Lateral bearing capacity analysis of pile foundation using a spring modelling system

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Abstract. Pile foundations are often required to resist lateral loads and moments in addition to their primary use as axially loaded members. The interaction between material strength of axial, moment and shear against load capacity and soil interaction is the most important factors in the pile analysis. This study aims to obtain the lateral bearing capacity of pile foundation using a spring modelling system which will be calculated manually for the Kv spring constant in the vertical direction and the kh coefficient in the horizontal direction using the Nakazawa method and SAP 2000 v14.2.5 program. The result shows that the maximum shear load and the maximum axial tensile load received by the pile is still within the allowable shear load and allowable axial tensile load capacity resulting from the manual calculation. However, the maximum axial compression load and maximum moment is exceeded its each allowable capacity. Hence, it is necessary to re-modelling by adding the depth or number of piles.

1. Introduction

Pile foundations are common foundation used in the construction, especially in the pillar bridge construction. Piles are often required to resist lateral loads and moments in addition to their primary use as axially loaded members. The goals are to determine deflections and stresses in the selected soil-pile system in order that they may be controlled within tolerable limits [1]. Nowadays, most of pile foundation’s planning separate the strength calculation of axial bearing capacity and lateral bearing capacity. The calculation analysis is done without involving interaction between material strength of axial, moment and shear against load capacity and soil interaction. In fact, soil-structure interaction is one of the most important factors in the analysis [2].

Soil as a damper cannot be assumed to be the whole fixed. In subgrade reaction approach, it is assumed that soil acts as a series of independent linear elastic springs [2]. Pile is divided into several segments (mass) where each segment has a center of mass in the middle and the ground is considered as a linear spring [3]. The discrepancy between the modelling of pile foundation at this time with the actual conditions in the construction project field will affect to the lateral bearing capacity. So that we need an analysis of the calculation of the lateral bearing capacity of pile foundations in the construction of bridge piers using a spring modelling system. Soil that is modelled as an elastic has the ability to resist the load depending on the estimated spring constant Kv in the vertical direction and the estimated coefficient of kh from the subsurface soil reaction in the horizontal direction [4].
The structural data analysis as same as with the previous research that is taken from the construction of the bridge’s pile of Surabaya’s Outer West Ring Road (planning project) STA 0+400, Surabaya, Indonesia [5].

The purpose of this paper is to obtain the lateral bearing capacity of pile foundation using a spring modelling system which will be calculated manually for the $K_v$ spring constant in the vertical direction and the $k_h$ coefficient in the horizontal direction using the Nakazawa method and SAP 2000 v14.2.5 program. By conducting these methods, it is expected that the results are closer to the actual conditions in the construction project field.

1.1 Literature Review

1.1.1. Lateral Load. Piles are always required to be designed to withstand the lateral loads in addition to the compression and tension loads [6]. Pile foundations often receive inclined loads which are generally the resultant of dead loads and horizontal loads due to wind, earthquakes, water pressure, ground pressure, etc. The horizontal component of the inclined load is usually relatively small compared to the vertical component. However, for certain cases such as retaining walls, bridge pillars and piers, the horizontal force acting is quite large and is a fixed load, which means that the load works throughout the life of the building [7].

The allowable lateral loads on pile is determined from the following two criteria; 1. Allowable lateral load is obtained by dividing the ultimate (failure) load by an adequate factor of safety; 2. Allowable lateral load is corresponding to an acceptable lateral deflection. The smaller of the two above values is the one actually adopted as the design lateral load. Method of calculating lateral resistance of vertical piles can be broadly divided into two categories:

- Methods of calculating ultimate lateral resistance
- Methods of calculating acceptable deflection at working lateral load.

According to Prakash and Sharma (1990), methods of calculating lateral resistance of vertical piles among others Brinch Hansen’s method (1961) and Broms’ method (1964). Both of them are based on earth pressure theory. Brinch Hansen’s method applicable for c-Ø soils and layered system, but this method only can applied for short piles and requires trial-and-error solution to locate point of rotation. Otherwise, Broms’ method applicable for short and long piles, considers purely cohesive and cohesionless soils, and considers free-head and fixed-head piles that can be 2analysed separately, but this method cannot applied to layered system and does not consider c-Ø soils.

Methods of calculating acceptable deflection at working load among others Modulus of subgrade reaction approach (Reese and Matlock, 1956) and Elastic approach (Poulos, 1971). Modulus of subgrade reaction approach is assumed that soil acts as a series of independent linearly elastic springs. This method is relatively simple and can incorporate factors such as nonlinearity, variation of subgrade reaction with depth, and layered systems. Moreover, this method has been used in the practice for a long time so a considerable amount of experience has been gained in applying the theory to practical problems. However, this method has some disadvantages such as it ignores contuity of the soil and modulus of subgrade reaction is not a unique soil property but depends on the foundation size and deflections.

Furthermore, the elastic approach, in this method the soil is assumed as an ideal elastic continuum. It is based on a theoretically more realistic approach and it can give solutions for varying modulus with depth and layered system. But this method is difficult to determine appropriate strains in a field problem and the corresponding soil module. It needs more field verification by applying theory to practical problems [3].

Different from the methods above, this is using a calculation method adapted from technical standard in Japan called Nakazawa method [4]. As we know, Japan is an earthquake-prone country dominated by soft soil. This is similar with the condition in Indonesia [5]. In this method, the lateral bearing capacity of pile foundation is obtained by the manual calculation of spring constant $K_v$ in the vertical direction.
and the coefficient of $k_h$ from the subsurface soil reaction in the horizontal direction at each depth of soil foundation.

2. Research Methodology

2.1 Calculation of Pile Structural Capacity.

The pile foundation used in the construction planning is strong, if it is able to withstand the loads that act on the pile. This can be determined by comparing the allowable stress of the pile material and the loads that act on the pile. The allowable stress of the pile material is the force strength per unit area based on the pile material used to obtain the allowable axial compression capacity, the allowable axial tensile capacity, the allowable shear capacity, and the allowable moment capacity. This value is the maximum strength of the pile that is allowed to withstand loads acting on the pile by considering the strength of the material from the pile itself which is formulated by SNI T-12-2004 [8] as follows:

**Allowable axial compression capacity**

$$P_u = \phi \cdot P_n \text{ compression}$$

$$= 0.7 \{(0.60 \cdot f_{c'} \cdot A_g) - (0.70 \cdot f_{pu} \cdot A_{sp} \cdot n)\}$$

**Allowable axial tensile capacity**

$$P_u = \phi \cdot P_n \text{ tensile}$$

$$= 0.8 \{(0.50 \sqrt{f_{c'}} \cdot A_g) + 0.85 (0.70 \cdot f_{pu} \cdot A_{sp} \cdot n)\}$$

**Allowable shear capacity**

$$V_u = \phi \cdot V_n$$

$$= \phi (V_c + V_s)$$

$$= 0.75 \left[ \left(1 + \frac{N_u}{14A_g}\right) \left(\frac{\sqrt{f_{c'}}}{6}\right) b_y d \right] + \left[ \frac{A_v f_y d}{s} \right]$$

Information:

- $P_n \text{ compression}$ = The nominal compressive axial limit strength of the structural components (N)
- $P_n \text{ tensile}$ = The nominal tensile axial limit strength of the structural components (N)
- $V_n$ = The nominal limit of shear strength of structural components (N)
- $V_c$ = Shear strength of concrete (N)
- $V_s$ = Shear strength of shear reinforcement (N)
- $N_u$ = Ultimate axial load (N)
- $\phi$ = Reduction factor
- $f_{c'}$ = Compressive strength of concrete (Mpa)
- $f_y$ = Yield stress of non-prestressed reinforcement (Mpa)
- $f_{pu}$ = Tensile strength of pc bar (Mpa)
- $A_g$ = The cross-sectional area of the pile (mm$^2$)
- $A_{sp}$ = The cross-sectional area of PC bar (mm$^2$)
- $A_v$ = The area of the shear reinforcement in the range s (mm$^2$)
- $n$ = Number of reinforcement
- $b_y$ = Diameter (mm)
- $d$ = Distance from the outer compression area to the center of the tensile reinforcement (mm)
- $s$ = Spacing of shear reinforcement parallel to longitudinal reinforcement (mm)
Besides getting the allowable stress of the pile material by manual calculation, this value can also be obtained from the Wika Beton pile brochure specifications, 2017 [9]. Table 1 shows the specification of Wika Beton production piles for a diameter of 600 mm

2.2 Calculation of Lateral Bearing Capacity.

In this study, the spring constant Kv and the coefficient of kh are calculated manually by using Nakazawa method then inputed into SAP 2000 program as a spring stiffness and generate maximum shear force or called lateral bearing capacity.

Estimated Kv (spring constant) in the vertical force of the pile is an elastic constant which is expressed as a force in the vertical direction and can cause displacement on the masthead. Kv is used in the calculation of the size of the pole head reaction or elastic decline that occurs [10]. The following is the equation for estimating Kv constants [4].

\[
K_v = a \cdot \frac{A_p \cdot E_p}{l}
\]

For steel pipes \( a = 0.027 \frac{l}{D} + 0.2 \)
For prestressed concrete \( a = 0.041 \frac{l}{D} - 0.27 \)
For cast in situ \( a = 0.022 \frac{l}{D} - 0.05 \)

**Information:**
- \( a \) = Multiplier factor based on pile material
- \( A_p \) = Net cross-sectional area of pile (cm²)
- \( E_p \) = Modulus of elasticity of pile (cm²)
- \( l \) = Pile length (cm)
- \( D \) = Pile diameter (cm)

The formula above is used when \( l/D \geq 10 \)

| Size (mm) | Class | Bending moment | Allowable Decompression |
|-----------|-------|----------------|-------------------------|
|           |       | Crack (ton.m)  | Break (ton.m) | compression (ton) | tension (ton) |
| 600       | A1    | 17.00          | 25.50         | 252.70          | 70.52 |
|           | A2    | 19.00          | 28.50         | 249.00          | 77.68 |
|           | A3    | 22.00          | 33.00         | 243.20          | 104.94 |
|           | B     | 25.00          | 45.00         | 238.30          | 131.10 |
|           | C     | 29.00          | 58.00         | 229.50          | 163.67 |

**Table 1. Pile specification**

Source: Wika Beton Brochure, 2017

The following is the equation for estimating the coefficient of soil reaction below the surface in a horizontal force [4].

\[
k_h = k_0 \cdot y^{1/2}
\]

\[
k_0 = 0.2 \cdot E_0 \cdot D^{3/4}
\]

**Information:**
- \( k_0 \) = Value k if the shift on the surface is made 1 cm (kg / cm²)
- \( y \) = Value of deformation (cm)
- \( E_0 \) = Modulus of foundation soil deformation, usually estimated from \( E_0 = 28 \) N using N value from standard penetration experiments (standard penetration test)
- \( D \) = Pile diameter (cm)
3. Data and Analysis Result
The structural data analysis is taken from the construction of the bridge’s pile of Surabaya’s Outer West
Ring Road (planning project) STA 0+400, Surabaya, Indonesia.
Spun pile specification
Pile diameter, \( D \) : 0.6 m
Pile class : C
Pile material : Prestressed concrete
Concrete quality, \( f_{c'} \) : 52 MPa
Concrete volume weight, \( W_c \) : 2500 kg/m\(^3\)
Number of piles in group, \( n \) : 25
Pile depth, \( l \) : 16 m

3.1 Allowable axial compression capacity
\[
P_u = \emptyset \cdot P_{n\text{ compression}}
\]
\[
P_{n\text{ compression}} = 0.7 \left\{ (0,60 \cdot f_{c'} \cdot A_g) - (0,70 \cdot f_{pu} \cdot A_{sp} \cdot n) \right\}
\]
\[
= 0.7 \left\{ (0,60 \cdot 52 \text{ MPa} \cdot 157.080 \text{ mm}^2) - (0,70 \cdot 1030 \text{ MPa} \cdot 89.92 \text{ mm}^2 \cdot 26) \right\}
\]
\[
= 0.7 \left\{ 4.900.896 \text{ N} - 1.685.640,32 \text{ N} \right\}
\]
\[
= 2.250.678,98 \text{ N}
\]
\[
= 229,51 \text{ ton}
\]

3.2 Allowable axial tensile capacity
\[
P_u = \emptyset \cdot P_{n\text{ tensile}}
\]
\[
P_{n\text{ tensile}} = 0.8 \left\{ (0,50 \cdot \sqrt{f_{c'}} \cdot A_g) + 0.85 (0,70 \cdot f_{pu} \cdot A_{sp} \cdot n) \right\}
\]
\[
= 0.8 \left\{ (0,50 \cdot \sqrt{52 \text{ MPa}} \cdot 157.080 \text{ mm}^2) + (0,85 \cdot (0,70 \cdot 1030 \text{ MPa} \cdot 89.92 \text{ mm}^2 \cdot 26) \right\}
\]
\[
= 0.8 \left\{ 566.359,99 \text{ N} + 1.432.794,27 \text{ N} \right\}
\]
\[
= 1.599.323,41 \text{ N}
\]
\[
= 163,09 \text{ ton}
\]

3.3 Allowable shear capacity
\[
V_u = \emptyset \cdot V_n
\]
\[
V_n = \emptyset \left( V_c + V_s \right)
\]
\[
= 0.75 \left\{ (1 + \frac{N_u}{14A_g}) \left( \frac{\sqrt{f_{c'}}}{6} \cdot b_w d \right) + \left[ \frac{A_v \cdot f_y d}{s} \right] \right\}
\]
\[
= 0.75 \left\{ (1 + \frac{1.821.595 \text{ N}}{14 \cdot 157.080 \text{ mm}}) \left( \frac{\sqrt{52}}{6} \cdot 600 \text{ mm} \cdot 560,65 \text{ mm} \right) + \left[ \frac{12,57 \text{ mm}^2 \cdot 40 \text{ MPa} \cdot 560,65 \text{ mm}}{100 \text{ mm}} \right] \right\}
\]
\[
= 0.75 \left\{ 739.176,00 \text{ N} + 2.818,13 \text{ N} \right\}
\]
\[
= 556.495,60 \text{ N}
\]
\[
= 56,75 \text{ ton}
\]

3.4 Spring constant \( K_v \) (z-axis)
The spring constant \( K_v \) at each depth is obtained by first calculating the \( a \) value according to the material of the pile, which is made of prestressed concrete by using equation 1. The results of the recapitulation of the spring constant \( K_v \) at each depth are shown in Table 2 below.
Table 2. Recapitulation of the spring constant $K_v$

| Depth (m) | $K_v$ (kN/m) | Depth (m) | $K_v$ (kN/m) | Depth (m) | $K_v$ (kN/m) |
|----------|--------------|----------|--------------|----------|--------------|
| 1        | 0.00         | 11       | 419609.99    | 21       | 531616.61    |
| 2        | 0.00         | 12       | 439211.15    | 22       | 537216.94    |
| 3        | 0.00         | 13       | 455796.74    | 23       | 542330.29    |
| 4        | 7985.66      | 14       | 470012.97    | 24       | 547017.52    |
| 5        | 137353.30    | 15       | 482333.70    | 25       | 551329.78    |
| 6        | 223598.40    | 16       | 493114.33    | 26       | 555310.32    |
| 7        | 285202.04    | 17       | 502626.66    | 27       | 558996.01    |
| 8        | 331404.78    | 18       | 511082.06    | 28       | 562418.43    |
| 9        | 367340.23    | 19       | 518647.42    | 29       | 565604.83    |
| 10       | 396088.60    | 20       | 525456.25    | 30       | 568578.80    |

Source: Calculation result, 2019

3.5 Coefficient $k_h$ (x and y-axis)
The soil reaction coefficient below the surface in a horizontal direction at each depth is obtained by first calculate the value of $k_0$ (eq 6.) and the value of $k_h$ (eq 5.) whilst the shift on the surface is made of 1 cm (kg/cm$^3$). To find the value of the $k_h$ coefficient per unit length, it must be multiplied by the diameter of the pile and the length of the segment. The results of the recapitulation of the coefficient $k_h$ at each depth are shown in Table 3 below.

Table 3. Recapitulation of the spring constant $k_h$

| Depth (m) | $k_h$ (kN/m) | Depth (m) | $k_h$ (kN/m) | Depth (m) | $k_h$ (kN/m) |
|----------|--------------|----------|--------------|----------|--------------|
| 1        | 0.00         | 11       | 39739.27     | 21       | 47381.43     |
| 2        | 0.00         | 12       | 39739.27     | 22       | 47381.43     |
| 3        | 15284.33     | 13       | 42796.13     | 23       | 47381.43     |
| 4        | 18341.20     | 14       | 47381.43     | 24       | 51966.74     |
| 5        | 22926.50     | 15       | 51966.74     | 25       | 55023.60     |
| 6        | 29040.23     | 16       | 50438.30     | 26       | 55023.60     |
| 7        | 30568.67     | 17       | 45853.00     | 27       | 51966.74     |
| 8        | 35153.97     | 18       | 42796.13     | 28       | 48909.87     |
| 9        | 36682.40     | 19       | 45853.00     | 29       | 61137.34     |
| 10       | 38210.83     | 20       | 47381.43     | 30       | 68779.50     |

Source: Calculation result, 2019

3.6 SAP 2000 v14.2.5
The value of the spring constant $K_v$ and the coefficient $k_h$ at each depth obtained by using the manual calculation of the Nakazawa method are then input into the SAP 2000 v14.2.5 program to produce lateral bearing capacity. The modelling of bridge pillar construction with 25 pile foundations without springs is shown in Figure 1.
Then, input the spring constant value $K_v$ for the $z$-axis in Translation 3 and the $k_h$ coefficient for the $x$ and $y$-axis in Translation 1 and Translation 2 at each depth from the manual calculation of the Nakazawa method shown in Table 2 and Table 3 into Joint Springs setup through Assign - Joint - Springs command (Figure 2.)

Figure 3 shows a modelling of bridge pillar construction with 25 pile foundations with springs. The springs modelling is inputted per 1 meter as explained. The following table is the force generated by the piles in spring modelling using SAP 2000 v14.2.5.
Table 4. Recapitulation of the force generated by piles in the spring modelling

| Output Case     | Step Type | P  | Vx  | Vy  | Mx  | My  |
|-----------------|-----------|----|-----|-----|-----|-----|
| SERVICE 1D      | MAX       | -14.98 | 1.07 | 2.27 | 3.45 | 3.72 |
| SERVICE 1D      | MIN       | -900.81 | -8.38 | -0.29 | -1.00 | -12.65 |
| SERVICE 1T      | MAX       | -13.64 | 1.08 | 2.27 | 3.45 | 3.75 |
| SERVICE 1T      | MIN       | -843.47 | -8.38 | -0.29 | -1.00 | -12.55 |
| SERVICE 2D      | MAX       | -15.94 | 1.10 | 0.00 | 0.00 | 3.81 |
| SERVICE 2D      | MIN       | -923.55 | -8.60 | 0.00 | 0.00 | -12.99 |
| SERVICE 2T      | MAX       | -14.21 | 1.11 | 0.00 | 0.00 | 3.85 |
| SERVICE 2T      | MIN       | -849.01 | -8.60 | 0.00 | 0.00 | -12.87 |
| EXTREME XD (1)  | MAX       | 1159.09 | 340.55 | 119.28 | 185.05 | 526.88 |
| EXTREME XD (1)  | MIN       | -2612.36 | -340.55 | -119.28 | -185.05 | -526.88 |
| EXTREME XT (1)  | MAX       | 1177.48 | 340.55 | 119.28 | 185.05 | 526.90 |
| EXTREME XT (1)  | MIN       | -2595.05 | -340.55 | -119.28 | -185.05 | -526.85 |
| EXTREME YD (1)  | MAX       | 1319.63 | 102.21 | 397.32 | 616.36 | 158.13 |
| EXTREME YD (1)  | MIN       | -2772.95 | -102.21 | -397.32 | -616.36 | -158.13 |
| EXTREME YT(1)   | MAX       | 1340.07 | 102.21 | 397.32 | 616.36 | 158.16 |
| EXTREME YT(1)   | MIN       | -2755.64 | -102.21 | -397.32 | -616.36 | -158.10 |
| KUAT 1 D        | MAX       | -21.05 | 1.97 | 0.00 | 0.00 | 6.87 |
| KUAT 1 D        | MIN       | -1273.45 | -15.48 | 0.00 | 0.00 | -23.39 |
| KUAT 2 T        | MAX       | -18.65 | 1.99 | 0.00 | 0.00 | 6.92 |
| KUAT 2 T        | MIN       | -1170.24 | -15.48 | 0.00 | 0.00 | -23.21 |
| KUAT III        | MAX       | -17.34 | 1.03 | 10.60 | 16.08 | 1.61 |
| KUAT III        | MIN       | -1021.02 | -0.13 | -1.34 | -4.68 | -0.44 |

Source: Calculation result, 2019

Based on the pile load generated from spring modelling with a total of 25 piles and a length of 16 m, the maximum material capacity and pile loads/forces could be seen in Table 5. The conclusions shows the comparison between material capacity and loads received by piles. The design analysis is valid when material capacity is bigger than pile loads.

Table 5. Recapitulation of the material capacity and pile loads/forces

| No. | Type of load       | Material capacity (ton) | Pile load (ton) | Conclusions |
|-----|--------------------|-------------------------|-----------------|-------------|
| 1   | Axial compression  | 229.51                  | 282.76          | Exceeds     |
| 2   | Axial tensile      | 163.09                  | 136.66          | OK          |
| 3   | Shear              | 56.75                   | 40.52           | OK          |
| 4   | Moment             | 58.00                   | 62.85           | Exceeds     |

Source: Calculation result, 2019
The maximum shear load received by the pile is 397.92 kN or 40.52 ton. This value is still within the allowable shear load capacity resulting from the manual calculation of 56.75 ton. However, the maximum axial compression load received by the pile is 2,772.95 kN or 282.76 ton that is exceeds the allowable axial compression load capacity resulting from the manual calculation of 229.51 ton which is similar to the value in Wika Beton brochure (Table 1).

The maximum axial tensile load received by the pile is 1340.07 kN or 136.66 ton, this value is still within the allowable axial tensile load capacity resulting from the manual calculation of 163.09 ton which is equivalent with the value in Table 1. While the maximum moment received by the pile is 616.36 kN-m or 62.85 ton-m, this value also exceeds the allowable moment capacity of 58 ton-m from Pile specification in Table 1. Hence, it is necessary to re-modelling by adding the depth or number of piles for the further study.

4. Conclusions

The analysis result shows that the lateral bearing capacity of pile foundation with a spring modelling system by manual calculation for the $K_v$ spring constant in the vertical direction and the $k_h$ coefficient in the horizontal direction using the Nakazawa method and SAP 2000 v14.2.5 program. The pile load generated with a total of 25 piles and a length of 16 m, the maximum shear load and the maximum axial tensile load received by the pile is still within the allowable shear load and allowable axial tensile load capacity resulting from the manual calculation. However, the maximum axial compression load and maximum moment is exceeded its each allowable capacity. Hence, it is necessary to re-modelling by adding the depth or number of piles for the further study.

5. References

[1] DAVISSON MT, “Lateral Load Capacity of Piles,” Highw Res Rec, no. 33, pp. 104–112, 1970.
[2] O. Taheri, R. Z. Moayed, and M. Nozari, “Lateral Soil-Pile Stiffness Subjected to Vertical and Lateral Loading Lateral,” J. Geotech. Transp. Eng., vol. 1, no. 2, pp. 30–37, 2015.
[3] S. Prakash and H. D. Sharma, Pile Foundations in Engineering. 1990.
[4] S. Sosrodarsono and K. Nakazawa, MEKANIKA TANAH & TEKNIK PONDASI. JAKARTA: PT. PRADNYA PRAMITA, 2000.
[5] L. L. Lestari, J. Propika, and A. D. Puspasari, “Axial Bearing Capacity Analysis of Pile Foundation using Nakazawa Method,” J. IPTEK, vol. 24, no. 1, pp. 45–52, 2020.
[6] P. K. Jayasree, K. V. Arun, R. Oormila, and H. Sreelakshmi, “Lateral Load Capacity of Piles: A Comparative Study Between Indian Standards and Theoretical Approach,” J. Inst. Eng. Ser. A, vol. 99, no. 3, pp. 587–593, 2018.
[7] J. T. Hatmoko, Dinamika Tanah Dan Liquefaction. Yogyakarta: Cahaya Atma Pustaka, 2016.
[8] Badan Standardisasi Nasional Indonesia, “SNI T-12-2004 Perencanaan Struktur Beton untuk Jembatan,” pp. 1–142, 2004.
[9] WIKA, “Brochure The Precast Concrete Manufacturer,” 2017.
[10] D. K. Fitriyah, J. Propika, L. L. Lestari, H. Istiono, D. Pertiwi, and R. Sekartadji, “Pile Foundation Analysis on High - Rise Building using Finite Element-Spring Method on Sandy Clay Soil,” IOP Conf. Ser. Mater. Sci. Eng., vol. 462, no. 1, 2019.