



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS:

Lecture 17: Pile Foundations under Lateral Loads: Elastic Method for Cohesive Soils including degradation of modulus of subgrade reaction (k)

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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



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: Degradation of k
- Design Procedure for Piles
- Numerical Examples

Solution for Piles in Clay

Solutions similar to that presented for sandy soils have been obtained by Davisson (1962) and by Davisson and Gill (1963) for clays that occur in two layers. Assuming the modulus of subgrade reaction constant with depth i.e. $k_x = k_h = k$ and using R in place of T for clay, A_{yc} in place of A_y , letting $\phi(z) = 1$ in Equation for Soil Modulus function, Following equations are obtained for clay

$$\frac{d^4 A_{yc}}{dz^4} + \phi(z) A_{yc} = 0 \quad (1)$$

$$\phi(z) = \frac{kR^4}{EI} = 1 \quad (2)$$

Therefore,

$$R = \sqrt[4]{\frac{EI}{k}} \quad (3)$$

The depth coefficient is

$$z = \frac{X}{R} \quad (4)$$

Solution for Piles in Clay (Continued...)

The maximum depth coefficient is

$$Z_{max} = \frac{L_s}{R} \quad (5)$$

If both shear and moment act on a pile head, using B_{yc} for moment coefficient

$$y_x = A_{yc} \frac{Q_g R^3}{EI} + B_{yc} \frac{M_g R^2}{EI} \quad (6)$$

Similarly Eqn. (7c)

$$M_x = A_{mc} Q_g R + B_{mc} M_g \quad (7)$$

Where, A_{yc} = deflection coefficient for shear load on a free head pile in clay

B_{yc} = deflection coefficient for moment load on a free head pile in clay

A_{mc} = moment coefficient for shear load on free head pile in clay

B_{mc} = moment coefficient for moment load on free head pile in clay

The soil reaction diagram may be obtained by multiplying the y diagram with k , which is assumed constant along the depth of embedment of the pile.

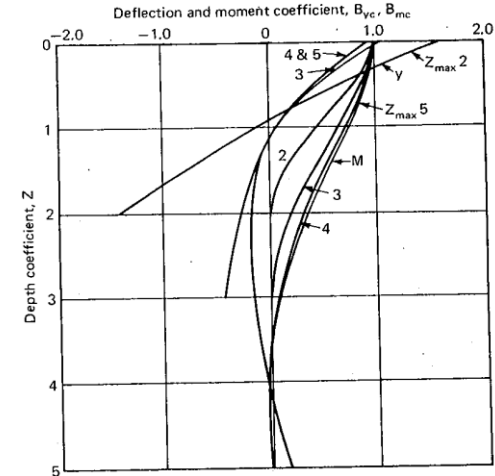
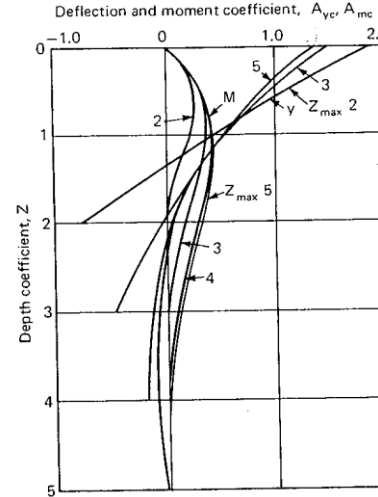
Solution for Piles in Clay (Continued...)

The solution for A and B may be obtained by using either the technique described by Matlock and Reese (1962) or analog computer (Davisson and Gill, 1963)

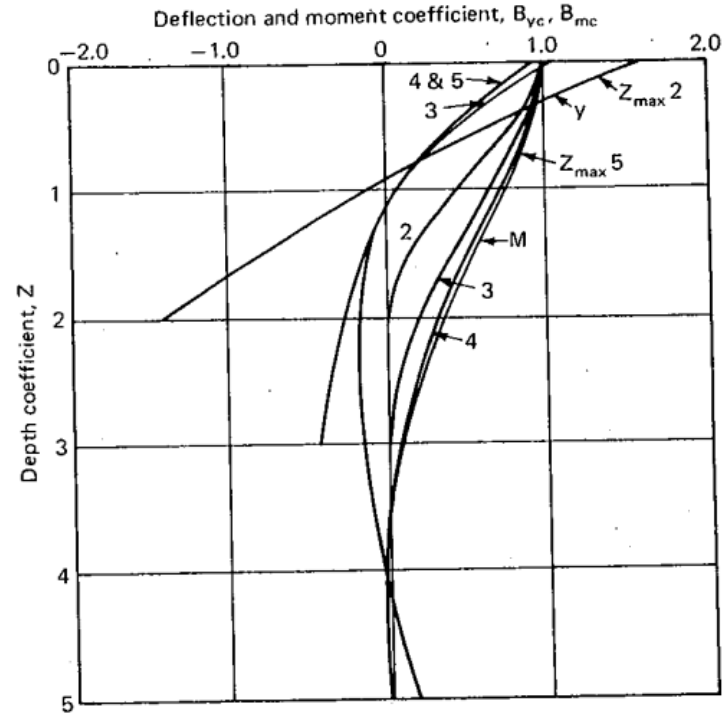
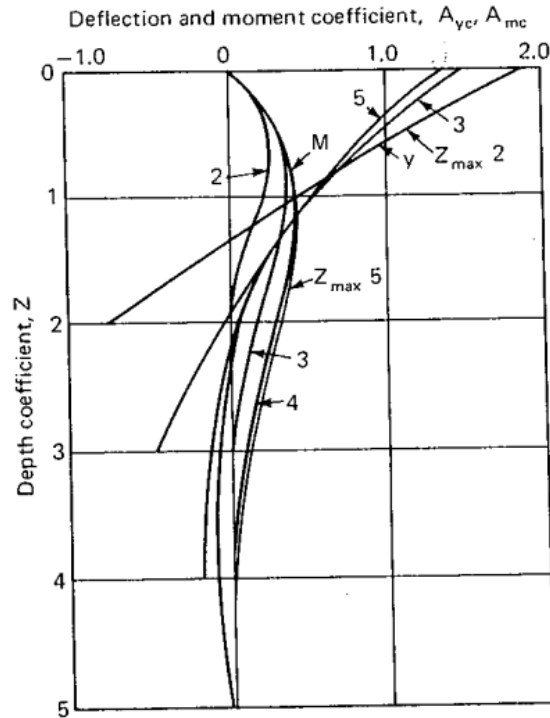
It may be seen from the deflection coefficient Fig.

For $Z_{max} = 2$ plot is straight line. Hence pile may be considered as rigid pile if $Z_{max} \leq 2$.

Similarly for $Z_{max} \geq 4$ pile may be considered as infinite long pile.



Solution for Piles in Clay (Continued...)



Modulus of Subgrade Reaction Degradation with Strain

Mwindo (1992) developed five empirical relationships of modulus degradation with shear strain (γ) for free-headed piles of different materials embedded in clays of different relative consistencies. The general form of the equations developed by Mwindo is:

$$\frac{k_h}{k_{hmax}} = a\gamma^{-b} \quad (1)$$

Values of the constants a and b obtained by Mwindo are listed as

Pile	Soil	a	b
Timber	Medium Clay	0.16	0.30
Timber	Stiff Clay	0.33	0.18
Steel Pipe	Stiff Clay	0.05	0.48
Prest. Cone.	Soft Clay	0.08	0.42
Prest. Cone.	Stiff Clay	0.19	0.27

Modulus of Subgrade Reaction Degradation with Strain(Continued...)

For pile-head loading conditions, the shear strain γ depends on the pile displacement, y at the pile head. Kagawa and Kraft (1980) have reported that more than 70 percent of the pile displacement is concentrated in the soil mass within two-pile radius depth. Therefore, the increase in shear strain due to soil-pile-interaction is concentrated in this zone.

The average normal strain (ϵ) in the direction of pile movement in the soil around the pile of radius r (or width $B = 2r$) can be approximated by

$$y = 5r\epsilon = 2.5B\epsilon \quad (2)$$

The same relationship was used by Matlock (1970) following the concept originally proposed by Skempton (1951) for footing settlement problems. As the soil strain orthogonal to ϵ is $-\nu \epsilon$, the maximum shear strain γ due to ϵ and $-\nu \epsilon$ is $(1+ \nu)\epsilon$. Thus, the average shear strain around a pile is given as

$$\gamma = \frac{1+\nu}{2.5B} y \quad (3)$$

Modulus of Subgrade Reaction Degradation with Strain(Continued...)

The Poisson's ratio ν of clay being approximately equal to 0.50, Eq. (3) becomes

$$\gamma = \frac{y}{1.667B} \quad (4)$$

Blaney and O'Neill (1986) used Eq. 4 to relate deflections and shear strains around piles in clays.

Although the original stipulation of strain by Kagawa and Kraft (1980) was for small deflections, it has been demonstrated by Prakash and Kumar (1996) that it is appropriate to use the same description of strain even with relatively large pile deflections.

p-y Method for Clays

Matlock (1970) proposed a procedure for determination of the p-y curve in soft clays. Reese et al (1975) extended this procedure for the determination of p-y curves for stiff clays below the water table. Reese and Welch (1975) developed a procedure for p-y curves in stiff clays above the water table. The results of these experiments were used to develop p-y curves (Reese 1984, Chen 1994).

Steps:

1. Develop the modulus degradation equation with strain for clays from analysis of field data from published literature.
2. Determine the range of k_{hmax}
3. Predicting the load-deflection curves.
4. Comparing the predictions with measured curves and the p-y method.

Modulus Degradation Equation

Stiff Clay

Here k_x is assumed constant with depth i.e. $k_x = k_h$. A pile is considered long and will behave as a flexible member if the ratio L/R is greater than or equals 4. If L/R is smaller than 2, the pile behaves as a rigid member, where L is the embedded pile length and R is the relative stiffness factor.

Calculate the degradation of modulus of subgrade reaction using the relation given by Prakash and Chen (1998)

$$\frac{k_h}{k_{hmax}} = 0.052\gamma^{-0.48} \quad (5)$$

This equation gives the degradation of the normalized modulus of horizontal subgrade reaction in stiff clays with shear strain irrespective of the pile material and undrained shear strength of clay

Modulus Degradation Equation (Continued...)

Soft Clay

Here k_x is assumed to vary linearly with depth as was the case for cohesionless soils.

i.e. $k_x = k_h x / L_s$.

A pile is considered long, if L/T is greater than or equal to 5. T is the relative stiffness factor in soils for which the modulus of subgrade reaction increases linearly with depth.

Deflection and moment calculation is same as piles in cohesionless soil. Here the degradation in modulus of subgrade reaction is calculated using the relation given by Prakash and Chen (1998).

$$\frac{k_h}{k_{hmax}} = 0.054\gamma^{-0.477} \quad (6)$$

Developing the Load-Deflection Curves

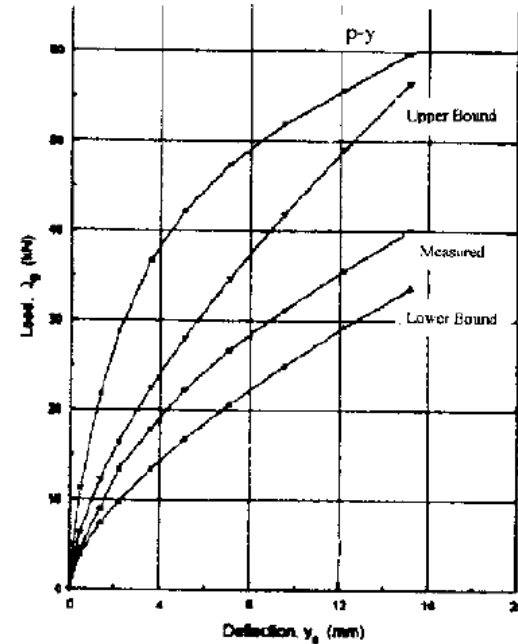
Stiff Clay

The range of $k_{h\max}$ has been determined from 300 and 600 S_u (undrained shear strength). A procedure to predict Q_g - y curves is described as follows:

1. Select a value of y_g for which Q_g will be computed
2. For the above deflection, calculate strain using Equation

$$\gamma = \frac{y}{1.667B}$$

3. Calculate the soil modulus k_h using Eqn. (5) & $k_{h\max} = 300 S_u$
4. Calculate the relative stiffness factor R
5. Calculate lateral load
6. Repeat steps 1-5 for all the deflections at which lateral loads are desired
7. Repeat steps 1-6 using $k_{h\max} = 600 S_u$
8. Then plot the load-deflection curves as shown in fig

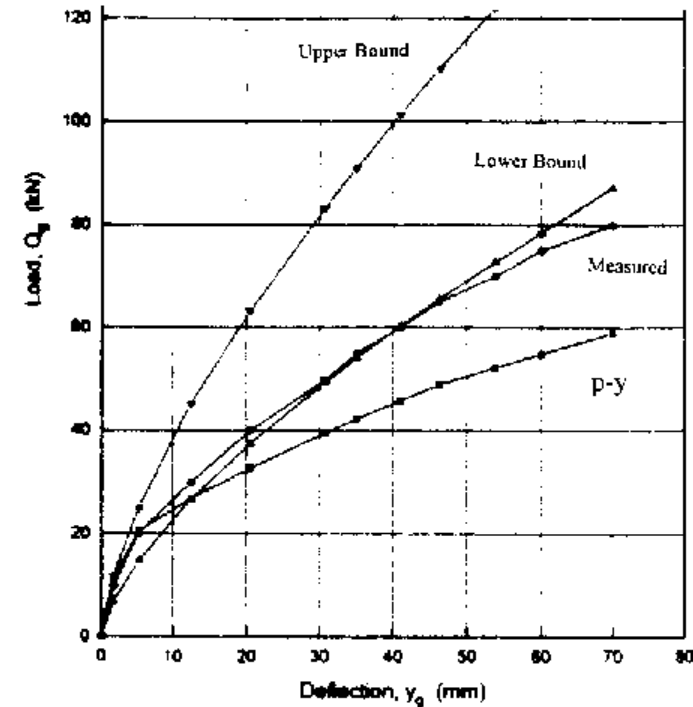


Developing the Load-Deflection Curves

Soft Clay

The range of $k_{h\max}$ has been determined from 800 and 1800 S_u . A procedure to predict Q_g - y curves is described as follows:

1. Select a value of y_g for which Q_g will be computed
2. For the above deflection, calculate strain using Equation
$$\gamma = \frac{y}{1.667B}$$
3. Calculate the soil modulus k_h using Eqn. (6) & $k_{h\max} = 800 S_u$
4. Calculate the relative stiffness factor T
5. Calculate lateral load for the selected deflection.
6. Repeat steps 1-5 for all the deflections at which lateral loads are desired
7. Repeat steps 1-6 using $k_{h\max} = 1800 S_u$
8. Then plot the load-deflection curves



Design Procedure for Pile in Cohesionless Soil

1. Determine the load on the top of the pile.
2. Determine the soil profile and estimate a proper value of k or η_h for the soil type.
3. Select trial section with known EI and its width.
4. Compute the value of relative stiffness

$$T = \left(\frac{EI}{\eta_h} \right)^{1/5}$$

Check $Z_{\max} = \frac{L_s}{T} \geq 5$, L_s is normally determined from other consideration e.g. depth of bedrock and / or vertical load carrying capacity of the pile

5. Estimate the fixity factor (λ) of the pile head. ($0 \leq \lambda \leq 1$)
6. Find the deflection $y_x = (C_y) \frac{Q_g T^3}{EI}$
Check $y_{\max} \leq y_{\text{permissible}} < (12.5 \text{ mm})$

Design Procedure for Pile in Cohesionless Soil (Continued...)

7. Determine the bending moment

$$M_x = C_m Q_g T$$
$$C_m = A_m - 0.93\lambda B_m$$
$$\text{Check } (M_x)_{max}, \quad f = \frac{(M_x)_{max}}{I} \cdot b \leq f_{permissible}$$

8. Soil reaction

$$p_x = C_p \frac{Q_g}{T}$$
$$C_p = A_p - 0.93\lambda B_p$$

Permissible allowable soil reaction $p_a = \frac{1+\sin \phi}{1-\sin \phi} \gamma b x$

where, ϕ = angle of internal friction, γ = unit weight of soil

b = width/dia. of pile, x = depth = $T.z$

Check $p_x \leq p_a$

References

1. Prakash S. (1981), "Soil Dynamics", McGraw-Hill Company, New York
2. Prakash and Chen (1998), "Non-Linear Lateral Pile Deflection Predictions in Clays", Proc. 4th International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, Paper No. 1.55, pp 384-395.

Thank You

