A Comparative Study of Pile Settlement Analysis Based on Soil Structure Interaction

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Abstract - *Soil is a complex, heterogeneous material, having a strongly nonlinear response under action of external load. Due to this the constitutive laws associated to various soil types (cohesive, non-cohesive, saturated or unsaturated etc.) are continuously developed and improved. Analysis of soil had been and still a very challenging task for engineers throughout the world. This is due to the non-linear behaviour of soil and inability of constitutive relations in predicting exact behaviour of soil. Material models such as Mohr-Coulomb model uses very complex constitutive relationship. Solution of this complex partial differential equation is tedious and time-consuming process; hence Finite Element Method is used to solve these equations. Present study focuses on the settlement analysis of pile foundation in a cohesive soil based on soil structure interaction between pile and soil by using Mohr- Coulomb model. The effects of pile spacing, pile configuration, and pile diameter of the pile group on the response of load is evaluated.*

Key Words: Mohr-Coulomb Model, Finite Element Method, Soil-Structure Interaction, Pile foundation, Friction pile,

1. INTRODUCTION

Structural foundations provide support for the main structures that appear above the soil level. Most civil engineering has structural elements with direct contact with the ground. Deep foundations are usually used when the bearing capacity of the surface soil is not sufficient to carry the loads imposed by a structure. So, the loads have to be transferred to a deeper level where the soil layer has a higher bearing capacity.

Friction pile transfers the load from the structure to the soil by the frictional force between the surface of the pile and the soil surrounding the pile such as stiff clay, sandy soil, etc. Friction can be developed for the entire length of the pile or a definite length of the pile, depending on the strata of the soil. In friction pile, generally, the entire surface of the pile works to transfer the loads from the structure to the soil. In every design of the pile foundation, the settlement analysis of the piles should be evaluated. It is commonly known that the behaviour of a group of piles under axial load is quite different from that of piles acting as a single construct. Piles in the group are additionally subject to the interaction of neighbouring piles resulting in mutual penetration and overlapping in the area of tension around the particular piles that work in the group Józefiak et al. [1] modelled a soil-pile system using FEM implemented in Abaqus software. The numerical results of pile bearing capacity and pile settlement were compared with static load test results of CFA piles. The finite element analysis with simple constitutive models and parameters' estimation shows quite good agreement with the field test settlements for the loading part.

Jalali et al. [2] investigated the pile-soil interaction and its effect on the pile settlement and shear stress in the interaction zone. The impact of loading on the pile displacement was explored applying Mohr-Coulomb as well as Hard-soil behaviour laws. The Static Analysis of PLAXIS revealed that the pile settlement may be measured more accurately for the interface coefficients of (0.7 to 1) with Mohr - Coulomb behaviour law of pile-soil compared to the Hard soil model.

Shaiana et al. [3] investigated on the results of numerical simulation of behaviour of piles as embedded in cohesionless soil under oblique loads are presented by using ABAQUS. This study provides a comparison of common techniques for analysis of single piles subjected to oblique loads in different inclination angle. The stiffness of pile is almost affected on the behaviour of pile subjected to combine vertical and lateral loading (oblique loads). The vertical and horizontal loads level itself strongly depends on the load inclination angle (α). The ultimate vertical pile capacity of the pile is decreased by additional horizontal load.

Johnson et. al [4] used 3D finite element modelling was used to explore the effect of pile shape, sand properties, pile length and loading conditions on the capacity of a pile. Using trends discovered by these simulations design charts were developed to aid consultants when determining the bearing capacity for oblique interaction for square piles. It was found through a carefully planned sensitivity analysis that sand properties and pile shape can influence the capacity of a pile extensively.

1.1 Soil Structure interaction

Structural displacement and ground displacement are interdependent. In the process in which the soil reaction affects the motion of the structure and the motion of the structure affects the soil response is called the Soil Structure Interaction (SSI). Interaction at the surface of the pile soil can result from the perfect contact where there is no relative sliding between the soil and the pile with the perfect sliding conditions, where no friction develops along the shaft of the pile. Initially, it was assumed that both the soil and the pile are deformed bodies and may undergo finite sliding.

SSI is generally neglected in traditional structural design methods. This is appropriate for light weight structures in relative hard soils such as less rigid building and simple rigid retaining walls. For heavy structures resting on soil such as high building cooling tower elevated highway SSI becomes prominent

2. MATERIAL AND MODEL

The finite element modelling and analysis of the problem is achieved using ANSYS software which has wide variety of elements and material models suited for the problem under consideration. ANSYS requires creation of model geometry, selection of appropriate element types, defining real constant sets in terms of cross-sectional details for various elements, defining material properties, assigning these element types, real constants and material properties to various components of the interaction system and finite element mesh discretization in its pre-processing module. Boundary conditions, analysis type and loads are defined in its solution module.

2.1 Mohr-Coulomb model

The Mohr-Coulomb model is the conventional model used to represent shear failure in soils and rocks. For example, report laboratory test results for sand and concrete that match well with the Mohr Coulomb criterion.

It is a perfectly elasto-plastic model of general scope; thus, it has a fixed yield surface. It involves five input parameters, that is, E and ν for soil elasticity, the friction angle ϕ and the cohesion c for soil plasticity, and the angle of dilatancy ψ. It is a good first-order model, reliable to provide us with a trustful first insight into the problem. Mohr-Coulomb model represents a first-order approximation of soil or rock behaviour. It is recommended to use this model for a first analysis of the problem considered. For each layer one estimates a constant average stiffness. Due to this constant stiffness, computations tend to be relatively fast and one obtains a first estimate of deformations.

3. VALIDATION

The validity of the numerical model was verified using ANSYS of the behaviour of a single pile under vertical loading based on the example of Johnson et al., 2006. Solid concrete piles with a diameter 0.5 m and length of 7.32 m considered. The parameters of the pile and soil are shown in Table-1 (Johnson et al., 2006)

Table -1: The parameters of the pile and soil

Material	Youngs modulus (MPa)	Poisson's ratio	Internal friction angle
Pile	30000	0.15	0
Soil 1	19	0.3	35°
Soil 2	52.8	0.4	40.5°

The interaction between the pile and the soil is simulated using a bounded interface between the pile and the soil. This type of interface is capable of describing the frictional interaction between the pile surface and the soil in contact. Several mesh densities and fixed boundary locations were trailed until a converged numerical solution was achieved. Then, this single pile is loaded with vertical load to verify the results accuracy between the present model and (Johnson et al., 2006) model. The comparison between the present FEM results and FEM results obtained by (Johnson et al., 2006) for the pile load-displacement response is shown in chart-1 and chart-2

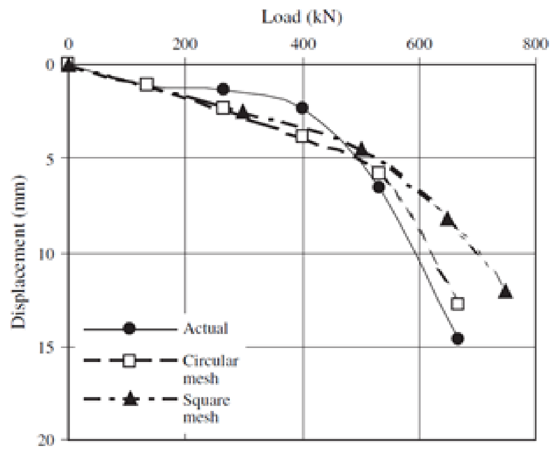


Chart -1: Vertical Load Displacement Graph.

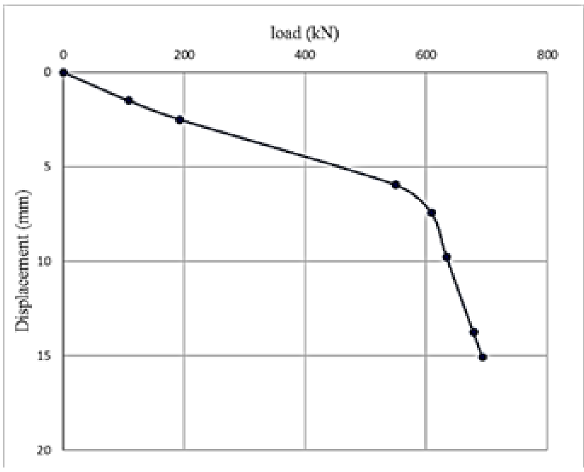


Chart -2: Present FEM Result.

Comparison between the results of ANSYS simulations of this case and the result obtained by (Johnson et al., 2006) shows very good agreement, giving confidence in the validity of this software and its use by the author.

4. PARAMETRIC STUDY

Influence of soil structure interaction is studied by varying diameter of pile and group spacing of pile. Keeping same soil properties, layering of soil based on soil report, Settlement analysis is conducted and results are interpreted.

4.1 Modelling of Pile Group and Soil

The soil and pile are modelled using the software Ansys Workbench 16.1. The dimensions of the pile, soil, soil properties are fixed using a soil investigation report conducted in Cochin region. The support and loading are chosen comply with the practical conditions. The diameter of the pile and group spacing is varied is given in table-2.

Table -2: Dimensions of the pile and group spacing.

Model	Pile Diameter (m)	Pile Group Spacing (m)
Model 1	0.5	1.5
Model 2	0.55	1.65
Model 3	0.45	1.35

4.2 Geometry

Piles are of 0.5m diameter and the centre to centre distance is taken as 3d, the length of the pile is taken as 27m. Total of 9 piles are arranged in symmetry for the pile group, the soil consists of four layers of uniform stratification.

4.3 Properties

The soil properties are collected from the soil report obtained. The circular cast-in-place test pile was made of solid reinforced concrete. The test pile properties and dimensions are summarized in Table-3.

Table -3: Test Pile Properties.

Material	Concrete
Length (m)	27
Outer Diameter (m)	0.5
Youngs Modulus (GPa)	30
Poisson's ratio	0.15

Using the SPT data and pre-existing empirical correlations the friction angle (Peck et al., 1974) and Young's modulus (Das, 1999) of the sand could be approximated. The sand was separated into four distinct homogenous layers with different properties. These layer properties are given in Table-4.

Table -4: Test Pile Properties.

Sand Layer	Layer depth (m)	Friction Angle (°)	Youngs Modulus (MPa)	Poisson's Ratio
Layer I	13.5	25	1	0.2
Layer II	1.5	30	1.2	0.25
Layer III	9	32	1.8	0.25
Layer IV	7	40	4.8	0.3

4.4Settlement considering Soil Structure Interaction

In this study three models are studied based on the variation of diameter and group spacing of the pile. The models are loaded vertically and oblique, evaluation of force reaction and total deformation are considered in this study. Soil properties and pile are mentioned above.

In static analysis, vertical displacement (settlement) of whole pile group has been considered. Loading has been done in single phase. Fig-1 to 3 shows the deformation of the pile group of varied diameter and group spacing. The figure below (Fig-1 to 3) clearly shows the deformation of the soil around the pile. It shows the interaction between the pile and soil. Vertical displacement depends on the soil properties and structural rigidity of the pile. In this study it can be seen that when the angle of the loading increases, the deformation at the bottom end of pile decreases in every case. The decrease in value is seen in all three configurations. In fig-1 to 3 it can be clearly seen that the vertical settlement decreases with the increasing loading angle.

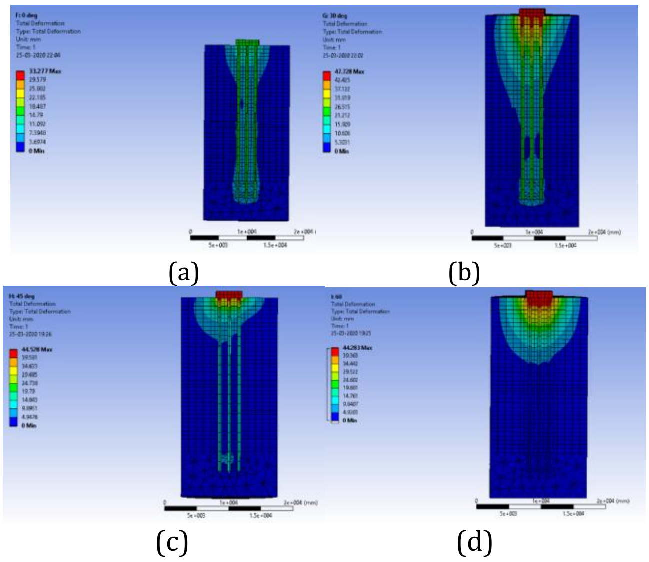


Fig -1: Total deformation of 0.5m diameter pile group (model 2) in (a) vertical load, (b) 30° load, (c) 45° load, (d) 60° load.

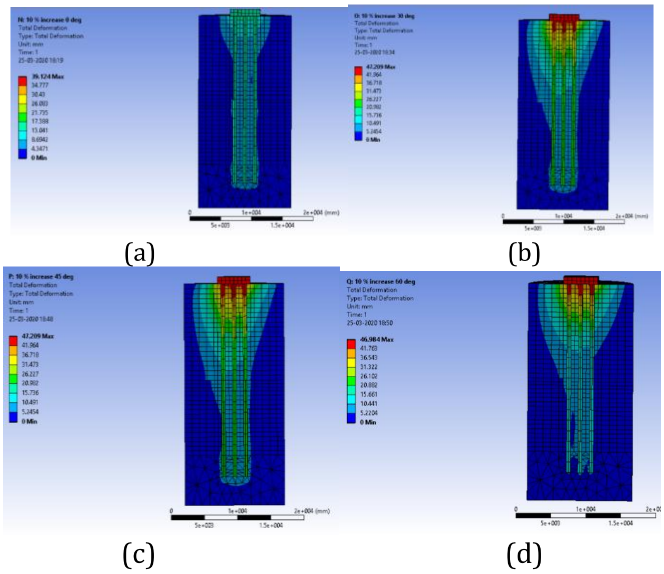
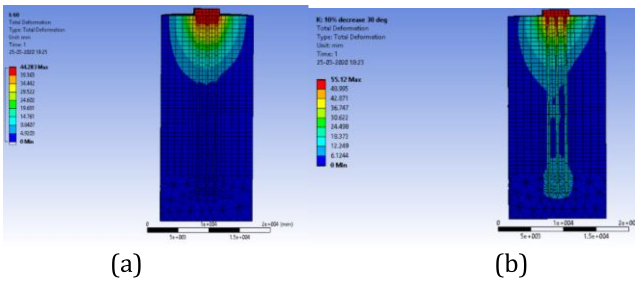


Fig -2: Total deformation of 0.55m diameter pile group (model 2) in (a) vertical load, (b) 30° load, (c) 45° load, (d) 60° load.



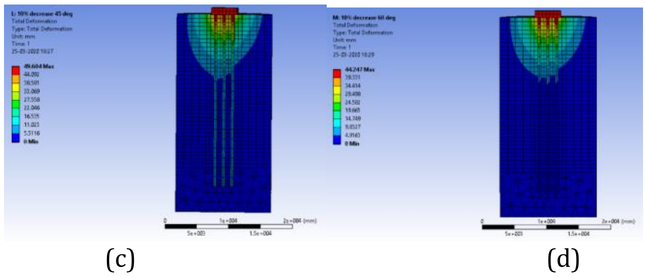


Fig -3: Total deformation of 0.45m diameter pile group (model 3) in (a) vertical load, (b) 30° load, (c) 45° load, (d) 60° load.

5. RESULTS AND DISCUSSION

5.1 Result of analysis of 0.5m diameter pile

Static analysis is carried out for the pile group with pile diameter 0.5m, 0.55m, 0.45m. The loads are given vertically, and 30°, 45°, 60° from the vertical. The charts 3 to 5 shows the load vs deformation graphs for each angle of loading.

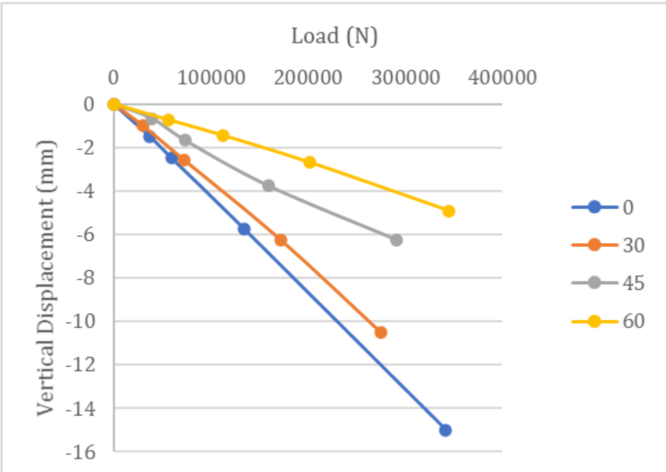


Chart -3: Load Vs Deformation Graph of 0.5 Diameter Pile

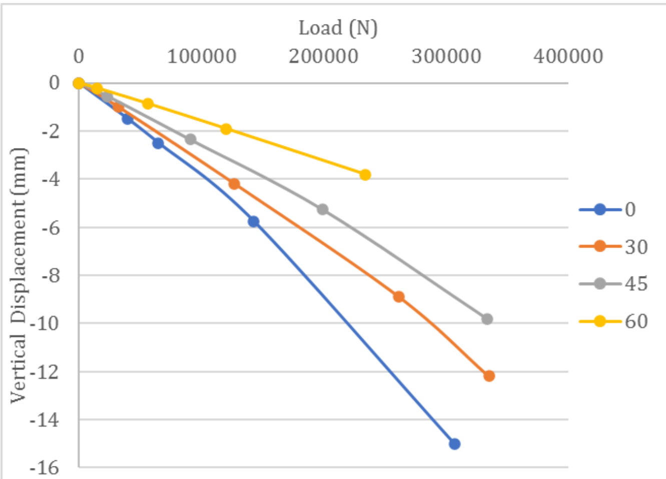


Chart -4: Load Vs Deformation Graph of 0.55 Diameter Pile

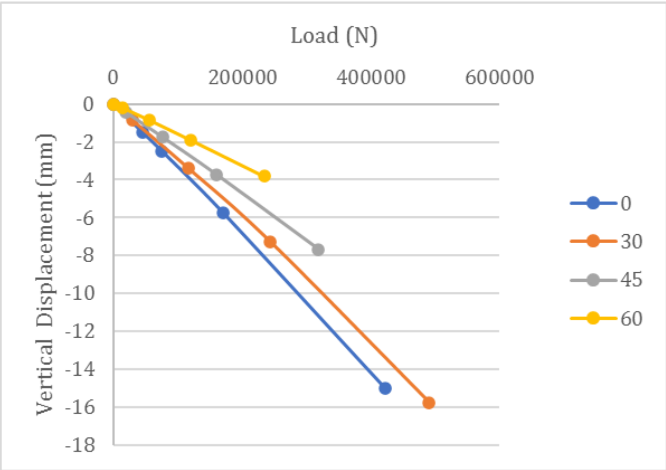


Chart -5: Load Vs Deformation Graph of 0.45 Diameter Pile

5.2 Relation between diameter of pile and settlement

Chart-3 to 5 shows the load vs vertical displacement curve. As in the parametric study the diameter and the group spacing have been varied. From chart-3 to 5 the vertical displacement of three models shows that the settlement decreases with the increase in horizontal loading. When the diameter is increased 10% and corresponding group spacing is provided, there is 10% decrease in the load carrying capacity for the same settlement. When the diameter is decreased 10% there is an increase of 23% in the load carrying capacity. It shows that the when diameter is increased there is decrease in the load carrying capacity.

5.3 Relation between angle of loading and vertical displacement

Static analysis shows that, total deformation (fig-1 to 3) is higher when the angle increases. The horizontal deformation in the top of the pile is more when the angle of loading increases. It shows how pile deforms in different loading conditions. The soil is compacted at the bottom of pile, which gives minimum horizontal deformation at the bottom of pile. For vertical loading the horizontal deformation is minimum. Which gives maximum load carrying capacity. The vertical displacement is decreased when the angle of loading is increased. This is because of the horizontal displacement happening in the pile group. The horizontal displacement also effects of the rigidity of pile and increasing bending stress. The increased horizontal displacement makes a decrease in the vertical load capacity. As the angle of loading increases the horizontal displacement increases and due to that the vertical load carrying capacity decreases.

5.4 Effect of length to diameter ratio in pile group

Several model analysis were conducted to investigate the effect of length to diameter (L/d) ratio to the load-deflection characteristics of laterally loaded pile group in cohesive soil. Chart-6 depicts the effect of L/d ratio on the load deflection characteristics of three pile group.

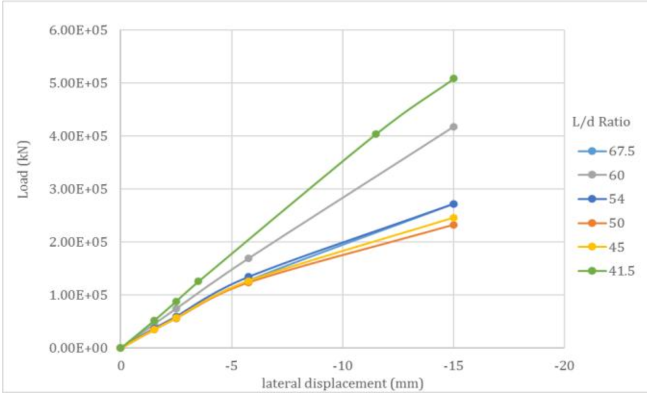


Chart -6: Effect of L/d ratio on the load deflection characteristics

It is noticeable that the load-deflection behaviours are non-linear in nature. L/d ratio greater than 30 is considered as long pile. Thus, the models analysed comes under long pile. The lateral load carrying capacity of pile increases with the increase of L/d ratio up to a limit. Chart-7 shows the variation of L/d ratio to load carrying capacity.

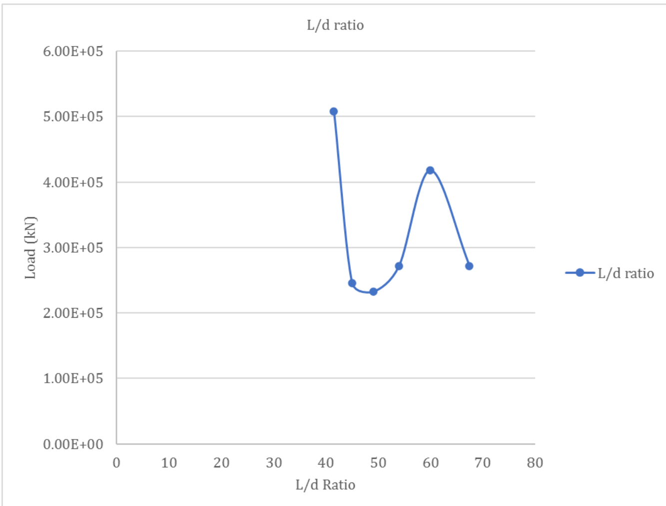


Chart -7: Variation of L/d ratio to load carrying capacity of group pile

From the chart-7 we can see that load is drastically high when the L/d ratio is lowest. Low L/d ratio means higher diameter. Higher diameter influences the spacing of the pile. and thus, high load carrying capacity. The L/d ratio after 40 , load decreases drastically, And again, increases after the value of 50. L/d ratio past 50, the load carrying capacity increases for a certain settlement value. It should also be noted that the slope of the load deflection curve is getting stiffer as the L/d ratio varies. This behaviour is factual whatever the configuration of pile group may be. The load capacity at condition for L/d values of 42 to 55 is almost same regardless of the configuration of the pile group

6. CONCLUSIONS

Soil Structure Interaction for the pile group for the settlement of pile is studied. Static analysis is conducted on the pile group. Relation between the load and deformation is studied by varying the diameter and group spacing of the pile group. Horizontal deformation increases with the increase of angle of loading. Total deformation of the top of pile is affected by the oblique loads. The vertical settlement in decreased when angle of loading increases. This is due to the increased horizontal displacement. When diameter is increased the load carrying capacity is reduced. The increased diameter increases the settlement. When the horizontal loading increases, the displacement at the bottom of pile group decreases. Due to that the compaction of soil below the pile group decreases affecting the load capacity of the pile group. There is a variation of load capacity comparing SSI and non-SSI model. The increased load is due to the fixed condition of the soil around the pile. The soil movement around the pile affects the settlement of the pile. Therefore, soil structure interaction has to include while conducting the settlement analysis of the pile group.

The effect of L/d ratio of the pile at a given spacing on the settlement behaviour and load carrying capacity is examined. For a group of pile, the interaction between the piles at a given spacing increases as the value of L/d increases. The load distribution of the pile group is almost non uniform as the outer piles taking most load and tend to formation of plastic hinges at the inclined loads. For a pile group of given dimensions, the settlement of the group under a given load is almost independent for a practical range of spacings. From a settlement consideration it is more economical to employ a smaller diameter with larger spacing.

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