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Soil-Structure Interaction for Building Structures

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Abstract: In the analysis of structures subjected to earthquake forces, it is usually assumed that the structure is fixed at the base to simplify the mathematical problem. This assumption leads to gross error in assessment of overall response under dynamic loads. The interaction phenomenon is principally affected by the mechanism of energy exchanged between the soil and the structure during an earthquake. In the present investigation, a multi-storied building which is located in Amaravati is chosen as the study area which consists of different types of soil / rock profiles at different locations. Many high rise structures are expected in future in the new city. Earthquake analysis is carried out when similar structure rests on different types of soils and the results of fundamental time periods, base shears and displacements are compared with the results obtained from fixed base condition.

I. INTRODUCTION

We know that ground motions results primarily from the three factors namely as

1) Source characteristics
2) Propagation path of waves and
3) Local site conditions.

Also, the Soil-Structure Interaction (SSI) problem has become an important feature of Structural Engineering with the advent of massive constructions on soft soils such as nuclear power plants, concrete and earth dams. Buildings, bridges, tunnels and underground structures may also require particular attention to be given to the problems of SSI. If a lightweight flexible structure is built on a very stiff rock foundation, a valid assumption is that the input motion at the base of the structure is the same as the free-field earthquake motion. If the structure is very massive and stiff, and the foundation is relatively soft, the motion at the base of the structure may be significantly different than the free-field surface motion. For code design buildings it is important to consider the effect of the SSI. The objective of this chapter is to understand the basic concept of the Soil-Structure Interaction, following the different methods of analysis with some solved examples.

A soil-structure interaction analysis evaluates the collective response of the structure, the foundation, and the geologic media underlying and surrounding the foundation, to a specified free-field ground motion. The term free-field refers to motions that are not affected by structural vibrations or the scattering of waves at, and around, the foundation. SSI effects are absent for the theoretical condition of a rigid foundation supported on rigid soil. Accordingly, SSI accounts for the difference between the actual response of the structure and the response of the theoretical, rigid base condition.

In Part 2 of FEMA P-750, NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (FEMA, 2009), SSI effects are categorized as inertial interaction effects, kinematic interaction effects, and soil-foundation flexibility effects. The terms kinematic and inertial interaction were introduced in 1975 by Robert Whitman (Kausel, 2010).

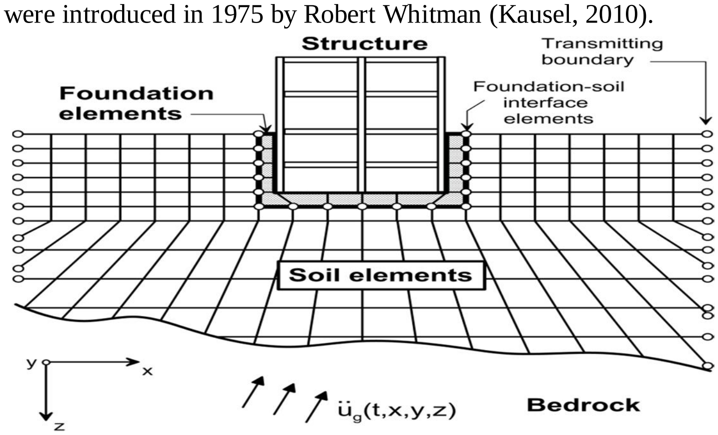

Figure 1- Analysis of soil- structure interaction

In the context of engineering analysis and design, these effects are related to –

a) *Foundation Stiffness and Damping:* Inertia developed in a vibrating structure gives rise to base shear, moment, and torsion. These forces generate displacements and rotations at the soil-foundation interface. These displacements and rotations are only possible because of flexibility in the soil-foundation system, which significantly contributes to overall structural flexibility (and increases the building period). Moreover, these displacements give rise to energy dissipation via radiation damping and hysteretic soil damping, which can significantly affect overall system damping. Since these effects are rooted in structural inertia, they are referred to as inertial interaction effects.
b) *Variations Between Foundation input Motions and free-field Ground Motions:* Foundation input motions and free-field motions can differ because of: (i) kinematic interaction, in which stiff foundation elements placed at or below the ground surface cause foundation motions to deviate from free-field motions due to base slab averaging, wave scattering, and embedment effects in the absence of structure and foundation inertia; and (ii) relative displacements and rotations between the foundation and the free-field associated with structure and foundation inertia.
c) *Foundation Deformations:* Flexural, axial, and shear deformations of structural foundation elements occur as a result of forces and displacements applied by the superstructure and the soil medium. These represent the seismic demands for which foundation components should be designed, and they could be significant, especially for flexible foundations such as rafts and piles.

II. METHODS OF ANALYSIS

Methods that can be used to evaluate the above effects can be categorized as direct and substructure approaches. In a direct analysis, the soil and structure are included within the same model and analyzed as a complete system. In a substructure approach, the SSI problem is partitioned into distinct parts that are combined to formulate the complete solution.

A. Direct Analysis

As schematically depicted in Figure 1-1, the soil is often represented as a continuum (e.g., finite elements) along with foundation and structural elements, transmitting boundaries at the limits of the soil mesh, and interface elements at the edges of the foundation.

Evaluation of site response using wave propagation analysis through the soil is important to this approach. Such analyses are most often performed using an equivalent linear representation of soil properties in finite element, finite difference, or boundary element numerical formulations (Wolf, 1985; Lysmer et al., 1999). Direct analyses can address all of the SSI effects described above, but incorporation of kinematic interaction is challenging because it requires specification of spatially variable input motions in three dimensions.

Because direct solution of the SSI problem is difficult from a computational standpoint, especially when the system is geometrically complex or contains significant nonlinearities in the soil or structural materials, it is rarely used in practice.

B. Substructure Approach

Proper consideration of SSI effects in a substructure approach requires: (i) an evaluation of free-field soil motions and corresponding soil material properties; (ii) an evaluation of transfer functions to convert free-field motions to foundation input motions; (iii) incorporation of springs and dashpots (or more complex nonlinear elements) to represent the stiffness and damping at the soil- foundation interface; and (iv) a response analysis of the combined structure- spring/dashpot system with the foundation input motion applied.

The superposition inherent in a substructure approach requires an assumption of linear soil and structure behavior, although in practice this requirement is often followed only in an equivalent-linear sense. As depicted in Figure 1-2, the steps in a substructure approach are as follows: Specification of a foundation input motion (FIM), which is the motion of the base-slab that accounts for the stiffness and geometry of the foundation. Because inertia is dealt with separately, the FIM applies for the theoretical condition of the base-slab and structure having no mass (Figure 1-2b). This motion generally differs from the free-field motion, involves both translational and rotational components, and represents the seismic demand applied to the foundation and structural system. The variation between free-field and foundation input motions is expressed by a transfer function that represents the ratio of foundation/free- field motion in the frequency domain. Since inertial effects are neglected, the transfer function represents the effects of kinematic interaction only. An essential first step in defining the FIM is to evaluate the free-field response of the site, which is the spatial and temporal variation of ground motion in the absence of the structure and foundation. This task requires that the earthquake input motion in the free field is known, either at a specific point (e.g., ground surface, rock-outcrop) or in the form of incident waves (e.g., oblique shear waves) propagating up from a reference depth.

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Having established the free-field motion, wave-propagation analyses are performed to estimate the foundation input motion along the planned soil- foundation interface, as depicted in Figure 1-2d. Equivalent linear properties for the soil (material damping) can be evaluated as part of this analysis.

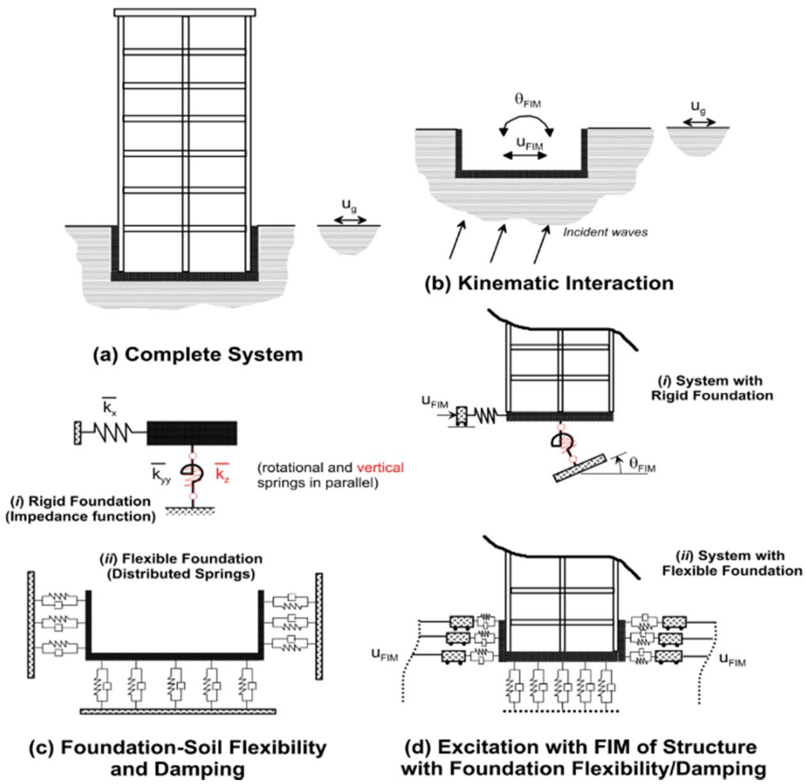

Figure -Direct analysis of soil-structure interaction by finite elements.

The stiffness and damping characteristics of the soil-foundation interaction are characterized using relatively simple impedance function models or a series of distributed springs and dashpots. Impedance functions represent the frequency- dependent stiffness and damping characteristics of soil-foundation interaction. Use of impedance function models for rigid foundations is illustrated in Figure 1-2c(i). Use of a series of distributed springs and dashpots acting around the foundation is illustrated in Figure 1-2c(ii).
The latter case of distributed springs and dashpots is needed when foundation elements are non-rigid, or when internal demands are required outcomes of the analysis.
The superstructure is modeled above the foundation and the system is excited through the foundation by displacing the ends of the springs and dashpots using the rocking and translational components of the FIM. It should be noted that FIM varies with depth. In the case of the distributed spring and dashpot model, differential ground displacements should be applied over the depth of embedment. This application of spatially variable displacements introduces a rotational component to the FIM, which is why a rotational component does not specifically appear in Figure.

1) Most of the civil engineering structures involve some type of structural element with direct contact with ground.
2) The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as soil-structure interaction.
3) In general conventional structural design methods neglect the SSI effects.
4) The effect of SSI, however, becomes prominent for heavy structures resting on relatively soft soils.
5) Most of the civil engineering structures involve some type of structural element with direct contact with ground. When the external forces, such as earthquakes, act on these systems, neither the structural displacements nor the ground displacements, are independent of each other. The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as soil-structure interaction (SSI).

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III. INERTIAL INTERACTION

Inertial interaction refers to displacements and rotations at the foundation level of a structure that result from inertia-driven forces such as base shear and moment. This chapter describes inertial soil-structure interaction effects. Inertial displacements and rotations can be a significant source of flexibility and energy dissipation in the soil- structure system.

Section 2.1 discusses system behavior and highlights some of the principal effects of inertial interaction and the conditions for which its effects are significant. The methods focus on single degree-of-freedom systems, but they can be extrapolated to multi-degree-of-freedom systems with a dominant first mode. Section 2.2 provides a relatively detailed description of how foundation springs and dashpots can be specified to represent the flexibility and damping associated with soil-foundation interaction in translational and rotational vibration modes for shallow foundations (e.g., footings and mats). Section 2.3 provides corresponding solutions for the stiffness and damping characteristics of deep foundations Some of the procedures given in Section 2.2 This program can also be used for pile foundations, although the results are relatively approximate.

Section 2.4 presents several models that can be used to evaluate shallow foundation response for conditions involving nonlinear material behavior or geometric nonlinearities.

IV. KINEMATIC INTERACTION

Kinematic interaction results from the presence of stiff foundation elements on or in soil, which causes motions at the foundation to deviate from free-field motions. One cause of these deviations is base-slab averaging, in which spatially variable ground motions within the building envelope are averaged within the foundation footprint due to the stiffness and strength of the foundation system. Another cause of deviation is embedment effects, in which foundation-level motions are reduced as a result of ground motion reduction with depth below the free surface. If the foundation is pile-supported, the piles interact with wave propagation below the base slab, which can further modify foundation-level motions at the base of a structure.

This chapter describes the phenomena of base-slab averaging, embedment effects, and kinematic pile response, and presents available models for analysis of these effects. Models for kinematic interaction effects are expressed as frequency- dependent ratios of the Fourier amplitudes (i.e., transfer functions) of foundation input motion (FIM) to free-field motion. The FIM is the theoretical motion of the base slab if the near-surface foundation elements (i.e., base slabs, basement walls) and the structure had no mass, and is used for seismic response analysis in the substructure approach described in Section 1.2.Shallow Foundations at the Ground Surface Base-slab averaging results from adjustment of spatially variable ground motions that would be present within the envelope of the foundation, which are averaged within the foundation footprint due to the stiffness and strength of the foundation system.

Base-slab averaging can be understood by recognizing that the motion that would have occurred in the absence of the structure is spatially variable. Placement of a foundation slab across these variations produces an averaging effect in which the foundation

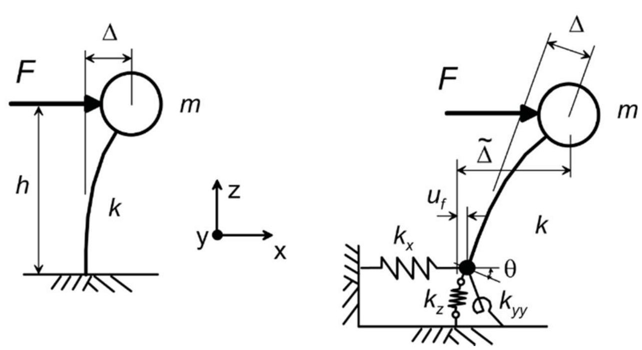

Figure- Deflections caused by force applied

Motion is less than the localized maxima that would have occurred in the free-field. Torsional rotations, referred to as the "tau effect" (Newmark, 1969), can also be introduced.

Motions of surface foundations are modified relative to the free-field when seismic waves are incoherent. Incoherence of the incident waves at two different points means that they have variations in their phase angle. Some incoherence is deterministic (i.e., predictable), because it results from wave passage. For example, as illustrated in Figure 3-1a, the presence of a non-zero vertical angle causes waves to arrive at different points along the foundation of a building at different times.

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V. SOIL-STRUCTURE SYSTEM BEHAVIOR

A rigid base refers to soil supports with infinite stiffness (i.e., without soil springs). A rigid foundation refers to foundation elements with infinite stiffness (i.e., not deformable). A fixed base refers to a combination of a rigid foundation elements on a rigid base. A flexible base analysis considers the compliance (i.e., deformability) of both the foundation elements and the soil.

Consider a single degree-of-freedom structure with stiffness, k, and mass, m, resting on a fixed base, as depicted in Figure 2-1a. A static force, F, causes deflection.

A. Effect of Non-Uniform Soil Profiles

In most cases, V_s profiles are evaluated away from foundations (i.e., in the free-field) and reflect a variation of shear modulus with depth. Variation in soil shear modulus with depth, and the presence of additional weight from a structure, complicates the

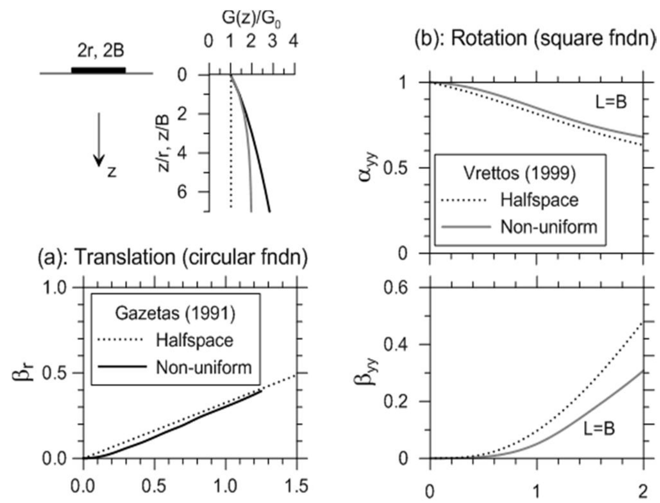

Figure-Plot of dynamic stiffness modifiers and radiation damping ratios versus dimensionless frequency.

Selection of an appropriate shear wave velocity in the calculation of static foundation stiffnesses.

To evaluate a single effective V_s value for use in computations, it is necessary to: (1) correct V_s values measured in the free-field to account for overburden pressures associated with the added weight of the structure; and (2) calculate an average effective V_s value over an appropriate depth range.

Figure 2-6 shows a plot of dynamic stiffness modifiers and radiation damping ratios comparing results for a uniform half-space and non-uniform profiles in which G varies with depth, as shown.

The effect on radiation damping is more pronounced in rotation (Figure 2-6b) than in translation (Figure 2-6a). Also, the effect on the rotational stiffness modifier for square foundations (Figure 2-6b) is modest.

Hence, the effect of variation in soil shear modulus with depth is most critical for static stiffness and radiation damping associated with foundation rocking. Because rocking is often an insignificant contributor to overall foundation damping, the practical impact of soil non-homogeneity is primarily related to its effect on static stiffness.

B. Effect of Flexible Structural Foundation Elements

Classical impedance function solutions, such as those presented in Table 2-2 and Table 2-3, strictly apply for rigid foundations. As illustrated in Figure 2-1, soil- foundation interaction for rigid foundations can be represented by individual springs for each foundation degree of freedom. Actual foundation slabs and basement walls, however, are non-rigid structural elements. The few theoretical solutions that exist apply to circular foundations supporting a rigid core, flexible perimeter walls or rigid concentric walls. Figure 2-7 shows the effect of flexible foundation elements on rotational stiffness and rotational radiation damping ratio for the cases of a circular foundation supporting a rigid core or flexible perimeter wall.

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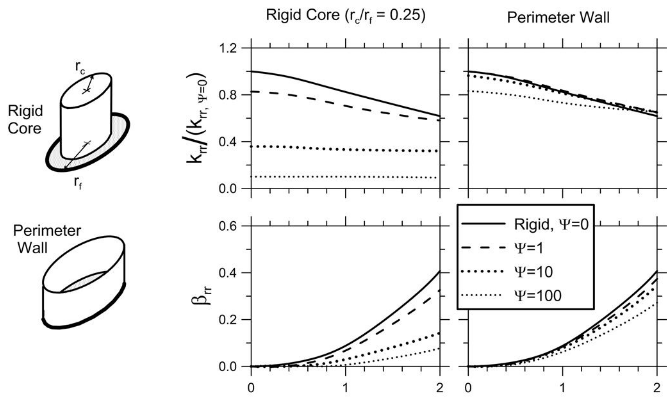

Figure- Effect of flexible foundation elements on rotational stiffness and rotational radiation damping ratio for circular foundations supporting a rigid core

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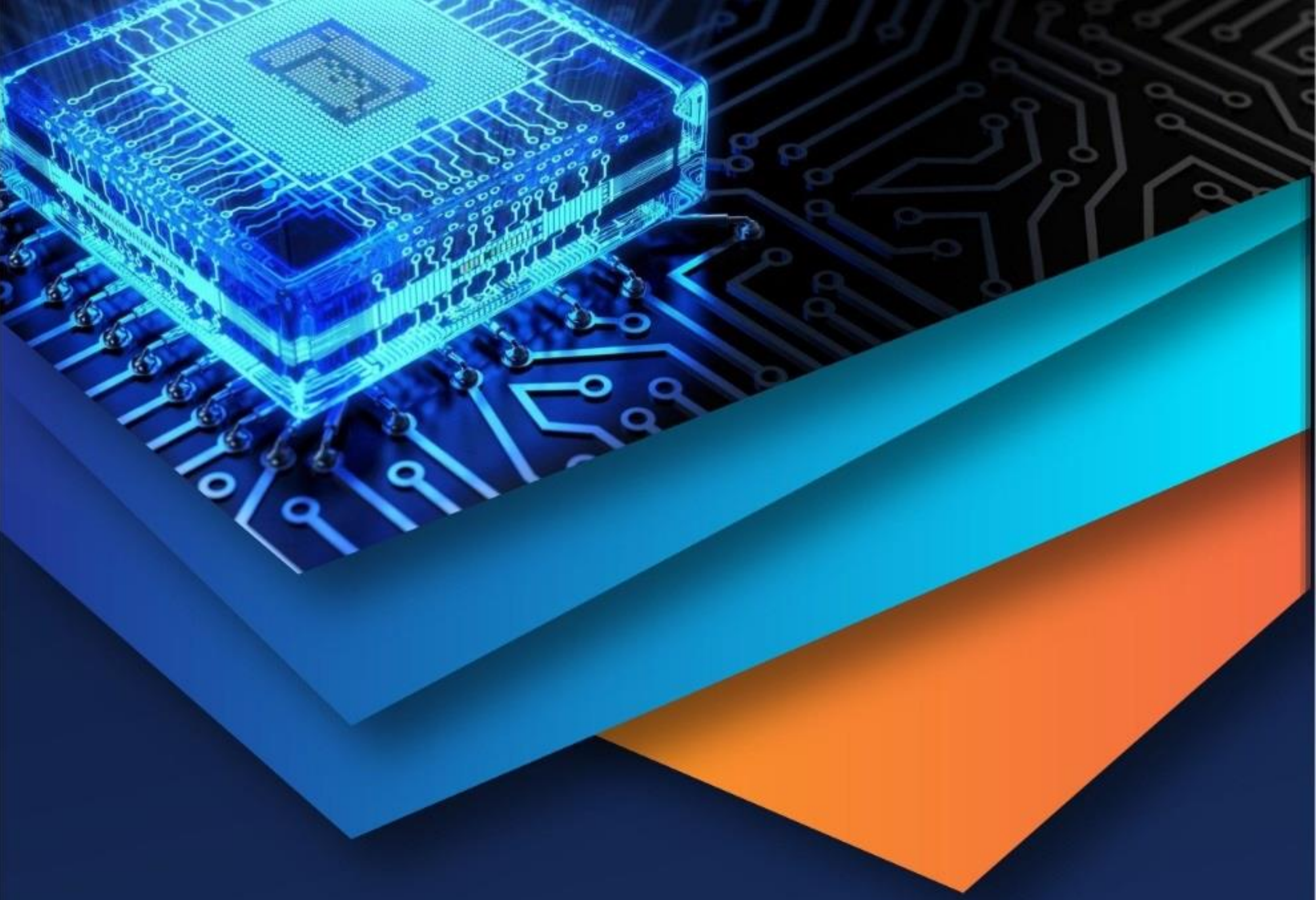

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