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The Numerical Investigation of Single Pile Interaction under Lateral Loading in M-Sand using Abaqus

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Abstract

This paper discusses the behaviour of single aluminium pile embedded in M-Sand under lateral loading by finite element software using Abaqus/CAE 6.14. This study was carried out for the different pile embedment lengths based on length to diameter ratios (L/d) 23,28,33. This study includes the effect of embedded pile length on lateral deflection of pile, lateral load capacity of pile ,horizontal modulus of subgrade reaction of M-Sand due to lateral loading of pile. From the study, It is concluded that the lateral deflection of the pile decreased with the increse of embedded pile length due to the passiveness of M-sand for same lateral loading. The lateral load carrying capacity of the pile was increased with the increse of pile length for same deflection about the half of pile diameter. The horizontal modulus of subgrade reaction was incresed for a minimum strainig of the pile during the lateral loading. This horizontal modulus of subgrade reaction plays a vital role in the design of foundation. It is concluded that for a minimum lateral displacement, the horizontal modulus of subgrade reaction increases the bearing pressure of the soil.

Keywords: *Soil-Pile interaction, Numerical Analysis, Finite element method, Lateral loading of pile, Modulus of subgrade reaction*

1. Introduction

Foundation is one of the parts of the structures which transfers the load from super structure to the hard stratum. Pile foundation is one of the types of a deep foundations. A pile is slender structural member made of steel, concrete or wood. Pile foundations are generally used when the soil below the ground surfsace is very weak, very expansive to support the load transferred from the structure. Pile foundations are use to resist lateral forces in addition to support the vertical loads in many structures like earth retaining structures and tall structures which are subjected to lateral loads such as earthquake loads and wind loads. Piles are also used to resist uplift loads in transmission towers, off-shore platforms. Soil Structure Interaction (SSI) describes the interaction between the soil and a structure built upon it. It is mainly an exchange of contact stress, where by the motion of gound structure system is influenced by the type of ground and the type of structure. The effect of SSI plays a vital role in the design of foundation system.

The lateral load carrying capacity of pile will be high in sand when compared to clay. The lateral displacement of pile in clay soil can be minimized by introducing the sand layer in the clay soil. (Shanwaz Ahemed et al, 2020). The embedded depth of the pile and the resultant direction had significant influence on the lateral deformations. The bending moment of the pile was increased with the increase of vertical load (Dongsheng Xu et al, 2020). The pile bearing capacity subjected to lateral load increases with increase of pile length due to pile shaft resistance and sand stiffness in the effective stress passive wedge zone (Ameer A. Jebur et al, 2017). The vertical load induces an additional bending moment of the pile due to the lateral deformation of the pile. The soil densification effect plays a dominant role in the early horizontal loading while the P-Δ effect is strengthened as the horizontal load increases (Wenjun Lu et al, 2018).

The lateral load carrying cappacity of pile also depnds on ground slope, relative density of soil. The increase in pile-soil relative stiffness increases the lateral resistant against the lateral load and hence the depth of fixity reduces for increase in relative density (K. Muthukkumaran et al, 2015). The behaviour of single pile under uplift loading mainly depends on the embedded length to diameter ratio and the soil properties (Khaled E. Gaaver, 2013). The load-deflection behaviour single pile is nonlinear for independent uplift and lateral load tests, as well as combined loading (K. Madusudaan Reddy et al, 2015).
In this study, the numerical study of single aluminium pile under lateral loading in M-Sand was analysed using Abaqus software for different length to diameter ratios of pile.

2. Material

In this study M-Sand was used as soil material and aluminium was used as a pile material. M-Sand is an artificial sand produced from crushing hard stone into small sand sized angular shaped particles. It does not contain any organic matter and soluble content. The fineness modulus, the specific gravity, the angle of internal friction, void ratio of the M-Sand were determined. The particle size distribution curve of M-Sand was shown in figure 1.

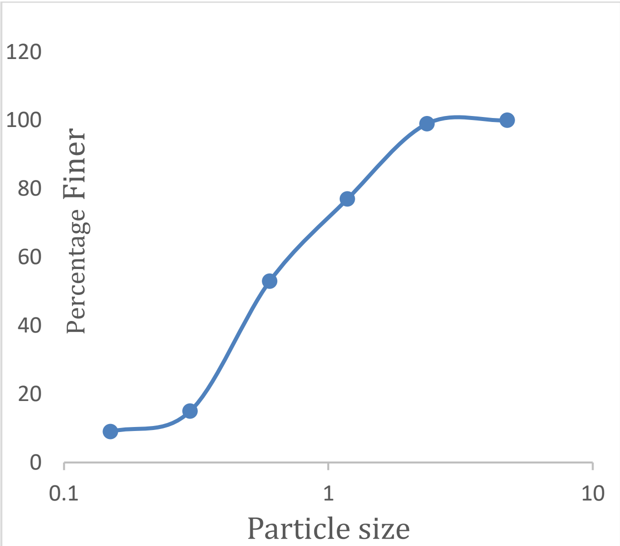

Fig.1. Particle Size Distribution Curve

For a well graded sand the coefficient of uniformity and the coefficient of curvature value should be lies within the value of 2-6 and 1-3 respectively. The M-Sand coefficient of uniformity C¬¬u¬ and the Coefficient of curvature C¬¬¬¬c are 5.26 and 1.08 respectively. The angle of internal friction was determined by direct shear test and the value is 350. The various physical properties of M-Sand were listed in Table-1.

Table 1 Physical Properties of M-Sand

Sl no	Parameters	Value
1	Specific Gravity, G	2.575
2	Fineness Modulus	2.57
3	Effective Diameter, D_{10}	0.175
4	Coefficient of uniformity, C_u	5.26
5	Coefficient of curvature, C_c	1.08
6	Density of M-Sand, ρ kg/m^3	1718.
7	Void ratio, e	0.75
8	Angle of internal friction, ϕ	35°

An aluminium pile of 25.4 mm diameter and uniform thickness of 1 mm is used as a pile material. Three different L/d ratios are used for analysis. L/d ratios of model pile are considered as 23, 28, and 33. The Young's modulus and Poisson's ratio of aluminium pile is assumed as 69000 MPa and 0.33 respectively.

3. Modelling of Soil-Pile System

The soil-pile system was modelled and analysed using Abaqus/CAE 6.14. software. The basic principle of this software is finite element method. The M-Sand model of 1m X 1m X 1m and the aluminium pile of 25.4 mm with a uniform thickness of 1mm were drawn in the part section. The embedded length of the pile for three different L/d ratios are 584.2mm, 711.2 mm, 838.2 mm. The properties of the M-Sand and the pile section were assigned to the model. The soil pile model was assembled in the assembly section in Abaqus software. The solution technique adopted for the analysis was full newton iteration method. The interaction between the soil and pile interface was created using interaction command. There are various types of interaction available in Abaqus software such as Surface to surface contact, Self-contact, Standard Explicit Co-simulation type, Pressure penetration. The surface to surface contact was selected for this analysis. The M-Sand surface was selected as a master surface and the pile outer surface was selected as a slave surface. The friction coefficient between the sand surface and the pile surface was selected as 0.5. The assembly of M-sand-pile model and the interaction of M-sand and the pile were shown in figure 2 and figure 3.

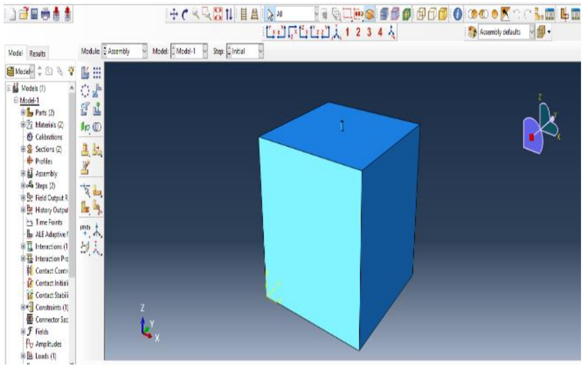

Fig. 2. Assembling of M-sand and Pile Part

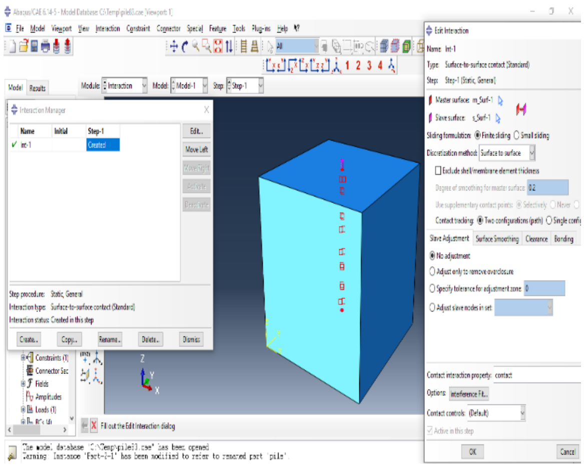

Fig. 3. Interaction of Pile and M-Sand

In this analysis, the pile was subjected to lateral loading. The concentrated force was applied on the top edge of the pile in lateral direction. The boundary condition of the model was created using create boundary condition command. The bottom surface of the sand portion was assigned as fixed support and side and top surfaces of the sand portion were assigned as a hinged support i.e. the displacements and rotations were allowed in the top and side surfaces of the M-Sand part. The loading and boundary condition were shown in figure 4.

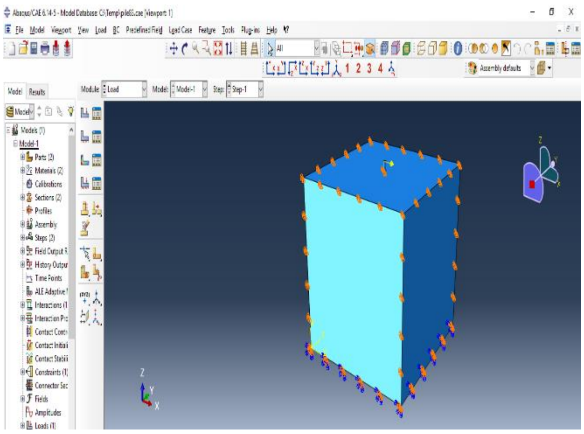

Fig.4. Loading and Boundary Condition

Abaqus/CAE can be using a variety of meshing techniques to mesh models of different topologies. In this analysis, the structured meshing was used to mesh the M-Sand and pile model. The size of the mesh was selected by trial and error method. The mesh size of 40 mm was selected for uniform behaviour. The four node tetrahedrane element was chosen as mesh element. The meshing part of the soil pile system was shown in figure 5. By following the above steps, the various M-Sand and Pile models were developed fordifferent L/d ratios of pile such as 23, 28, and 33.

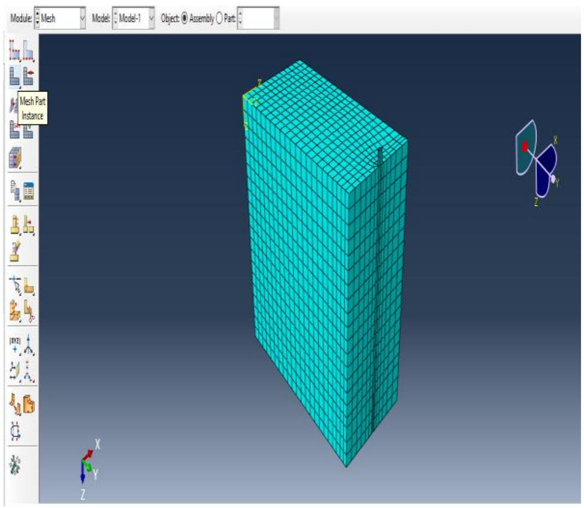

Fig.5. Meshing of pile-M-Sand system

4. Results and Discussions

The soil pile interaction under lateral loading in M-Sand was analysed using Abaqus/CAE for three different L/d ratios of aluminium pile such as 23, 28, and 33. From the lateral loading of piles, corresponding lateral displacements were obtained. The strain, subgrade modulus were calculated from the lateral displacements of piles.

4.1. Lateral Displacements

The initial lateral load of 10 N was applied at the top edge of the pile. The load was increased by 10 N until the lateral displacement of the pile becomes the half of the pile diameter or 20 mm whichever is lesser as per IS 2911: 1985, Part IV. Hence the piles were laterally loaded and the corresponding lateral displacements were obtained. The L/d ratio of 23 pile was loaded until 30 N and the lateral displacement of 13.978 mm was obtained. The L/d ratio of 28 pile was loaded until 50 N and the lateral displacement of 14.362 was obtained. The L/d ratio of 33 pile was loaded until 70 N and the lateral displacement of 12.248 mm was obtained. the lateral load and the corresponding lateral displacements were tabulated in Table 2.

Table 2. Lateral Displacements of piles

Sl no	Lateral Load in N	Lateral Displacement in mm		
		L/d 23	L/d 28	L/d 33
1	0	0	0	0
2	10	3.894	1.358	0.675
3	20	9.543	4.653	2.598
4	30	13.978	7.752	4.897
5	40	-	10.682	6.364
6	50	-	14.362	8.875
7	60	-	-	10.432
8	70	-	-	12.948

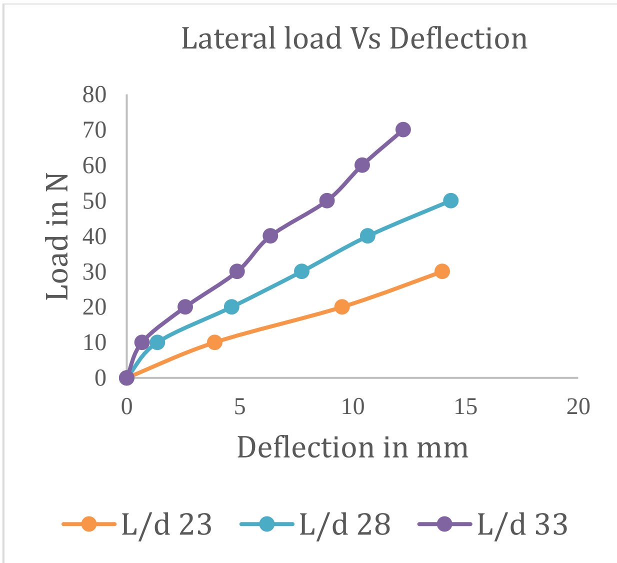

Fig.6. Lateral load and Lateral deflection of piles.

Figure 6 shows the graph of lateral load and displacement. The graph shows that the lateral displacement of the L/d ratio 23 pile was higher than the lateral displacement of the L/d ratio 28 pile and

L/d ratio 33 pile for same lateral loading. It clearly shows that the lateral displacement decreases with the increase of embedded pile length. The lateral load carrying capacity is increased with the increase of pile embedded length. As per IS 2911: 1985, Part IV, the ultimate lateral capacity may be considered corresponding to the specified maximum defection value of 12 mm is reached. The maximum lateral load carrying capacity of different length of the pile was tabulated in Table 3.

Table 3. The Ultimate Load Carrying Capacity of piles

Sl no	L/d ratio	Ultimate Load Carrying Capacity in N
1	23	25.540
2	28	43.582
3	33	68.625

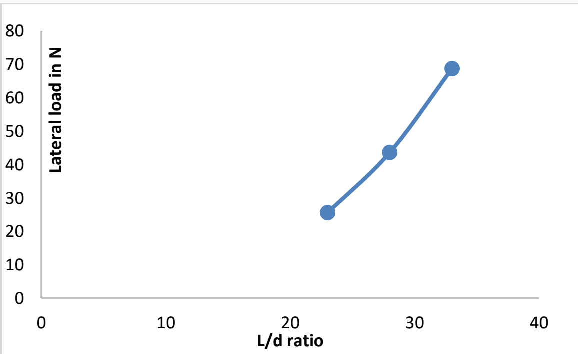

Fig.7. lateral load capacity Vs L/d ratio

Figure 7 shows that the ultimate load carrying capacity increases with the increase of L/d ratio of pile. This could be due to increase of the passive resistance with increase in pile length.

4.2. Modulus of Subgrade Reaction

The subgrade modulus, also known as modulus of subgrade reaction is the stiffness parameter typically used in designing the foundation. The parameter is expressed in units of MN/m^3. Physically, it is defined as the contact bearing pressure of foundation against the soil that will produce a unit deflection of the foundation. The use of parameter implies a linear elastic response, and therefore in design the pressure generated by the subgrade modulus is always limited by the allowable bearing pressure of the soil. The subgrade modulus is mathematically represented as follows:

$K = P_i / Y_i$

Where P_i= Bearing pressure of the soil

Y_i= Deflection of the foundation

By lateral loading of the pile, we can calculate the horizontal subgrade modulus reaction (K_h) which is the function of strain. Kumar S (1993), gives the mathematical expression for the horizontal subgrade modulus reaction as follows:

$K_h / K_{h\,max} = 0.052\gamma^{-0.48}$

Where K_{hmax}= Maximum horizontal subgrade modulus reaction

γ = Lateral Strain=Y_i/1.667d

d= diameter of pile.

For a medium dense sand, the maximum value of horizontal subgrade modulus reaction recommended by Terzaghi lies between 9 MPa/m to 80 MPa/m. For this study the M-Sand is considered as a medium dense sand and the value of K_{hmax}=40 MPa/m was taken. The lateral strain and the corresponding horizontal modulus of subgrade reaction was computed by the above method for different L/d ratios of the piles. The horizontal subgrade modulus forL/d ratiosof the pile 23,28, and 33 were shown in figure 8, figure 9, and figure 10 respectively.

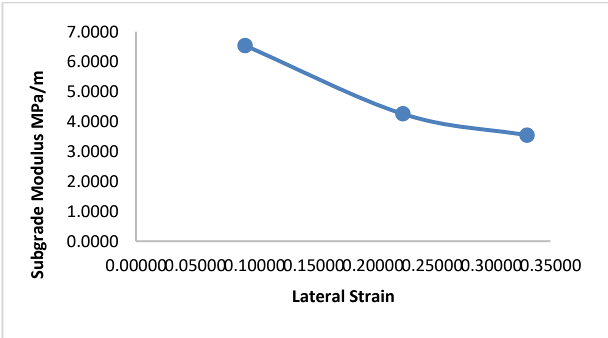

Fig.8.K_h for L/d ratio23 pile

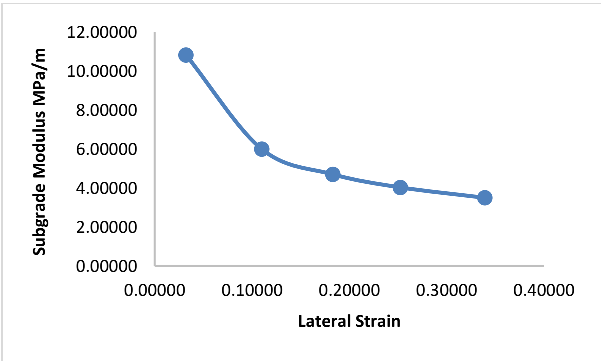

Fig.9.K_h for L/d ratio28 pile

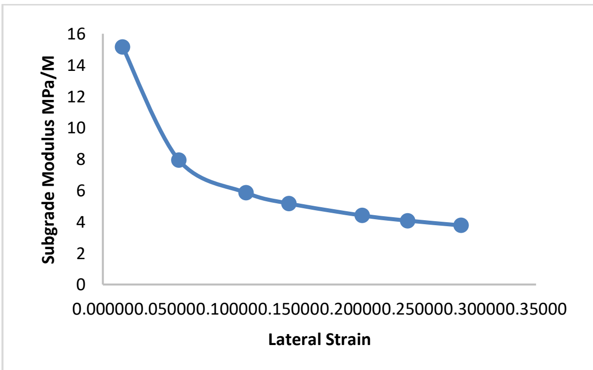

Fig.9.K_h for L/d ratio 33 pile

From the graphs of subgrade modulus, it was observed that the subgrade modulus versus lateral strain curves of all piles becomes nearly asymptotic in nature. The subgrade modulus is higher for the minimum straining of the pile.

Conclusions

The numerical investigation of single aluminium pile embedded in M-Sand soil subjected to lateral loading for different length of the pile was analysed using Abaqus/CAE 6.14. The pile was loaded until the maximum lateral deflection of the pile becomes half of the diameter of the pile. The following conclusions are made from the finite element analysis.

This numerical model is used to predict the behaviour of single pile subjected to lateral loading in sand.

1.The lateral displacement of the pile was decreased with the increase of embedded length of the pile in sand due to its increase in passive resistance. The lateral displacement was decreased to 64.97 % when the L/d ratio of the pile was increased to 23 to 33 for a same loading condition.

2.The lateral loading capacity of pile was increased with the increase of pile length embedded in sand. The lateral loading capacity was increased to 62.78 % when the L/d ratio of the pile was increased to 23 to 33 for a lateral displacement of 12.7 mm i.e. the half of the pile diameter as lateral displacement.

3.The horizontal subgrade modulus reaction was increased with the increasing length of the pile embedded in sand. The horizontal subgrade modulus was not constant below the foundation. The horizontal subgrade modulus of reaction was increased with decrease in lateral strain under lateral loading.

4.The horizontal subgrade modulus reaction is the function of bearing pressure and the deflection of the foundation. By calculating the horizontal subgrade modulus and the lateral deflection we can compute the bearing pressure developed in the sand. It plays a vital role in designing the foundation of structures.

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