Lateral response of pile due to combined load under free and fixed conditions

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Abstract: Pile foundations are used to support both vertical and horizontal loads in many geotechnical projects, such as coastal and offshore engineering. In this project, the Finite Difference Method is proposed to solve the differential equation governing the lateral and axial pile response. Initially, the behaviour of the pile subjected to lateral load will be analysed. The effect of various parameters like pile head fixity, the cohesion of surrounding soil, pile diameter, and length of the pile on lateral pile response will be analysed. Finally with these conditions, the deflections profile of the pile subjected to both lateral and axial load is investigated. By using python code we can easily find out the increase in diameter of pile, cohesion of surrounding soil effect on pile head and effect of increase in combined load will be studied. The above stated parameters will be studied for combined loading also under the free and fixed head conditions.

1 Introduction

A pile is a long, slender foundation part that can be driven or built of structural steel, wood, or concrete. In order to transfer vertical (axial) forces, piles are frequently utilized. Tall buildings, bridges, offshore platforms, defense structures, dam and lock structures, transmission towers, earth retaining structures, wharves, and jetties are a few examples of constructions where piles are frequently utilized as foundations [1-2].

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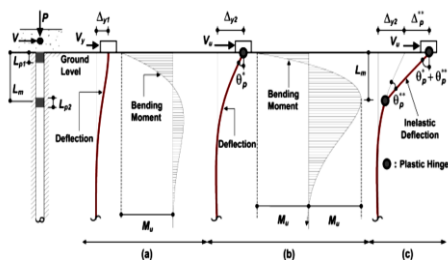
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Fig 1.1 Deflected shape and bending moment distribution of a laterally loaded fixed-head pile (a) first yield limit state, (b) second yield limit state, and (c) ultimate limit state. (Source: Song et. Al 2004)

1.1 Importance of the study

Some of the circumstances in which we will offer pile foundation include [3-6]
- When there is a high groundwater table.
- The superstructure imposes heavy and irregular loads.
- Other foundations are either too expensive or impractical.
- When the soil is compressible at shallow depths.
- When scouring is a possibility because the area is close to a riverbed, the beach, etc.
- When a deep drainage system or canal is located close to the building.
- When bad soil conditions make it impossible to excavate dirt to the appropriate depth.
- When excessive seepage intake renders pumping or any other method of maintaining the foundation trenches dry impracticable.

1.2 Subgrade Reaction

In the Winkler soil model, it is assumed that the pressure p and deflection y at a site are connected via a subgrade response modulus, which for horizontal loading is symbolised by the symbol[7-8]. Thus,

$P = kh*y$

Where *kh* has the units of force/length.
An equation has been restated frequently as

$w = K*y$

The pile is usually assumed to act as a thin strip whose behaviour is governed by the beam equation [9]

$$Ep*Ip \ (d^4y/dz^2) = -y*d$$

Where,
  Ep = modulus of elasticity of pile
  Ip = moment of inertia of pile section
  z = depth in soil
  d = width or diameter of the pile

1.3 Elastic Reaction
Here, we take into account the soil's continuous character. The elastic model also has the benefit of allowing for consistent study of both immediate movements and overall final motions.[10-11]

1.4 Objective
1) The objective of the present study is to find the effect of various soil parameters (Cohesion, modulus of Elasticity) and pile parameter (Moment of inertia, Grade of Concrete, Poison ratio, Length of pile, Diameter of pile).
2) The Effect of Combined load on lateral pile response is figured by using python algorithm code.

2 Methodology

2.1 Algorithm

The algorithm for the lateral deflection of the pile under combined load is :

STEP-1: START

STEP-2: Declare variables H = (lateral load), P = (Axial load), M= (moment), L = (length of the pile), d = (diameter of the pile), n = (number of sections of the pile, is divided into), f= (grade of concrete), es= (modulus of soil), C = (cohesion of soil), Vs = (Poisson ratio of soil), G, K and Load

STEP-3: Initial calculations for required values i.e., delta (Length of pile section) and Moment of inertia of pile section.

STEP-4: Take input subgrade reaction as variable (K) and pile head condition as variable (G).

If subgrade reaction = constant, K=0; else K=1.

If pile head is fixed, G=0; else G=1.

STEP-5: Declare a (n x n) matrix and (1 x n) i.e., A & B matrix for storing the co-efficient of deflection and the constant value of the equation.

STEP-6: Calculate "a" value from ES (modulus of soil).

STEP-7: Fill the value which is common and the value which depends on the loading and pile head condition.

STEP-8: Calculate the constant matrix values and the inverse of the above matrix.

STEP-9: Multiply them to get the deflection at different points on the pile.

STEP-10: Print the displacement of the pile at the different nodes.

STEP-12: Put the deflection points in Excel Sheet and plot the displacement profile for the governing condition that we have (i.e., loading condition and pile head condition).

STEP-13: STOP.

3 Results and discussion

3.1 Code:

The Full project source code is uploaded in the Github, [CLICK HERE](#)

```python
# Importing libraries

import math
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
```

```python
H = float(input('Enter H = '))              # Lateral load
p = float(input('Enter P = '))              # Axial load
M = float(input('Enter M = '))              # Moment
L = int(input('Enter L =') )                # Length of pile
d = float(input('Enter d = '))              # Diameter of pile
n = int(input('Enter n =') )                # no of Sections the pile is divided into
f = float(input('Enter f =') )              # Grade of concrete
ei = 5000*(f**(1/2))                        # As per IS 456 code
v = float(input('Enter v = '))              # Poisson's Ratio of soil
n = n+1
```

```python
K = float(input('Enter 0 if k is constant or 1 for varying k = '))
G = float(input('Enter 0 for fixed headed pile and 1 for free headed pile '))
```

```python
A = []                                  # Main matrix storing the coefficients of deflections from the equations
B = []                                  # constant matrix storing the constant values of equations

# initiation of A and B

A = np.zeros((n,n))
B = np.zeros(n)

# Calculations to simplify the assignment

M1 = (M*(de**2))/(ei*ip)
H1 = (H*(de**3))/(ei*ip)

# calculating the 'a' value from Es

w = (ei*ip)/(de**2)
o = p-4*w
if K!=0:
    a=[]
    k=[]
    for i in range (n):
        C = float(input('C = '))        # Cohesion of soil
        es = 100*C
        k.append((0.65/d)*((((es*d**4)/(ei*ip))**(1/12))*(es/(1-v**2))))
        a.append((6*w) - (2*p) + (k[i]*(de**2)))
else:
    C = float(input('C = '))            # Cohesion of clay
    es = 100*C
    k = (0.65/d)*((((es*d**4)/(ei*ip))**(1/12))*(es/(1-v**2)))
    a = (6*w) - (2*p) + (k*(de**2))
```

```python
z=np.linalg.inv(A)

# Filling Constant matrix



if G == 0:
    B[0] = H1
    B[1] = 0
else:
    B[0] = H1 + 2*M1 -p*M1
    B[1] = -M1

# Multiplying the constant matrix and inverse of coefficient matrix

res = z @ B

# To plot the results on the graph

if res[0]<0 and G == 0:
    res = res*(-1)
res_df=pd.DataFrame(res)
res_df.to_csv("res.csv")
# The Y values corresponding to the nodes are being stored in y

y = []
g = L                                   # To get the depth values of nodes
while(g>0):
    y.append(g)
    g = g - (L/n)
y=y[:-1]
```

```
print('Resultant lateral displacement of pile due to applied load = ',res_df)

# Plotting the displacement profile

plt.plot(res,y)
plt.xlabel("Displacemnt")
plt.ylabel("Depth")

if G == 1:
    plt.title("Displacement due to combined load on free pile")
else:
    plt.title("Displacement due to combined load on fixed head pile")
plt.show()
```

3.2 Input/Output

Table 1. Base pile and soil conditions

Paramater	Base value	Range	**Units**
Lateral load	100	100-1000	MPa
Axial load	100	0.5H – 3H	Mpa
Moment	0	H*d – H*3d	KN-m
Length of pile	25	-	M
Diameter of pile	0.6	0.2	M
Grade of Concrete	30	-	MPa
Cohension	50	20-100	MPa
Poisson Ratio	0.49	-	-

The deflection profile of pile under the loading in given conditions and combined loading case is shown in figure 1.

Table 2. Calculations of base pile under combined loading

| S No.	Fixed head	Free head	S No.	Fixed head	Free head
0	9.53E-06	1.21E-02	13	-3.07E-14	7.31E-15
1	4.81E-04	3.42E-04	14	-8.81E-16	1.47E-14
2	3.20E-05	-2.18E-04	15	5.52E-16	8.39E-16
3	-7.44E-06	-2.14E-05	16	5.44E-17	-2.37E-16
4	-1.13E-06	2.90E-06	17	-7.35E-18	-3.25E-17
5	7.23E-08	6.19E-07	18	-1.57E-18	2.54E-18
6	2.74E-08	-1.64E-08	19	4.10E-20	8.17E-19
7	3.93E-10	-1.34E-08	20	3.41E-20	4.06E-21
8	-5.19E-10	-5.71E-10	21	1.46E-21	-1.60E-20
9	-4.25E-11	2.29E-10	22	-5.81E-22	-1.15E-21
10	7.48E-12	2.66E-11	23	-7.34E-23	2.10E-22
11	1.35E-12	-2.77E-12	24	3.11E-23	1.73E-22
12	-5.89E-14	-7.15E-13	25	3.62E-22	2.00E-21
			26	-1.22E-24	-6.73E-24
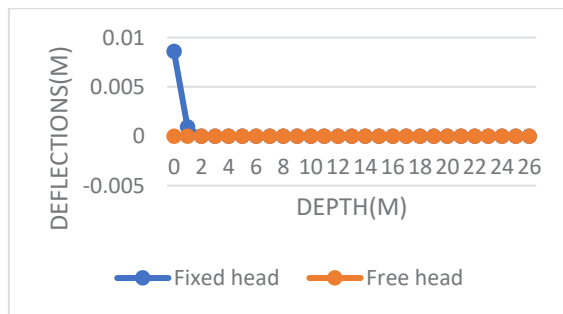
Fig. 1. Base Pile Profile under combined loading

The comparison between pile top deflection under fixed head condition and free head condition are shown below with variation of various parameters.

3.2.1 Influence of Moment on deflection profile of Combined loaded pile

Table 3.3. Calculations of Influence of Moment on deflection profile of Combined loaded pile

| S No.	M-60	M-180	S No.	M-60	M-180
0	9.53E-06	9.53E-06	13	-3.07E-14	-3.07E-14
1	4.81E-04	4.81E-04	14	-8.81E-16	-8.81E-16
2	3.20E-05	3.20E-05	15	5.52E-16	5.52E-16
3	-7.44E-06	-7.44E-06	16	5.44E-17	5.44E-17
4	-1.13E-06	-1.13E-06	17	-7.35E-18	-7.35E-18
5	7.23E-08	7.23E-08	18	-1.57E-18	-1.57E-18
6	2.74E-08	2.74E-08	19	4.10E-20	4.10E-20
7	3.93E-10	3.93E-10	20	3.41E-20	3.41E-20
8	-5.19E-10	-5.19E-10	21	1.46E-21	1.46E-21
9	-4.25E-11	-4.25E-11	22	-5.81E-22	-5.81E-22
10	7.48E-12	7.48E-12	23	-7.34E-23	-7.34E-23
11	1.35E-12	1.35E-12	24	3.11E-23	3.11E-23
12	-5.89E-14	-5.89E-14	25	3.62E-22	3.62E-22
			26	-1.22E-24	-1.22E-24
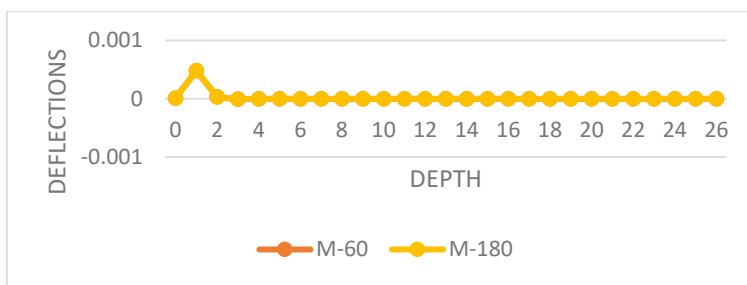
Fig. 2. Influence of Moment on deflection profile of Combined loaded pile

3.2.2 Influence of Diameter of Pile on deflection profile of Combined loaded pile

Table 3.4. Calculations of Influence of Diameter of Pile on deflection profile of Combined loaded pile

S No.	D-0.4	D-1	S No.	D-0.4	D-1
0	8.58E-03	3.64E-06	13	5.86E-19	4.26E-11
1	9.27E-04	-7.05E-06	14	-1.80E-21	3.01E-12
2	-2.18E-05	-3.65E-06	15	-1.69E-21	-4.17E-12
3	-2.74E-06	-7.31E-07	16	-1.50E-25	-2.27E-12
4	5.43E-08	1.44E-07	17	4.89E-24	-4.84E-13
5	8.07E-09	1.60E-07	18	1.58E-26	7.69E-14
6	-1.31E-10	5.34E-08	19	-1.40E-26	9.75E-14
7	-2.37E-11	3.35E-09	20	-8.97E-29	3.40E-14
8	3.04E-13	-5.42E-09	21	4.02E-29	2.65E-15
9	6.93E-14	-2.88E-09	22	3.85E-31	-3.23E-15
10	-6.58E-16	-5.95E-10	23	-1.15E-31	-1.73E-15
11	-2.02E-16	1.06E-10	24	-1.47E-33	1.46E-18
12	1.26E-18	1.25E-10	25	1.73E-34	9.07E-16
			26	1.32E-35	-3.44E-19
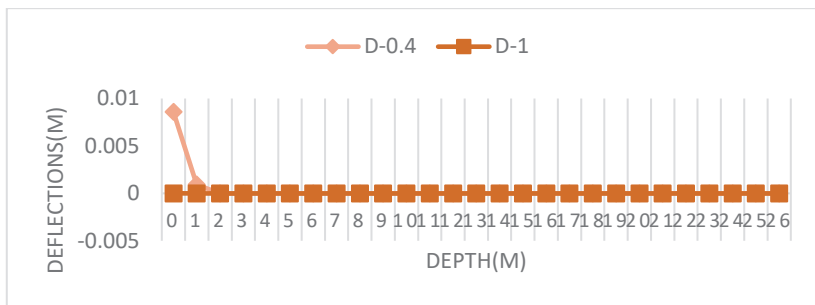
Fig. 3. Influence of Diameter of Pile on deflection profile of Combined loaded pile

4 Conclusion

This paper described the step-by-step procedure used in the python designed in Visual Studio Code. Based on the findings, which include the correlation between deflection and other relevant parameters like H (Lateral Load), P (Axial Load), d (diameter of the pile), f (grade of concrete), C (cohesion of the soil), and Vs (Poisson's Ratio), it can be said that the deflection profile of the pile varies depending on the governing circumstances. (Specifically, the state of the loading and the pile head).

Moreover, other characteristics can be coupled to the deflection profile of the pile under combined loading as needed. The following are a few of the common relations that may be derived:

 i.   In both instances, the pile top deflection rose by 90% while the lateral loading increased by a factor of ten.
 ii. When the moment is raised three times, the pile top deflection for a free head pile rose by 67%.
 iii. For free head piles, the pile top deflection falls by 48.6%, and when the diameter is raised by 60%, it falls by 99.95%.
 iv. Also, in order to properly do the task that is expected of us, we may observe and compare the many relationships we have above.

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