Dynamic Earth Pressure Problems and Retaining Walls

● Behavior of Retaining Walls During Earthquakes

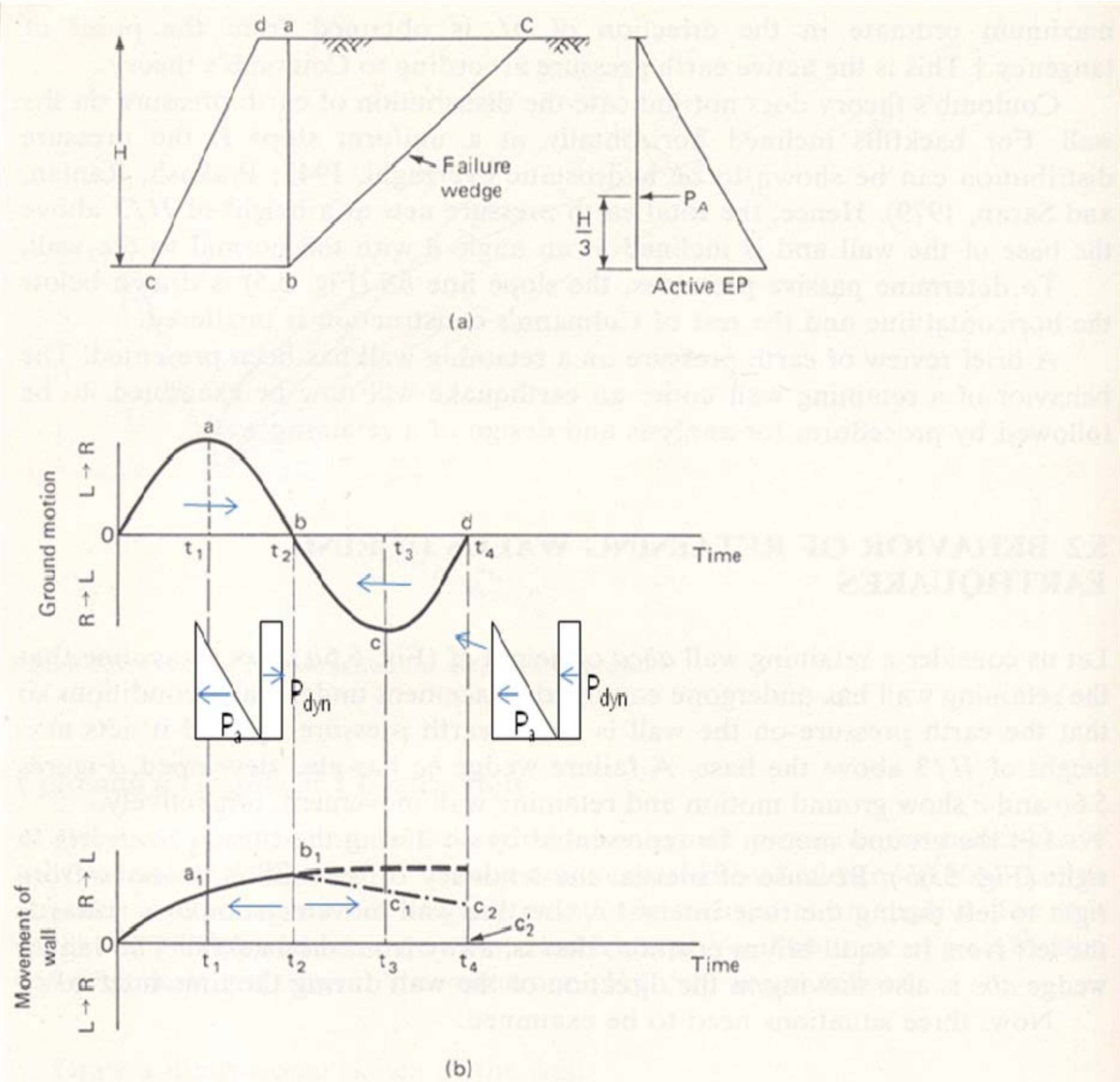


Figure 5.6 Response of retaining wall to ground shaking. (*a*) Retaining wall. (*b*) Ground motion. (*c*) Wall displacement.

- Permanent displacement = $\overline{c_2 c_2'}$ due to one cycle of ground motion

- Hence, questions are :

  ① What is the change in earth pressure?

  ② Where is its point of application?

  ③ How much displacement of the wall occurs?

  (What is the permissible displacement ?)

- Modification of Coulomb`s Theory

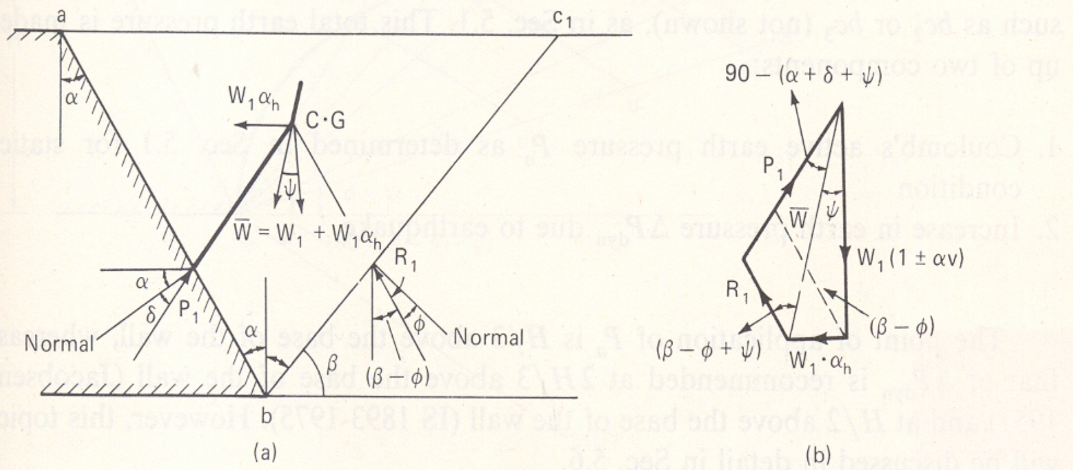


Figure 5.7 Active earth pressure under earthquake loads. (*a*) Forces acting on the failure wedge. (*b*) Forces polygon.

- Inertia forces on the trial wedge in horizontal and vertical directions

  = $W_1 a_h / g$ and $W_1 a_v / g$ respectively

  (a_h : horizontal acceleration, a_v: vertical acceleration)

- During the worst conditions for wall stability $W_1 a_h / g$ acts toward the wall, $W_1 a_v / g$ acts downward (or upward)

- $\alpha_h = \dfrac{a_h}{g}$, $\alpha_v = \dfrac{a_v}{g}$

  horizontal, vertical seismic coefficients

- The forces acting on the wedge abc_1 :

  - Weight of the wedge abc_1, W_1, acting at its CG.
  - Earth pressure P_1 inclined at an angle δ to normal to the wall
  - Soil reaction R_1 inclined at an angle ϕ to normal to the face bc_1
  - Horizontal inertia force $W_1\alpha_h$
  - Vertical inertia force $W_1\alpha_v$

- Constant force polygon to obtain $P_1 (= P_{total} = P_a + \Delta P_d)$

- The maximum value of P_{total} is determined by considering other trial surfaces
- Analytically,

$$P_{total} = \frac{1}{2}\gamma H^2 \frac{\cos^2(\phi - \psi - \alpha)(1 \pm \alpha_v)}{\cos\psi \cos^2\alpha \cos(\delta + \alpha + \psi)} \times \frac{1}{\{1 + [\frac{\sin(\phi + \delta)\sin(\phi - i - \psi)}{\cos(\alpha - i)\cos(\delta + \alpha + \psi)}]^{\frac{1}{2}}\}^2}$$

- Modified Culmann`s construction

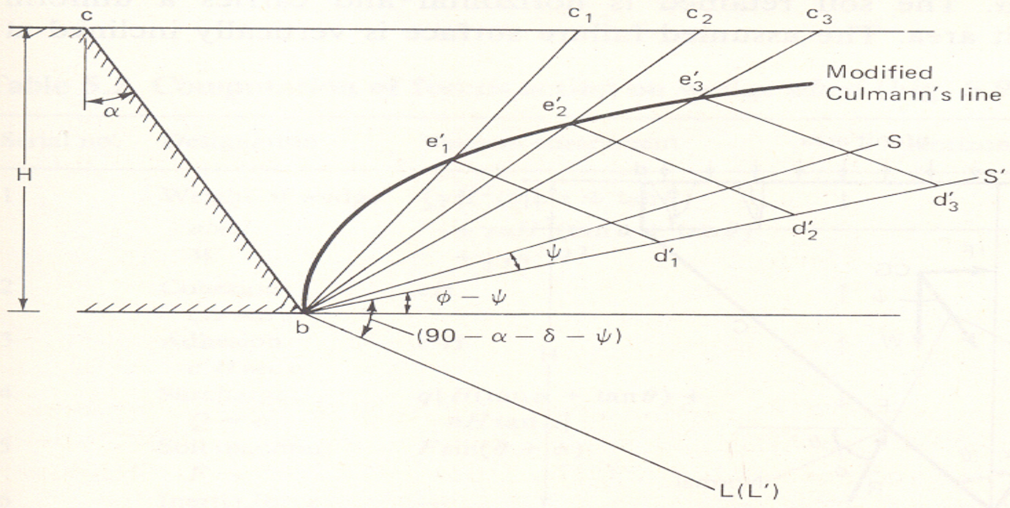


Figure 5.8 Culmann's construction for earthquake loading.

- bS' at an angle $\phi-\psi$ with the horizontal line
- bL' = bL
- use $\bar{W}$ $(W_1\alpha_h + W_1(1+\alpha_v))$

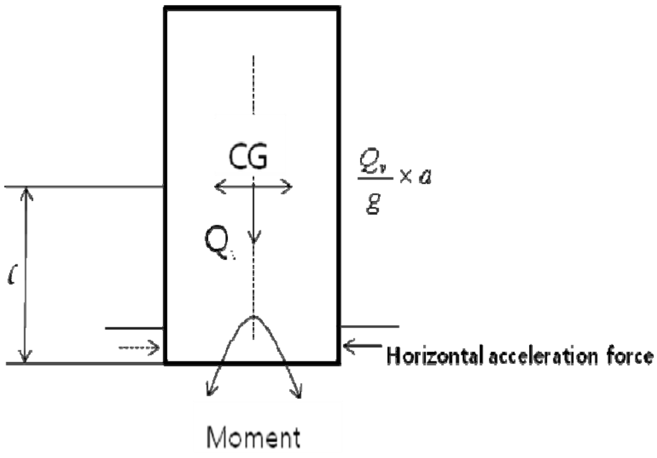
- Point of Application of the total $(P_a)_{dyn}$
  - at midheight of the wall
  - at the upper third point of the wall

- Displacement analysis
  - no information on permissible displacement of retaining wall

1. Draw a dimensional sketch
2. Draw a line $\overline{bS'}$ and $\overline{bL}(=\overline{bL'})$
3. Intercept bd_1, equal to the wt. of wedge abc_1, to a convenient scale along $\overline{bS'}$
4. Draw a line d_1e_1 parallel to $\overline{bL}(=\overline{bL'})$
5. Trace a Culmann's line
6. Draw a line parallel to $\overline{bS'}$ and tangential to the Culmann`s line.
7. Find $\overline{de}\rightarrow P_a$ obtained

- Earthquake Loads on Footings (Pseudostatic method)

Effect of moment only



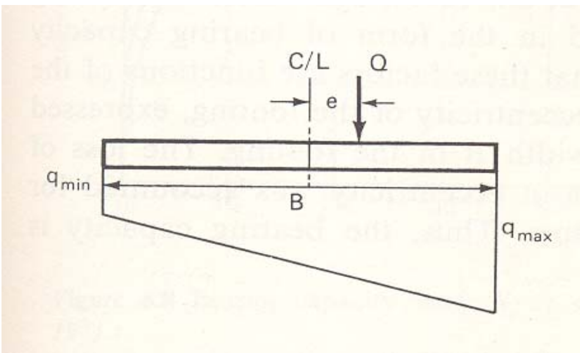
- Eccentricity

$$e = \frac{M}{Q_v}$$

M : moment$(= \frac{Q_v}{g} \times a \times l)$

Q_v : central vertical static load

due to the shaking of structure → i.e., horizontal acceleration force
(lumped mass at CG)



- For $e < \frac{B}{6}$

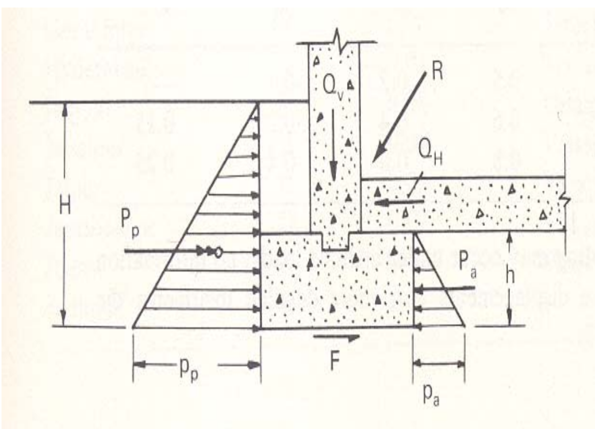
$$q_{max} = \frac{Q}{A}(1 + 6\frac{e}{B})$$

- For $e > \frac{B}{6}$

$$q_{max} = \frac{Q}{A}(\frac{4B}{3B - 6e})$$

- Effective width, $B' = B - 2e$

Effect of trust only



- Inclination

$$FS = \frac{P_p + F - P_a}{Q_H}$$

F : Frictional Resistance

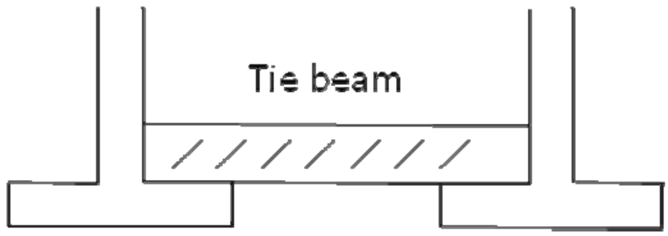
- $P_a = \frac{1}{2} k_a \gamma h^2$

- $P_p = \frac{1}{2} k_p \gamma H^2$, take $(\frac{1}{2} \sim \frac{1}{3})$ of P_p

- At the present state of practice for earthquake loading

  - Bearing capacity & settlement may be calculated by the pseudostatic method

  - Interconnecting beams (Tie beams) be provided to tie the foundations.



It should be capable of carrying, in tension or compression, a force equal to $A_a/4$ of the largest footing or column load (A_a =effective peak acceleration). ATC(1978)

- Tie beams

  - transmits the unbalanced shear and moment

  - reduces the differential settlement

  - PC pile – no use(depends on the building class & earthquake intensity)

Dynamic Analysis for Pile Foundations

- Evaluate the free-vibration characteristics of pile-soil system

↓

Calculate the spectral displacement (y_g)

↓

Maximum bending moment ($M_{\max}$)

Computation of soil reaction ($P(x)$)

- Preliminaries
  - Soil properties are known ($k, n_h \ldots$)
  - Pile characteristics are known (size, EI, length, type)
  - Lateral load-deflection of the pile under static conditions

- nondimensional frequency factor (F_{SL1})

(based on parametric study) (k varies linearly with depth)

$$F_{SL1} = w_{n1}\sqrt{\frac{W}{g \cdot n_h \cdot T^2}}, \quad T = \sqrt[5]{\frac{EI}{n_h}}$$

w_{n1} : the first natural angular frequency (rad/sec)

W / g : the lumped mass at the pile top

k : the soil modulus

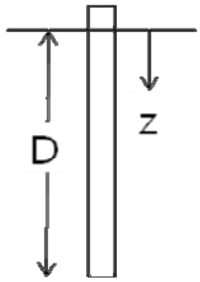
T : the relative stiffness factor

- the depth coefficient(Z)

$$Z = \frac{z}{T} \quad \text{(if } Z_{\max} < 2\text{, rigid body / if } Z_{\max} > 5\text{, long pile)}$$

- the max. depth coefficient ($Z_{\max}$)

$$Z_{\max} = \frac{D}{T}$$



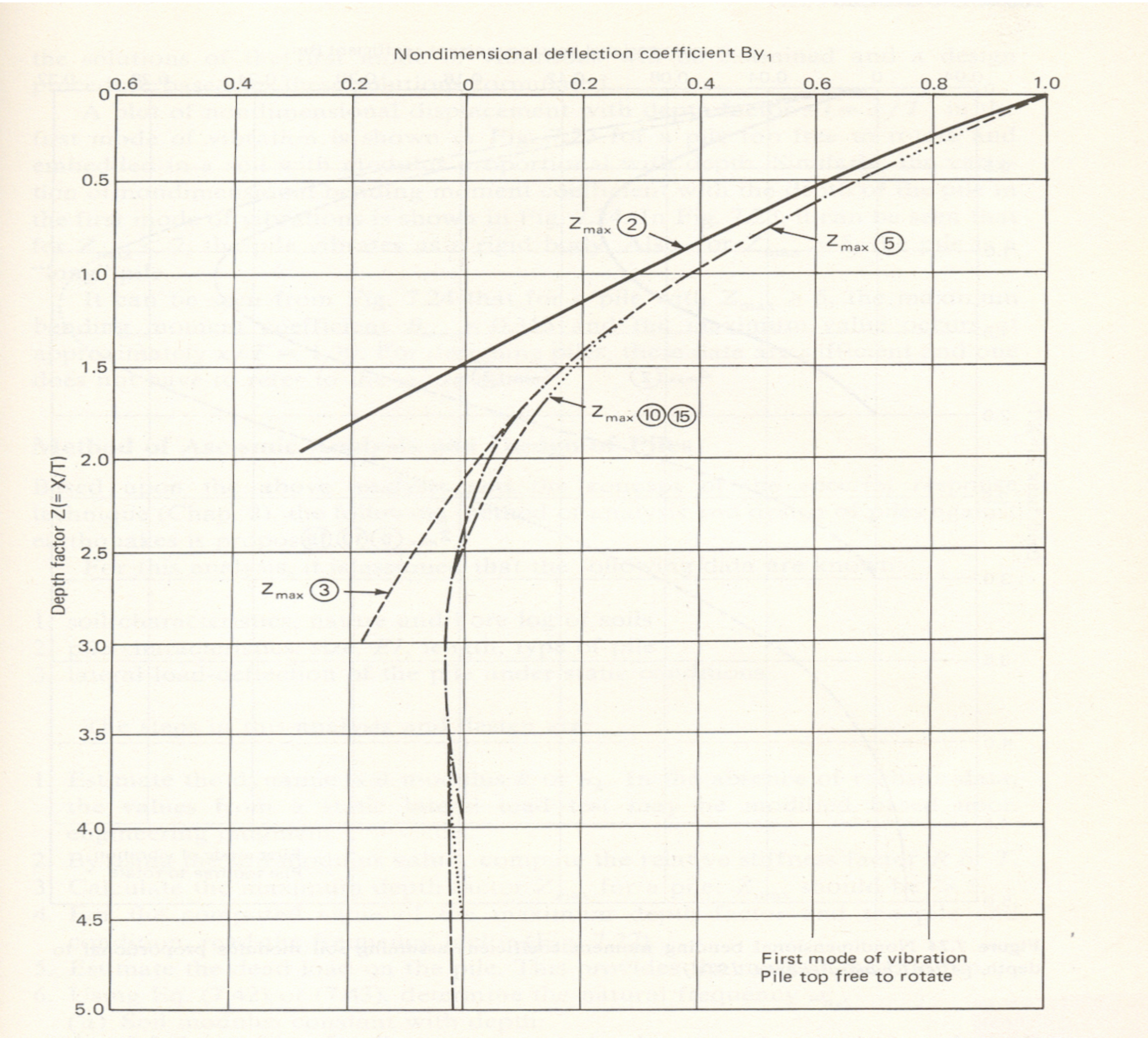


Figure 7.23 Nondimensional deflection coefficients assuming soil modulus proportional to depth. *(After Chandrasekaran, 1974.)*

- max. bending moment coefficients (Fig 7.24)

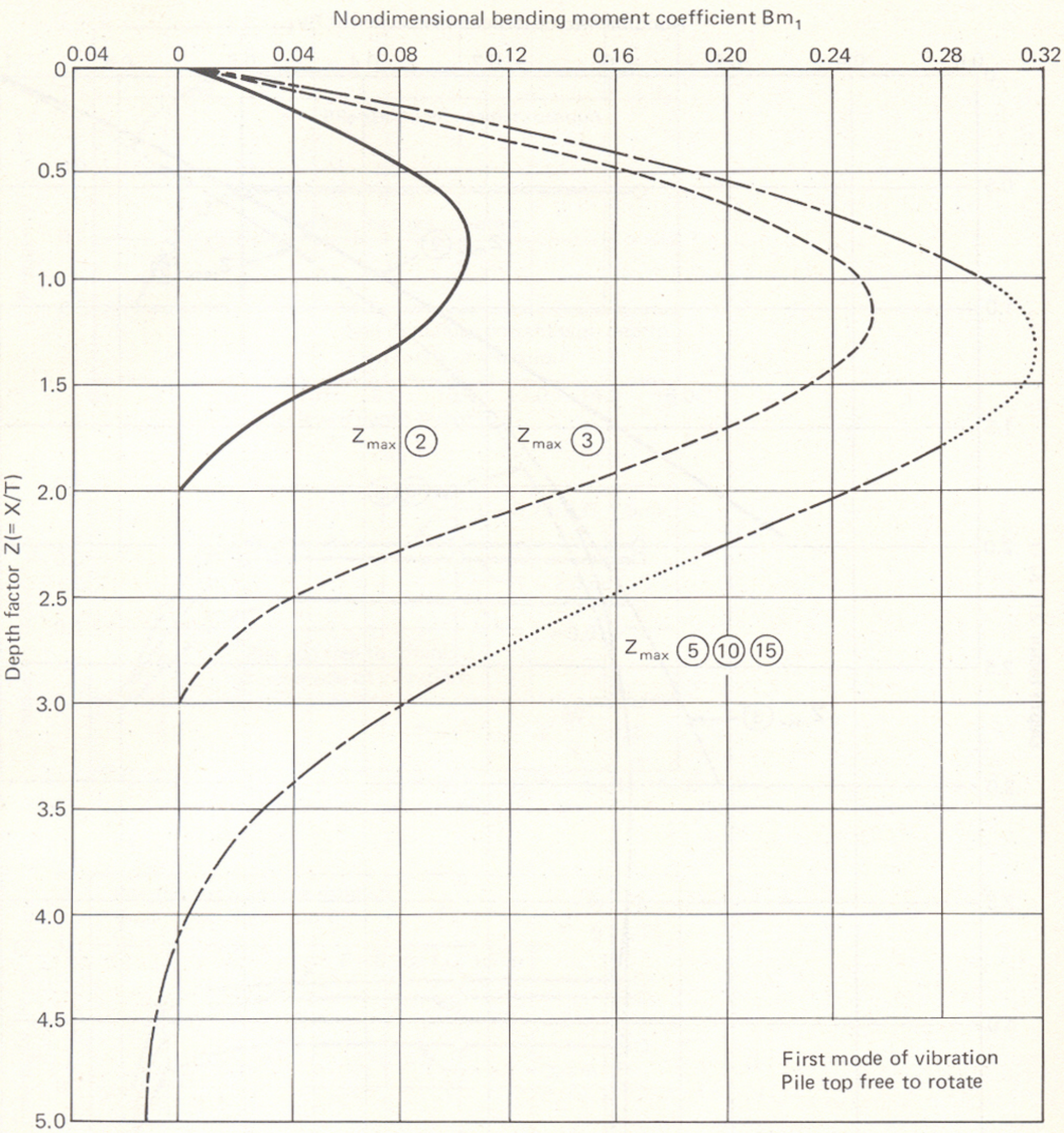


Figure 7.24 Nondimensional bending moment coefficient assuming soil modulus proportional to depth. *(After Chandrasekaran, 1974.)*

Step-by-step procedures

① Estimate the dynamic soil modulus k (or n_h)

(modified value from a static lateral load test based on the engineering judgement)

② Compute the relative stiffness factor, T

③ Calculate the maximum depth factor $Z_{\max}$ for a pile ; ($Z_{\max}$ should be > 5)

④ Read the frequency factor F_{SL1} for the $Z_{\max}$ and the pile end condition from Fig 7.22

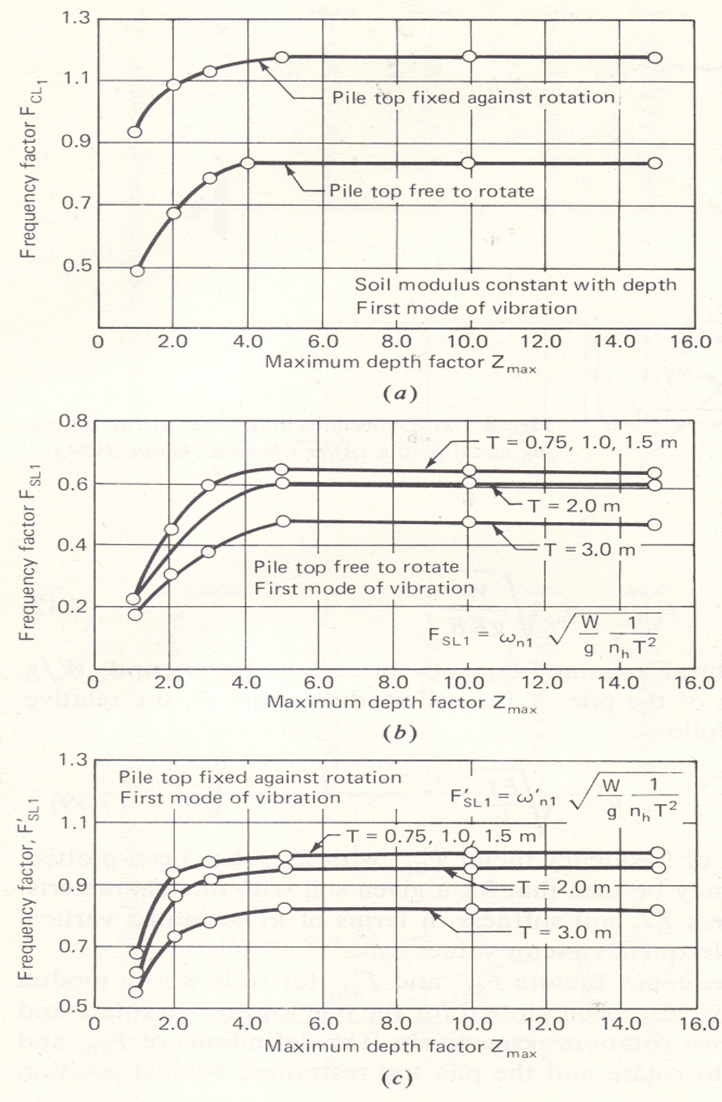


Figure 7.22 Nondimensional frequency factors in first mode of vibrations. (*a*) Soil modulus constant with depth. (*b*) Soil modulus linearly varying with depth and pile top free. (*c*) Soil modulus linearly varying with depth and pile top restrained against rotation. *(After Prakash and Chandrasekaran, 1977.)*

⑤ Estimate the dead load on the pile top

→ $m_t = W / g$

⑥ Determine the natural frequency → w_{n1}

→ $w_{n1} = F_{SL1} \div \sqrt{\dfrac{W}{gn_h T^2}}$

⑦ Compute the time period

→ $T_{n1} = 2\pi / w_{n1}$

⑧ From Fig 7.25 determine the spectral displacement S_d for assumed damping

(for pile-soil system 5% damping may be assumed)

→ maximum displacement of the pile head

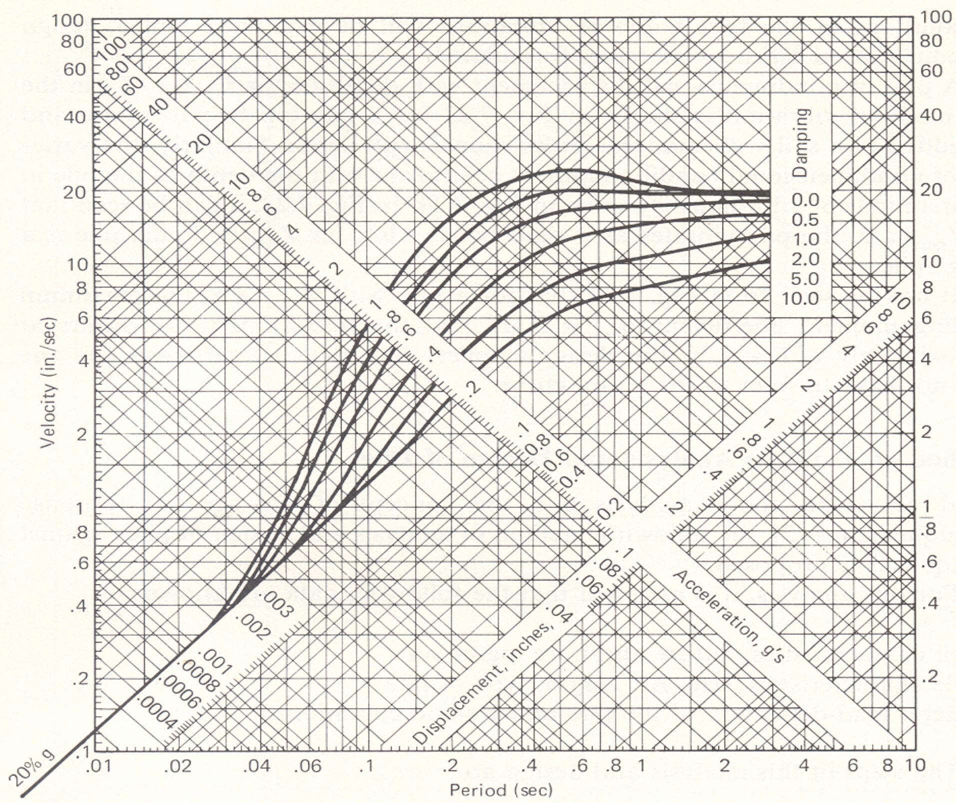


Figure 7.25 Combined plot of design spectrum giving S_a, S_v, and S_d as a function of period and damping, scaled to 20 percent of acceleration at zero period. *(Reproduced with permission of Prentice-Hall Inc., Englewood Cliffs, N.J., from "Design Spectrum" by G. W. Housner in Earthquake Engineering, ed., R. L. Wiegel.)*

⑨ Estimate the maximum bending moment in the pile section

→ $M_{\max} = B_{me1} \times n_h T^3 \times S_d$ (From table 7.7)

Table 7.7 Maximum values of coefficient B_{me}*

Maximum depth factor $Z_{\max}$	Coefficient B_{me}: Pile top free to rotate	Coefficient B_{me}: Pile fixed at top against rotation, − ive	Coefficient B_{me}: Pile fixed at top against rotation, + ive
2	0.100	0.93	0
3	0.255	0.93	0.10
5–15	0.315	0.90	0.28

* After Chandrasekaran (1974).

→ Pile section needs to be checked against this moment

⑩ Compute the soil reaction

→ $P_z = n_h \cdot z \cdot y_z$ (displacement of the pile at z) (refer to table 7.8 & Example 7.3)

Compare this with the allowable

→ Soil reaction : $P_a = \dfrac{1+\sin\phi}{1-\sin\phi}\gamma \cdot b \cdot z \quad (kg/cm)$

$$= K_p \cdot \sigma_v \cdot b$$

Table 7.8 Computation of y_x and p_x along the pile length (Example 7.3)

x, cm	Z	A_y	$y_x = 0.821\, A_y$, cm	$n_h x$ kg/cm²	$p = n_h xy$, kg/cm
0	0	2.435	2.00	0	0
100	0.84	1.164	0.955	161.2	153.94
200	1.68	0.327	0.268	322.4	86.40
300	2.52	0.029	0.024	483.6	11.61
400	3.36	− 0.066	− 0.054	644.8	− 34.82
500	4.21	− 0.042	− 0.034	806.0	− 27.40
600	5.05	− 0.009	− 0.007	967.2	− 6.77

Example 7.3 A pile carries a vertical load of 77.6 t and the base shear on the top of the pile cap is 3 t. If the soil is sandy in character with $\phi = 30°$ and $n_h = 1.612\ \text{kg/cm}^3$ under dynamic loading, determine the

1. maximum displacement of the pile head
2. maximum bending moment in the pile
3. soil reaction diagram along the length of the pile

Assume that EI of the pile $= 3.8 \times 10^{10}\ \text{kg}\cdot\text{cm}^2$, that the diameter of the pile = 30 cm, and that the length of piles in groups = 12.2 m.

SOLUTION

Step 1

$$n_h = 1.612\ \text{kg/cm}^3$$

Step 2

$$T = \sqrt[5]{\frac{EI}{n_h}}$$

$$= \sqrt[5]{\frac{3.8 \times 10^{10}}{1.612}} = 118.7\ \text{cm}$$

$$= 1.187\ \text{m}$$

Step 3

$$Z_{\max} = \frac{12.2}{1.187} = 10.27$$

Because $Z_{\max} > 5$, it is a "long" pile.

Step 4 From Fig. 7.22*b* and *c*, for $Z_{\max} > 5$ and $T = 1.187$ m,

$$F_{SL_1} = 0.65 \text{ for free pile head}$$

$$F'_{SL_1} = 1.00 \text{ for pile head restrained against rotation}$$

Step 5

$$M_t = 77.6 \times \frac{1\ \text{t/s}^2}{981\ \text{cm}}$$

Step 6 From Eq. (7.43),

$$\omega_{n_1} = F_{SL_1} \div \sqrt{\frac{W}{g}\frac{1}{n_h T^2}} \qquad (7.43)$$

$$= 0.65 \times \sqrt{\frac{981}{77.6} \times \frac{1.612}{1000} \times 118.7^2}$$

$$= 11.014\ \text{rad/s}$$

therefore, $f_{n_1} = \dfrac{11.014}{2\pi} = 1.753\ \text{Hz}$

Step 7

$$T_{n_1} = \frac{2\pi}{\omega_{n_1}} = \frac{1}{1.753} = 0.570\ \text{s}$$

Step 8 From Fig. 7.25, for $T_{n_1} = 0.57$ s, $\xi = 5\%$ spectral displacement $S_d = 0.8$ in(2.0 cm).

The maximum deflection of the pile top is 2.0 cm.

Step 9 Maximum bending moment

$$= B_{me} \times n_h T^3 S_d \qquad (7.45)$$

$$= 0.315 \times \frac{1.612}{1000} \times (118.7)^3 \times 2.0 = 1698\ \text{t}\cdot\text{cm}$$

Step 10

$$y_g = A_y \frac{Q_g T^3}{EI} = A_y B(\text{constant})$$

For soils with modulus increasing linearly with depth

$$A_y = 2.435$$

Therefore, (constant) in the above equation is $\dfrac{2.0}{2.435} = 0.821$. Therefore, $y_x = 0.821 \times A_y$.

The solution of deflection and soil reaction along the pile length is presented in Table 7.8.

⑪ Check on Design

1. Estimate the fixity of the pile head. In the absence of a realistic estimate, 50 percent fixity may be assumed.

2. Compute displacement. For 50 percent fixity, the displacement under seismic loading condition is $\frac{2.0+1.0}{2}=1.5cm$. For any other fixity of the pile head, linear interpolation may be made.

3. Compute the maximum bending moment as for displacements

$$M_{\max}=1213 \quad t \cdot cm(-)$$

4. The soil reaction needs to be interpolated at each point and a new diagram obtained