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(Research Article)

Simulating the model for consolidation of short bored pile in pure friction soil media

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Abstract

In this paper, the analysis of a numerical study for consolidation analysis of short bored pile subjected to axial loads is presented. An analysis of short-bored pile is performed using finite element analysis software Abaqus CAE with the base of procured experimental data in sand media and a comparative analysis on Ansys FEA. Three models in combination of pile and footing system were developed by the application of incremental axial load for which the displacement upon each load was analyzed taking in consideration the stresses and strains. A parametric study was conducted to study the effect of load on and it's observed displacement on the pile with or without footing. A close correlation is found between the results obtained by the FE models and the Experimental Model solution. The results indicates that the load bearing capacity of pile–footing system increases drastically when both acts together instead of acting individually.

Keywords: Experimental Models; Friction Soils; Mohr-Coulomb; Abaqus CAE; Stress Parameters; Displacement Analysis

1. Introduction

The foundation of High-rise Structures the pile group type foundation has always been dominant in practice. The pile foundation in provision has two parts enlisted as the pile and the raft footing connected to the pile. The underestimation of the contribution of raft footing with pile foundation has led to the many researches that incorporate the capacities of both the entities as a single unit. In context of raft footing provision over the pile the contributions can be seen as serving the design philosophy with capacity distribution as a single unit and secondly it also adheres to the serviceability requirements of structure. In both above mentioned cases raft also contributes in the safety, serviceability, design philosophy and economy of the structure. The pile and raft footing system is called as combined pile-raft foundation (CPRF) and has led to dramatic changes in the load carrying capacities of the foundation.

In recent past, many researchers have advocated the use of pile foundation with raft footing and its application [1-7]. On the other hand, many researchers have supported the fact that with high flexural rigidity of the raft in bearing capacity approach the differential settlement does not possess any issue with its application [8-12]. On another side it is a flaw that neither of them has put forth any simplified design methodology considering safety and serviceability with differential settlement in design philosophy.

In present study an expressive development is made to estimate Serviceability and Bearing Capacity of CPRF in dense Sand Soil Media by Finite Element Approach. The proposed estimate of CPRF by finite element approach is found to coincide with the experimental results with a slight difference of ±5-unit values. Therefore, a mathematical model of simple equation taking in consideration the safety, serviceability and economy, to predict the load sharing capacity is developed and is found to be applicable to the real-time individual system entities.

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2. Idealisation of load-bearing mechanism of CPRF

The load carrying capacity of CPRF can be expressed in terms of pile capacity and unpiled raft capacity multiplied with their interaction factors.

$$Q_{CPRF} = \alpha_{pr}\alpha_{pp}\sum Q_{Singke\ pile} + \alpha_{rp}Q_{unpiled\ raft} \text{(Eq. 1)}$$

Here,

Q_{CPRF}, $Q_{single\ pile}$ and $Q_{unpiled\ raft}$ are the load-bearing capacity of the CPRF, single pile and unpiled raft foundation respectively. α_{pr}, α_{pp} and α_{rp} are pile-raft, pile-pile and raft-pile interaction factors respectively.

This factor provides the load bearing capacity of CPRF through the compatibility equation Eq. 1.

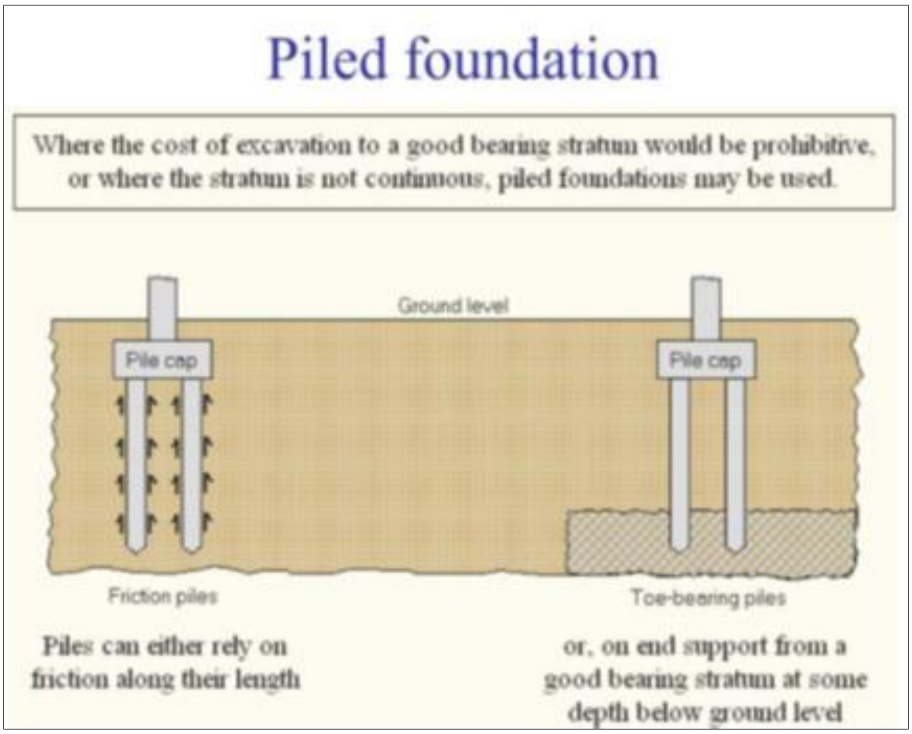

Figure 1 Load carrying capacity of the pile foundation in soil media

At development stage these CPRF parameters are available which makes the numerical analysis of the model in Finite Element Analysis easy.

3. Numerical simulation

The Finite element analysis was carried out by developing an axis-symmetric 2-D model in ABAQUS FEA (13) with the same material entities as that of ANSYS FEA model picked up from the Model made out of Experimental base.

In all the three procedures Mohr-Coulomb Model with perfect elastic contact between pile and soil media is adapted to analyse the model interaction with the soil media. Several researchers have developed and studied this type of model in various formats and in various FEA software, to simulate the behaviour of soil media and the effect of contribution of raft footing in the model (7, 14-17, 26).

In developing the FEA model the discretization of mesh was developed using the structured mesh library function of Abaqus FEA. The Pile and Raft footing were developed as individual solid models and assembled as to interact in smooth function.

The boundary conditions were developed as to replicate the tank edges as that in experimental model and were developed keeping in view the effective zone of reaction of the soil media after application of load on the pile foundation.

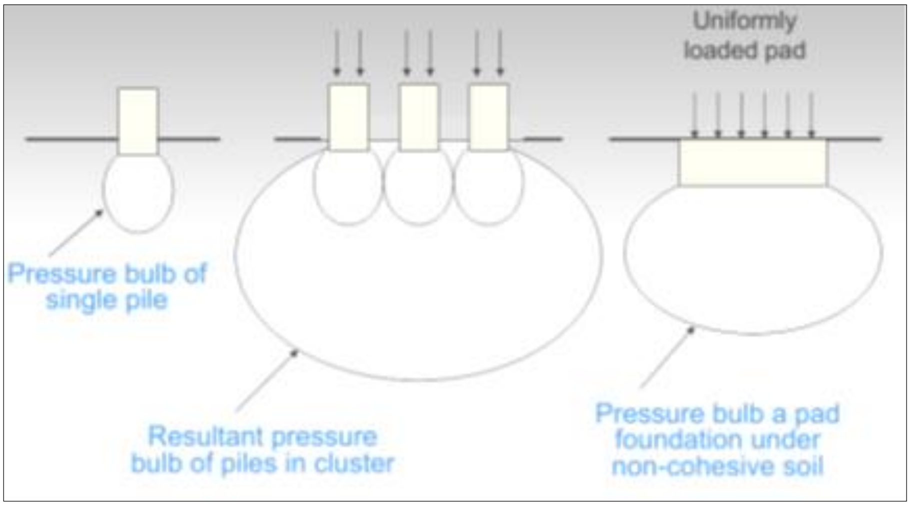

Figure 2 Effective stress zone of pile foundation

The rigidity of the pile and raft was maintained by fixing the thickness in a structured ratio (18). The elastic modulus of sand (19) lies in the range of 25,000-50,000 KPa to validate the hyperbolic load-deformation relationship reported by (21).

In addition, to the above negligible influence of Poisson's ratio on load-deformation characteristics of the foundation systems was observed.

4. Theoretical validation of the developed model

Static Formulae for Estimating the Load Capacity of Piles:

The Static resistance offered by the soil or rock at the base of pile and along its surface to the load applied on the pile is calculated through Static Formula.

The basic Principle involved in unit point-bearing resistance of a pile is given by

$$\boxed{f_p = cN_c + \sigma' N_q + 0.5\gamma B N_\gamma} \text{(Eq. 2)}$$

Here, c is the unit cohesion of the soil at the pile tip, σ' is effective overburden pressure at the base of pile, γ is the density of the soil at pile tip, B is width/ diameter of pile and N_c, N_q, and $N_\gamma$are the bearing capacity factors.

For deep foundations Eq. 2 is modified as,

$$\boxed{fp = cNc + \sigma' Nq} \text{(Eq. 3)}$$

For calculating the total bearing resistance of pile is given as

$$\boxed{Qp = f_p A_p} \text{(Eq. 4)}$$

And total skin friction resistance is given by

$$\boxed{Q_s = f_s A_s} \text{(Eq. 5)}$$

The ultimate load bearing capacity of the pile is calculated as

$$\boxed{Q_u = f_p A_p + f_s A_s} \text{(Eq. 6)}$$

Piles in Sands:For pure phi soils

$$\boxed{Q_u = \sigma' N_q + f_s A_s} \text{(Eq. 7)}$$

It is further noted that the point load bearing capacity of pile in granular soils increases proportionally with the length of the pile embedded in the soil but until the critical length of the embedment of pile, after which there is no reasonable increase in the load bearing capacity of the pile. This is the result of arching action which is visible only in granular soils.

The unit skin friction resistance is given by

$$\boxed{f_s = \sigma_h \tan \delta - K\bar{\sigma} \tan\delta} \text{(Eq. 8)}$$

Here, σ_h is the average horizontal pressure over the pile length which is acting normal to the pile surface, K is the lateral earth pressure coefficient, and δ is the angle of friction between the pile and the soil.The total skin friction resistance is given by

$$\boxed{Q_s = f_s A_s} \text{(Eq. 9)}$$

As per Indian StandardsIS– 2911 (Part I), δ = ϕ and the value of K lies in between 1 to 3 from loose- to medium-dense sand.

4.1. Piles in Clay

Load of piles in clay/ cohesive soils are mostly carried by skin friction resistance of the pile shaft. For clay soils as friction angle is taken as zero for undrained conditions. Hence, the load carrying capacity becomes a function of reduction factor α which depends on the undrained shear strength of the soil. For soft clays the value of α is nearly 1 and may decrease to nearly 0.3 with the increase in the stiffness of clay. To avoid any loss of strength in clay due to sensitivity by remoulding or by thixotropy a minimum difference of 30 days is provided between driving the pile and loading of pile. This becomes the reason for providing pile load test data for calculation of load carrying capacity by Static Formulas.

5. Codal formulas as per is codes

5.1. Static Formula as per IS Code for Piles in Sand

$$Q_U = A_P(1/2\gamma' d N_\gamma + \sigma' K_p N_q) + \sum_{i=1}^{n} K\sigma_{si} \tan\delta A_{si} \quad \text{(Eq.10)}$$

Here, A_p is the cross-sectional area of pile at the bottom, d is the diameter of the shaft of pile, γ' is the effective unit weight of soil at pile tip, $\sigma'_p$is the effective stress at the pile tip, K is the coefficient of earth pressure, σ'_{si} is the average effective stress for the soil layer, A_{si} is the surface area of pile for the i^{th} soil layer, $N_\gamma$is the bearing capacity factor for general shearand $N_q$is the bearing capacity factor depending on the method of installation of pile and the angle of internal friction as per IS code 6403-1981.

5.2. Static Formula as per IS Code for Piles in Clay:

As per Indian Standard Code IS – 2911 (Part I)-1979, the ultimate load capacity of a pile in cohesive soil, i.e., is calculated by the following equation

$$Q_u = cN_cA_p + \alpha\bar{c}A_s \text{(Eq. 11)}$$

Here, c is the cohesion at the pile tip, N_c the bearing capacity factor, A_p is the cross- sectional area of pile tip, α is the adhesion factor/ reduction factor also called as the shear mobilization factor, $\bar{c}$ is the average cohesion over the pile length, and A_s is the surface area of pile shaft.

Dynamic Formulae for Estimating the Load Capacity of Piles:

Dynamic formulas are based on the laws governing impact of elastic bodies. The input energy of hammer blow is equated with work done in overcoming the resistance of ground to the penetration of the pile. Here, allowance is considered for lossof energy due to elastic contractions of the pile or pile cap, subsoil and losses due to the inertia of pile.

$$W_h = Q_u S \text{(Eq. 12)}$$

Here, W is the weight of the hammer, h is the height of fall of the hammer, Q_u is the ultimate load capacity of pile and S is the pile penetration recorded per blow.

5.3. Types of Dynamic Formula

- Engineering News formula.
- Hiley's formula.
- Danish formula.

For estimating the load carrying capacity of piles, Engineering News formula is considered as the simplest and most popular dynamic formula.

Hiley's formula has been developed later to overcome the limitations that were found in the Engineering News formula.

Table 1 Some currently used dynamic formulas

Method	**Equation, Ru**
ENR, 1893	Eh/(S+C)
Modified ENR, 1965	1.25ehEh(wr+n2Wp)/((S+C) *(wr+wp))
Eytelwein, 1961	EhWh/(S*(Wh+Wp))
Gates, 1957	a(ehEh)1/2 (b-logS)
Janbu, 1967	ehEh/kuS
Hiley, 1961	ehEh(wr+n2Wp)/((S+0.5(C1+C2+C3))*(wr+wp))

Here, $E_h$is hammer energy, S is pile's set per blow, e_h is hammer efficiency, W_r is weight of hammer ram, W_p is weight of pile, n is coefficient of restitution, A is area of cross section of pile, L is length of pile, E is modulus of elasticity.

6. Model parameters

The finite element software ABAQUS CAE is used in the analysis to find the consolidation of single pile using 2-D system of model. For better simulation of the consolidation analysis and elimination of boundary effect, MOHR-COULOMB model is used. The foundation material used is pure friction soil with specific parameters described in table 1.

Table 2 Soil Parameters Used

Dimensions of the Experiment Pit Used	**L (m)**	1.2
	B (m)	0.75
	H (m)	1.35
Dry Unit Weight (KN/m^3)		1500
Friction Angle (deg)		37
Cohesive Force (KPa)		0.0001

Table 3 Material Parameters used for Pile Prototype

Diameter of Bars Used in Analysis (mm)	10
	18
	22
	25
Unit Weight (KN/m^3)	25
Modulus of Elasticity(Kg/m2)	200000
Poisson's Ratio	0.33

The Footing disc used upon the Mild Steel Pile prototype has the following parameters as shown in Table 3.

Table 4 Material Parameters used for Footing over Pile Model

Diameter of Footing Used (mm)	**150**
Thickness of Footing Disk (mm)	10
Unit Weight (KN/m^3)	25
Modulus of Elasticity(Kg/m2)	200000
Poisson's Ratio	0.33

Table 5 Relation between Length of Pile and Diameter of Pile

Diameter of pile (mm)	L/D Ratio	Length of pile (mm)
10	10	100
	15	150
	20	200
	25	250
18	5	90
	10	180
	15	270
	20	360
	25	450
22	5	110
	10	220
	15	330
	20	440
	25	550
25	5	125
	10	250
	15	375
	20	500
	25	625

In this paper, the failure mode for large diameter piles is studied in model form with experimental validation of the data on the base of which the data in the finite element software is analyzed. In the calculation of the vertical ultimate bearing capacity of single pile foundation, the plain strain condition is taken into consideration, with elastic parameters being valid throughout the simulation. The model is used for the simulation of pile foundation structure have the parameters as shown in Table 2.

The assembly of the system being tested is as shown in the figure 2. The figure is developed for various diameter of pile as mentioned in table 2. The co-relation of the pile diameter and length of pile is shown in table 4.

7. Analysis methodology

The 2-D Finite Element Model Analysis using ABAQUS has the capability of taking the initial stresses in the soil mass into account.

After declaring the material properties of the parts of the developed section assumption is made as Solid, Homogenous, Linear and Elastic Material Sections.

The Pile with respective Length/ Diameter Ratio is modeled with Equation type analysis Constraint with Steady- State Dynamic, Direct Analysis for Contact type interaction between surfaces of pile and soil media.

The actual condition of tank type are formed by applying Boundary Conditions on Base, Right Side and Left Side as restrained in both lateral and axial direction for zero displacement of the soil element, ensuring block of soil as required.

Declaration of JOB is made for complete analysis for failure, displacement and stresses calculation.

8. Pile-soil responses

8.1. Estimation of Only Pile Model in Abaqus FEA

The only Pile Model is a simple shaft with friction loading conditions. It is observed from the analysis that the response of pile to loading in soil media resembles to the responses of pile as those caused by tunneling or groundwater lowering (refer figure 10), forming an internal bulge in the soil media and stress bulb around the pile lining as that of elastic foundations.

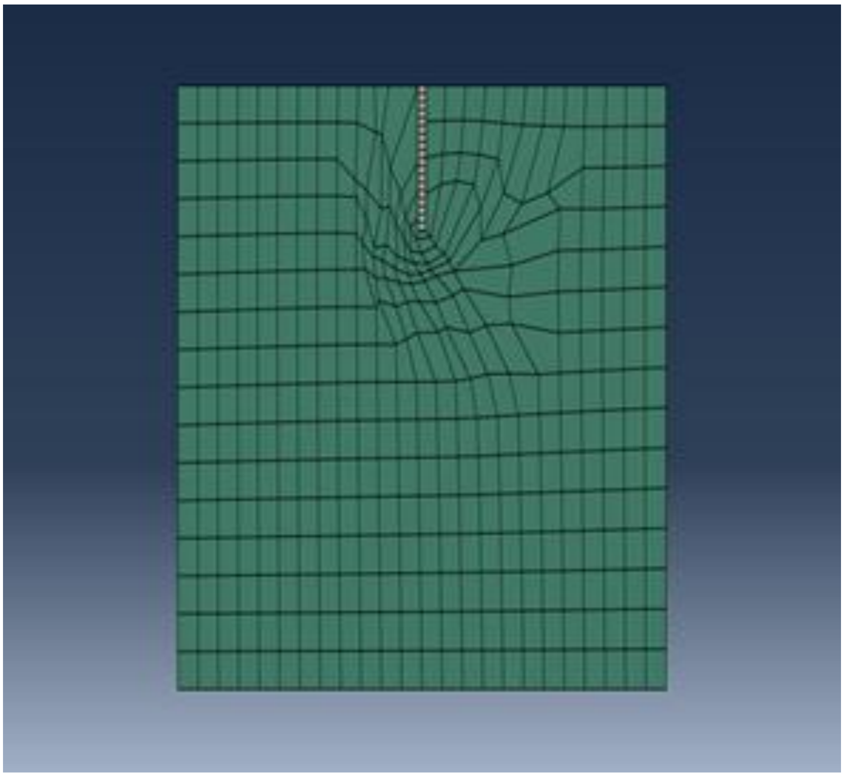

Figure 3 Assembly of Only Pile in Sand Soil Media

It is also seen in this case that the skin friction acting on the boundary of the pile also plays a vital role in the displacement responses formed in by the only pile footing model after the application of load.

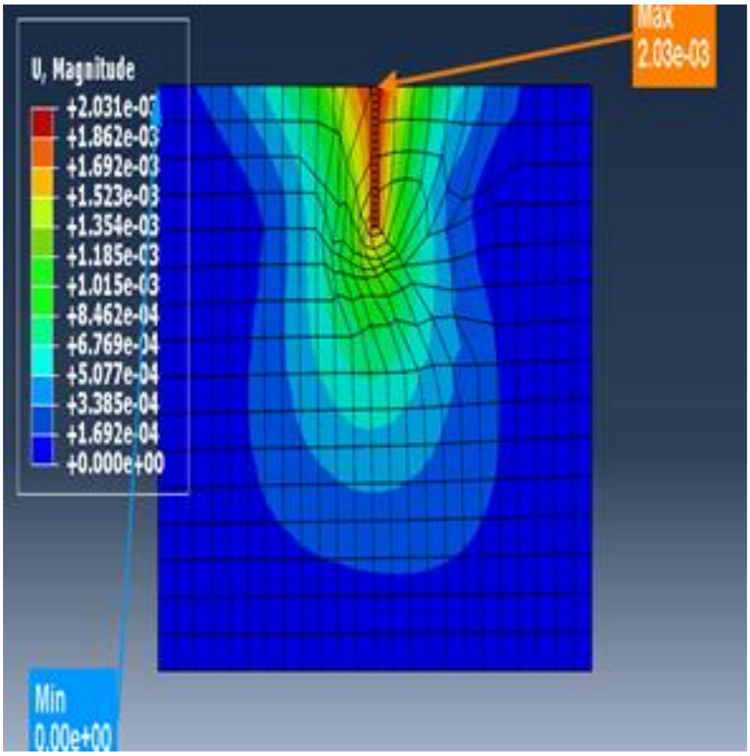

Figure 4 Axial Displacement of Only Pile in Sand Soil Media

8.2. Estimation of Only Footing Model in Abaqus FEA

The analysis of only footing plate is recorded as the vertical sink of the raft, the displacement is restricted by the surface area in contact with the soil media.

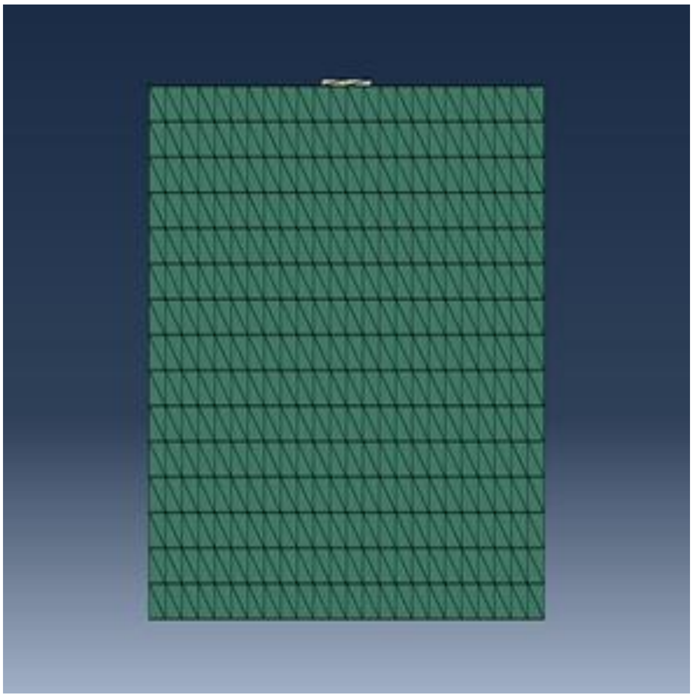

Figure 5 Assembly of Only Raft Footing in Sand Soil Media

The greater the surface area for resisting the load applied lower would be the displacements caused, but higher would be the bending caused in the raft footing (Refer Figure 11).

The surfaces in contact with the soil media reacts to the load applied in the similar manner as that of perfectly friction contact model.

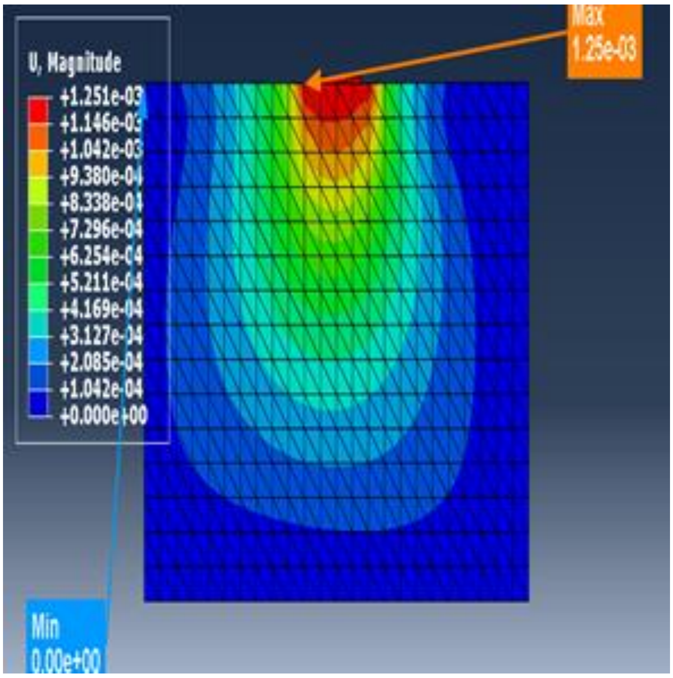

Figure 6 Axial Displacement of Only Footing in Sand Soil Media

8.3. Estimation of Combined Pile and Raft Footing (CPRF) Model in Abaqus FEA

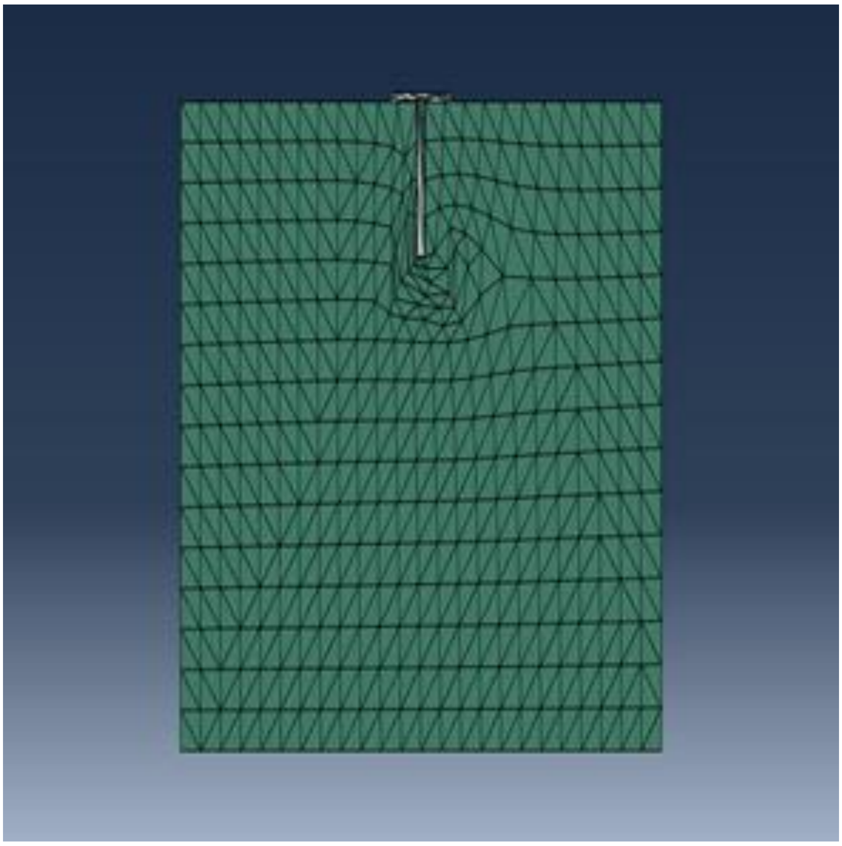

Figure 7 Assembly of Combined Pile and Raft Footing in Sand Soil Media

The displacement pattern observed by CPRF Model is similar to that of combined results formed by only pile model and only footing model with a little distortion in the shape that results due to the addition of only pile and only raft Footing in combined form displacement pattern.

So it can be concluded that the displacement pattern observed in CPRF Model is a combined effect of superimposition of Only Pile and Only Raft Footing (refer Figure 12).

The displacement formed is again in contribution of skin friction on the surfaces of the CPRF model (Refer Figure 13). The pressure bulb resembles exactly to the hypothesis accepted for the bulb formation of elastic foundation.

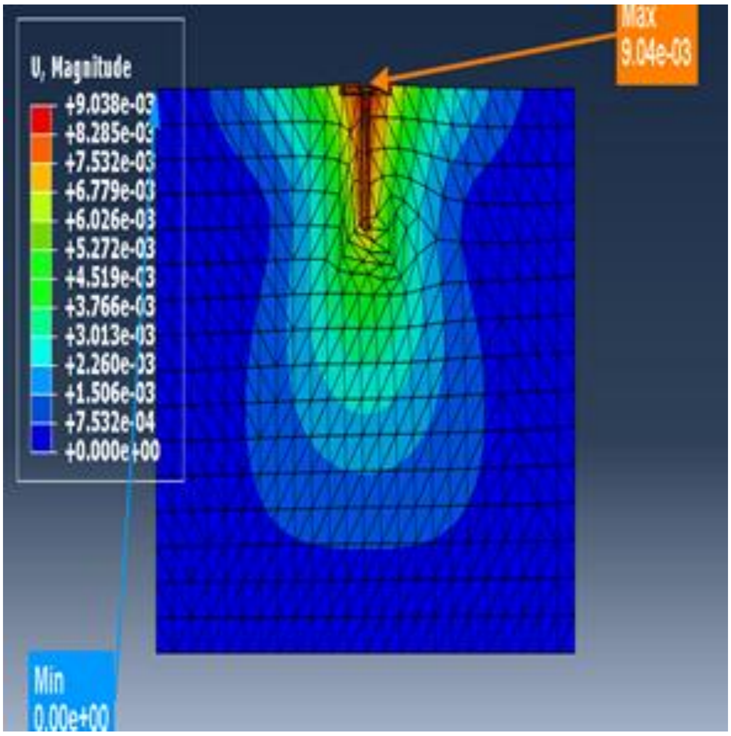

Figure 8 Axial Displacement Combined Pile and Raft Footing in Sand Soil Media

8.4. Comparative Analysis of Combined Pile and Raft Footing (CPRF) Model in Abaqus FEA, Ansys FEA and Experimentally Procured Data

After analyzing all the models and data corresponding to above specified data it was found that the optimum pile dimensions were of 18 mm pile with L/D ratio of 10 for 150 mm diameter footing. Hence a comparative analysis of it is made for all the three conditions.

The settlement caused due to the application of axial load is depicted in following figures each having its own analytical border.

The settlement observed in the experimental model is as observed and penned. It acknowledges our presented hypothesis that the load carrying capacity of the CPRF model is greater than that of Only Pile and Only Raft Footing models. This is due to the established fact that the displacement is related to friction and the surface area of each model in the contact with the soil media.

In practical hypothesis a benchmark of 15 mm settlement is made and termed as maximum allowable value of consolidation. Considering load value corresponding to 15 mm settlement bench mark, refer Figure 9, Only Pile is 230 N on Only Footing is 2600 N, whereas the load observed on the CPRF model is 4250 N. This share of load by CPRF is nearly 30 % more than that of additive loading capacity of Only Pile and Only Footing Model.

The next step of comparative analysis involves further accurate results with graphical representations in ANSYS FEA Software.

Table 6 Experimental Data for Load Settlement Observed in the Optimum Dimension Model

Load Settlement Observations F.D.: 150 mm, P.D.: 18 mm, L/D: 10 and Df/Dp: 8.33						
S. No.	**Settlement in mm**	**Load Pile Alone in N**	**Load Footing Alone in N**	**Load Combined Unit (FWP) in N**	**Load Shared by Pile in FWP in N**	**Load Shared by Footing in FWP in N**
1	0	0	0	0	0	0
2	1	100	320	1600	160	1440
3	2	110	680	2070	190	1880
4	3	120	910	2400	200	2200
5	4	125	1160	2750	220	2530
6	5	130	1410	3050	240	2810
7	6	135	1620	3300	260	3040
8	7	145	1770	3500	275	3225
9	8	150	1940	3700	290	3410
10	9	165	2090	3800	310	3490
11	10	175	2250	3900	340	3560
12	11	185	2350	4000	370	3630
13	12	200	2420	4100	380	3720
14	13	210	2480	4200	400	3800
15	14	220	2550	4250	420	3830
16	15	230	2600	4250	435	3815

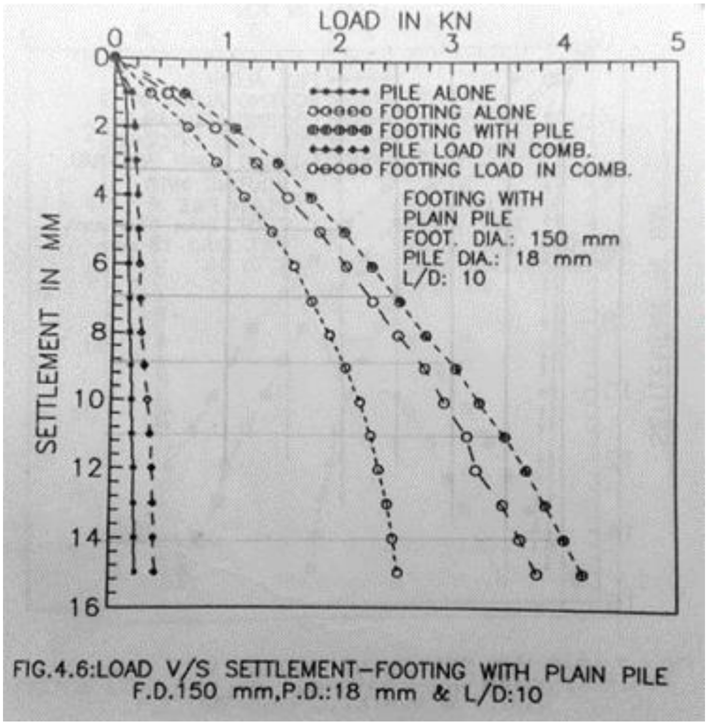

FIG.4.6:LOAD V/S SETTLEMENT–FOOTING WITH PLAIN PILE F.D.150 mm,P.D.:18 mm & L/D:10

Figure 9 Comparative Load Displacement Curve Observed by Model Analysis in ANSYS FEA

In this analysis, Refer Figure 10, values of load corresponding to particular displacement values are recorded. In this observation set it is clearly visible that the load Carrying capacity of Only Pile (Pile Alone) is the least and has a kink of failure at the top most load values. The next observation is made for Only Footing (Footing Alone) which has a comparable high in load bearing capacity in the system with a lowered kink of failure.

In the last, observations are made for CPRF model (Footing with Pile) in which it is again observed that the load bearing capacity curve is highest for system with least displacement values adhering to the elastic curve failure theory of forming a parabolic curve in load-settlement analysis in the elastic region of the system.

9. Results

The calculated results were found to align with the experimentally acquired results and had evolved following graphs in that consideration.

After experimentally testing the values of only pile, only footing and pile and footing together the model Abaqus CAE model and conclusion were drawn as the pressure bulbs observed in all the all cases were graphically similar to that of the elastic foundations for axial loading applied upon each system in this regards it is found that the stresses and strains observed were also comparably high than only pile and only footing models.

The contact surface area of the model increases the frictional resistances which delays the failure load capacity. Also the pressure bulb formed in the pile with footing setup is greater than that of only pile and only footing.

As per the experimental and analytical model it is found to be true that the most optimum pile is of 18 mm diameter with Length by Diameter Ratio of 10, upon which further studies are made. Pile with Footing model is capable of resisting 16% more axial load than that of only pile and only footing models. (Refer table 6).

Table 7 Failure load study

Basic model	Primary model	Failure load difference percentage
Pile with footing	Only pile	16.27%
	Only footing	16.07%

9.1. Graphical Interpretation of CPRF Model by Abaqus FEA

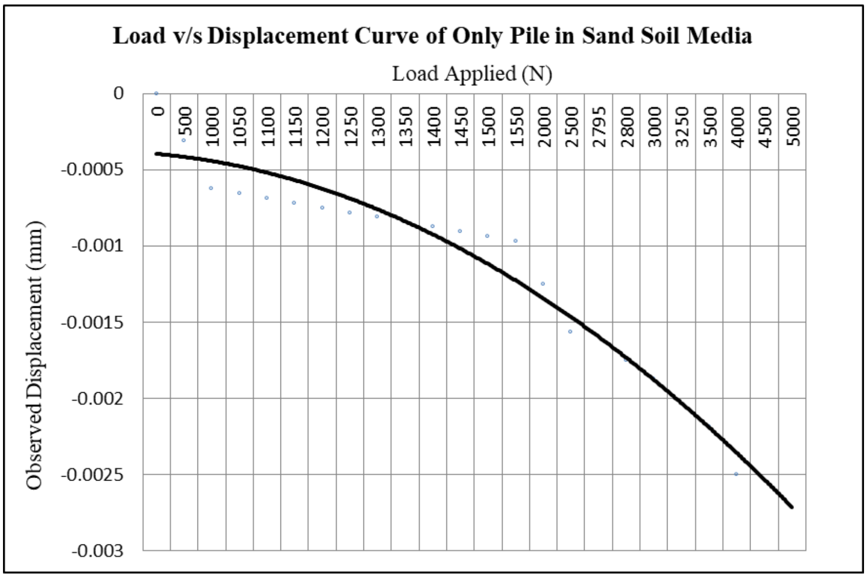

Figure 10 Load v/s Displacement Curve of Only Pile in Sand Soil Media

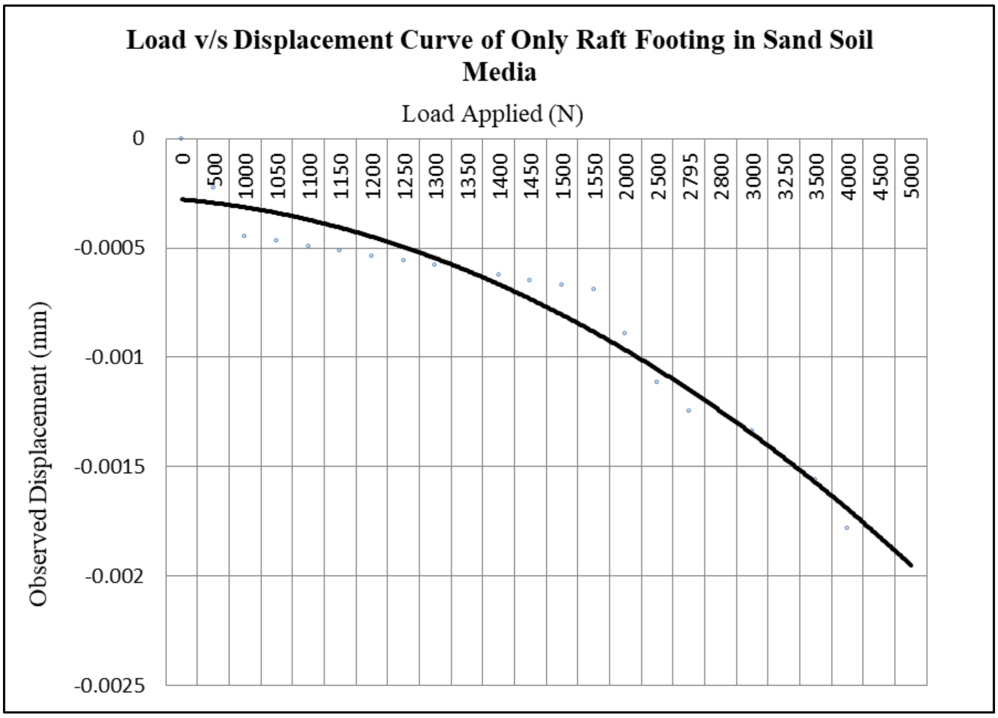

Figure 11 Load v/s Displacement Curve of Only Raft Footing in Sand Soil Media

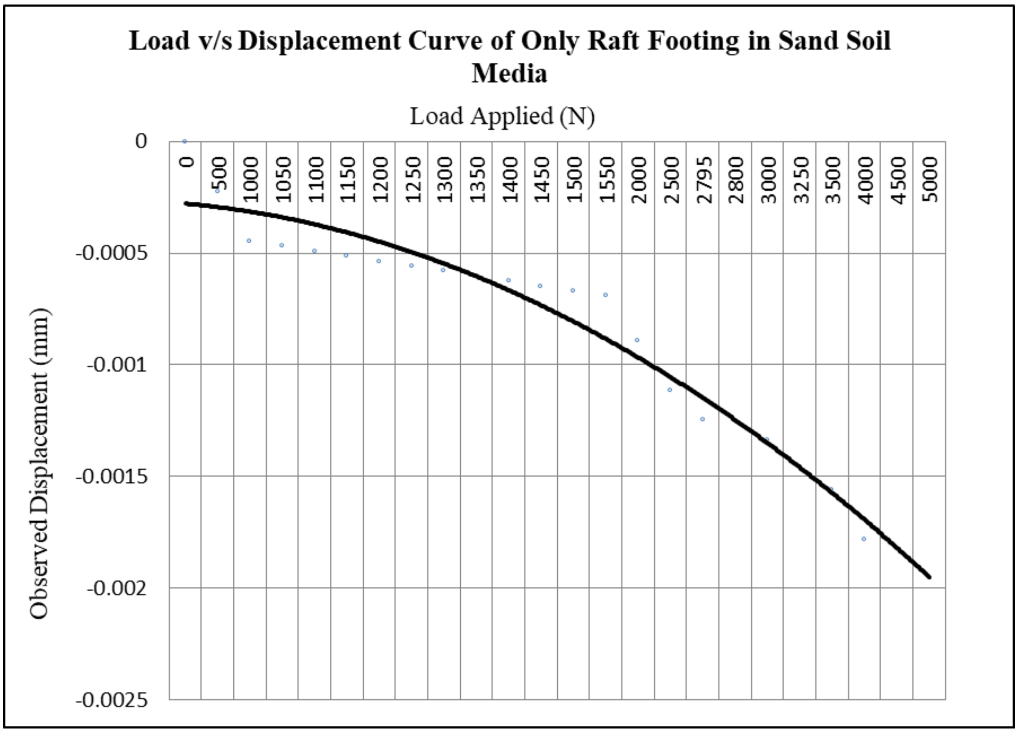

Figure 12 Curve for Load v/s Algerbric Sum of Displacements Only Pile and Only Raft Footing in Sand Soil Media

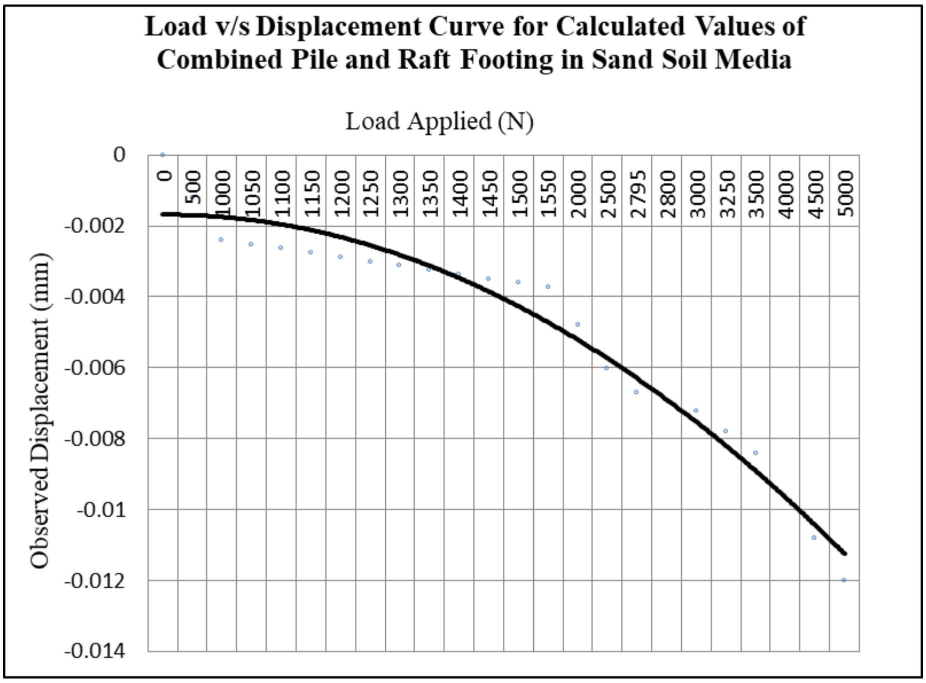

Figure 13 Load v/s Displacement Curve for Calculated Values of Combined Pile and Raft Footing in Sand Soil Media

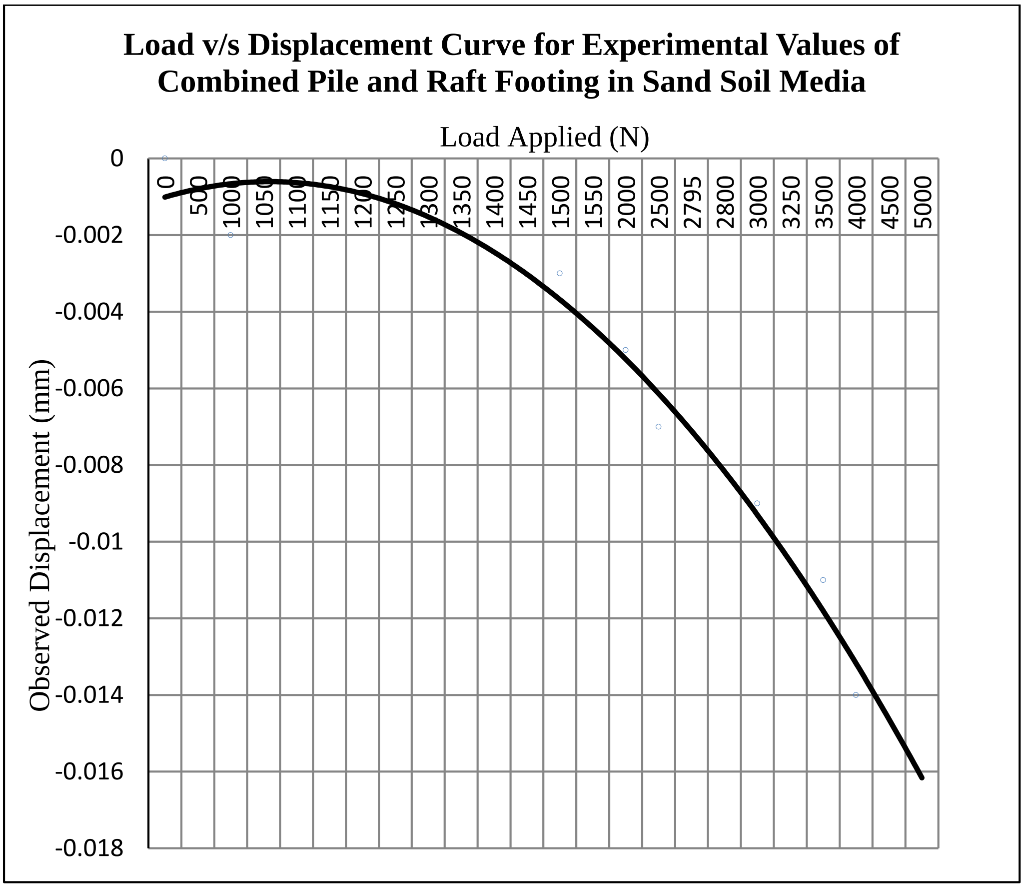

Figure 14 Load v/s Displacement Curve for Experimental Values of Combined Pile and Raft Footing in Sand Soil Media

10. Conclusion

From the study undertaken it can be concluded that the contact surface area of pile affect the load carrying capacity to a greater extend and there exist a optimum contact surface area of the system that makes up the maximum load carrying capacity and has maximum responsive stresses, it can be linked to the yielding capacity of the pile. By observations it is also concluded that the CPRF unit is capable of taking higher load than that of individual units and their assembled model. Hence a combined unit CPRF model is recommended in place of simple pile foundation for higher load carrying capacity and least settlement in structure.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

Meghna Pathak, Ravindra Pathak and Jagdish Narayan Vyas declare that they have no conflict of interest.

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