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Model Study on Single Pile Subjected To Axial and Inclined Load Embedded In Contaminated Soil

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Abstract. With substantial increase of industrialization, large quantities of toxic waste remains untreated, which is a serious geo-environmental issue. Pile foundation is being extensively used at many such sites to support weak soils, where the load transfer mechanism is either through skin friction, end bearing, or both. Present research paper focuses on influence of contamination on load-settlement characteristics of RCC model pile foundation for two different slenderness ratios (8 and 10) by carrying out experimental model test on both contaminated and non-contaminated soil subjected to various load inclinations (0°, 30°, 45°, and 60°) from vertical axis. Various parameters analyzed and compared in this study are ultimate inclined bearing capacity, deflection, moment, soil resistance (p), engineering properties of soil, mineralogical content of soil,and effect of lateral component on inclined bearing capacity. Various theories are used toestimate vertical and lateral capacity of the pile. P-Y curve is also constructed, and used to calculate deflection, moment and soil resistance for the applied load. Experimental result of the model test is compared with the inclined capacity calculated using Meyerhof's interaction equation. This investigation has revealed that contamination of soil leads to reduction in the bearing capacity. Also, there is a direct correlation established between increase in angle of load inclination with reduced bearing capacities,and increase in L/d ratio with increase in bearing capacities of pile.

Keywords: Axial Load, Inclined Load, Contaminated Soil, Pile foundation

1. Introduction

Due to the illicit practices of disposing waste without proper treatment by chemical industries, large amounts of land has not only detorited for agriculture purposes, but also has severely impacted the engineering properties of soil. In Nandesari region located on the outskirts of Vadodara, vast amounts of land present there could be eventually used for the expansion of the city, or to meet the growing energy demands of the city by repurposing the land to harness the solar or wind energy. However, rapid economic growth in the past decades has given rise to manyindustries in this region. And unfortunately, the chemical waste generated by these industries has been blatantly discharged in nearby land, which has not only polluted the soil but has also

infiltrated groundwater. On site visit, discoloration of soil and ground water is conspicuously visible. Large quantities of toxic waste present in the soil and groundwater might have affected theengineering properties of soil. Hence, before any development can take place, a thorough investigation is indispensable to study the changes in soil behaviour and avoid any catastrophes.

Since this land would be far more suited for wind and solar farms, pile foundation should be adopted as it aids in increasing the bearing capacity and reducing the settlement of the structure. Additionally, suitable analysis must be carried out which encompass various load cases such as horizontal loads generated by wind and the vertical loads of the structure. Conventionally, the analysis of vertical and lateral components are carried out separately, and the combined effect of these components is not taken into consideration.

Although several researchers like Broms (1964), J.B. Hansen (1970), Meyerhof and Ranjan (1973)have tried to establish empirical relationships by experimental results; the variation in these valueshas befuddled engineers to adopt one method over the other. Also, the effect of contaminated soilon pile capacity subject to axial and inclined compressive loads has been rarely studied. This is the primary impetus behind the focus of the present research paper, where model tests are conducted on a single pile to study the interaction of the pile with both contaminated and non- contaminated soil.

2. Experimental Investigation

2.1 Foundation medium

In this model study, contaminated soil is procured from Nandesari district, Gujarat state where industrial pollution is more pronounced. For comparison purposes, a non-contaminated soil of similar classification is collected within 4 km of the site. The properties of the contaminated and non-contaminated soil are determined as per the I.S code and results obtained are shown in table 1.

Table 1: Index and Engineering Properties of soil

Sr. no.	Properties of soil	Contaminated soil	Non-contaminated soil
1	Type of soil	SP-SM	SP-SM
2	Specific gravity (G)	2.33	2.67
3	Cohesion (c)	6	4
4	Angle of internal friction (Φ)	30	34
5	Angle of wall friction ()	25	28
6	Relative density (Dr)	60	60
7	Density of soil (y)	16.6	17.2
8	Optimum moisture content(OMC)	11%	13%
9	Maximum dry density (MDD)	18.8	19.6
10	Liquid limit	27%	21%
11	pH value of soil	8.0	7.2

2.2 Industrial waste water

Since industries are not abiding by the regulations of proper treatment of waste-water before discharging in surroundings, it becomes crucial to investigate the water to check for any lethal contaminants. Additionally, the chemicals present in the waste-water could potentially impact engineering properties of soil, so it becomes necessary to analyse the water to determine contaminants and its concentration present. The results of chemical analysis of effluent (industrialwastewater) is given in table 2.

Table 2: chemical analysis of industrial waste water

Sr. no.	parameters	value
1	pH	7.73
2	Organic matter	4747 mg/l
3	Oil & grease	22 mg/l
4	chlorides	11360 mg/l
5	sulphates	3014 mg/l
6	magnesium	87.7 mg/l
7	sodium	2225 mg/l

2.3 Tests on contaminated soil

Although the contaminated water is chemically tested to determine the pollutant present, it is necessary to find out the changes in the composition of soil in presence of this contaminated water.Hence, X-ray diffraction (XRD) test & EDAX test was conducted on the contaminated soil to analyse the chemicals and elements present in the soil which are present in table no.

3 & 4.

Table 3: XRD test results

Sr. no.	Chemical name	Formula
1	Alumina	$K_2Al_{24}O_{37}$
2	Calcium chloride Dihydrate	$C_aCl_22(H_2O)$
3	Aluminum Phosphate	$AlPO_4$
4	Silicon Dioxide	SiO_2
5	Alunite	$KAl_3(SO_4)_2(OH)_6$
6	Magnesium Calcium Carbonate	$(C_a, M_g)CO_3$

Figure 1: Contaminated soil

Table 4: EDAX test results

Elements	Weight %	Elements	Weight %
Ca	5.75	**K**	1.26
Na	1.87	**Ti**	0.89
Al	9.39	**Cr**	4.32
S	1.12	**Fe**	12.34
Cl	0.45	**O**	43.67

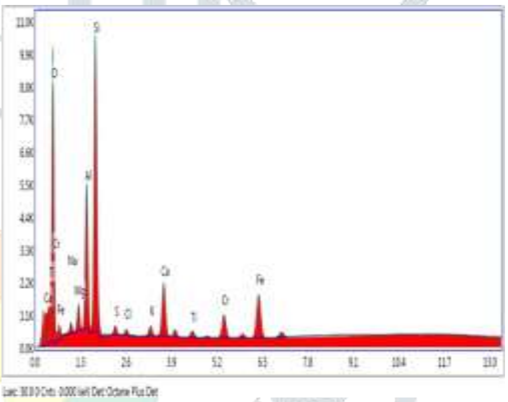


Figure 2: X-ray diffraction peaks contaminated soil

3. Experimental setup

Model tank of 0.75m × 0.75m× 0.75m is adopted for this test. The dimension of the model tank isdetermined by taking the pressure bulb of the pile into account. Soil samples for contaminated andnon-contaminated model tests are procured from Nandesari district near Vadodara. Engineering properties of soils are mentioned in table 1.

Two concrete piles having 360mm and 450mm embedded length are used in the test procedure having L/D ratio of 8 and 10 respectively. The piles of 45mm diameter are casted from a PVC pipeand 6mm of steel reinforcement is provided at the center of the pile. The piles were cured for 28 day to achieve its optimum strength. Mechanical screw jack (5 tonne capacity) and a proving ringof 50 KN capacity were used to apply load on the pile.

Experimental assembly consisted of a C section loading frame with capability of applying 30°, 45° and 60° inclined loads at the top of the pile cap as shown in the figure. Steel chains were usedto place the pile in center, equidistant from all four sides, and its head extending 10cm above the soil surface. After the pile was carefully supported with the help of chains, the tank was filled withsoil with 60% relative density in five layers of 150mm thickness. Round bottom hammer of 0.15mdiameter and 50N weight was used to compact the soil to achieve the intended density of 16.6 KN/m3 for contaminated soil, and 17.2 KN/m3 for non-contaminated soil. Two dial gauge of sensitivity 0.01mm were placed on the top and the side of pile cap to measure vertical and lateral displacement

Figure 3: experimental setup for inclined load

4. Research methodology

As per I.S.2911 (part 4) maintained load test method (MLT) was adopted. The failure load was taken to be that load at which the load vs pile head displacement curve passes into a steep and fairly straight tangent.

Theoretically, value of vertical load carrying capacity of pile is calculated using the I.S 2911 Codemethod:-

$$Qu = A_P \left(C N_C + \frac{1}{2} N_\gamma \gamma D + P_D Nq\right) + \left(K P_{Di} \tan\delta + \alpha C\right) A_S \qquad \ldots\ldots (1)$$

Where, Qu = ultimate bearing capacity, A_P = c/s area of pile toe, D =diameter of pile, y = effective unit weight of soil, P_D = effective overburden pressure at pile toe,$_C$, Nq, N^γ = bearing capacity factors, PDi = effective overburden pressure for pile shaft, δ = angle of wall friction between pile and soil, A_S = surface area of pile

Theoretical value of lateral load carrying capacity of pile is calculated using the Broms (1964) method for short restrained pile.

$$QH = 1.5\, y\, L^2 D\, K_P \qquad \ldots\ldots (2)$$

Where, K_P = coefficient of passive earth pressure,
L = length of the pile

The pile rigidity is related to a stiffness factor T which is expressed as,

—

$$T = \sqrt[5]{\frac{EI}{yh}} \qquad \text{....... (3)}$$

Where, EI = stiffness of the pile & h = coefficient of subgrade reaction. The stiffness factor is usedto determine the behaviour of the pile. If L≥4T then the pile behaves as a long flexible pile and forL≤2T then the pile behaves as a short rigid pile. Because either piles of L/D ratio 8 and 10 are notless than 2T or greater than 4T, the behaviour of the pile is intermediate pile.

Since the length of the pile was closer to 2T then 4T and rotational failure was more dominant thenformation of plastic hinges, lateral load carrying capacity was calculated as a short rigid pile.

The ultimate inclined load carrying capacity Qui of a vertical pile subjected inclined load can be expressed by the interaction equation of Meyerhof (1981a) given as

$$\left(Qu\cos\alpha\right)^2 + \left(\frac{Qu\sin\alpha}{Qa}\right)^2 = \frac{1}{Qn} \qquad \text{.....(4)}$$

Where, α = inclination of the load with respect to the vertical axis of pile, Qa & Qn are the verticaland lateral ultimate capacity of pile respectively. The theoretical value of vertical and inclined ultimate load carrying capacity of pile are compared with the experimental value of ultimate loadcarrying capacity of pile.

Inclined loads can be divided into two components: vertical and lateral. With increase in angle ofload inclination, analysis of lateral load becomes important since it is responsible for the failure ofthe pile. Hence, P-Y curves under static conditions were theoretically developed using methodology proposed by Reese and Matlok (1974).The py curve then is used to determine the deflection and moment across the pile for design purposes. From the lateral component of the

obtained experimental inclined load, the maximum moment and maximum deflection (displacement) are calculated using the py curve.

P-Y curves constructed for both contaminated and non-contaminated soil are primarily used to estimate the resistance offered by the soil subject to lateral loading. This numerical approach can be used to analyse the interaction of a pile with soil with varying depth and soil type. Ideally the P-Y curve should be generated from a full scale model test using an instrumented pile, however this method is not cost effective. Using the P-Y curve other parameters such as moment and deflection can be determined. Following equations were used to estimate the ultimate resistance of soil per unit length of pile.

For Soil close to the ground surface:

$$P_{st} = \square\, x \frac{o\ x \tan\phi \sin\beta}{\tan(\beta-\phi)\cos\alpha} + \frac{\tan\beta}{\tan(\beta-\phi)}(d + x\tan\square\tan\square)$$

$$+ K_0\, X \tan \square\, (\tan \square \sin \square - \tan \square) - K_A d) \quad \ldots\ldots (5)$$

For Soil well below ground surface:

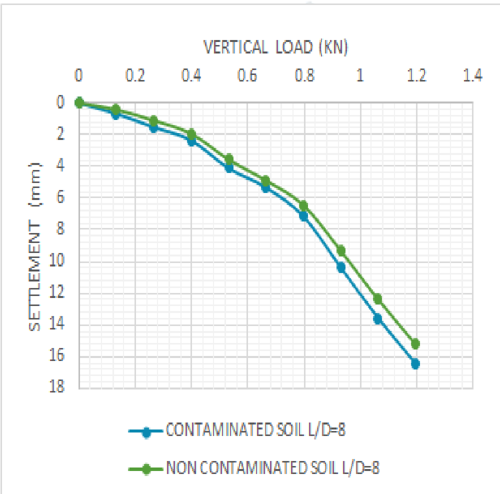
$$P_{sd} = K_A\, d\, \square\, x\, (\tan^8 \square - 1) + K \quad d\, \square\, x \tan \square \tan^4 \square \quad \ldots\ldots\ldots (6)$$

Where, $\square = \frac{\phi}{2}$, $\square = 45° + \frac{}{2}$, $K_O = 0.4$, $K_A = \tan^2(45° - \frac{\phi}{2})$ and
$\square$ = *effective* unit weight of soil

5. Results and Discussions

Load vs vertical Displacement

Vertical displacement of the pile having L/d ratio 8 and 10 is shown in figure 4 and 5.
The vertical load tests indicate greater load carrying capacity for non-contaminated soil for boththe piles. Additionally, with increase in L/d ratio subsequent increase in load carrying capacity is observed. Experimentally, failure load is calculated by plotting two tangent lines along the initial and latter portion of the load displacement curves. Although non-contaminated soil has greater load carrying capacity, the difference in the value is less.



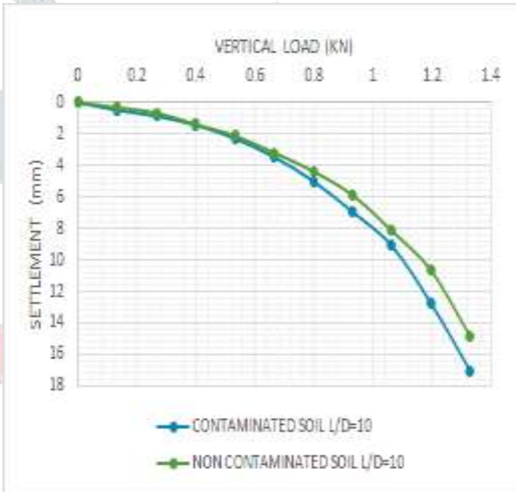
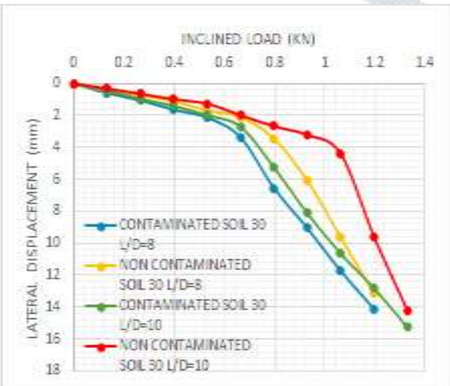


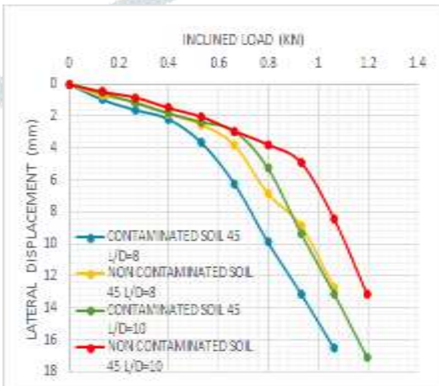
Figure 4: load vs settlement curve for L/D=8 **Figure 5:** load vs settlement curve for L/D=10

Effect of angle of load inclination and L/D ratio

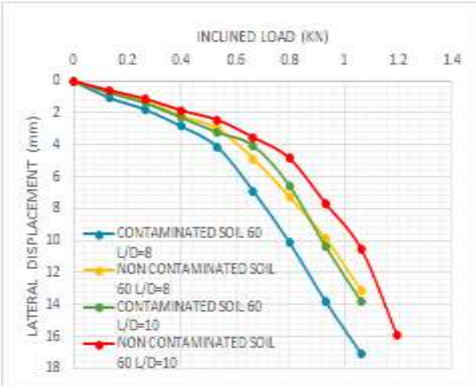
Of the two components of inclined load, the lateral component is the governing load for the model tests conducted at 30°, 45° and 60° angle of inclination from the vertical axis. Also, fromthe figure no. 7, we can clearly deduce the increase in bearing capacity with increase in L/d ratio.However, from figure no.6, an increase in angle of load inclination from 30° to 60°, decrease inultimate lateral load carrying capacity is observed.



(a) 30° load inclination

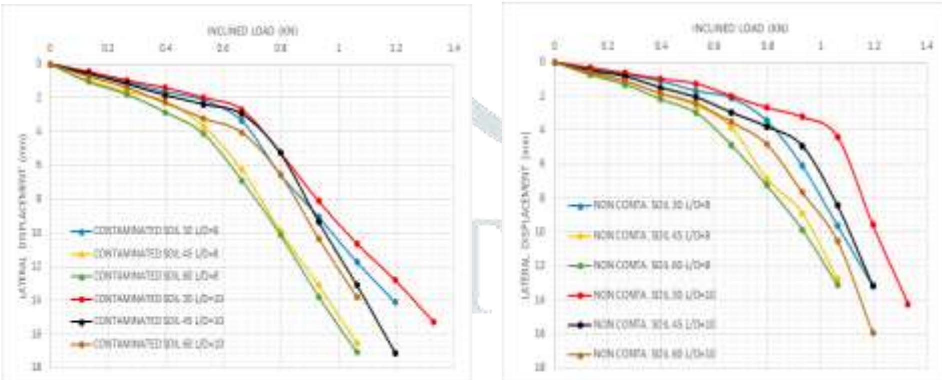


(b) 45° load inclination



(c) 60° load inclination

Figure 6: inclined load vs lateral displacement for 30°, 45° & 60° load inclination



(a) For L/D = 8 & 10 contaminated soil (b) For L/D = 8 & 10 non-contaminated soil

Figure 7: inclined load vs lateral displacement for L/D = 8 & 10

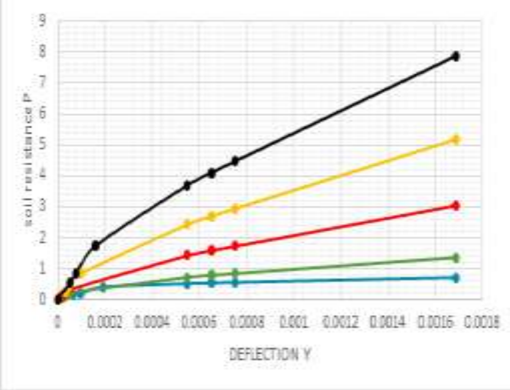
For the lateral carrying capacity, passive resistance offered by the soil plays a considerable rolein determining the effect of soil on the pile. Horizontal modulus of subgrade reaction is dependent on many factors such as the behaviour of pile-soil and size of pile. Since the length of the pile is greater for L/d ratio 10, more surface area is available for soil to resist the movementof the pile. This increase in mobilization of passive resistance is responsible for the increase in ultimate load carrying capacity of the pile. Furthermore, horizontal modulus of subgrade reactionfor contaminated soil differs from non-contaminated soil. From the experimental results of model tests and soil tests, it is evident that the resistance offered by non-contaminated soil is greater compared to contaminated soil.

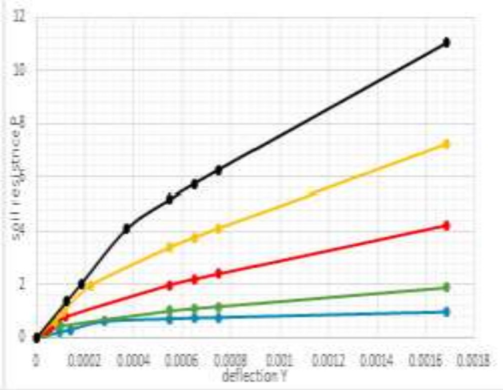
Effect of chemicals on index and engineering properties of soil

The index & engineering properties of the contaminated and non-contaminated soil are determined as per the Indian standard code. Specific gravity of soil is an important characteristicin determining how much heavier or lighter soil particles are compared to waters at 25° C. A shown is table 1 specific gravity of soil clearly decreases in presence of contaminants. Moreover,angle of internal friction is also found to decrease, which directly affects the behaviour of pile asseen in the experimental results. This is mainly caused due to seepage of contaminated water inthe pore spaces of sand and by assuming the formation of hydrate sulphates in presence of excesswater. Hydrate sulphate undermines the bonds between the soil particles, thus decreasing the soilstrength. Other engineering properties are also affected in similar ways.

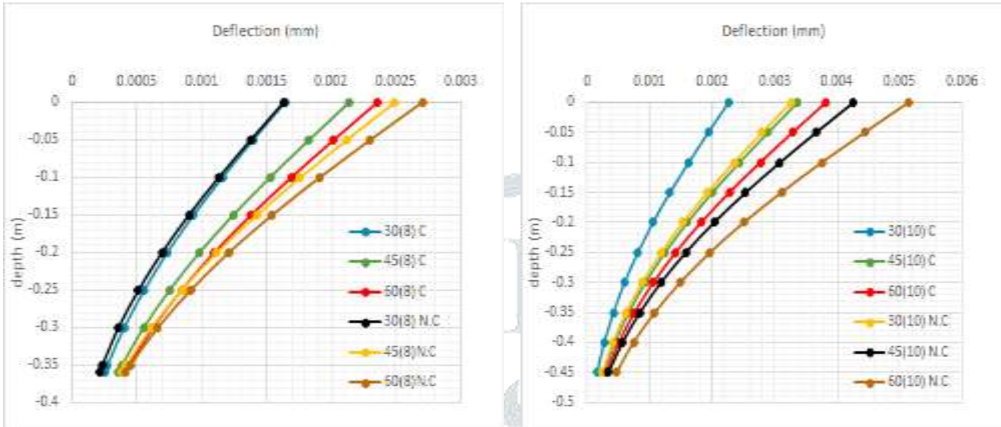
Analysis of soil pile interaction using P-Y curve

Using P-Y curves, deflection is determined along the depth of the pile. Figure 8 shows the deflection pattern observed along the end of the pile theoretically. Deflection is determined using the ultimate lateral load carrying capacity of the pile and the P-Y curve constructed for both the soil which are shown in figure no. 8. Since the ultimate lateral load carrying capacity of both contaminated and non-contaminated soil is different under the similar loading conditions, observed deflection also varies significantly. Though pile resisting in non-contaminated soil shows more deflection as shown in figure 8, the value of ultimate lateral load for which deflectionis determined is also significantly larger. Additionally, the deflection pattern of the pile along the depth for both contaminated and non-contaminated soil reveals the behaviour of the pile is intermediate.





(Fig. 8a) P-Y curve for contaminated soil **(fig.8b)** P-Y curve for non-contaminated soil



(a) For L/D = 8 (b) For L/D = 10

Figure 9: Deflection pattern of pile calculated using P-Y curve

Comparison of experimental results with theoretical results of ultimate load carrying capacityof pile

From table 5 and 6 we can ascertain that the experimental value of ultimate inclined load carrying capacity is validated with the theoretical value of ultimate inclined load carrying capacity calculated using Meyerhof interaction equation without any significant discrepancies in values. As shown in table, for the pile subjected to inclined loading at 60 degrees of L/d ratio 10 the theoretical value is overestimated by 4.75%, which isn't a considerable deviation. Also, with subsequent increase in angle of inclination, reduction in the ultimate bearing capacity of the pileis observed. Maximum ultimate bearing capacity of 1.04 KN is observed for a pile of L/d ratio 10 subject to axial load resting in non-contaminated soil. Maximum deviation of 40% is observedbetween the values of contaminated and non-contaminated soil subjected to similar loading conditions.

Table 5. Theoretical and experimental ultimate bearing capacity value of pile inContaminated soil

Degree of loading	L/D ratio	Theoretical value (KN)	Experimental value(KN)
0	8	0.582	0.67
0	10	0.746	0.885
30	8	0.532	0.61
30	10	0.728	0.75
45	8	0.493	0.52
45	10	0.711	0.73
60	8	0.461	0.45
60	10	0.695	0.68

Table 6. Theoretical and experimental ultimate bearing capacity value of pile inNon-contaminated soil

Degree of loading	L/D ratio	Theoretical value (KN)	Experimental value(KN)
0	8	0.746	0.81
0	10	0.964	1.04
30	8	0.670	0.70
30	10	0.925	1.05
45	8	0.613	0.65
45	10	0.891	0.93
60	8	0.568	0.58
60	10	0.859	0.82

From the above table 7 and 8, it becomes apparent that the experimental value of deflection fromthe model test is comparable to the theoretical value of deflection determined from the P-Y curve without significant variation. For design purposes, values of moments along the pile depthare also determined using the P-Y curve. Maximum moment and deflection of 0.1361 KN.m and5.8mm are obtained for piles of L/d ratio 10 subjected to 60 degree load inclination resting in non-contaminated soil. Difference of maximum deflection and moment in contaminated and non-contaminated soil is approximately 20% and 25% respectively. Moreover, 12% difference in value is observed between theoretical and experimental values deflection.

Table 7. Theoretical and experimental value of displacement of pile inContaminated soil

Degree of loading	L/D ratio	Theoretical value of Displacement from P-Y Curve (mm)	Experimental value of lateral displacement from inclined load test (mm)	Theoretical value of max. moment from P-Y curve (KN·m)
30	8	1.64	2.2	0.0511
30	10	2.26	2.7	0.06486
45	8	2.13	2.6	0.06279
45	10	3.4	3.5	0.09292
60	8	2.35	3.1	0.06746
60	10	3.82	3.8	0.1054

Table 8. Theoretical and experimental value of displacement of pile innon-contaminated soil

Degree of loading	L/D ratio	Theoretical value of Displacement from P-Y Curve (mm)	Experimental value of displacement from inclined load test (mm)	Theoretical value of max. moment from P-Y curve (KN·m)
30	8	1.63	2.1	0.05674
30	10	3.26	3.8	0.09205
45	8	2.49	2.9	0.0772
45	10	4.26	4.9	0.1176

60	8	2.70	3.2	0.08413
60	10	5.14	5.8	0.1361

6. Conclusion

- Overall, there is decrease observed in strength parameter and density of contaminated soil by 12% and 5% respectively. In terms of ultimate load carrying capacity of pile, maximum difference of 40% was observed between contaminated and non-contaminated soil subjected to similar loading conditions.
- With increase in L/d ratio, a subsequent linear increase in observed in both vertical and inclined load carrying capacity of pile. Furthermore, maximum value of deflection and moment calculated from py curve for contaminated and non-contaminated soil is (3.82 mm and 5.14 mm) and (0.1054 KN.m and 0.1316 KN.m) respectively.
- Experimental value of ultimate load carrying capacity of pile subjected to inclined loading is comparable with the theoretical values determined using Meyerhof's interaction equation.
- Also, the P-Y curve generated was successful in ascertaining the deflection observed in inclined model tests. Since the solution of P-Y curves rests on the assumption that governing load is lateral load and there is no effect of vertical component of load on lateral deflection, thedeflection values estimated are not completely accurate. Approximate difference of 12% is observed in experimental and theoretical values determined using the P-Y curve.

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