



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS:

Lecture 18: Pile Foundations under Lateral Loads - Numerical Examples

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ERD of Foundations - Modules

1. Introduction
2. Shallow Foundations
- 3. Pile Foundations**
4. Well Foundations
5. SSI for Deep Foundations



Module - 3

Pile Foundations

Module -3: Chapters

1. Piles for Static Vertical Load
2. Lateral Loads on Piles
3. Dynamic Analysis of Piles
4. Design for Lateral and Dynamic Loads
5. Codal Provisions



Chapter 2: Lateral Loads on Piles

- Introduction
- Conventional Method of Analysis
- Elastic Method using Winkler Approach
- Solution for Piles in Cohesionless Soil
- Solution for Piles in Clay
- Design Procedure for Piles
- Numerical Examples



Numerical Example-1

A pile in sand, 10 m long with head free to deflect and rotate is acted upon by a lateral load of 3000 kg. The EI of the section is 3.5×10^{10} kg-cm². The pile undergoes a deflection of 12 mm. If the piles in the group were restrained against rotation to the extent of 50 percent of the fully restrained piles, determine the maximum bending moment and the soil reaction on the piles. Also plot the deflected shape of the pile. Assume that the width of the pile is 30 cm and that the unit weight of soil is 1.8 g/cm³. Neglect group action. $\phi=30^\circ$.

Solution:

$$\text{Total deflection, } y = y_A + y_B = A_y \frac{Q_g T^3}{EI} + B_y \frac{M_g T^2}{EI} = A_y \frac{Q_g T^3}{EI}$$

Maximum deflection is at the top of pile

$$\begin{aligned} \text{At } z = 0, A_y &= 2.435 \\ 1.2 &= 2.435 \frac{3000 * T^3}{3.5 * 10^{10}} \end{aligned}$$

Solution for Piles in Cohesionless Soil (Continued...)

Below Table provide the coefficient A and B. which is applicable when $Z_{max} \geq 5$

Coefficient, A for long pile

Z	A_y	A_S	A_M	A_V	A_p
0.0	2.435	- 1.623	0.000	1.000	0.000
0.1	2.273	- 1.618	0.100	0.989	- 0.227
0.2	2.112	- 1.603	0.198	0.956	- 0.422
0.3	1.952	- 1.578	0.291	0.906	- 0.586
0.4	1.796	- 1.545	0.379	0.840	- 0.718
0.5	1.644	- 1.503	0.459	0.764	- 0.822
0.6	1.496	- 1.454	0.532	0.677	- 0.897
0.7	1.353	- 1.397	0.595	0.585	- 0.947
0.8	1.216	- 1.335	0.649	0.489	- 0.973
0.9	1.086	- 1.268	0.693	0.392	- 0.977
1.0	0.962	- 1.197	0.727	0.295	- 0.962
1.2	0.738	- 1.047	0.767	0.109	- 0.885
1.4	0.544	- 0.893	0.772	- 0.056	- 0.761
1.6	0.381	- 0.741	0.746	- 0.193	- 0.609
1.8	0.247	- 0.596	0.696	- 0.298	- 0.445
2.0	0.142	- 0.464	0.628	- 0.371	- 0.283
3.0	- 0.075	- 0.040	0.225	- 0.349	0.226
4.0	- 0.050	0.052	0.000	- 0.106	0.201
5.0	- 0.009	0.025	- 0.033	0.013	0.046

Coefficient, B for long pile

Z	B_y	B_S	B_M	B_V	B_p
0.0	1.623	- 1.750	1.000	0.000	0.000
0.1	1.453	- 1.650	1.000	- 0.007	- 0.145
0.2	1.293	- 1.550	0.999	- 0.028	- 0.259
0.3	1.143	- 1.450	0.994	- 0.058	- 0.343
0.4	1.003	- 1.351	0.987	- 0.095	- 0.401
0.5	0.873	- 1.253	0.976	- 0.137	- 0.436
0.6	0.752	- 1.156	0.960	- 0.181	- 0.451
0.7	0.642	- 1.061	0.939	- 0.226	- 0.449
0.8	0.540	- 0.968	0.914	- 0.270	- 0.432
0.9	0.448	- 0.878	0.885	- 0.312	- 0.403
1.0	0.364	- 0.792	0.852	- 0.350	- 0.364
1.2	0.223	- 0.629	0.775	- 0.414	- 0.268
1.4	0.112	- 0.482	0.688	- 0.456	- 0.157
1.6	0.029	- 0.354	0.594	- 0.477	- 0.047
1.8	- 0.030	- 0.245	0.498	- 0.476	0.054
2.0	- 0.070	- 0.155	0.404	- 0.456	0.140
3.0	- 0.089	0.057	0.059	- 0.213	0.268
4.0	- 0.028	0.049	- 0.042	0.017	0.112
5.0	0.000	0.011	- 0.026	0.029	- 0.002

Numerical Example-1 (Continued...)

$$T = 179.15 \text{ cm}$$

$$\text{Check } Z_{\max} = \frac{L_s}{T} = \frac{10 \times 100}{179.15} = 5.58 \geq 5 \text{ (O.K.)}$$

$$\text{Now Pile deflection, } y = y_A + y_B = A_y \frac{Q_g T^3}{EI} + B_y \frac{M_g T^2}{EI} = (A_y - 0.93 * 0.5 B_y) \frac{Q_g T^3}{EI}$$

$$y = (A_y - 0.465 B_y) \frac{Q_g T^3}{EI}$$

$$\text{Bending Moment, } M = (A_m - 0.465 B_m) Q_g T$$

$$\text{Soil Reaction, } p = C_p \frac{Q_g}{T} = (A_p - 0.465 B_p) \frac{Q_g}{T}$$

The value of y , M and p are computed in tabular form and are plotted as shown in next slide.

Numerical Example-1 (Continued...)

$x,$ m	$Z = \frac{x}{T}$	A_y	$0.465B_y$	C_y	$y,$ cm	A_m	$0.465B_m$	C_m	$M,$ t·cm,	A_p	$0.465B_p$	C_p	$p,$ kg/cm,
1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	0.0	2.435	0.755	1.680	0.828	0	- 0.465	- 0.465	- 250	0.000	0	0	0
0.36	0.2	2.112	0.601	1.511	0.745	0.198	0.465	- 0.267	- 1,43	- 0.422	- 0.120	- 0.302	- 5.06
0.72	0.4	1.796	0.466	1.330	0.655	0.379	0.459	- 0.080	- 43	- 0.718	- 0.186	- 0.532	- 8.91
1.07	0.6	1.496	0.350	1.146	0.565	0.532	0.446	0.086	46	- 0.897	- 0.210	- 0.687	- 11.50
1.43	0.8	1.216	0.251	0.965	0.476	0.649	0.425	0.244	1,20	- 0.973	- 0.201	- 0.772	- 12.93
1.79	1.0	0.962	0.169	0.793	0.391	0.727	0.396	0.331	1,77	- 0.962	- 0.169	- 0.793	- 13.28
2.15	1.2	0.738	0.104	0.634	0.312	0.767	0.360	0.407	2,19	- 0.885	- 0.125	- 0.760	- 12.73
2.87	1.6	0.381	0.013	0.368	0.181	0.746	0.276	0.470	2,55	- 0.609	- 0.022	- 0.587	- 9.83
3.58	2.0	0.142	- 0.032	0.175	0.086	0.628	0.188	0.440	2,36	- 0.283	0.065	- 0.318	- 5.83
5.37	3.0	- 0.075	- 0.041	- 0.034	- 0.017	0.225	0.027	0.198	1,06	0.226	0.125	0.101	1.69
7.16	4.0	- 0.050	- 0.013	- 0.037	- 0.018	0.000	- 0.019	0.020	10	0.201	0.052	0.149	2.50
8.96	5.0	- 0.009	0.000	- 0.009	- 0.004	- 0.033	- 0.012	- 0.021	- 11	0.046	- 0.001	0.047	0.79

Numerical Example-1 (Continued...)

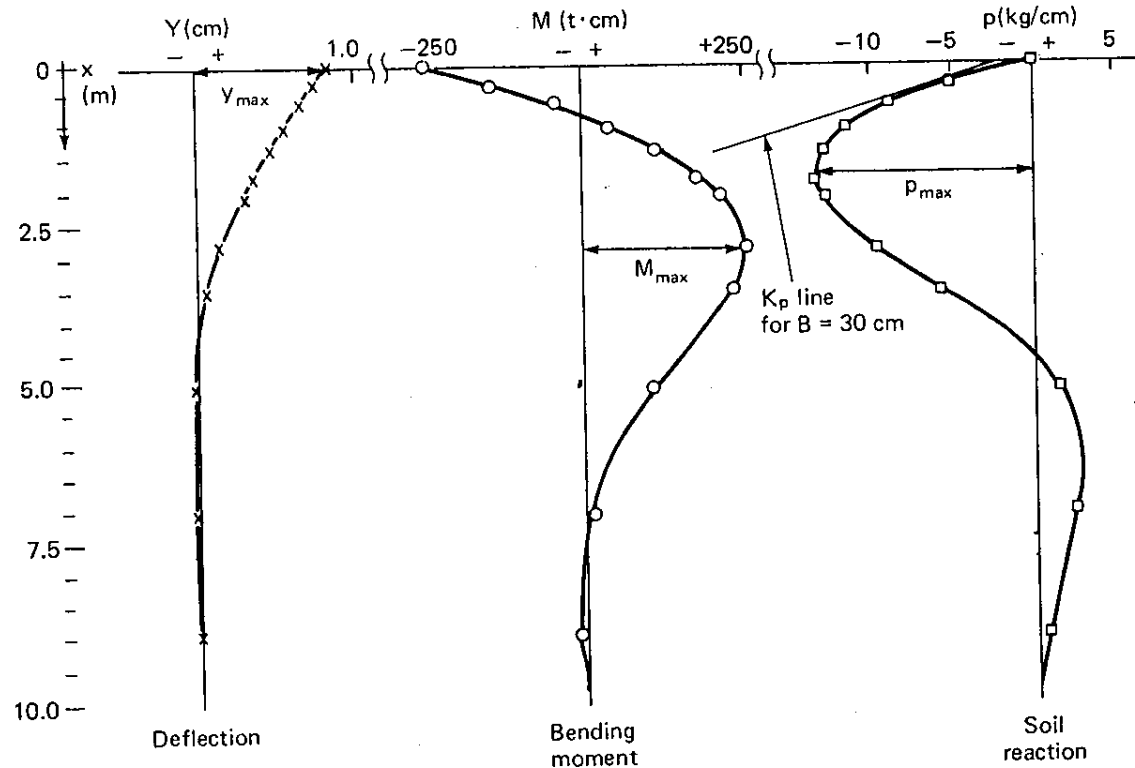
The maximum $M = 255 \text{ t-cm}$
and $p_{\max} = 13.5 \text{ kg/cm}$

$$p_a = \frac{1+\sin \phi}{1-\sin \phi} \gamma b x =$$

$$\frac{1+\sin 30}{1-\sin 30} 1.8 * 30 * Tz$$

$$= 162 T^*z$$

p_a line has been plotted on
the soil reaction diagram.



Numerical Example-2

A 15 m long cylindrical RCC pile of diameter 600 mm is installed in a deposit of uniform sand, in which modulus of subgrade reaction increases with depth, to carry a lateral load of 100 kN. Given that the unit modulus of subgrade reaction (η_h) = 10×10^6 N/m³, unit weight of soil = 18 kN/m³, $\phi = 30^\circ$, and for concrete $E = 25$ Gpa. Assume that the pile head is partially fixed (with $\lambda = 0.5$) and nondimensional coefficients for laterally loaded long piles (obtained by the solution of basic differential equation for beam on elastic foundation) are given in the enclosed table. Determine:

- (a) The maximum lateral deflection (along the pile depth)
- (b) The maximum bending stress (along the pile depth)
- (c) Show in tabular form variation of soil reaction (p_x) and permissible soil reaction (p_a) with the pile depth up to a point until $p_x > p_a$

Solution for Piles in Cohesionless Soil (Continued...)

Below Table provide the coefficient A and B. which is applicable when $Z_{max} \geq 5$

Coefficient, A for long pile

Z	A_y	A_S	A_M	A_V	A_p
0.0	2.435	- 1.623	0.000	1.000	0.000
0.1	2.273	- 1.618	0.100	0.989	- 0.227
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0.3	1.952	- 1.578	0.291	0.906	- 0.586
0.4	1.796	- 1.545	0.379	0.840	- 0.718
0.5	1.644	- 1.503	0.459	0.764	- 0.822
0.6	1.496	- 1.454	0.532	0.677	- 0.897
0.7	1.353	- 1.397	0.595	0.585	- 0.947
0.8	1.216	- 1.335	0.649	0.489	- 0.973
0.9	1.086	- 1.268	0.693	0.392	- 0.977
1.0	0.962	- 1.197	0.727	0.295	- 0.962
1.2	0.738	- 1.047	0.767	0.109	- 0.885
1.4	0.544	- 0.893	0.772	- 0.056	- 0.761
1.6	0.381	- 0.741	0.746	- 0.193	- 0.609
1.8	0.247	- 0.596	0.696	- 0.298	- 0.445
2.0	0.142	- 0.464	0.628	- 0.371	- 0.283
3.0	- 0.075	- 0.040	0.225	- 0.349	0.226
4.0	- 0.050	0.052	0.000	- 0.106	0.201
5.0	- 0.009	0.025	- 0.033	0.013	0.046

Coefficient, B for long pile

Z	B_y	B_S	B_M	B_V	B_p
0.0	1.623	- 1.750	1.000	0.000	0.000
0.1	1.453	- 1.650	1.000	- 0.007	- 0.145
0.2	1.293	- 1.550	0.999	- 0.028	- 0.259
0.3	1.143	- 1.450	0.994	- 0.058	- 0.343
0.4	1.003	- 1.351	0.987	- 0.095	- 0.401
0.5	0.873	- 1.253	0.976	- 0.137	- 0.436
0.6	0.752	- 1.156	0.960	- 0.181	- 0.451
0.7	0.642	- 1.061	0.939	- 0.226	- 0.449
0.8	0.540	- 0.968	0.914	- 0.270	- 0.432
0.9	0.448	- 0.878	0.885	- 0.312	- 0.403
1.0	0.364	- 0.792	0.852	- 0.350	- 0.364
1.2	0.223	- 0.629	0.775	- 0.414	- 0.268
1.4	0.112	- 0.482	0.688	- 0.456	- 0.157
1.6	0.029	- 0.354	0.594	- 0.477	- 0.047
1.8	- 0.030	- 0.245	0.498	- 0.476	0.054
2.0	- 0.070	- 0.155	0.404	- 0.456	0.140
3.0	- 0.089	0.057	0.059	- 0.213	0.268
4.0	- 0.028	0.049	- 0.042	0.017	0.112
5.0	0.000	0.011	- 0.026	0.029	- 0.002

Numerical Example-2

Given $L_s = 15\text{m}$, $D=600\text{mm}=0.6\text{m}$, $E=25\text{ GPa}$, $\eta_h=10*10^6\text{ N/m}^3 = 10^7\text{ N/m}^3$,
 $\gamma = 18\text{ KN/m}^3$, $\phi = 30^\circ$, $\lambda = 0.5$, $Q_g = 100\text{ kN}$.

$$L_s / D = 15/0.6 = 25 \text{ (OK)}$$

$$I = \frac{\pi D^4}{64} = \frac{\pi * 0.6^4}{64} = 6.36 * 10^{-3} \text{ m}^4$$

$$T = \left(\frac{EI}{\eta_h} \right)^{\frac{1}{5}} = \left(\frac{25 * 10^9 * 6.36 * 10^{-3}}{10^7} \right)^{\frac{1}{5}} = (15.90)^{\frac{1}{5}} = 1.739 \text{ m} = 1.74 \text{ m}.$$

$$\text{Check } \frac{L_s}{T} = \frac{15}{1.74} = 8.62 > 5 \text{ (OK)}$$

Numerical Example-2

(a) Maximum lateral deflection:

$$y_x = C_y \frac{Q_d T^3}{EI}, \quad C_y = A_y - \lambda * 0.93 B_y \\ = (A_y - 0.465 B_y)$$

Deflection will be maximum wherever C_y is maximum.

Thus C_y will be maximum at $Z = 0$,

$$C_y = 1.680.$$

$$(y_x)_{\max} = 1.68 * \frac{100 * 10^3 * 1.739^3}{15.9 * 10^7} \\ = 5.557 * 10^{-3} \text{ m} = 5.557 \text{ mm (Ans)}$$

Z	A_y	B_y	C_y
0	2.435	1.623	1.680
0.1	2.273	1.453	1.597
0.2	2.112	1.293	1.510
0.3	1.952	1.143	1.421
0.4	1.796	1.003	1.330
0.5	1.644	0.873	1.238

Numerical Example-2 (Continued...)

(b) The maximum bending stress, $M = C_m Q_g T$

where, $C_m = A_m - 0.465B_m$

The maximum value of C_m is at $z = 1.6$ $C_m = 0.470$

$$(M_x)_{max} = C_m Q_g T$$

$$(M_x)_{max} = 0.470 * 100 * 10^3 * 1.739$$

$$(M_x)_{max} = 81.733 * 10^3 \text{ N-m}$$

Maximum bending stress

$$(\sigma_b)_{max} = \frac{(M_x)_{max}}{I} \cdot \frac{D}{2}$$

$$(\sigma_b)_{max} = \frac{81.733 * 10^3}{6.36 * 10^{-3}} \cdot \frac{0.6}{2} = 3.855 * 10^6 \text{ N/m}^2$$

z	A _m	B _m	C _m
0	0	1.0	-0.465
0.1	0.1	1.0	-0.365
0.2	0.198	0.999	-0.267
0.3	0.291	0.994	-0.171
1.2	0.787	0.775	+0.407
1.4	0.772	0.688	+0.452
1.6	0.746	0.594	+0.470
1.8	0.696	0.498	+0.464
2.0	0.628	0.404	+0.440

Numerical Example-2 (Continued...)

(c) Variation of soil reaction,

$$p_x = C_p \frac{Q_g}{T}$$

where,

$$C_p = A_p - 0.465B_p$$

$$p_x = C_p \frac{Q_g}{T} = C_p \frac{100}{1.739} = 57.504 \text{ kN/m}$$

As C_p varies with depth soil reaction also varies.

Allowable soil reaction p_a is given by

$$p_a = \frac{1 + \sin \phi}{1 - \sin \phi} \gamma b x = \frac{1 + \sin 30}{1 - \sin 30} 18 * 0.6 * x = 32.4x \text{ kN/m}$$

Where $x = Tz = 1.739z$

Now $p_a = 32.4 * 1.739z = 56.03436z \text{ kN/m}$

Numerical Example-2 (Continued...)

Computation of p_x and p_a is done in tabular form:

Z	A_p	B_p	$A_p - 0.465B_p$ $= C_p$	$57.504 C_p$ $= p_x$	$56.34 Z$ $= p_a$
0	0	0	0	0	0
0.1	-0.227	-0.145	-0.160	-9.1762	5.634
0.2	-0.422	-0.259	-0.302	-17.341	11.268
0.3	-0.586	-0.343	-0.427	-24.526	16.902
0.4	-0.718	-0.401	-0.532	-30.565	22.536
0.5	-0.822	-0.436	-0.619	-35.61	28.170
0.6	-0.897	-0.451	-0.687	-39.52	33.80
0.7	-0.947	-0.449	-0.738	-42.45	39.44
0.8	-0.973	-0.432	-0.772	-44.40	45.07
0.9	-0.977	-0.403	-0.790	-45.41	50.71

Numerical Example-3

A cylindrical RCC pile of diameter 600 mm and length 18 m is installed in a uniform sand deposit, in which modulus of subgrade reaction is increasing with depth. Assuming the pile head is fully free and using the Reese and Matlock theory, find the lateral load, the pile may safely carry. The permissible maximum lateral deflection in the pile is 10 mm and allowable bending stress is 10 N/mm². Given that the unit modulus of subgrade reaction (η_h) = 10×10^6 N/m³, unit weight of soil = 18 kN/m³, $\phi = 30^\circ$, and for concrete $E = 25$ GPa. The nondimensional coefficients for laterally loaded long piles are given in enclosed sheet. (Note: Justifying the critical condition, find the load in one attempt and round it to lower tenth and then apply all the checks).

Solution:

Given $D = 600\text{mm}$ $L_s = 18\text{m}$, fully free

$y_{\text{allow}} = 10 \text{ mm}$ $\sigma_{\text{allow}} = 10 \text{ N/mm}^2$, $\eta_h = 10 \times 10^6 \text{ N/m}^3$, for soil $\gamma = 18 \text{ kN/m}^3$, $\phi = 30^\circ$
 $E = 25 \text{ GPa} = 25 \times 10^9 \text{ N/m}^2$

Solution for Piles in Cohesionless Soil (Continued...)

Below Table provide the coefficient A and B. which is applicable when $Z_{max} \geq 5$

Coefficient, A for long pile

Z	A_y	A_S	A_M	A_V	A_p
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0.3	1.952	- 1.578	0.291	0.906	- 0.586
0.4	1.796	- 1.545	0.379	0.840	- 0.718
0.5	1.644	- 1.503	0.459	0.764	- 0.822
0.6	1.496	- 1.454	0.532	0.677	- 0.897
0.7	1.353	- 1.397	0.595	0.585	- 0.947
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1.6	0.381	- 0.741	0.746	- 0.193	- 0.609
1.8	0.247	- 0.596	0.696	- 0.298	- 0.445
2.0	0.142	- 0.464	0.628	- 0.371	- 0.283
3.0	- 0.075	- 0.040	0.225	- 0.349	0.226
4.0	- 0.050	0.052	0.000	- 0.106	0.201
5.0	- 0.009	0.025	- 0.033	0.013	0.046

Coefficient, B for long pile

Z	B_y	B_S	B_M	B_V	B_p
0.0	1.623	- 1.750	1.000	0.000	0.000
0.1	1.453	- 1.650	1.000	- 0.007	- 0.145
0.2	1.293	- 1.550	0.999	- 0.028	- 0.259
0.3	1.143	- 1.450	0.994	- 0.058	- 0.343
0.4	1.003	- 1.351	0.987	- 0.095	- 0.401
0.5	0.873	- 1.253	0.976	- 0.137	- 0.436
0.6	0.752	- 1.156	0.960	- 0.181	- 0.451
0.7	0.642	- 1.061	0.939	- 0.226	- 0.449
0.8	0.540	- 0.968	0.914	- 0.270	- 0.432
0.9	0.448	- 0.878	0.885	- 0.312	- 0.403
1.0	0.364	- 0.792	0.852	- 0.350	- 0.364
1.2	0.223	- 0.629	0.775	- 0.414	- 0.268
1.4	0.112	- 0.482	0.688	- 0.456	- 0.157
1.6	0.029	- 0.354	0.594	- 0.477	- 0.047
1.8	- 0.030	- 0.245	0.498	- 0.476	0.054
2.0	- 0.070	- 0.155	0.404	- 0.456	0.140
3.0	- 0.089	0.057	0.059	- 0.213	0.268
4.0	- 0.028	0.049	- 0.042	0.017	0.112
5.0	0.000	0.011	- 0.026	0.029	- 0.002

Numerical Example-3 (Continued...)

$$L_s/D = 18/0.6 = 30 \text{ (o.k.)}$$

$$I = \frac{\pi}{64} D^4 = \frac{\pi}{64} 0.6^4 = 6.36 \times 10^{-3} \text{ m}^4$$

$$T = \left(\frac{EI}{\eta_h} \right)^{1/5} = \left(\frac{25 \times 10^9 \times 6.36 \times 10^{-3}}{10 \times 10^6} \right)^{1/5} = 1.739 \text{ m}$$

$$\frac{L_s}{T} = \frac{18}{1.739} = 10.35 > 5 \text{ (o.k.)}$$

$$EI = 25 \times 10^9 \times 6.36 \times 10^{-3} = 1.59 \times 10^8 \text{ N-m}^2$$

The safe load can be found from the test data the pile is critical in soil reaction and for fully free case it occurs at $z = 0.1$ where, $A_p = 0.227$, after that though A_p increase but not proportionate to depth. A_p is maximum at $z = 0.9$ where $A_p = -0.977 (< 9 \times 0.227)$. Note that p_a increases proportionate to depth. Thus critical check is $p_x = p_a$ at $z = 0.1$.

Numerical Example-3 (Continued...)

at $z = 0.1$ for $\phi = 30^\circ$, $\sin\phi = 0.5$, $x = Tz = 0.1T$, $b = D = 0.6$ m

$$p_x = A_p \frac{Q_g}{T} = 0.227 \frac{Q_g}{1.379} = 0.1305 Q_g \text{ kN/m}$$

$$\text{and } p_a = \frac{1+\sin\phi}{1-\sin\phi} \gamma b x = \frac{1+0.5}{1-0.5} 18 * 0.1 * 1.739 * 0.6 = 5.634 \text{ kN/m}$$

$$\text{Thus, } 0.1305 Q_g = 5.634, Q_g = 43.175 \text{ kN}$$

$$Q_g = 40 \text{ kN} \quad \text{Ans.}$$

Checks, For $Q_g = 40$ kN

at $z = 0$

$$y_{max} = (A_y) \frac{Q_g T^3}{EI} = (2.435) \frac{40 * 1.739^3}{1.59 * 10^8} = 3.22 * 10^{-3} \text{ m} = 3.22 \text{ mm} < 10 \text{ mm (ok)}$$

Numerical Example-3 (Continued...)

Maximum value of M_x is where A_m is maximum i.e. at $z = 1.4$, $A_m = 0.772$

$$(M_x)_{max} = A_m Q_g T = 0.7772 * 40 * 1.739 = 53.70 \text{ kN-m}$$

$$\begin{aligned} (\sigma_b)_{max} &= \frac{(M_x)_{max}}{I} \cdot b = \frac{53.70 * 10^3}{6.36 * 10^{-3}} \cdot \frac{0.6}{2} \\ &= 2.53 * 10^6 \text{ N/m}^2 = 2.53 \text{ N/mm}^2 < 10 \text{ N/mm}^2 \text{ O.K.} \end{aligned}$$

at $z = 0.1$

$$p_x = A_p \frac{Q_g}{T} = 0.277 \frac{40}{1.739} = 5.22 \text{ kN/m}$$

$$p_a = 5.634 \text{ kN/m}$$

$$p_x < p_a \text{ (O.K.)}$$

References

1. **Prakash S. (1981), "Soil Dynamics", McGraw-Hill Company, New York**
2. **Ranjan G. and Rao A.S.R. (2004), "Basic and Applied Soil Mechanics", New Age Int. Ltd., New Delhi.**

Thank You

