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Design Charts for Seismic Analysis of Pile Groups

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ABSTRACT -: **In the seismic analysis of pile groups an important parameter is the frequency of pile group system. Non-dimensional design curves and tables are developed for seismic analysis of long piles for different configurations of pile group. These curves are formulated for spacing of 2d, 4d and 6d, and are useful in estimating the period of vibration of the pile-soil system. The formulation is based on the stiffness of pile group system computed from the stiffness of individual piles, accounting interaction effects. An illustration is presented herein to highlight the application of design curves for seismic analysis of pile supported structures.**

KEY WORDS -: seismic, pile, soil, pile stiffness, group stiffness.

1. INTRODUCTION

Pile foundations are essential when heavy structures are to be supported by weak soils. In addition to vertical loads, piles are encountered by lateral loads due to wind, sea-waves, and earthquakes. Seismic resistant design of pile groups is a complex problem due to the uncertainties involved in it. Poulos (1971 a & b) presented an analysis for laterally loaded piles and pile groups where in the interaction between two identical vertical piles subjected to horizontal load and moment is analyzed and then extended to pile groups. Prakash and Puri (1993) presented a method for seismic analysis of single pile wherein they developed two sets of non-dimensional frequency curves for cohesive and cohesionless soils. Extensive parametric studies by Novak M and El-Sharnouby (1984) concluded that static interaction factor approach is also accurate for dynamic analysis if the frequency range is low, as in case of earthquakes.

Seismic behaviour of pile groups depends on soil characteristics, pile properties and spacing of piles in a group. The seismic resistant design of pile group involves assessment of lateral load capacity and stiffness of the pile group system. The lateral load behaviour of a pile depends on whether it behaves as a long flexible pile or a short rigid pile (IS:2911). An attempt has been made to develop design curves and charts for different configurations of pile groups to permit the design of pile groups for seismic loading conditions. In the present study, long piles in a group are analyzed.

2 MATHEMATICAL MODEL

In the seismic analysis of structures supported on pile foundations an important parameter is the frequency of soil-pile-structure system. The frequency depends on stiffness of soil, pile and pile-soil-pile interaction. The behaviour of a single pile based on the concept of 'Beam on an elastic foundation' is given by

$$E_p I_p (d^4 y / dx^4) + K_s y = 0 \qquad (1)$$

y = displacement of pile
E_p = modulus of Elasticity of pile material
I_p = moment of inertia of pile cross section
d = diameter (or) width of pile
$K_s = K_h.d$
K_s and K_h both represent soil modulus in N/mm^2 and N/mm^3 respectively.

The horizontal stiffness of long pile with pile head fixed is obtained from the solution of the above equation.

Stiffness of pile $K_p = 4\beta^3 E_p I_p$ (2)

Where $\beta = \sqrt{K_s / 4E_p I_p}$

The interaction effect of piles can be incorporated by using interaction factors for the piles in a group. The horizontal interaction factor mainly depends on soil characteristics, pile properties and spacing of piles. The interaction factors developed by Poulos (1971b) for static lateral loads are sufficiently accurate for dynamic loads if the frequency range is low. The frequency range for earthquakes is usually low. Hence, static interaction approach can be used for seismic analysis. Based on interaction factor concept the stiffness of pile group can be computed from Equation (3), Moinuddin Ahmed & Babu Rao (2005).

Pile Group Stiffness $K_g = \dfrac{4\beta^3 E_p I_p}{\alpha_h}$ (3)

n = No. of piles in a group
α_h = Group Interaction Factor

Equation (3) can be rewritten as

$$K_g = \frac{1}{\beta L}\frac{n}{\alpha_h} K_s L$$

$$K_g = f.K_s.L$$

L = Length of pile

Group stiffness parameter $f = \frac{1}{\beta L} \frac{n}{\alpha_h}$ (4)

The group stiffness parameter ‘f’ can be computed from design curves. This parameter ‘f’ is a function of interaction factors, number of piles and the spacing of piles in a group. Using the value of ‘f’ and the weight acting over the pile cap, the period of the vibration of the group can be determined.

Period of Vibration $T = 2\pi\sqrt{W / g.f.K_s.L}$ (5)

For the validation of the mathematical model experimental tests were conducted for pile groups, Moinuddin Ahmed & Babu Rao (2005).

3. DESIGN CHARTS

Using Equation (4), design charts (Table 1 – 4) were developed for Group stiffness parameter ‘f’ for different values of pile-soil stiffness factor ‘βL’.

Table No. 1 - Group stiffness parameter ‘f’ for 2 x 2 pile group

βL	s/d = 2	S/d = 4	s/d = 6
1	1.580	2.020	2.270
2	0.790	1.010	1.135
3	0.527	0.673	0.756
4	0.395	0.505	0.567
5	0.316	0.404	0.454
6	0.263	0.336	0.378
7	0.226	0.288	0.324
8	0.197	0.252	0.284
9	0.175	0.224	0.252
10	0.158	0.202	0.227
11	0.144	0.184	0.206
12	0.132	0.168	0.189
13	0.121	0.155	0.175
14	0.113	0.144	0.162
15	0.105	0.135	0.151
16	0.099	0.126	0.142
17	0.093	0.119	0.134
18	0.088	0.112	0.126
19	0.083	0.106	0.119
20	0.079	0.101	0.114
21	0.075	0.096	0.108
22	0.072	0.092	0.103
23	0.069	0.088	0.099
24	0.066	0.084	0.095

Table No. 2 - Group stiffness parameter ‘f’ for 3 x 3 pile group

βL	s/d = 2	s/d = 4	s/d = 6
1	2.160	2.970	3.512
2	1.080	1.485	1.756
3	0.720	0.990	1.170
4	0.540	0.742	0.878
5	0.432	0.594	0.702
6	0.360	0.495	0.585
7	0.309	0.424	0.502
8	0.270	0.371	0.439
9	0.240	0.330	0.390
10	0.216	0.297	0.351
11	0.196	0.270	0.319
12	0.180	0.247	0.293
13	0.166	0.228	0.270
14	0.154	0.212	0.251
15	0.144	0.198	0.234
16	0.135	0.186	0.219
17	0.127	0.175	0.207
18	0.120	0.165	0.195
19	0.114	0.156	0.185
20	0.108	0.148	0.176
21	0.103	0.141	0.167
22	0.098	0.135	0.160
23	0.094	0.129	0.153
24	0.090	0.123	0.146

Table No. 3 - Group stiffness parameter ‘f’ for 4 x 4 pile group

βL	s/d = 2	S/d = 4	s/d = 6
1	2.700	3.850	4.660
2	1.350	1.925	2.330
3	0.900	1.283	1.553
4	0.675	0.962	1.165
5	0.540	0.770	0.932
6	0.450	0.642	0.777
7	0.386	0.550	0.666
8	0.337	0.481	0.583
9	0.300	0.428	0.518
10	0.270	0.385	0.466
11	0.245	0.350	0.424
12	0.225	0.320	0.388
13	0.208	0.296	0.358
14	0.193	0.275	0.333
15	0.180	0.257	0.311
16	0.169	0.241	0.291
17	0.159	0.226	0.274
18	0.150	0.214	0.259
19	0.142	0.203	0.245
20	0.135	0.192	0.233
21	0.129	0.183	0.222
22	0.123	0.175	0.212
23	0.117	0.167	0.203
24	0.112	0.160	0.194

Table No. 4 - Group stiffness parameter 'f' for 4 x 6 pile group

βL	s/d = 2	s/d = 4	s/d = 6
1	3.320	4.820	5.925
2	1.660	2.410	2.963
3	1.107	1.607	1.975
4	0.830	1.205	1.481
5	0.664	0.964	1.185
6	0.553	0.803	0.988
7	0.474	0.689	0.846
8	0.415	0.603	0.741
9	0.369	0.536	0.658
10	0.332	0.482	0.593
11	0.302	0.438	0.539
12	0.277	0.402	0.494
13	0.255	0.371	0.456
14	0.237	0.344	0.423
15	0.221	0.321	0.395
16	0.208	0.301	0.370
17	0.195	0.284	0.349
18	0.184	0.268	0.329
19	0.175	0.254	0.312
20	0.166	0.241	0.296
21	0.158	0.230	0.282
22	0.151	0.219	0.269
23	0.144	0.210	0.258
24	0.138	0.201	0.247

4. PILE CAP DISPLACEMENT

Spectral acceleration co-efficient for the known period of vibration can be evaluated by using equations given in IS 1893-2002, based on the type of soil. The pile cap displacement can then be calculated by using Spectral acceleration co-efficient Sa/g and pile group stiffness, according to the seismic zone of the site, Importance Factor and Response Reduction Factor.

Horizontal Seismic force (Q) = Design Seismic coefficient x Weight of structure

$Q = A_h \times W$ (IS: 1893-2002)

where $A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$

$$Q = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}W$$

Pile cap displacement (δ) = Q/K_g

$$\delta = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}\frac{W}{K_g} \qquad (6)$$

Substituting K_g, Equation (6) can be re-written as

$$\delta = \frac{W}{f.K_s L}\frac{S_a}{R}\frac{Z}{2}\frac{I}{R} \qquad (6.1)$$

5. APPLICATION OF DESIGN CHARTS

The design charts are useful in the computation of period of vibration of pile groups. These charts are developed for three different spacing of piles namely 2d, 4d and 6d. These spacing are adopted because they are commonly used in practice and recommended by IS:2911 and also other International codes. However for intermediate values of s/d, group stiffness parameter can be obtained by interpolation. A typical example is presented herein to illustrate the application of design charts.

5.1 Example

For the seismic analysis of a 4 x 4 concrete pile group, the following information is available.
Pile diameter=750 mm.
Soil Modulus = 75000 KN/m^3
Pile Length = 10 m
Pile spacing to diameter ratio = 4
Weight on pile cap = 12,000 KN
Modulus of Elasticity of pile material =0.20 X 10^8 kN/m^2
Importance Factor=1.5
Response Reduction Factor=4.0
Compute Pile cap displacement for the pile group.
Moment of Inertia of pile $I_p = \pi d^4/64 = \pi (0.75)^4/64 = 0.1553$ 10^{-4} m^4

$K_s = K_h \times d = 75000 \times 0.75 = 56250$ KN/m^2

$$\beta = \sqrt[4]{K_s / 4E_p I_p} = 0.4612 \ m^{-1}$$

βL = 4.61

Using design charts,
f = 0.835
Period of vibration of the group is given by

$$T = 2\pi\sqrt{\frac{W}{g.f.K_s.L}}$$

T = 0.32 Sec
For medium soil Sa/g = 2.5 (As per IS: 1893 – 2002)
I = 1.5, R = 4.0
For Zone IV, Z = 0.24

Pile cap displacement $\delta = \frac{W}{f.K_s L}\frac{S_a}{R}\frac{Z}{2}\frac{I}{R}$

δ = 2.874 x 10^{-3} m (or) 2.874 mm

6. CONCLUSIONS

1. Seismic response of pile group depends on type of soil, pile, diameter, modulus of elasticity of pile material and pile spacing.
2. Rational evaluation of soil modulus is essential for proper estimation of pile stiffness since the frequency of pile group largely depends on the stiffness of piles.
3. It is observed from design charts that the Group Stiffness parameter ‘f’ decreases with increase in pile soil stiffness factor ‘βL’ and the parameter ‘f’ has insignificant change at higher values of ‘βL’.

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