar (2015) determine the bearing capacity factors using the lower-bound theorem of the limit analysis.

The collapse load is expressed in terms of the bearing-capacity factors

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

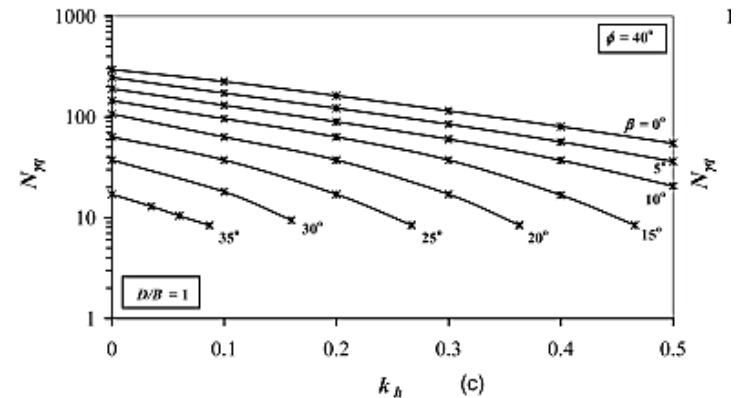
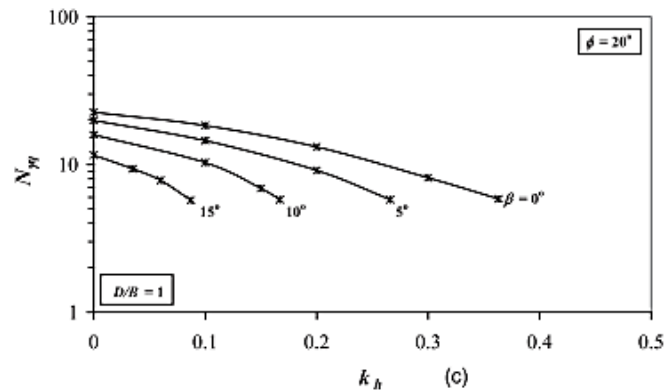
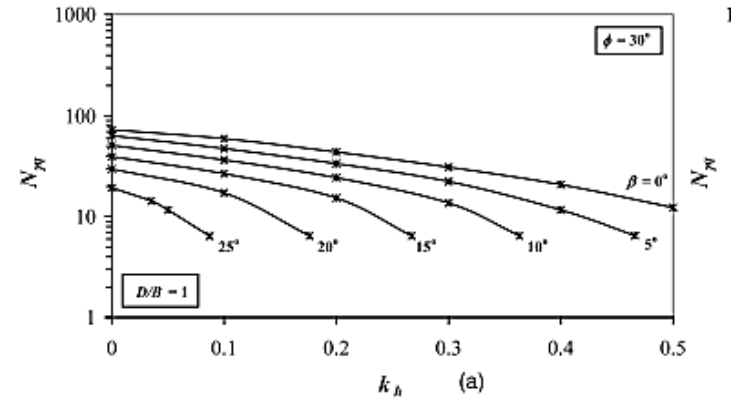
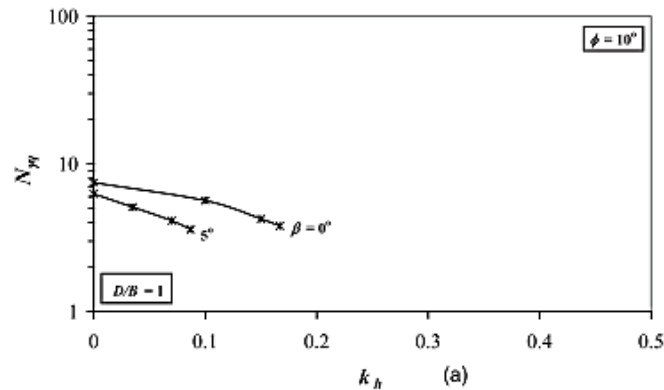
Chakraborty and Kumar (2015) - Continue

Variation of N_c with k_h and β



Chakraborty and Kumar (2015) - Continue

Variation of $N_{\gamma q}$ with k_h and β



Codal Provisions

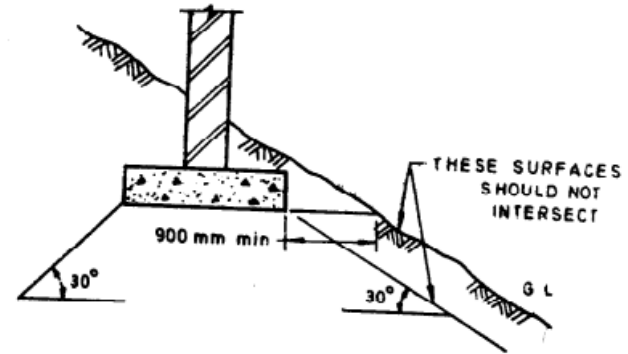
- **IS 1904 (1986)**
- **Eurocode 8 -Part 5 (1998)**

Codal Provision: IS 1904 (1986)

The depth of the footings shall be such that the difference in footing elevations shall be subject to the following limitations:

a. When the ground surface slopes downward adjacent to a footing, the sloping surface shall not intersect a frustum of bearing material under the footing having sides which make an angle of 30° with the horizontal for soil.

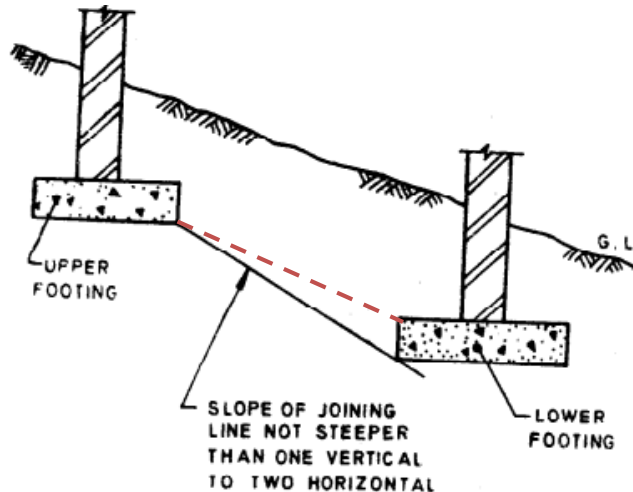
The horizontal distance from the lower edge of the footing to the sloping surface shall be at least 60 cm for rock and 90 cm for soil (see Figure).



Foundations at Different Levels

b. In the case of footings in granular soil, a line drawn between the lower adjacent edges of adjacent footings shall not have a steeper slope than one vertical to two horizontal (see Figure).

c. In case of footing of clayey soils, a line drawn between the lower adjacent edge of the upper footing and the upper adjacent edge of lower footing shall not have a steeper slope than one vertical to two horizontal (see Figure).



Codal Provision: IS 1904 (1986)

Landslips Areas

- a. The construction of structures on slopes which are suspected of being unstable and are subject to landslide shall be avoided.
- b. On sloping ground on clay soils, there is always a tendency for the upper layers of soil to move downhill, depending on type of soil, the angle of slope, climatic conditions, etc. In some cases, the uneven surface of the slope on a virgin ground will indicate that the area is subject to small land slips and, therefore, if used for foundation, will obviously necessitate special design consideration.
- c. Where there may be creep of the surface layer of the soil, protection against creep may be obtained by following special design considerations.
- d. On sloping sites, spread foundations shall be on a horizontal bearing and stepped. At all changes of levels, they shall be lapped at the steps for a distance at least equal to the thickness of the foundation or twice the height of the step, whichever is greater. The steps shall not be of greater height than the thickness of the foundation, unless special precautions are taken.

Codal Provision: IS 1904 (1986)

Landslips Areas

- e. **Cuttings, excavations or sloping ground near and below foundation level may increase the possibility of shear failure of the soil. The foundation shall be well beyond the zone of such shear failure.**
- f. **If the probable failure surface intersects a retaining wall or other revetment, the latter shall be made strong enough to resist any unbalanced thrust. In case of doubt, as to the suitability of the natural slopes or cuttings, the structure shall be kept well away from the top of the slopes, or, the slopes shall be stabilized.**
- g. **Cuttings and excavations adjoining foundations reduce stability and increase the likelihood of differential settlement. Their effect should be investigated not only when they exist but also when there is possibility that they are made subsequently.**
- h. **Where a structure is to be placed on sloping ground, additional complications are introduced. The ground itself, particularly if of clay, may be subject to creep or other forms of instability, which may be enhanced if the strata dip in the same direction as the ground surface. If the slope of the ground is large, the overall stability of the slope and substructure may be affected. These aspects should be carefully investigated.**



Codal Provision: Euro-code 8 (1998)

General expression: The stability against seismic bearing capacity failure of a shallow strip footing resting on the surface of homogeneous soil, may be checked by relating the soil strength, the design action effects at the foundation level, and the inertia forces in the soil.

For purely cohesive soil. For purely cohesive soils or saturated cohesionless soils the ultimate bearing capacity under a vertical concentric load N_{max} is given by

$$N_{max} = (\pi + 2) \frac{\bar{c}}{\gamma_M} B \quad (1)$$

Where, c is the undrained shear strength of soil (c_u) for cohesive soil, or the cyclic undrained shear strength, $\tau_{cy,u}$, for cohesionless soils; γ_M is the partial factor for material properties.

Codal Provision: Euro-code 8 (1998)

Purely cohesionless soil. For purely dry cohesionless soils or for saturated cohesionless soils without significant pore pressure building the ultimate bearing capacity of the foundation under a vertical centered load N_{max} is given by

$$N_{Max} = \frac{1}{2} \rho g \left(1 \pm \frac{a_v}{g} \right) B^2 N_\gamma \quad (2)$$

Where, g is the acceleration of gravity; a_v is the vertical ground acceleration

N_γ is the bearing capacity factor, a function of the design angle of the shearing resistance of soil ϕ_d .

Numerical Examples

- On Saturated Clay
- On Granular Soil

Numerical Problem

Q1. shows a continuous foundation on the top of a saturated clay slope. Estimate the ultimate bearing capacity by

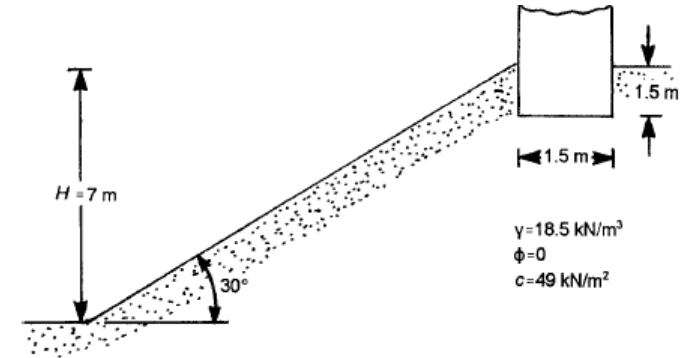
- a. Meyerhof's method and
- b. Hansen and Vesic's method

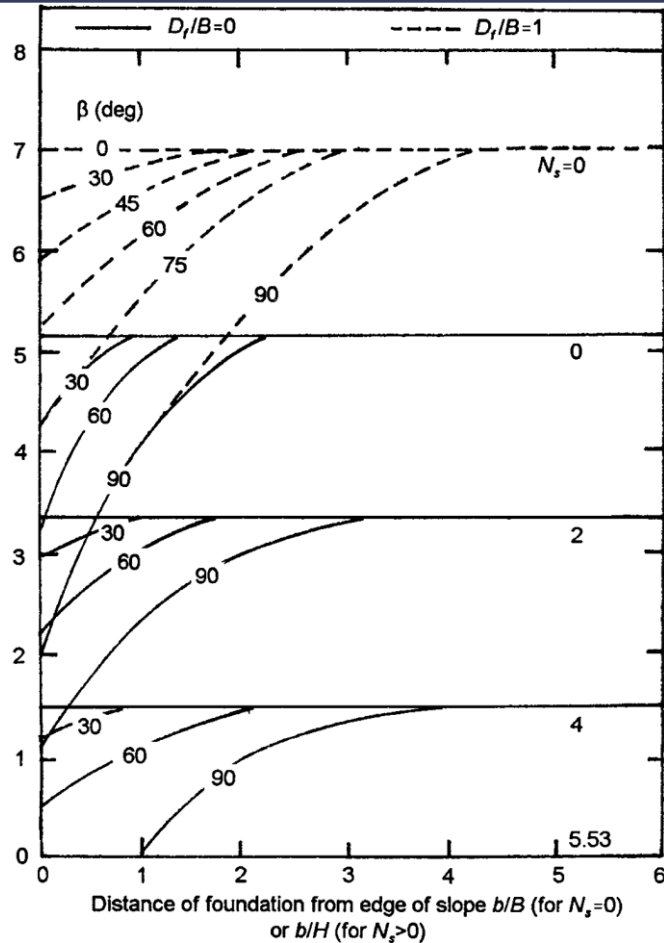
Solution:

a. $q_u = cN_{cq}$

Given $\frac{D_f}{B} = \frac{1.5}{1.5} = 1$, $\frac{b}{B} = \frac{0}{1.5} = 0$. Since $\frac{H}{B} > 1$, use $N_s = 0$.

Now see the chart





b.

Value of N_{cq} is about 6.5. So

$$q_u = (49)(6.5) = 318.5 \text{ kN/m}^2$$

$$\begin{aligned}
 q_u &= (5.14 - 2\beta)c + \gamma D_f(1 - \tan\beta)^2 - \gamma B \sin\beta(1 - \tan\beta)^2 \\
 &= \left[5.14 - (2) \left(\frac{\pi}{180} \times 30 \right) \right] (49) + (185)(1.5)(1 - \tan 30) \\
 &\quad - (185)(1.5)(\sin 30)(1 - \tan 30)^2 \\
 &= 203 \text{ kN/m}^2
 \end{aligned}$$

Thus value obtained by Hansen and Vesic is quite low compared to that shown by Meyerhof.

Numerical Problem Cont..

Q2. shows a continuous foundation on a slope of a granular soil. Estimate the ultimate bearing capacity by

- Meyerhof's method
- Saran and Handa's method and
- The stress characteristic solution

Solution

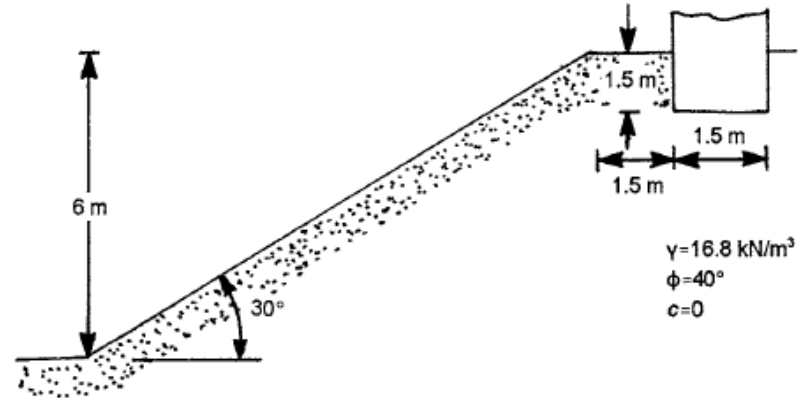
- a. For granular soil ($c = 0$) from Eq. (4.81)

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

$$\text{Given } \frac{b}{B} = \frac{1.5}{1.5} = 1, \frac{D_f}{B} = \frac{1.5}{1.5} = 1, \phi = 40^\circ, \text{ and } \beta = 30^\circ.$$

See the chart for factor

$$q_u = \frac{1}{2} (16.8)(1.5) \left(\frac{70 + 110}{2} \right) = 1134 \text{ kN / m}^2$$



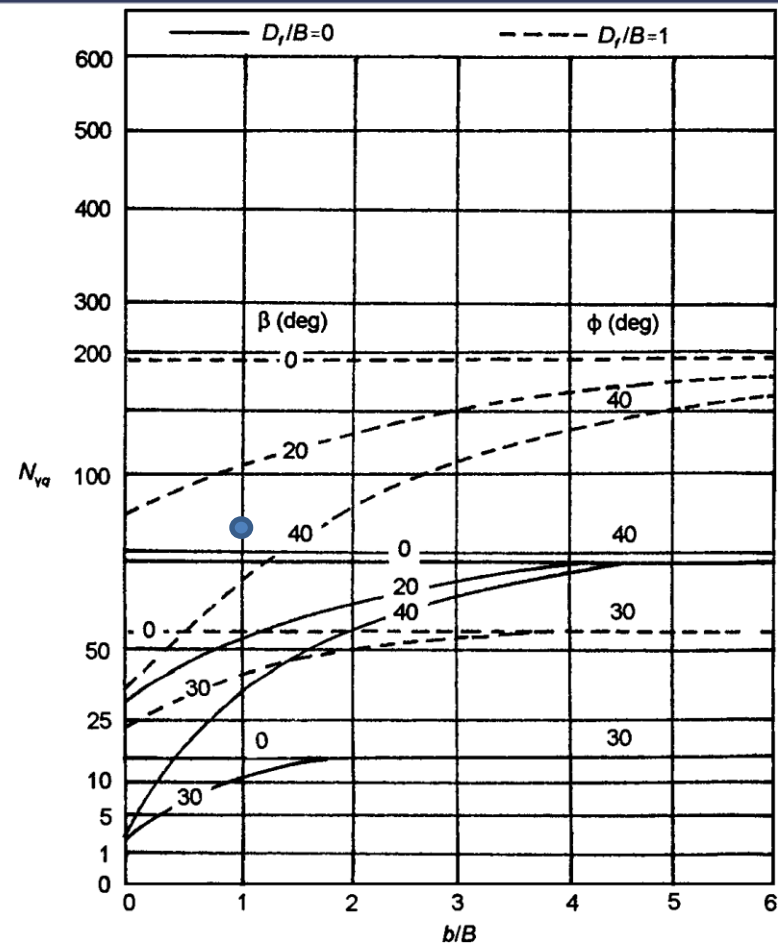


TABLE 4.2 Bearing Capacity Factors Based on Saran, Seed, and Handa's Analysis

Factor	β (deg)	$\frac{D_f}{B}$	$\frac{b}{B}$	Soil friction angle, ϕ (deg)						
				40	35	30	25	20	15	10
N_c	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				
N_q	30	1	1	131.34	64.37	28.89				
	25			151.37	66.59	28.89				
	≤ 20			166.39	66.59	28.89				
	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	
N_{γ}	30	1	1	28.31	24.14	22.5				
	20			42.25	41.4	22.5				
	≤ 10			81.30	41.4	22.5				
	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			

b. For $c = 0$, from Eq. (4.88)

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

For $\frac{b}{B} = 1$, $\frac{D_f}{B} = 1$, $\phi = 40^\circ$, and $\beta = 30^\circ$, the value of $N_\gamma = 131.34$ and the value of $N_q = 28.31$ (Table 4.2)

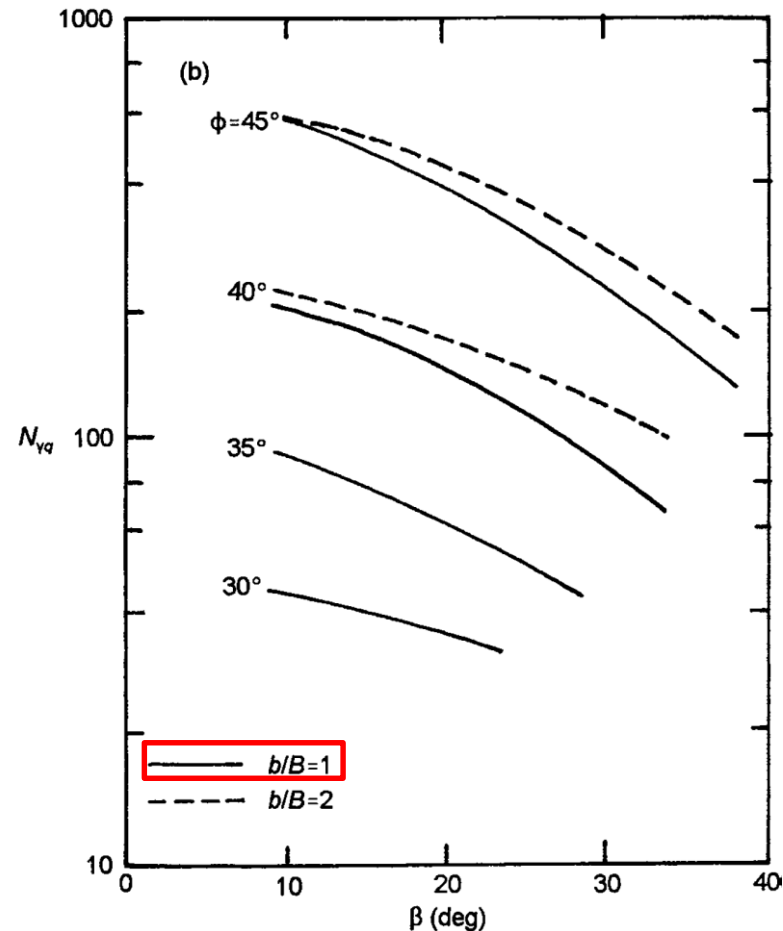
$$q_u = (16.8)(1.5)(28.31) + \frac{1}{2}(16.8)(1.5)(131.34) = 2368 \text{ kN / m}^2$$

c. From Eq.

$$q_u = \frac{1}{2}\gamma B n_{\gamma q}$$

See The chart $N_{\gamma q} = 110$

$$q_u = \frac{1}{2}(16.8)(1.5)(110) = 1386 \text{ kN / m}^2$$



Reference

1. Chakraborty, D. and Kumar, J. (2015): Seismic Bearing Capacity of Shallow Embedded Foundations on a Sloping Ground Surface, Int. J. Geomech., ASCE 15(1): 1943-5622
2. Das, B.M. (1999): Shallow foundations: bearing capacity and settlements, CRC Press LLC, USA.
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5. Kumar, J. and Mohan Rao, V. B. K. (2003): Seismic bearing capacity of foundations on slopes, Geotechnique 53, No. 3, 347–361



Thank You

