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Numerical Analysis of the Bearing Capacity of Stone Columns Improved Ground

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Abstract— Stone columns are a suitable technique for increasing the bearing capacity of soft and weak soils. In this study the results of a series of finite element analyses on square footing rested on both improved and unimproved soft soil were presented. The developed model was validated by one of the existing experimental reports. Afterwards, the parametric studies were performed to determine the effective geometrical and mechanical parameters and their effects on the bearing capacity of footing. Results indicated that the bearing capacity of footing can be considerably improved by implementation of stone columns. It was observed that the bearing capacity ratio (BCR) increases with increasing friction angle of stone column and decreasing cohesion and friction angle of soft soil.
Keywords— Bearing Capacity, Square Footing, Stone Column, Numerical Analysis

I. INTRODUCTION

Deep vibratory method such as vibro-compaction and vibro-replacement are ground improvement techniques to improve the bearing capacity and settlement of weak soils. In the vibro-compaction technique, vibrator penetrates into the soil and by applying the lateral forces causes the soil particles to re-arrange into a denser state. This technique reaches its technical and economic limits in saturated sands with high silt contents, as fine particles attenuate the horizontal forces imparted by the vibrating poker [1]. Due to the limitations of vibro-compaction in cohesive soils, vibro stone columns were developed in the early 1950s. In this method, when the vibrator poker penetrate the soil, the excavated borhole, backfilled in successive stages with coarse aggregate, which is compacted by re-lowering the poker. This process results in stone columns which are tightly inter-locked with the surrounding soil [2]. Stone columns can easily be constructed up to a diameter of 1.5 meter and typically replace 10–35% of the in situ soil [3]. Stone columns can be used to increase bearing capacity of the foundation, reduce total and differential settlements, increase the slopes stability, accelerate the consolidation time and decrease the liquefaction potential. For some structures such as liquid storage tanks, abutments, embankments, and factories rested on compressible soils that can tolerate some settlement, stone columns are an economical improvement method. In this paper a numerical simulation carried out on the stone columns improved ground and effects of mechanical and geometrical characteristics of the model on the bearing capacity, were investigated.

II. NUMERICAL ANALYSIS

Two-dimensional axisymmetric FE numerical simulations were performed using Plaxis commercial program [4]. The aim of this study is evaluate the bearing capacity of the square foundation on the ground improved with small groups of stone columns. Thus, 2×2, 3×3 and 5×5 groups of stone columns were considered. For simulation of group of stone columns in axisymmetric configuration, group of stone columns were replaced by equivalent rings of stone columns such that same areas were created. An example of this idealization is shown in Fig. 1. Similar modeling simulation was used by others [5-8].

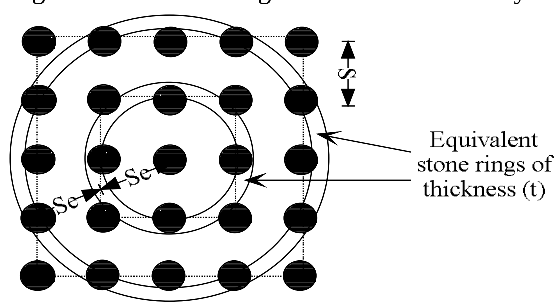

Fig. 1 Concentric rings idealization for group of 5×5

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The model mesh was generated using 15-node triangular elements. The left and right boundaries were only permitted to move vertically and the bottom of the model was constrained against both horizontal and vertical movements. It was assumed that foundation is rigid. Hence, a uniform settlement applied in the vertical direction to all nodes at the soil-footing interface. It was assumed that the stone columns located on a rigid substrate (end bearing stone column) and the groundwater level is in the same level of the clay bed. Mesh refinement was done for elements around the footing and stone columns where the stresses are concentrated in these regions. Typical adopted mesh is shown in Fig. 2. An elastic-plastic Mohr Coulomb (MC) model with drained behaviour was selected for both the clay and stone column. Benchmark material properties were considered to be in accordance with study of Nassaji and Asakereh [9], that are presented in table 1.

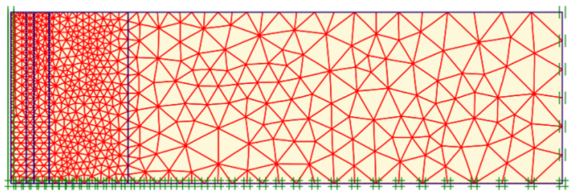

Fig. 2 Typical mesh shape for numerical analysis

TABLE I
BENCHMARK MATERIAL PROPERTIES

Parameter	Soft soil	Stone column
E (kPa)	3000	60000
υ	0.35	0.3
φ′(°)	20	42
ψ(°)	-	12
C′(kPa)	5	-
γ_{sat} (kN/m^3)	18	20

Accuracy of the developed model was verified by laboratory studies conducted by Narasimha Rao et al. [10]. They performed a series of laboratory tests to determine the load bearing capacity of single stone columns. The tank diameter and height of soft clay used in their study were 650 mm and 350 mm, respectively. Loading were applied through a load plate with a diameter of 50 mm on a stone column with diameter of 25 mm and height of 225 mm. Properties of the materials in their study are presented in table 2. Geometry of the created model for validation is presented in Fig. 3. Fig. 4 compares the results obtained from the model test and numerical simulation, which matches well.

III.RESULTS

In the parametric analysis of the this section, behaviour of stone columns improved ground, is evaluated through a dimensionless parameter (BCR), which is defined as follows:

$$BCR = \frac{q_{improved}}{q_{unimoroved}} \quad (1)$$

Where, $q_{improved}$ and $q_{unimproved}$ are ultimate bearing capacities of the footing on stone columns improved ground and on unimproved ground, respectively. Should be noted that in this study, the ultimate bearing capacity was considered equal to pressure at a settlement of 10% of the footing width, unless before this settlement, the maximum pressure is observed.

A. Effect Of Soil Cohesion

A series of FEM analysis were conducted to investigate the effect of soil cohesion on CBR values. Results of these analyses for 2×2, 3×3 and 5×5 groups of stone columns are presented in Fig. 5. It is seen that BCR decreases with increase in cohesion, that the value of this reduction is higher in smaller groups of stone columns.

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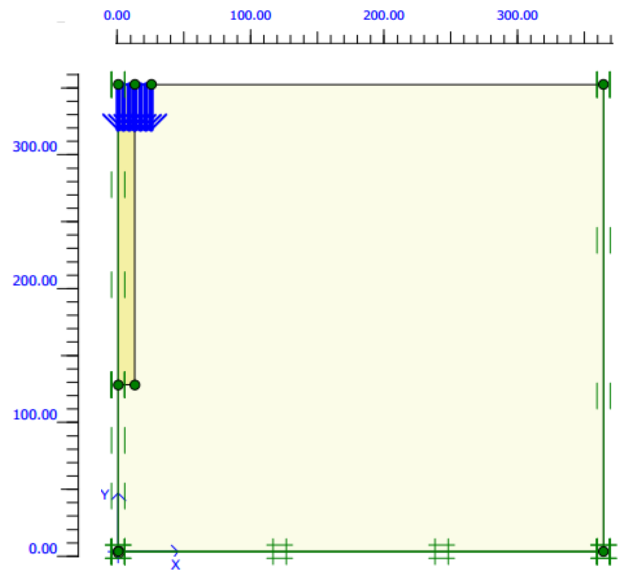

Fig. 3 Geometry of the model for validation

TABLE II
PROPERTIES OF MATERIALS USED FOR VALIDATION [1]

Parameter	Soft soil	Stone column
E (kPa)	4000	45000
υ	0.45	0.3
φ(°)	0	38
C_u (kPa)	20	0

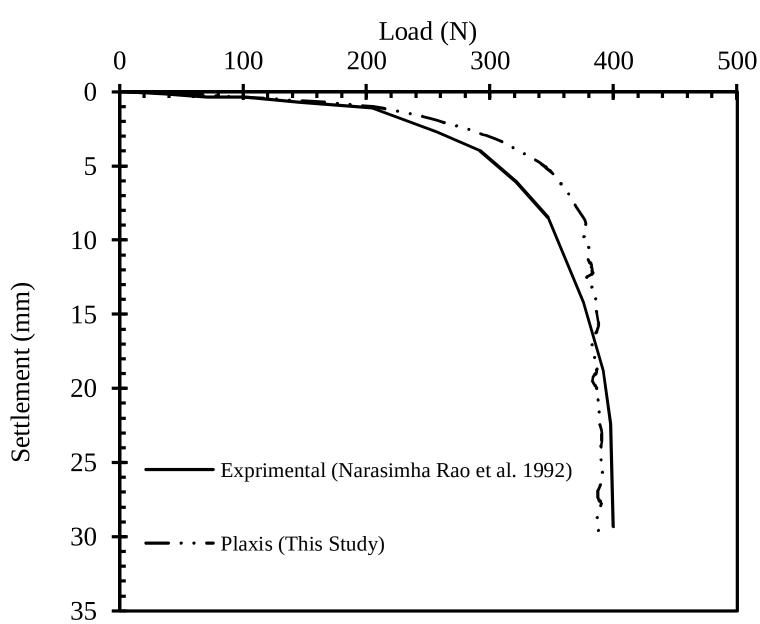

Fig. 4 Validation of PLAXIS

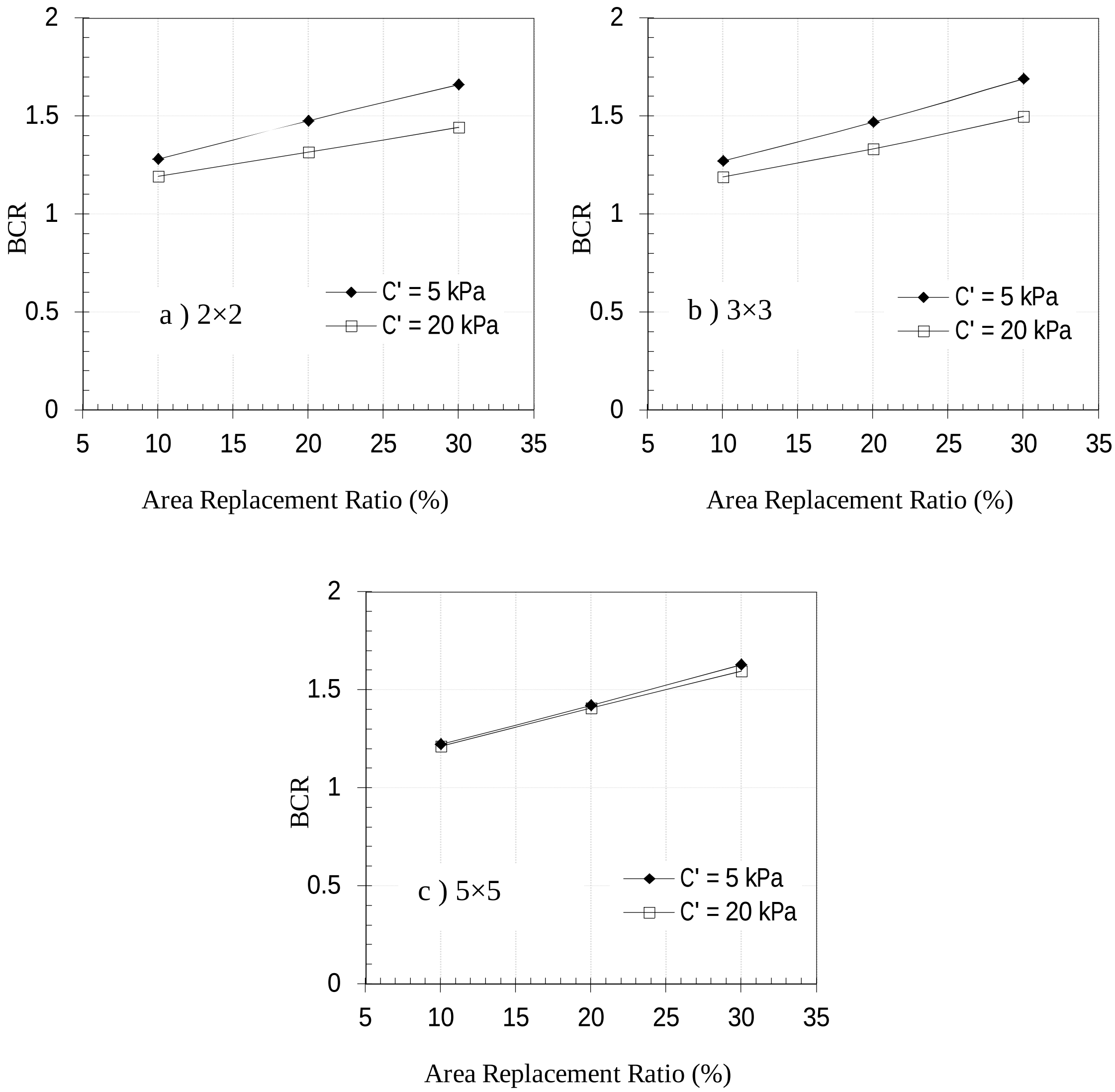

Fig. 5 Effect of soil cohesion on BCR

B. *Effect Of Soil Friction Angle*

Effect of friction angle of the surrounding soil on the BCR for 2×2, 3×3 and 5×5 groups of stone columns, are shown in Fig. 6. According to this figure, can be said that with increasing the soil friction angle, BCR decreases slightly. The amount of this reduction, is more explicitly in higher area replacement ratio.

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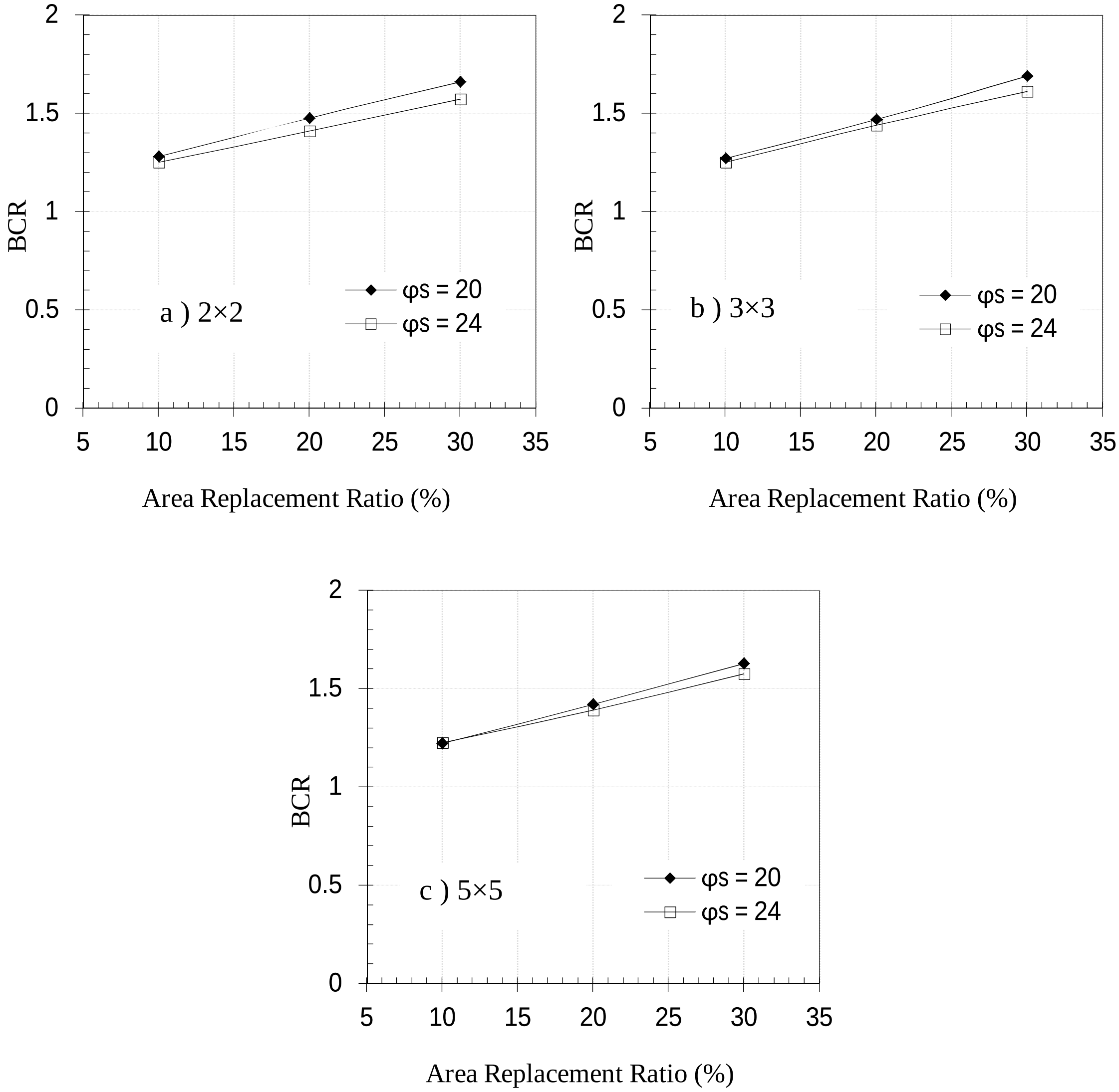

Fig. 6 Effect of soil friction angle on BCR

C. Effect Of Stone Column Friction Angle

Fig. 7 is shown effect of stone column friction angle on BCR values for 2×2, 3×3 and 5×5 groups of stone columns. It can be seen that the BCR increases with increasing friction angle of stone column. BCR variations due to stone column friction angle variations, are more obvious in the greater area replacement ratios, because of increasing participation of the columns in load bearing in greater area replacement ratios.

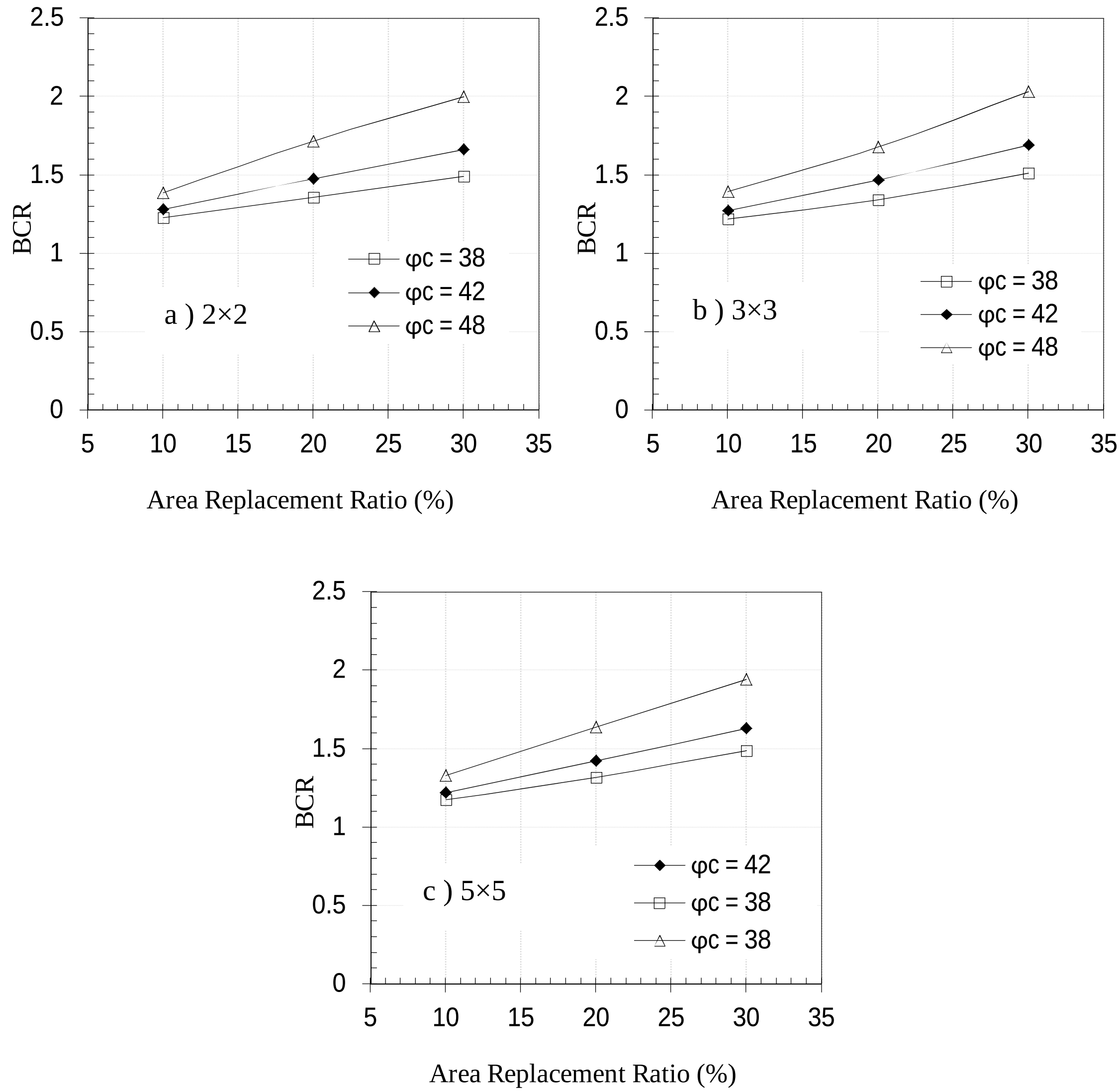

Fig. 7 Effect of stone column friction angle on BCR

IV. CONCLUSIONS

In this study numerical investigations were performed to evaluate the behaviour of square footing on the stone columns improved ground. Mohr–Coulomb failure criterion considered for both the soil and stone column. Based on performed analyses, the following conclusions are drawn:

BCR decreases with increase in soil cohesion, that the value of this reduction is higher in smaller groups of stone columns.

With increasing the soil friction angle, BCR decreases slightly. The amount of this reduction , is more explicitly in higher area replacement ratio.

BCR increases with increasing friction angle of stone column. BCR variations due to stone column friction angle variations, are more obvious in the greater area replacement ratios, because of increasing participation of the columns in load bearing in greater area replacement ratios.

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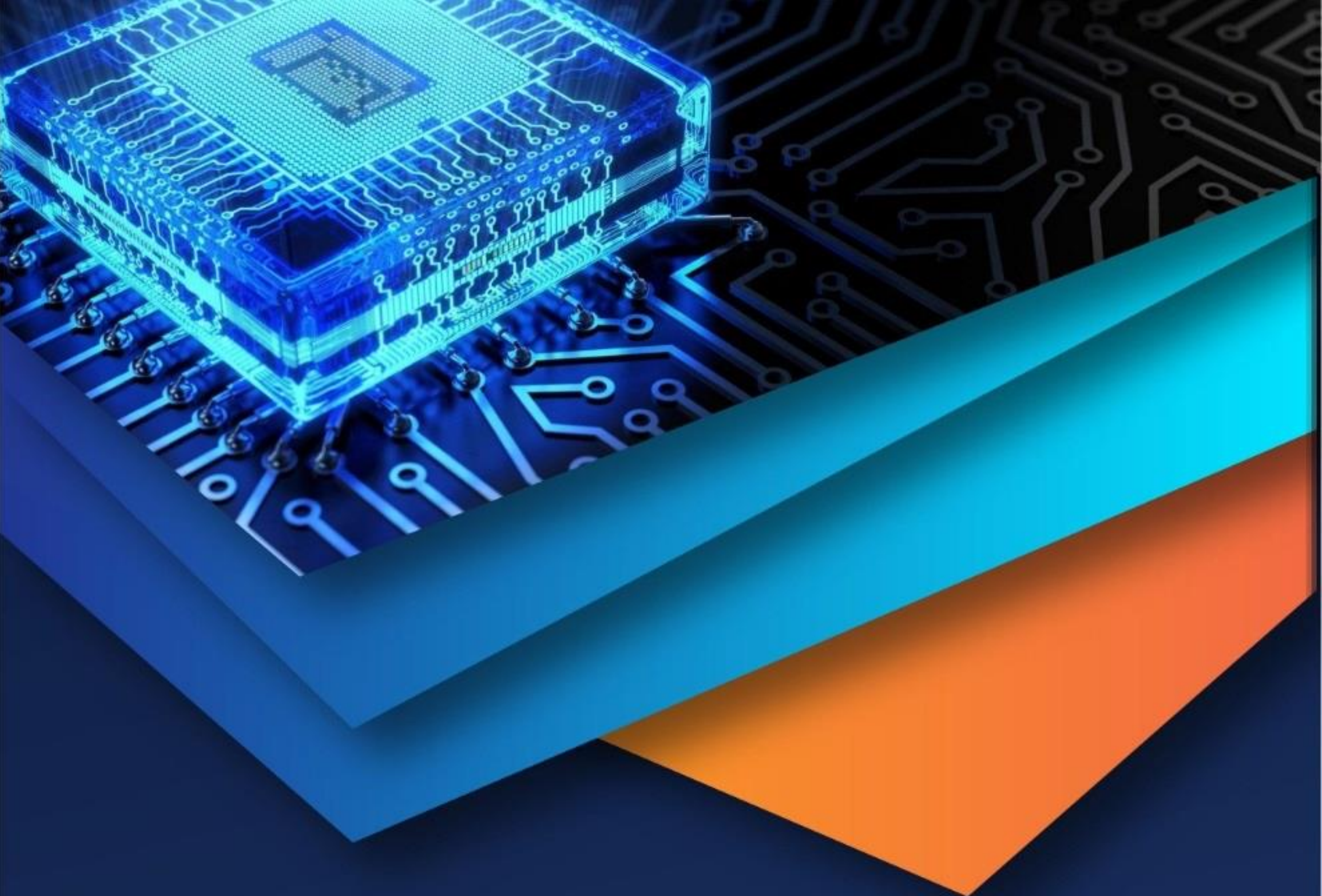

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