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Seismic Analysis of Pile Groups

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Abstract

Engineering design of structures due to earthquake is a unique problem.Pile foundations are commonly used to support heavy structures on weak soils. Piles are commonly used in groups. Seismic resistant design of pile group involves assessment of stiffness of an individual pile and the stiffness of pile group accounting interaction effects. The natural period of the pile-soil-structure system is an important parameter for the estimation of seismic force which depends on group stiffness.

Keywords: *Pile, soil, stiffness, seismic*

Introduction

Engineering design of structures due to earthquake is a unique problem. The loading caused due to an earthquake is abnormal. Damage to the structure can be prevented if the lateral deflection of the structure is minimized. It is essential to study the seismic effects on foundations of structures for rational earthquake resistant design of structures. Adequate earthquake resistance may be provided either by the conventional approach of increasing the strength or by reducing the stiffness.

Pile foundations

Pile foundations are commonly used to support heavy structures on weak loads. They are also used for foundations of structures such as transmission towers and offshore platforms which are subjected to uplift. Piles are commonly placed in groups. They are formed by a number of closely spaced piles connected to each other by means of a rigid pile cap.

Lateral load behaviour of piles

In addition to vertical loads, piles are also encountered by lateral loads due to wind, sea-waves and earthquakes. The lateral load behaviour of a long pile is different from that of a short pile. As per IS: 2911(1979), a pile is classified as a long pile if L/R >4, otherwise it is designated as a short pile. Long piles are flexible and only the upper part of the pile participates in deflection due to lateral load. This length of pile which undergoes displacement is called as the 'Critical length of pile'. Below critical length horizontal deflection of the pile will be zero up to its remaining length and the pile length looses its significance. In case of a short rigid pile subjected to lateral load the complete pile rotates as a unit.

Pile-soil-pile interaction

The lateral load behaviour of a single pile is different from that of a pile group due to the interaction effects between piles. The deflection of any pile in a group causes movement of the surround soil and piles, thus leading to larger deflection of the pile group than for the single piles subjected to the same load per pile. This mechanism is termed as pile-soil-pile-interaction. The interaction effects between piles in a group mainly depend on pile spacing. The minimum spacing recommended as per IS:2911(1979) is 2.5d (d is pile diameter). If the spacing between piles is more than 8d then the interaction effect is negligible and the piles in a group behave as individual piles (Duncan et al 1994).

Seismic response of long piles

The seismic resistant design of pile groups is a complex problem due to the uncertainties involved in determining the deformation state of piles. Seismic behaviour of pile group depends on soil characteristics, pile properties and spacing of piles in a group. Seismic resistant design of pile group involves assessment of stiffness of an individual pile and the stiffness of pile group accounting interaction effects. The natural period of the pile-soil-structure system is an important parameter for the estimation of seismic force which depends on group stiffness.

Design curves

Non-dimensional curves and charts were developed for different configurations of pile groups to permit the design of pile groups for seismic loading conditions and for three different spacing namely 2d,4d& 6d (Moinuddin A &BabuRao D 2006). These curves were plotted with pile soil stiffness factor 'βL' versus Group stiffness parameter 'f''. Pile soil stiffness factor is a function of Soil modulus, Modulus of Elasticity of the pile material and geometric properties of pile. The Group stiffness factor 'f ' can be evaluated from the design charts or curves. Using the value of 'f ' and the weight of superstructure acting on the pile cap, the period of vibration of the group can be determined. Spectral acceleration coefficient for the known period of vibration can be evaluated by the equations given in IS:1893-2002, based on the type of soil.

Steps for evaluation of seismic force and deflection of a pile supported structure

1. The behaviour of a long pile based on the concept of 'Beam on an elastic foundation' is governed by the differential equation $E_pI_p(d^4y / dx^4) + K_s\, y = 0$ where y= displacement of pile along its length, E_p= Modulus of Elasticity of pile material, I_p=Moment of inertia of the pile cross section, d=diameter of the pile and K_s is the Soil Modulus. The solution of this differential equation yields the horizontal stiffness of the long pile.

Stiffness of pile $K_p = (4\beta^3E_pI_p)^{1/2}$

where$\beta = (K_s/4E_pI_p)^{1/2}$ and $K_s = K_h.d$, K_s and K_h are soil modulus in N/mm^3 and N/mm^2 respectively & d is the diameter of pile in mm.

2. The stiffness of a pile group can be determined using the interaction factors developed by Poulos (1971). The static interaction factors are sufficiently accurate for dynamic loads if the frequency range is low. In case of earthquakes, frequency range is low.

Pile group stiffness $K_g = (K_p \times n) / \alpha_h$

n = number of piles in a group
α_h= Group Interaction Factor

3. The period of vibration of the pile group system is obtained by the relation

$T = 2\pi\, (W/g.f.K_s.L)^{1/2}$ (Moinuddin A &BabuRao D - 2006)

f = Group stiffness parameter
L = Length of the pile
W = weight of the super structure acting on the pile cap

4. Spectral acceleration coefficient for the known period of vibration can be evaluated by the equations given in IS:1893-2002, based on the type of soil. The values of Sa/g given below are for 5% damping. If the damping is other than 5% then Sa/g can be multiplied by a factor given in Table 3, IS:1893-2002.

For Rocky or Hard soil sites

$1 + 15\,T$ - $0.00 \le T \le 0.10$
Sa/g = 2.5 - $0.10 \le T \le 0.40$
$1.00/T$ - $0.40 \le T \le 4.00$

For medium soil sites

$1 + 15\,T$ - $0.00 \le T \le 0.10$
Sa/g = 2.5 - $0.10 \le T \le 0.55$
$1.36/T$ - $0.55 \le T \le 4.00$

For soft soil sites

$1 + 15\,T$ - $0.00 \le T \le 0.10$
Sa/g = 2.5 - $0.10 \le T \le 0.67$
$1.67/T$ - $0.67 \le T \le 4.00$

5. The design horizontal seismic coefficient is given by $A_h = (Z/2)\,(I/R)\,(Sa/g)$

Base shear or Horizontal Seismic force $Q = (Z/2)\,(I/R)\,(Sa/g) \times W$ (IS:1893-2002)

where Z = Zone factor
I = Importance factor, depending upon the functional use of the structure.
R = Response reduction factor.

6. The pile cap displacement can be calculated by using horizontal seismic force and group stiffness (K_g).

Pile cap displacement $\delta = Q/K_g$

$\delta = (Z/2)\,(I/R)\,(Sa/g)\,(W/ f.K_s.L)$

Table1

Example

For the seismic analysis of a 4x4 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 = 12000 kN
Modulus of Elasticity of pile material (concrete) = 0.2 x108 kN/m^2
Importance factor (I) = 1.5
Response reduction factor = 4.0
Site location: Zone IV

Compute pile cap displacement for the pile group.

Sol:Moment of inertia of the pileI_p = $\pi d^4 /64$ =$0.155x10^{-4}$ m^4

Soil modulus $K_s = K_h.d$ = 75000x0.75 = 56250 kN/m^2

$\beta = (K_s / 4E_pI_p)^{1/2}$ =0.4612 m^{-1}
βL = 4.61

Using the design charts, f = 0.835

Period of vibration of the pile group is given by

$T = 2\pi (W/g.f.K_s.L)^{1/2}$
T = 0.32 sec

For medium soil Sa/g = 2.5 (As per IS:1893-2002)

I = 1.5, R = 4.0

For seismic zone IV , Z = 0.24

$\delta = (Z/2) (I/R) (Sa/g) (W/ f.K_s.L)$
$\delta = 2.87x10^{-3}$m

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