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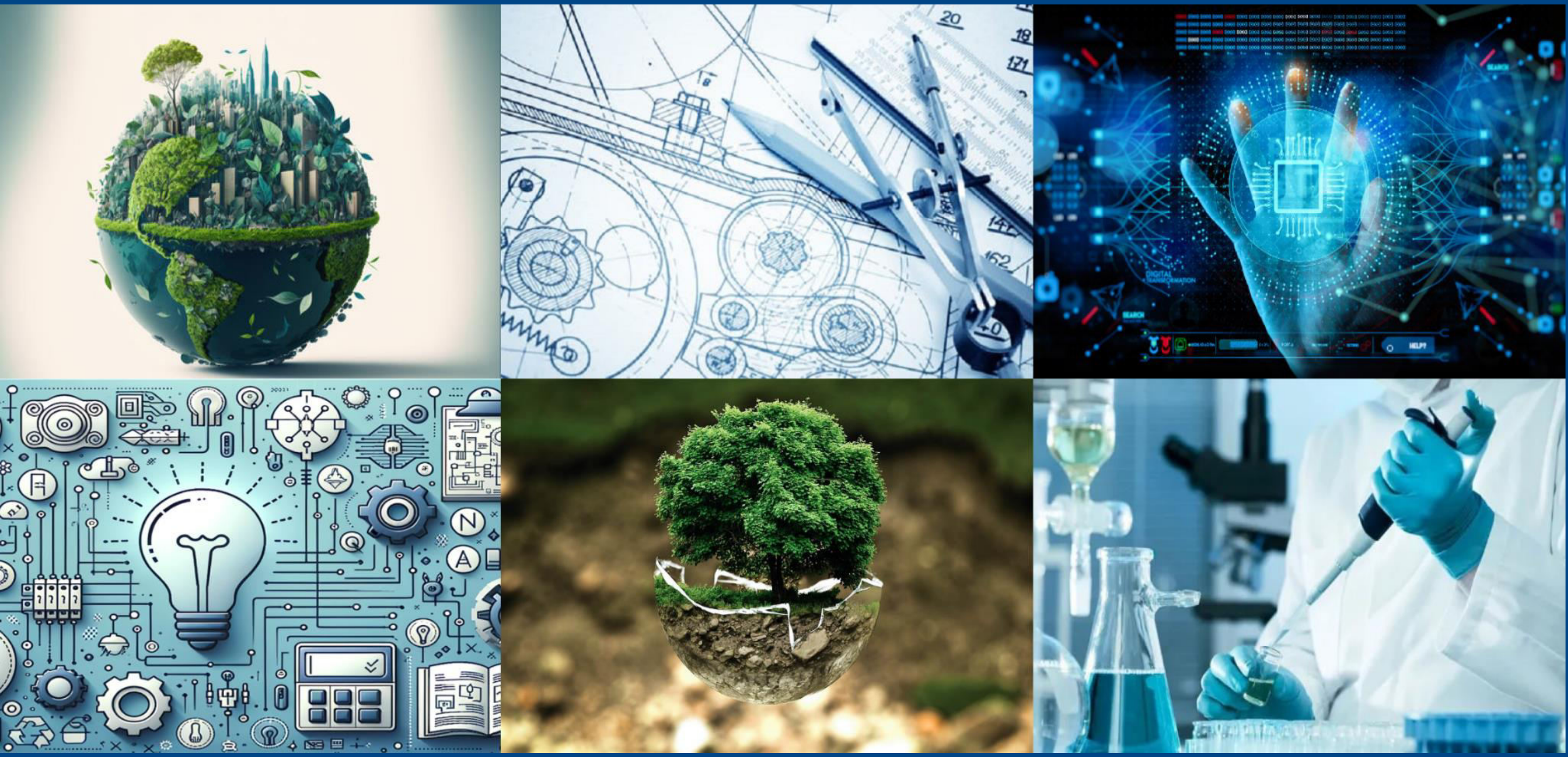

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Analytical Investigation of Soil–Structure Interaction Effects on Seismic Performance of Reinforced Concrete Frame Buildings

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ABSTRACT: Soil–Structure Interaction (SSI) is a critical factor influencing seismic performance of Reinforced Concrete (RC) frame buildings. Conventional seismic analysis generally assumes a fixed-base condition which neglects flexibility of supporting soil and may lead to unrealistic estimation of structural response. This investigates effect of SSI on RC frame buildings by comparing fixed-base and flexible-base models under seismic loading. Study evaluates key response parameters under different soil conditions including hard, medium & soft soil. Results indicate that incorporation of soil flexibility increases the natural time period and structural displacements while reducing base shear values. However, increased drift and deformation demand highlight greater vulnerability of structures particularly in soft soil conditions. Study concludes that SSI significantly alters seismic response and should be considered in design practice to ensure realistic and safer earthquake-resistant structures.

KEYWORDS: Soil–Structure Interaction, Reinforced Concrete frame buildings, Seismic performance, Base shear & Inter-storey drift

I. INTRODUCTION

Reinforced Concrete (RC) frame buildings are widely used in modern construction because of their strength, flexibility in design and ability to resist both vertical and lateral loads. In earthquake-prone regions, seismic performance of these structures becomes a major concern. Response of a building during seismic activity depends not only on its structural properties but also on the characteristics of the supporting soil. Interaction between soil and structure during ground motion is known as Soil–Structure Interaction. In most traditional seismic analyses, buildings are assumed to have a fixed base, meaning that foundation is considered rigid and non-deformable. In real field conditions, soil is not perfectly rigid and undergoes deformation when subjected to seismic forces. This deformation changes the way seismic energy is transferred to structure thereby affecting its overall response.

This plays an important role in modifying key structural parameters as natural time period, base shear, storey displacement & inter-storey drift. Generally, soil flexibility increases the natural time period and displacement demand while reducing base shear. These changes can significantly influence seismic safety and serviceability of structures, especially in medium and soft soil conditions. Ignoring SSI effects may lead to inaccurate estimation of structural response and unsafe design assumptions. Therefore, it is necessary to consider soil flexibility for realistic seismic analysis. This helps in understanding actual behavior of structures during earthquakes & improving seismic design accuracy.

II. OBJECTIVES OF STUDY

1. To evaluate SSI effect on various dynamic properties of structure.
2. To evaluate SSI effect on structure response as Roof Displacement, Beam Moment and Column Moment.
3. To evaluate the effectiveness of two SSI models as Elastic Continuum Model (ECM) and Spring model (Winkler Model).
4. To investigate the effectiveness of different provisions to counterbalances the SSI effect.

III. LITERATURE REVIEWS

Ashok Sharma & Rakesh Mehta (2025) present recent advancements in Soil–Structure Interaction analysis for Reinforced Concrete frame buildings. Authors review modern analytical techniques, computational models and numerical methods used in SSI studies. Emphasis is placed on improved simulation tools that consider nonlinear soil behavior and dynamic loading effects. Study also discusses SSI influences seismic response parameters. Findings suggest that advanced modeling techniques provide more accurate predictions of structural behavior compared to traditional fixed-base assumptions. Paper concludes that SSI integration is essential for reliable earthquake-resistant design of RC structures.

Santoso, A. K. & Saito, T. (2024) investigate dynamic Soil–Structure Interaction effects on seismic behavior of base-isolated Reinforced Concrete buildings. Study evaluates soil flexibility influences performance of isolation systems under earthquake excitation. Analytical simulations show that SSI can modify isolation efficiency, structural displacement & energy dissipation characteristics. Results indicate that soil conditions significantly affect effectiveness of base isolation systems. SSI should be considered in the design of base-isolated structures to ensure accurate performance prediction and enhanced seismic safety.

Singh, Y. & Ghosh, S. (2023) present an analytical investigation of Soil–Structure Interaction effects on earthquake response of RC frame buildings. Study compares fixed-base and SSI models under seismic loading using numerical analysis. Key parameters as natural period, base shear, storey displacement and drift are evaluated. Results show that SSI increases structural flexibility and deformation demand while reducing base shear values.

Dasgupta, K. & Banerjee, S. (2022) investigate impact of Soil–Structure Interaction on seismic response of mid-rise Reinforced Concrete buildings. Authors develop numerical models considering both fixed-base and flexible-base conditions to evaluate structural behavior under earthquake loading. Results show that SSI significantly increases natural time period, storey displacement and inter-storey drift while reducing base shear values. Eeffect is more pronounced in soft soil conditions compared to hard soil.

Choudhury, T. & Ghosh, S. (2021) authors model RC frames under varying soil conditions to assess changes in seismic response. Study shows an increase in flexibility and displacement demand when soil effects are included. It concludes that fixed-base assumptions may not represent actual seismic performance accurately. The research recommends incorporating SSI in design practice for safer and more realistic structural analysis.

Aydin, E. et al. (2020) analyze soil flexibility affects the performance of energy dissipation devices as dampers under seismic loading conditions. Numerical simulations are carried out to compare fixed-base and SSI-inclusive models. Results show that ignoring SSI may lead to inefficient damper design and inaccurate estimation of seismic demand. Study concludes that soil flexibility significantly modifies structural response and must be considered while optimizing passive control systems for improved seismic safety and structural efficiency under earthquake excitations.

Kori, J. G. & Patil, S. S. (2019) evaluates seismic response of RC frame structures considering soil flexibility. Analytical models of multi-storey buildings are developed under both fixed-base & SSI conditions. Study focuses on variations in natural time period, base shear and displacement response. Effect becomes more significant in soft soil conditions. These conclude that ignoring soil–structure interaction may underestimate deformation demands and lead to unsafe design. Study recommends incorporating SSI effects for accurate seismic performance evaluation of RC framed buildings.

Arboleda-Monsalve & Chouw (2018) examines seismic Soil–Structure Interaction effects on multi-storey buildings subjected to earthquake loading. Study uses analytical and numerical approaches to evaluate soil flexibility influences dynamic response parameters. Different soil conditions are considered to understand variability in structural behavior. SSI increases structural flexibility and displacement demands while reducing base shear. Study emphasizes importance of incorporating soil flexibility in seismic analysis for realistic performance evaluation of multi-storey building structures.

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IV. METHODOLOGY

Methodology involves analytical modeling & seismic analysis of R.C. frame buildings with & without Soil–Structure Interaction**.**

1. Building Description

In present analytical study, multi-storey Reinforced Concrete (R.C.) frame buildings of different heights namely G+5, G+7, G+10 & G+12 are considered to evaluate effect of Soil–Structure Interaction on seismic performance. These buildings represent low-rise to high-rise categories commonly used in urban infrastructure. Each building is assumed to have a regular, symmetrical plan configuration to eliminate torsional effects and ensure uniform distribution of mass and stiffness. A constant storey height is maintained throughout all models to ensure consistency in dynamic analysis. The structural system consists of moment-resisting R.C. frames designed as per relevant Indian Standard codes, ensuring realistic structural behavior. Beams and columns are designed based on standard loading conditions including dead load, live load & seismic load. Material properties are selected according to codal provisions. This consistent structural configuration helps isolate the influence of soil flexibility on seismic response.

2. Soil Modeling

Soil behavior is modeled using equivalent linear spring elements placed at foundation level to represent Soil–Structure Interaction effects. These springs simulate both translational and rotational stiffness of soil allowing realistic representation of foundation flexibility. Stiffness values are computed using geotechnical parameters. These parameters define the resistance of soil against horizontal, vertical & rotational movements of the foundation system. Medium soil conditions are considered, representing typical site conditions in urban areas. Spring-based modeling approach enables comparison between rigid & flexible foundation behavior and helps in understanding soil deformation influences overall structural response.

3. Structural Modeling

Fixed-base model: This model assumes that foundation of structure is perfectly rigid and completely restrained against all translations and rotations. In this idealized condition, no soil deformation is considered & structure is assumed to be fixed at its base. Seismic forces are directly transferred to superstructure without accounting for soil flexibility which often leads to higher stiffness and lower displacement estimates.

Flexible-base model: This model incorporates effect of Soil–Structure Interaction by introducing soil stiffness through equivalent spring elements at foundation level. These springs represent translational & rotational flexibility of supporting soil. Unlike the fixed-base condition, this model allows foundation movement and energy dissipation through soil deformation, resulting in a more realistic representation of structural behavior under seismic loading.

4. Seismic Analysis

Seismic analysis is performed using the linear dynamic response spectrum method as per IS 1893 (Part 1). This method evaluates the maximum expected seismic response of structures considering different vibration modes. These ensure that the analysis reflects realistic earthquake loading conditions. Modal analysis is carried out to determine natural frequencies and mode shapes of the structure. Response spectrum method is then applied to obtain critical response values. This comparison clearly highlights influence of Soil–Structure Interaction on increasing structural flexibility and deformation demands.

V. RESULT & DISCUSSION

Seismic response of fixed-base & Soil–Structure Interaction considered models is evaluated and compared.

1. Natural Period

Inclusion of Soil–Structure Interaction (SSI) results in an increase in fundamental natural period of all building models. Percentage increase is observed to be higher for taller buildings indicating greater soil flexibility effects. This increase is more significant for taller buildings indicating a stronger influence of soil deformability on global structural stiffness.

Table 1: Fundamental Natural Time Period (sec)

Building Type	Fixed Base	With SSI	% Increase
G+5	0.84	1.24	47.60 %
G+7	1.09	1.56	43.10 %
G+10	1.41	2.11	49.60 %
G+12	1.68	2.48	47.60 %

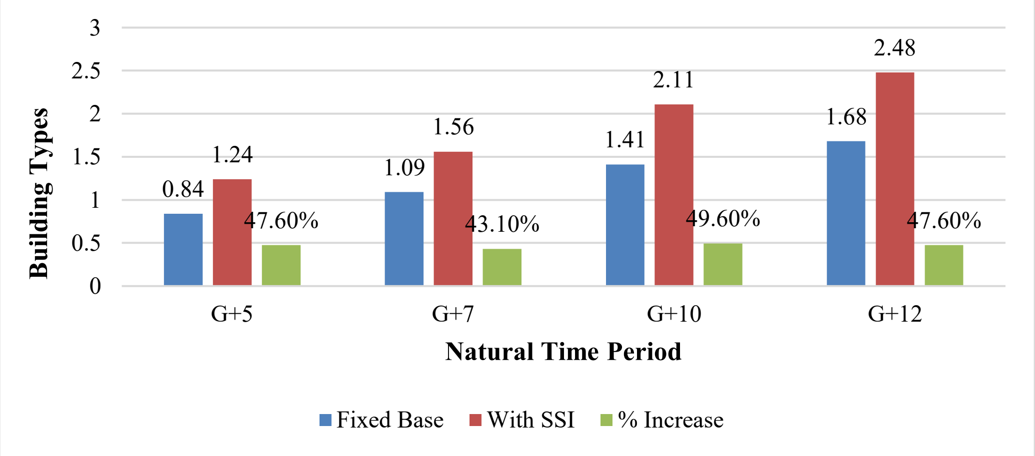

Figure 1: Fundamental Natural Time Period

Fundamental natural time period of buildings shows a significant increase when soil–structure interaction effects are considered compared to fixed-base condition. For G+5 building, time period increases from 0.84 s to 1.24 s representing a 47.60% rise. Similarly, G+7 building shows an increase from 1.09 s to 1.56 s with a 43.10% increase. In case of the G+10 building, time period increases from 1.41 s to 2.11 s which is highest percentage increase of 49.60%. For G+12 building, value rises from 1.68 s to 2.48 s again showing a 47.60% increase. Results clearly indicate that inclusion of SSI leads to a substantial increase in fundamental natural time period of all building types, implying a reduction in structural stiffness and an increase in flexibility due to soil–foundation interaction effects.

2. Base Shear

A reduction in base shear is observed in Soil–Structure Interaction models compared to fixed-base models. This reduction occurs due to lengthening of natural period which shifts structure to a lower spectral acceleration region.

Table 2: Base Shear Comparison (kN)

Building Type	Fixed Base	With SSI	% Reduction
G+5	1820	1420	22.00 %
G+7	2340	1815	22.40 %
G+10	2985	2250	24.60 %
G+12	3650	2700	26.00 %

Comparison of base shear for different building heights shows a clear reduction when soil–structure interaction is considered as compared to fixed-base condition. For G+5 building, base shear decreases from 1820 kN to 1420 kN resulting in a 22.00% reduction. Similarly, G+7 building experiences a reduction from 2340 kN to 1815 kN, corresponding to a 22.40% decrease. In case of G+10 building, base shear reduces from 2985 kN to 2250 kN showing a 24.60% reduction while the G+12 building shows a decrease from 3650 kN to 2700 kN with the highest reduction of 26.00%. Results indicate that inclusion of SSI significantly reduces base shear demand in all building models, which is mainly due to increased flexibility and energy dissipation at the soil–foundation interface leading to lower seismic force transmission to superstructure.

3. Storey Displacement

Flexible-base models exhibit higher lateral displacements at all storey levels. Increase in displacement demand is more prominent at upper storeys which may affect serviceability & non-structural components.

Table 3: Maximum Roof Displacement (mm)

Building Type	Fixed Base	With SSI	% Increase
G+5	18.5	32.8	77.30 %
G+7	26.2	45.6	74.00 %
G+10	38.4	68.9	79.40 %
G+12	52.0	93.5	79.80 %

Comparison of maximum roof displacement for different building heights clearly indicates a significant increase when soil–structure interaction is considered as compared to fixed-base condition. For G+5 building, roof displacement increases from 18.5 mm to 32.8 mm showing a 77.30% rise. Similarly, G+7 building exhibits an increase from 26.2 mm to 45.6 mm corresponding to a 74.00% increase. In case of the G+10 building, displacement increases from 38.4 mm to 68.9 mm resulting in a 79.40% rise while G+12 building shows an increase from 52.0 mm to 93.5 mm which is highest at 79.80%. Results demonstrate that considering SSI significantly amplifies roof displacements in all building models, indicating increased flexibility and reduced stiffness of soil–structure system which leads to greater lateral movement under seismic loading.

4. Inter-Storey Drift

Soil–Structure Interaction leads to increased inter-storey drift values, although they remain within permissible limits for studied cases. Drift demand increases with building height. Increase in drift ratio with SSI indicates greater deformation demand which can affect structural & non-structural safety if not properly controlled.

Table 4: Maximum Inter-Storey Drift Ratio

Building Type	Fixed Base	With SSI
G+5	0.0019	0.0032
G+7	0.0023	0.0038
G+10	0.0028	0.0045
G+12	0.0034	0.0056

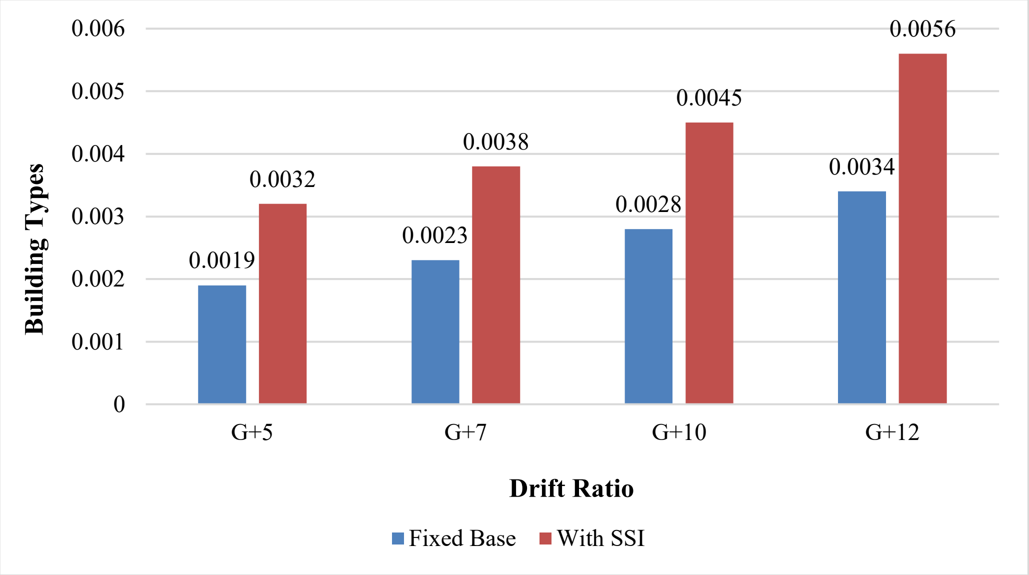

Figure 2: Maximum Inter-Storey Drift Ratio

Comparison of maximum inter-storey drift ratio clearly shows an increase when soil–structure interaction is considered as compared to fixed-base condition for all building types. For G+5 building, drift ratio increases from 0.0019 to 0.0032. Similarly, G+7 building shows an increase from 0.0023 to 0.0038 while G+10 building rises from 0.0028 to 0.0045. In case of G+12 building, drift ratio increases from 0.0034 to 0.0056 which is the highest among all models. Results indicate that inclusion of SSI leads to higher inter-storey drift demands in all structures, implying greater lateral deformation & reduced stiffness of soil–structure system under seismic loading conditions.

VI. CONCLUSION

This highlights significant influence of soil–structure interaction on seismic response of multi-storey reinforced concrete frame buildings of different heights. These clearly demonstrate that inclusion of SSI leads to notable changes in key dynamic & response parameters when compared with fixed-base condition. Fundamental natural time period increases considerably for all building models indicating a reduction in overall stiffness & an increase in structural flexibility due to foundation–soil interaction effects. This increase ranges approximately from 43% to 50% showing that SSI has a strong influence on dynamic characteristics of structure.

At same time, base shear values are found to decrease in all cases under SSI conditions, with reductions ranging from about 22% to 26%. This indicates that seismic force demand transferred to superstructure is reduced due to energy dissipation & flexibility at the soil–foundation interface. Despite reduction in base shear, displacement response of structures increases significantly. Maximum roof displacement shows a substantial rise of nearly 74% to 80% while inter-storey drift ratios also increase for all building heights indicating higher lateral deformation demands. It simultaneously amplifies displacement & drift responses which may govern design in many cases. Therefore, considering soil–structure interaction is essential for achieving realistic & safe seismic performance assessment of medium- to high-rise Therefore, incorporating soil–structure interaction in seismic analysis provides a more realistic assessment of structural behavior & is essential for ensuring safe & reliable earthquake-resistant design of R.C. frame buildings.

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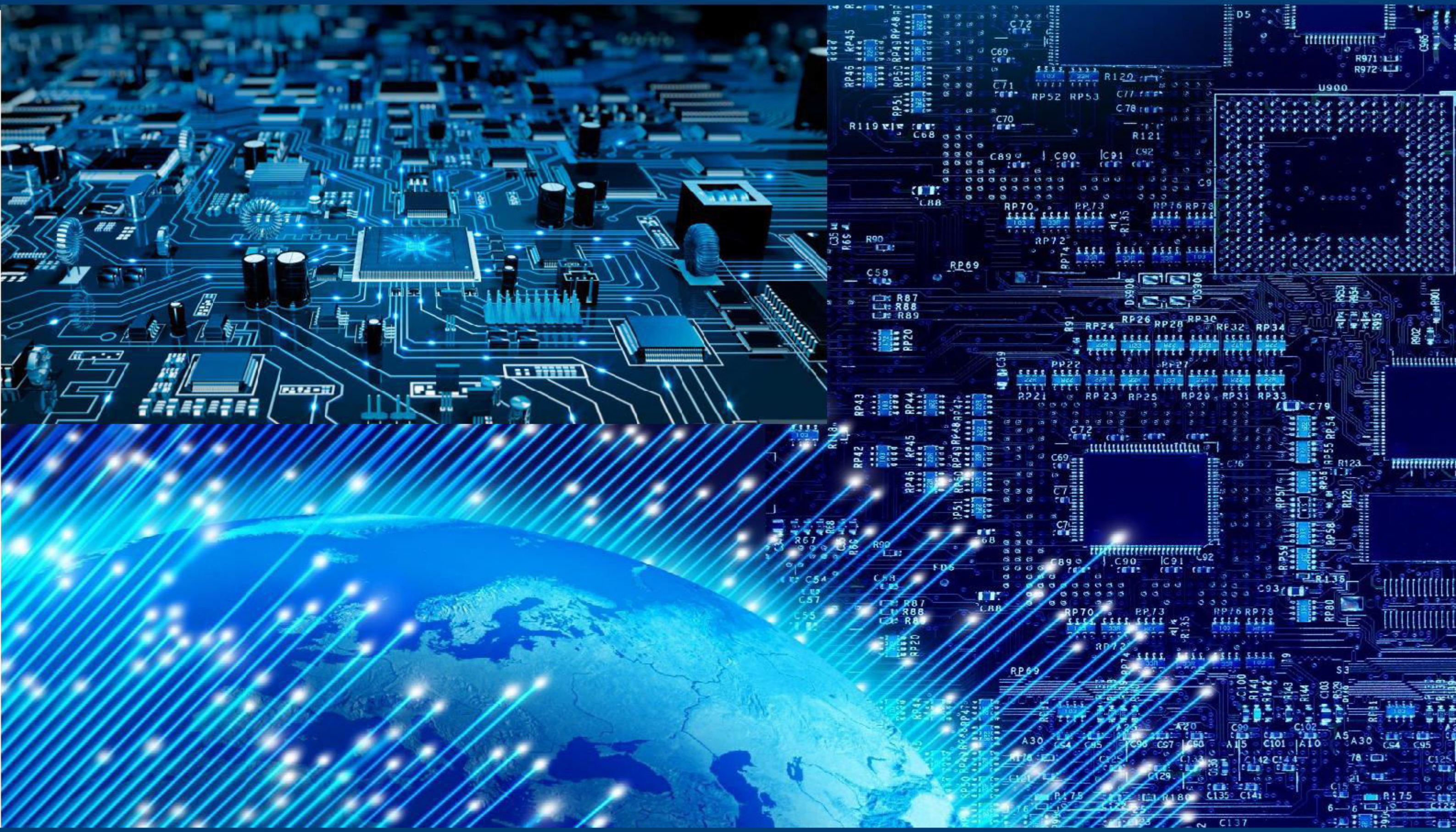

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