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Numerical Analysis of Pile-Raft Foundations on Soft Soils Improvement Using PLAXIS 3D

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Abstract: Soft soil deposits present serious challenges to foundation design due to excessive compressibility and low load-carrying capacity. To overcome these limitations, deep foundation systems such as piles and pile–raft foundations are commonly adopted to enhance stiffness and control settlement. The present study evaluates the performance of raft, pile, and pile–raft foundation systems resting on soft soil through three-dimensional finite element modelling. Numerical simulations were performed using PLAXIS 3D to analyse settlement behaviour under an applied pressure of 500 kN/m². A parametric investigation was conducted by varying pile diameters (0.8 m, 1.0 m, and 1.5 m) and embedment depths (10 m, 20 m, and 30 m). The findings demonstrate that pile–raft foundations provide an effective and practical solution for mitigating excessive settlement in soft soil conditions.

Keywords: Soft Soil, Raft Foundation, Pile Foundation, Pile–Raft System, Finite Element Modelling, Settlement Behaviour, PLAXIS 3D.

I. INTRODUCTION

Soft soils such as clay and silt are commonly found in coastal regions, river deltas, reclaimed lands, and floodplains. These soils exhibit high compressibility and low bearing capacity, leading to excessive settlement when subjected to structural loads. Conventional shallow foundations are often inadequate in such conditions. Deep foundations such as pile systems are commonly used; however, designing piles to carry the entire structural load can be uneconomical. Pile–raft foundations provide an efficient alternative where both raft and piles contribute to load resistance. Instead of ignoring raft contribution, the system allows effective interaction between raft, piles, and soil. This composite behaviour improves stiffness and reduces total and differential settlements.

A. Pile Raft Foundation

A pile raft foundation is a composite foundation system comprising a raft foundation supported by a limited number of piles, where both the raft and piles contribute to resisting the applied structural loads. Conventional pile foundations, in which piles are designed to carry the entire load, pile raft foundations allow effective load sharing between the raft, piles, and supporting soil. This system is particularly advantageous for structures founded on soft soils, as it reduces excessive total and differential settlements and economical.

II. OBJECTIVES

1) To model and analyse raft, pile, and pile–raft foundation systems using PLAXIS 3D.
2) To investigate the influence of pile diameter (0.8 m, 1.0 m, 1.5 m), pile length (10m, 20m, 30m), and number of piles (4 X 4) on foundation performance, particularly load-bearing capacity and settlement.
3) To optimize pile dimensions and configurations for safe, economical, and efficient load distribution.
4) To compare the performance of raft, pile, and pile–raft systems under identical loading conditions.
5) To develop a foundation design methodology adaptable to high structural demands and challenging soil conditions.

III. REVIEW OF LITERATURE

1) Vijaykumar, Dr. S K Prasad (2014) This paper examines key parameters affecting the performance of pile–raft foundation systems. The focus of the present work shows the mechanism of pile-raft foundation system in a uniform soil when subjected to uniformly distribute axial force for the purpose of clarity. Parametric studies have been made by varying the length of pile and number of piles. The parameter studied include settlement, total axial force, shear force, bending moment in both the directions, shear stress at the base of the pile and base of the raft in different directions. The length of pile varied from 4 to 22m at the interval of 6m and number of piles have been changed from 25, 17, 9, 5 to 4 piles.

2) Er. Akshay Wadhwa, Er. Mohd Aamir (2017) This paper studies factors influencing pile–raft foundation performance, where load is shared between raft and piles. Key parameters include pile number, length, diameter, spacing, and soil–pile elastic properties such as Young's modulus and Poisson's ratio. The analysis focuses on load capacity, settlement, and soil stresses to evaluate foundation behaviour.
3) Thasleena Haris and Niranjana K, (2019) This paper highlights the performance of piled raft foundations in sandy, clayey, and layered soils, showing their effectiveness in problematic subsoil conditions. The system can carry high vertical loads while controlling settlement, differential settlement, and tilting within permissible limits, making it more cost-effective than conventional pile foundations. Since piled raft foundations involve complex soil–structure interaction, collaboration between structural and geotechnical engineers is essential to achieve safe and economical designs.
4) Phung Duc Long (2013) this paper highlights Settlement analysis for piled raft foundations. In piled raft foundations, piles are not designed to take the full load but only to reduce the settlement to an allowable level. This method can be used in combination with FEM method for a conceptual design of a piled raft foundation, with a desired settlement. The foundation is currently designed as a conventional piled foundation. Piled raft foundation is studied as an alternative option. At a chosen settlement of 20mm, a considerable number of piles can be saved. 3D FE analyses are performed to verify the settlement of the foundation system.
5) Amey R. Khedikar, Saurabh M. toned (2021) this paper studies about the Dynamic Analysis of Multistoried Building Resting on a Combined Pile Raft Foundation. This research paper discusses the perspective of using pile as settlement reducers and the conditions under which such a technique may be effective. Comparison of analysis of a high-rise structure resting on raft foundation and same resting on pile-raft foundation has been made. For the analysis, a 15 storied RC building has been considered with SBC of 135kN/m^2. The building and foundation have been modelled, analysed and designed. An attempt has been made to compare various parameters like displacement, stresses, moments etc. on analysis and design of the above-mentioned high-rise structure resting on raft foundation and pile-raft foundation.
6) Vijaykumar, S K Prasad (2022) this paper studies about the load transfer mechanism from foundation to soil in pile raft foundation is a complex phenomenon because of the involvement of many foundation components in different regions. An attempt is made to explain the load transfer mechanism from pile raft to soil in a homogeneous soil. The foundation is subjected to increasing concentric vertical load from zero till failure. The foundation is considered to be rigid and elastic and soil is deformable and behaviour of soil is non-linear. From the present work, the following inferences are made.

IV. NUMERICAL MODELLING

A three-dimensional finite element analysis was carried out using PLAXIS 3D to investigate the behaviour of raft, pile, and pile–raft foundation systems resting on soft soil. The analysis focused on evaluating settlement characteristics under static loading conditions.

A. Model Geometry and Boundary conditions

The soil domain was modelled as a 60 m × 60 m × 60 m block to eliminate boundary influence on foundation response. The bottom boundary was fully fixed, while vertical boundaries were restrained in the horizontal direction and free in the vertical direction. The ground surface was kept free.

A square raft of dimensions 15 m × 15 m was considered. For pile and pile–raft systems, a 4 × 4 pile group configuration was adopted with a centre-to-centre spacing of 3D.

Table-1: Properties of material

Property	Soft Soil	Raft	Pile
Unit Weight, γ (kN/m³)	17	25	25
Young's modulus, E (kN/m²)	3000	20×10^6	20×10^6
Poisson's ratio, v	0.35	0.2	0.2
Shear Strength, τ (kN/m²)	20	-	-

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The raft was represented using plate elements, while piles were modelled as embedded beam elements to account for axial resistance and shaft interaction with surrounding soil. Pile diameters of 0.8 m, 1.0 m, and 1.5 m and lengths of 10 m, 20 m, and 30 m were considered to evaluate their influence on settlement behaviour.

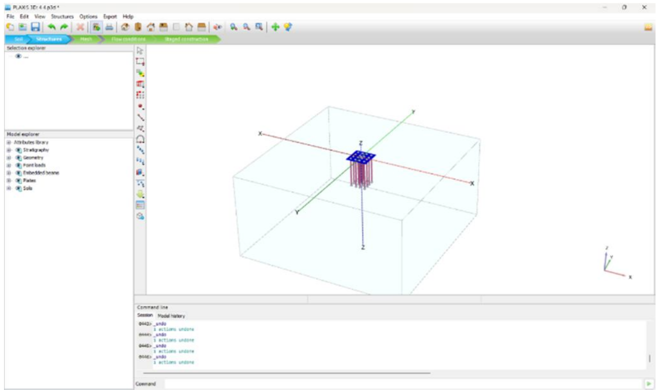

Fig-1: Structural model of pile raft foundation

A uniformly distributed load was applied over the raft surface up to a maximum pressure of 500 kN/m². The load was applied incrementally to obtain load–settlement response curves. A plastic analysis was performed to capture soil yielding and stress redistribution effects.

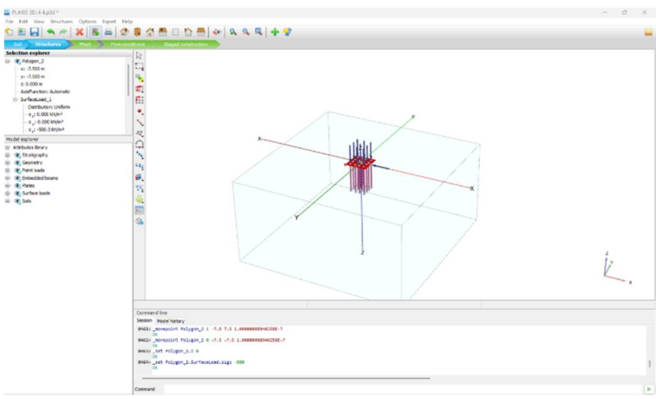

Fig-2: Load Application on pile raft foundation

V. RESULTS

A parametric study is performed to investigate the influence of pile diameter and pile length on settlement behaviour. Pile and pile–raft systems are analysed for diameters of 0.8 m, 1.0 m, and 1.5 m, with embedment depths of 10 m, 20 m, and 30 m. The raft foundation is analysed separately to establish the baseline settlement response under identical loading conditions.

A. Variation of Bearing Capacity of Soft Soil with Raft Foundation

Chart-1 shows the load–settlement behaviour of a Raft foundation for the soft soil. In the graph it shows the settlement of raft foundation about linear increase of load when the load increases the settlement was increasing. For 200 kN/m² the settlement comes around 145mm.

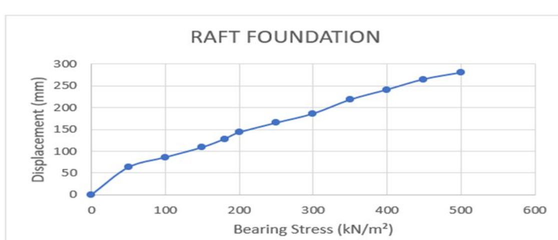

Chart-1: Bearing Capacity Variation in Soft Soil Raft Foundation

With gradual increase of the load at 300 kN/m² the settlement was 197mm and when at 500 kN/m² the settlement was 280mm. it shows the raft foundation leads to excises settlement in the soft soils.

B. Variation of Bearing Capacity of Soft Soil with Pile Foundation

Chart-2 shows the load–settlement behaviour of a pile foundation with 0.8m diameter piles, analysing vertical displacement under varying bearing pressures for pile lengths of 10 m, 20 m, and 30 m.

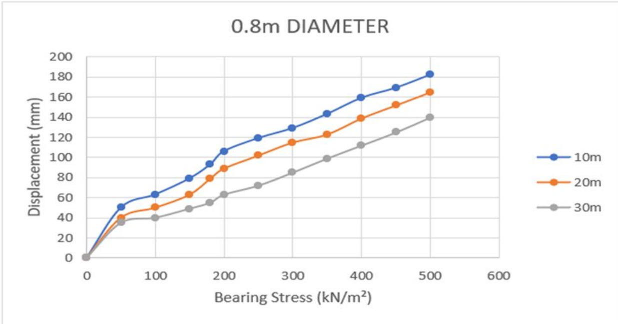

Chart-2: Bearing Capacity Variation in Soft Soil with 0.8 m Pile Diameter

As we can see, settlement reduces with increasing pile length. At 500 kN/m² load, 10 m piles settlement about 180 mm, 20 m piles about 165 mm, and 30 m piles about 140 mm.

Chart-3 shows the load–settlement behaviour of a pile foundation with 1.0m diameter piles, analysing vertical displacement under varying bearing pressures for pile lengths of 10 m, 20 m, and 30 m.

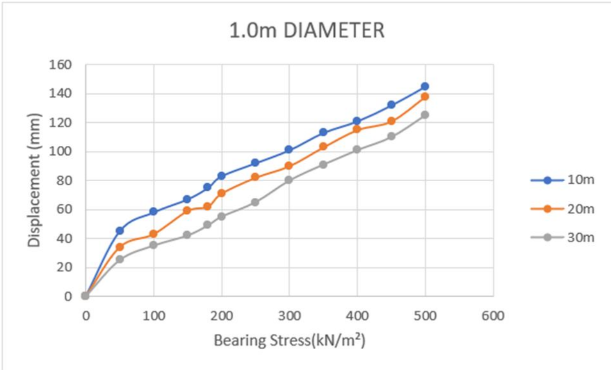

Chart-3: Bearing Capacity Variation in Soft Soil with 1.0 m Pile Diameter

Form the above chart at 500 kN/m², the settlement is approximately 145 mm for 10 m piles, about 138 mm for 20 m piles, and nearly 125 mm for 30 m piles.

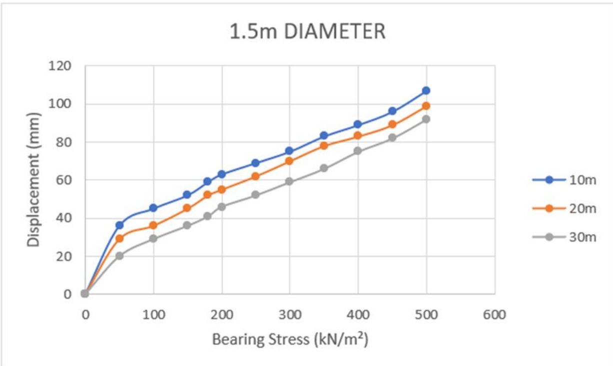

Chart-4: Bearing Capacity Variation in Soft Soil with 1.5 m Pile Diameter

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Chart-4 shows the load–settlement behaviour of a pile foundation with 1.5m diameter piles, analysing vertical displacement under varying bearing pressures for pile lengths of 10 m, 20 m, and 30 m.

At an applied bearing pressure of 500 kN/m², the settlement is approximately 115 mm for 10 m piles, about 98 mm for 20 m piles, and nearly 86 mm for 30 m piles. This indicates that increasing pile length improves the stiffness of the foundation and reduces settlement.

C. Bearing Capacity of Soft Soil with Pile Raft Foundation

The combined action of the raft and piles improves the overall stiffness of the foundation system. The raft helps in distributing the load over a larger area, while the piles transfer a significant portion of the load to deeper soil layers. For shorter piles (10 m), the settlement is comparatively higher because the load transfer to deeper soil is limited. As the pile length increases to 20 m and 30 m, greater shaft resistance is mobilized, leading to improved load sharing between the raft and piles and reduced settlement.

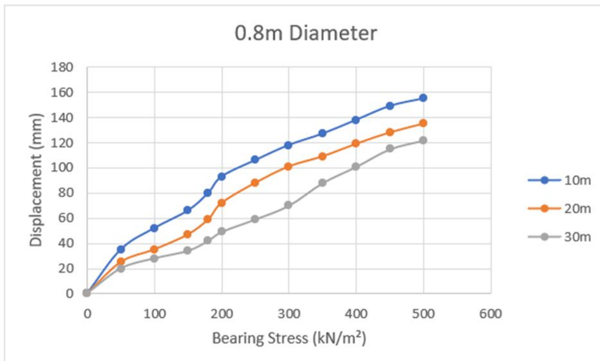

Chart-5: Bearing Capacity Variation in Soft Soil with 0.8 m Pile Diameter

Chart-5 shows the load–settlement behaviour of a pile–raft foundation with 0.8m diameter piles, analysing vertical displacement under varying bearing pressures for pile lengths of 10m, 20m, and 30m.

From the graph, at an applied bearing pressure of 500 kN/m², the settlement is approximately 155 mm for 10 m piles, 135 mm for 20 m piles, and 120 mm for 30 m piles.

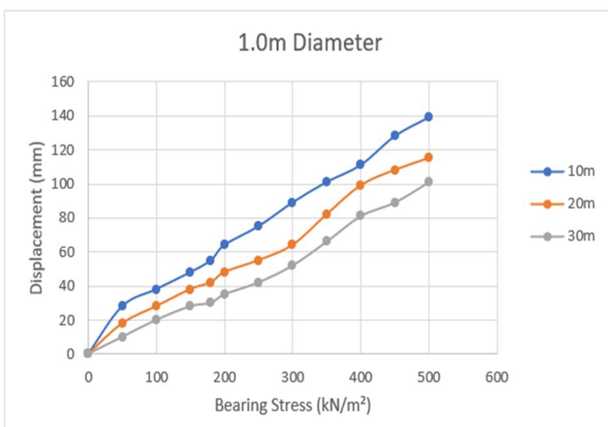

Chart-6: Bearing Capacity Variation in Soft Soil with 1.0 m Pile Diameter

Chart-6 shows the load-settlement behaviour of a pile-raft foundation with 1.0m diameter piles, analysing vertical displacement under varying bearing pressures for pile lengths of 10m, 20m, and 30m.

The response remains predominantly linear within the analysed loading range, indicating controlled deformation and stable soil–structure interaction. At a maximum pressure of 500 kN/m², the settlements are approximately 143 mm for 10 m piles, 136 mm for 20 m piles, and 121 mm for 30 m piles.

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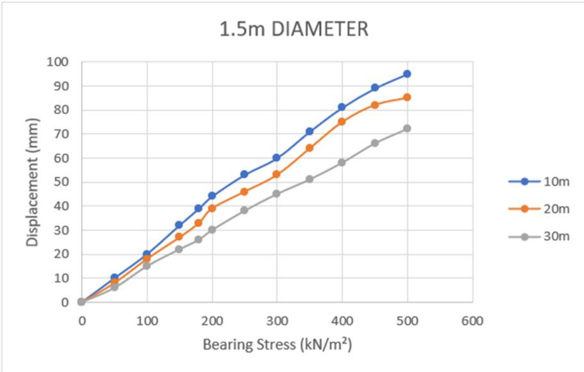

Chart-7: Bearing Capacity Variation with 1.5 m Pile Diameters

Chart-7 shows the load-settlement response of the 1.5 m diameter pile-raft foundation indicates a significant improvement in stiffness compared to smaller diameters. The displacement increases almost linearly with applied bearing pressure, suggesting stable composite action between the raft and piles throughout the loading range.

At the maximum applied pressure of 500 kN/m², the observed settlements are approximately 95 mm for 10 m piles, 85 mm for 20 m piles, and 70 mm for 30 m piles. Overall, the pile–raft foundation system significantly enhances the bearing capacity of soft soil and provides better settlement control compared to shallow foundation systems. Increasing pile length and diameter further improves the performance of the combined foundation system.

VI. CONCLUSIONS

1) The pile foundation significantly improved performance through mobilization of shaft friction and end- bearing resistance.
- For 0.8 m diameter piles, settlement reduction increased from 35.71% (10 m length) to 50.00% (30 m length).
- For 1.0 m diameter piles, reduction ranged from 48.21% to 55.36%.
- For 1.5 m diameter piles, reduction further improved from 58.93% to 69.29%.

2) The pile foundation demonstrated superior composite action compared to pile-only systems. The interaction between raft and piles resulted in efficient stress redistribution and improved stiffness mobilization.
- For 0.8 m diameter, settlement reduction ranged from 44.64% to 57.14%.
- For 1.0 m diameter, reduction increased from 50.00% to 64.29%.
- For 1.5 m diameter, the improvement reached a maximum of 75.0% for 30m length.

3) The rate of settlement reduction increases not only by the pile diameter, while the increase of length of the pile becomes comparatively moderate beyond 20 m. This suggests that diameter plays a dominant role in stiffness enhancement at higher depths.

4) Overall, the comparative analysis confirms that the pile–raft foundation system provides the most efficient and reliable solution for soft soil conditions, offering enhanced bearing capacity, reduced settlement, and improved structural stability when compared to isolated raft or pile foundations.

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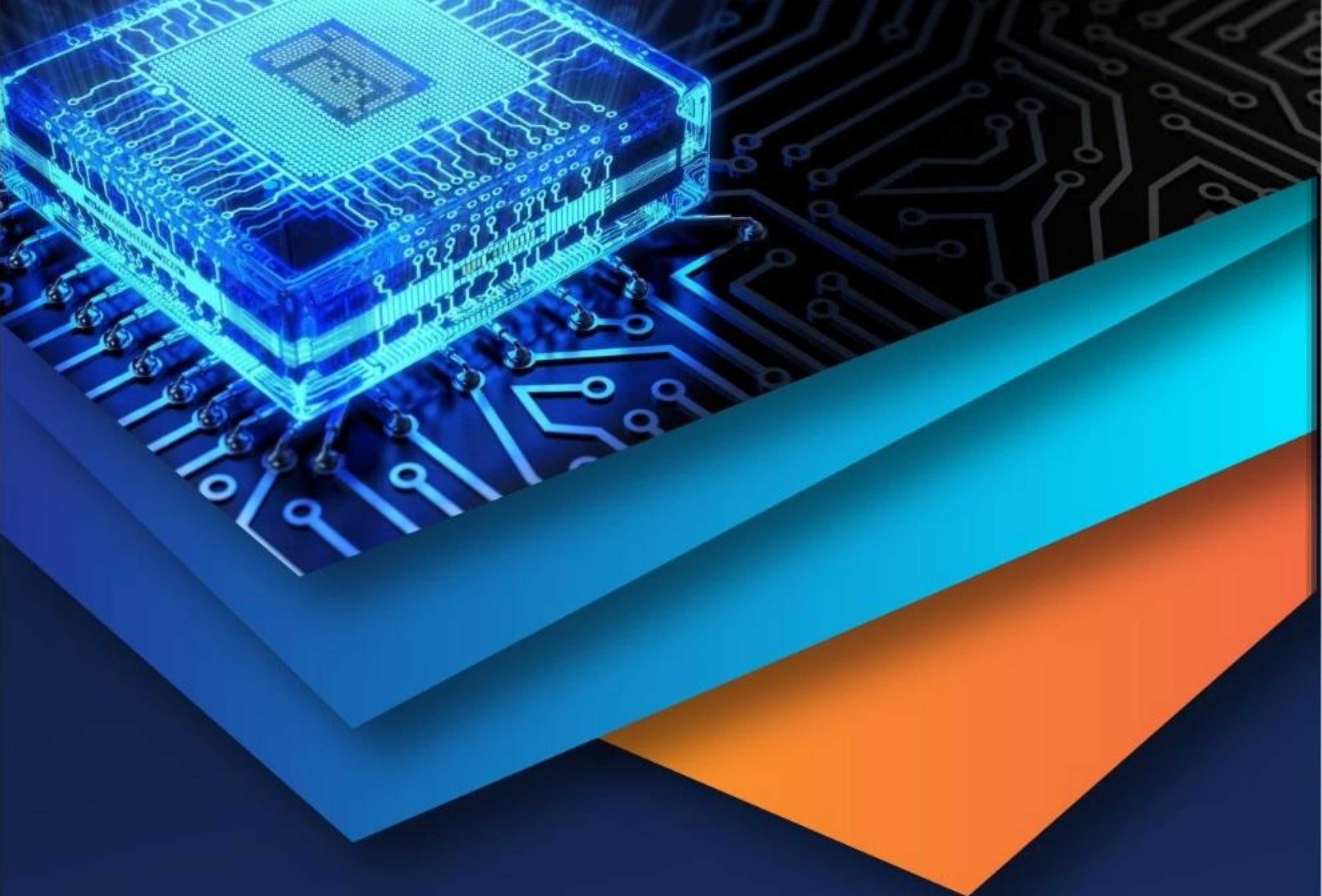

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