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THE EFFECT OF SOIL-STRUCTURE INTERACTION (SSI) ON STRUCTURAL STABILITY AND SUSTAINABILITY OF RC STRUCTURES

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A b s t r a c t

The issue of SSI involves how the ground or soil reacts to a building built on top of it. Both the character of the structure and the nature of the soil have an impact on the stresses that exist between them, which in turn affects how the structure and soil beneath it move. The issue is crucial, particularly in earthquake regions. The interaction between soil and structure is an extremely intriguing factor in increasing or reducing structural damage or movement. Structures sitting on deformable soil as opposed to strong soil will experience an increase in static settlement and a decrease in seismic harm. The engineer must take into account that the soil liquefaction problem occurs for soft ground in seismic areas. A reinforced concrete wall-frame dual framework's dynamic reaction to SSI has not been sufficiently studied and is infrequently taken into consideration in engineering practice. The structures' seismic performance when SSI effects are taken into account is still unknown, and there are still some misconceptions about the SSI idea, especially regarding RC wall-frame dual systems. The simulation study of the soil beneath the foundations significantly impacts the framework's frequency response and dynamic properties. Therefore, the overall significance of SSI in the structural aspect and sustainability aspects will be reviewed in this research.

Keywords: soil-structure interaction, structural stability, dynamic response, fragility assessment

1. INTRODUCTION

SSI is the connection between the subsoil and the built-up structure above it. Ground vibrations typically have a variety of effects on the structure. SSI is caused by the transfer of ground vibrations to the above-occupied structure. Soil structure interactions are particularly useful in earthquake impact analysis [1]. The SSI is determined by the subsoil type and the construction above it. The movement of the ground

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and the waves generated during seismic events affect the deformation of the structure above the soil. Various types of soil-structure interactions cause structural damage or deformations. When conducting a study, both the soil response and the structure are considered [2]. Interactions can be negotiated in the case of light structures as well as rigid soil conditions. Engineering aspects of studies are only required in the case of SSI when its effect is responsible for some type of damage or when there is an appreciable effect on the motion of the structure's basement as compared to normal ground conditions [3].

In the case of soil structure analysis, two specific parameters should be considered: foundation condition, and subsoil condition. The effect of interaction forces on soil movement is measured by the amount of force acting and the foundation's reliability [4].

1.1 SSI and structural response

The effect of SSI is very useful for a structural response, depending on traditional customs. As a result, the design codes that recommend SSI interactions during earthquake analysis have been ignored [5]. There will be a false concept that these interactions will provide positive flexibility to the structure and will significantly increase the safety part. Finally, it helps to improve the structure's natural period. It will also help to maintain a positive approach in the case of the damping ratio while considering dynamic loading conditions, there is a major concern regarding structural engineering design. There should be some structural control methods available to maintain the structure's strength and ductility. Aside from all traditional techniques, they can be provided with different control systems to improve performance and efficiency. SSI has traditionally been studied solely on the basis of time period and frequency. In the case of frequency conditions, the structure interaction is also defined by the specific frequency. Even though the soil system is nonlinear, the system is treated as a linear system [6]. Few studies have been conducted to determine how the system responds to a symmetric building while taking its SSI into account. Interactions through foundations increase the fundamental elastic-plastic period of structure when compared with fixed base considerations, but SSI considerations result in a drop in the structure's fundamental elastoplastic period. It was obvious that SSI impacts the mass and stiffness of the complete structural system. It also reduces the wall sections' major moment and shear ratios. SSI increases column ratios and tends to overload the vertical element's top [7].

1.2 Provision of seismic codes on the basis of SSI in structural response

It is commonly assumed that SSI is a purely positive impact that could be easily ignored for conservative design. Code for seismic design SSI features is optional, and by considering SSI as a positive influence, designers can decrease building design base shear. The fundamental idea behind the provisions is that a fixed-base system with a similar period and often a higher damping ratio may be utilized in place of the "soil-structure system" [8].

The vast majority of design algorithms employ overly simple design spectrums that achieve continuous acceleration up to a period and then monotonically fall after that. A structure with SSI is more flexible and has a longer natural period in comparison to a rigidly supported structure. Furthermore, consideration of the SSI influence results in an increase in the effective damping ratio of the system [9]. The spectrum's smooth idealization shows a decreased seismic response due to SSI, with longer natural periods and a damping ratio. This is the main argument for "seismic design codes" to decrease the design base shear when this impact is taken into account [10]. The same concept underpins contemporary popular "seismic design codes" like ASCE 7-10 as well as ASCE 7-16. Though the previously suggested concept, i.e., base shear drop, functions well for linear "soil-structure" systems, it is demonstrated that it is insufficient to fully represent the impact of SSI on yielding systems. Researchers assessed the effects of implementing the SSI elements of ASCE 7-10 and the NEHRP

("National Earthquake Hazards Reduction Program") 2015, which serve as the foundation for the ASCE's seismic design standard in 2016. They demonstrated that ASCE 7-10 SSI and NEHRP provisions consequence in unsafe designs along with surface foundations on moderately "soft soils", but NEHRP marginally enhances the present provisions for "squat structures". Both clauses result in conservative structure designs on very soft soils, in which NEHRP is even more conservative. Lastly, both options produce designs that are close to optimal for other systems [11].

2. DYNAMIC RESPONSE OF THE STRUCTURE SUBJECTED TO SSI

Several earthquakes have struck in recent years, causing structural harm to buildings. The significance of SSI for static as well as dynamic loads was a topic of concern for structural engineers [12]. It enhances the damping of the structural system and lengthens the structure period. The impact of SSI on the functionality of a building as a whole, especially on soft soils, is a subject of discussion among scholars [13]. Limit-state issue solutions based on soil mechanics generally model the soil and interface as constitutive entities, with the structural component being treated as either a stiff or completely flexible body [14]. Soft soil is more significantly affected by SSI than medium or hard soil. A variation of Winkler's springs was used by numerous researchers to simulate soil-structure interaction [15]. Winkler's approach, while straightforward, is inaccurate because it does not accurately record deflections, particularly for the sub-structure. Therefore, a contrast of the findings for the super as well as the sub-structure is essential to comprehend the impact of different modelling approaches [16].

2.1 Influence of SSI on Fragility Assessment of Structures

When a structural system or component is exposed to a broad variety of seismic action, they are more likely to fail to conduct adequately within a set limit state. This is known as seismic fragility. According to the definition given above, seismic fragility study may be viewed as a probabilistic metric for seismic performance evaluation of structural systems or components [17]. The damage chance matrix and fragility curve are the two distinct final results of seismic fragility analysis. Since it serves as a tool for determining the structural systems' safety buffer, seismic fragility analysis is regarded as the key component of the risk assessment process. Numerous studies that employ fragility analysis as a tool for evaluation have already been released [18].

Fundamental to studying SSI is predicting the system's reaction while ignoring the significance of non-linearity. When analysing and designing seismically isolated bridges, SSI impacts and the effect of higher modes of vibration are frequently disregarded. Several studies have looked into the efficiency of isolation tools for the seismic construction or retrofit of bridges in recent years [19]. Diagrams of the likelihood of exceeding a limit state, like collapse, against a measure of the "ground motion intensity", such as "spectral acceleration" at the basic period, are known as seismic fragility curves. The typical approach used for empirically assessing seismic vulnerability is the creation of DPMs ("Damage Probability Matrices"), where each element represents the likelihood that exposed buildings in a region subject to an earthquake with a particular level of ground motion maintain a provided level of damage [20]. For any structure type subjected to a certain seismic demand, the frequency of different damage states must be determined to estimate seismic susceptibility. It is necessary to normalize the number of buildings of a certain structural type in an area that exceeds or achieves a specific degree of damage for a ground motion to the overall number of such structures in the region [21].

1.3 Effect of SSI on different base conditions

A foundation is commonly considered to be simply connected to a rigid rock subjected to lateral "unidirectional acceleration" in classical structural design, while SSI is typically disregarded in the earthquake-resistant structure's design [22]. A set of piles could be used to support tall structures on medium- to soft-soil foundations, and pile-raft foundations are typically utilized to distribute the structural weight to the earth's depth. A collection of piles' static effects is fairly obvious, but because their dynamic impacts are unknown, they were not taken into account when designing the piles. "Piled-raft foundations" have a large positive impact on the seismic reaction of the superstructure when the structure is built on the surface, for example, a 40 percent drop in the base shear [23]. The usage of "piled-raft foundations" is not important and has little impact when the building is situated inside an excavation. For tall structures, the impacts of foundation rocking are quite substantial. The moments drift, and displacements of the model along with foundation rocking have been impacted in the research. Despite having a piled-raft foundation, this model's adverse impacts from foundation rocking were not eliminated. Further research is required to fill the knowledge gap in the area and improve predictions of the behaviour of superstructures within soft soil conditions [24]. Studies looked at the impacts of SSI and random differences in the crucial soil parameter values on steel building fragility. The soil's shear modulus was found to have a substantial influence on the fragility outcomes than soil parameters.

It has been shown that SSI could enhance the chance of failure with reference to the fixed-base scenario despite seasonal fluctuations in the soil parameters after converting the "fixed-base spectral accelerations" into its flexible-base equivalents and redrawing the SSI curves. The primary cause of this phenomenon was determined to be a rise in the story drifts of the building's lower portion as a result of SSI [25]. Studies of slope stability based on SSI interactions have also been performed. The hardening soil model, which requires less computational effort as compared to the Mohr-Coulomb soil system in slope stability problems, tends to determine the safety factor with a narrow posterior distribution, demonstrating that constitutive models that take into account the effect of strength within the elastic region are better suitable for efficient data assimilation. To handle unsaturated soil flow and look into differential settlement brought using rainfall infiltration, the van Genuchten model and Barcelona basic model have both been suggested as the best solutions for settlement issues. It should be mentioned that these have been combined with random fields in the FEM ("Finite Element Method") to account for soil heterogeneity [26]. The impact of SSPSI ("Seismic Soil-Pile Foundation-Structure Interaction") on the dynamic properties and elastic response of a scaled-model structure as well as pile foundation, including a parametric change of the lateral period of the pile and superstructure group, was once become the subject of research. According to parametric research on the variation of pile foundations' lateral stiffness, choosing a conservative design by placing more piles together in soft clay could produce a building that responds roughly equally to a fixed base condition. The cause might be that the results of conservative design in a substantial rise in the foundation's lateral stiffness, which causes the base condition to be nearly fixed [27].

2.3 Modelling Techniques in SSI

There are two primary methods utilized to determine the SSI system: the direct and substructure approach.

2.3.1 Substructure approach

The Indirect Method or (Substructure Method) divides the structure and the soil into independent structural systems for analysis. The seismic input placed to the designer using the approach is the ground motion within Free-field. The Time history approach or the response spectrum method in this methodology may be used to calculate the non-correlation between the ground and the structure. To determine the structure's reaction when inertial interaction is considered, the estimated outcome is utilized in the SSI analysis's Foundation Input Motion of the Kinematic Interaction System [28]. The structure’s final seismic response is determined using this technique by combining such impacts based on the superposition of these effects. It considers both the structure and soil separately, solves them, and then accounts for both in calculating the final seismic response. In other words, using impedance & transfer functions, the substructure method can solve inertial and kinematic interactions independently [29]- [30] Therefore, only by thoroughly studying a structure with few “degrees of freedom” could the dynamic properties of a big and complex structure be determined. Fig 1 depicts the Substructure method for the investigation of the SSI.

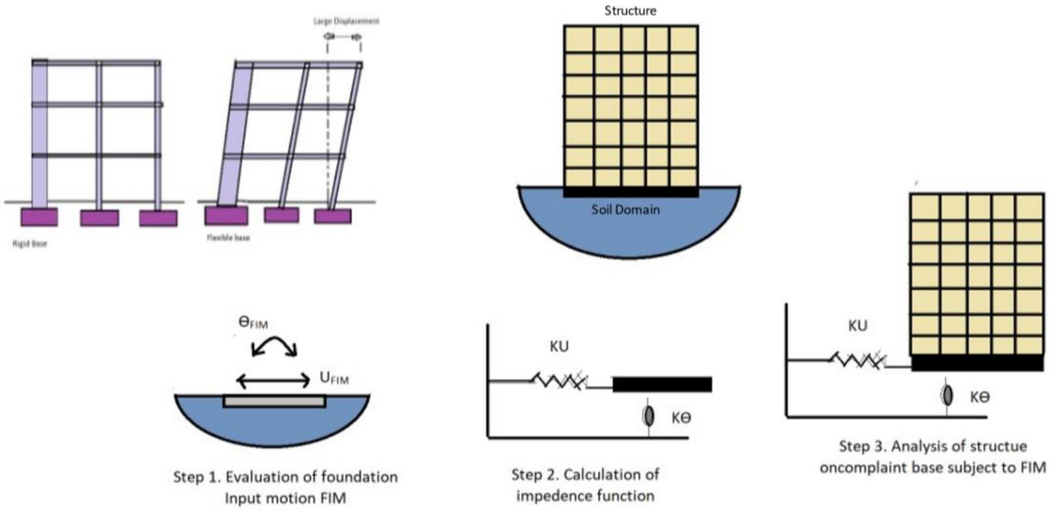

Fig. 1. Substructure method to the study of the SSI

2.3.2 Direct Approach

It is considered to be the most rigorous method for resolving SSI issues, particularly when dealing with complex structural geometry as well as non-linear soil. In this approach, structure and soil are simultaneously modelled as a single system and examined. Although this strategy is very effective at solving a variety of SSI issues, including both straightforward linear and difficult non-linear ones, it is also complicated, inefficient, and expensive, making it an illogical way to design typical structures [31]. There is a third method, known as the macro element method, in addition to the two previously stated ones. The soil medium is divided into the near as well as far fields using the macro element technique. Less study has used the macro element method because it is more recent than the direct and substructure approaches [32]. This approach models both the structure and soil within a single phase, taking into account both inertial & kinematic interaction. Structures produce inertial interaction owing to their inherent vibrations, which cause “foundation displacements” related to the free field as a consequence of base shear and base moment. While kinematic interaction happens as a result of stiff foundation materials on or within the soil, producing foundation motion to diverge from free field movements [33]. Superstructures and foundations are often found to have simpler and less complicated modelling than the soil medium underneath them. Superstructures and foundation modelling are often found to be less complicated and more straightforward than the soil medium underneath them. However, modelling the soil domain is the most difficult aspect of solving soil-structure interaction issues.

2.4 Soil Domain Modelling Techniques

There are various soil domain modelling techniques under different categories. Fig 2 Illustrates the different models of approach under various methods and modelling strategies.

2.4.1 Winkler model

The Winkler method is a soil modelling concept in which the subsoil is modelled as a set of springs that will deform when a weight is applied to it. We will consider the stress-strain behavior as linear in this approach [34]. This method only reflects one parameter, which is known as the subgrade reaction’s modulus. According to studies, the common formulation allows the Substructure Strategy that takes nonlinear soil behavior in free-field response into account in addition to that produced with structure [35]. There are primarily two exchanges occurring between the subsoil and the above structure. These are inertial contacts and kinematic interactions. The base shear and moment caused by the building's own vibrations' inertia result in foundation displacements relative to the free field. The damping produced by foundation-soil interaction and the flexibility of the foundation support may both be described by frequency-dependent foundation impedance functions [36]. Wave inclination, or foundation embedment, foundation movements might differ from free-field motions in the incidence of stiff foundation components on or within soil owing to ground motion incoherence. Using a frequency-dependent transfer function, the free-field motion is compared to the motion that would occur on the base slab if the slab and framework were massless. The foundations can be represented by essentially stiff slabs, according to building SSI studies. Thus, the system’s degrees of freedom is restricted, and it is possible to isolate the inertial and kinematic interactions [37]. Building SSI analyses presume that foundations can be represented by essentially rigid slabs. This limits the system's degrees of freedom and enables separation into inertial and kinematic interactions [38].

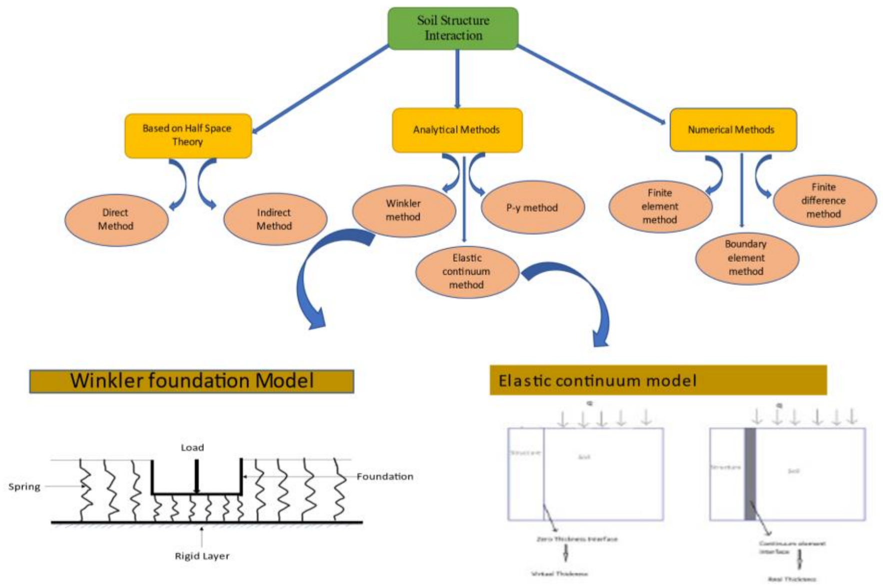

Fig. 2. Various modelling approaches to SSI determination

2.4.2 Lumped parameter models

Massless foundations lying on or immersed in “homogeneous elastic half-space” are examples of frequency-based models for the interactions between soil and structure [39]. This idea is known as a lumped parameter model. This model type substitutes a collection of masses, dashpots, and frequency-dependent springs within the direction of “degrees of freedom” for the soil domain. There are different adoptions in that. One of them is Spring and Dashpots by Gazetas [40]. Compared to the Winkler model's frequency-independent springs, the frequency-dependent impacts and “damping coefficients” of the model have a greater impact on the total structural response. It is determined, however, that the present model is not sufficiently precise to analyze complicated SSI issues [41].

2.4.3 Model of a discrete element cone by Wolf

Based on the previously presented truncated cone theory, Wolf (1994) developed this model. The central idea of this system is to substitute the soil domain for the translational and rotational parts of motion with a “semi-infinite truncated” cone. The system is made up of a hard circular base linked to the soil by a network of dashpots and springs located beneath every foundation [42]. Contrary to thorough approaches that deal with the extremely complex wave pattern made up of generalized surface waves and body waves and operate in the wave number domain. The approach is depending on the propagation of waves in cones, with reflections appearing at the interface between the layer, hard base, and a free surface. The wave propagation in cones approach is an efficient and affordable tool for designing foundations that can withstand dynamic loads, since it gives physical knowledge that is sometimes veiled by the difficulty of rigorous numerical solutions, demonstrates appropriate accuracy, and is easy to implement [43].

3. SOIL STRUCTURE INTERACTION EFFECTS ON BUILDINGS

After an earthquake, civil infrastructure sustains substantial losses that can be measured in terms of direct and indirect losses. Owners and insurance companies are very concerned about earthquake-related losses because large earthquakes cause a lot of social disruption and death [44]. Another significant phenomenon that was the subject of numerous research analyses has been the SSI impact on the seismic reaction of structures [45]. Building foundations frequently rely on soil, making them flexible bases. Though, the conventional approach of evaluating any building makes the implausible assumption that the building's foundation is rigid (fixed), when in fact the local condition of soil has a substantial effect on how the structure responds [46]. Seismic vibrations traveling via near-field exhibit greater amplification as compared to traveling via far field owing to the material as well as geometrical nonlinearity. Different seismic demand variables, such as inter-story drift, story shear, fundamental period and should be assessed and compared to a flexible base to better comprehend the behavior of SSI. When taking into account the pounding effect, research has shown that soil flexibility (SSSI) commonly had a significantly growing impact on the resultant “pounding forces” and caused the pounding to occur even at further clear distances. Both the flexible and fixed-base situations had virtually the same hammering tales. The only floors where there was more hammering were the top floors. At the obvious distance from the code, there was hardly any pounding. Increased story shears along with lateral displacements, especially in the stories of the taller structure directly above the surrounding shorter building, were shown to be mostly caused by pounding as compared to SSSI [47].

3.1 RC Buildings' Seismic Vulnerability in the Impacts of SSI

The nonlinear response study of a building under multiple ground motions is the finest tool for describing a structure's seismic vulnerability [48]. In such a study, the ends of several structural members grow plastic hinges. Based on its ability for ductility, each member can withstand a particular amount of rotation at the plastic hinge. Additionally, certain members, typically columns, are not allowed to be subjected to axial pressures that exceed their corresponding capacities. The member is classified as seismically susceptible if the maximum capacity is reached [49]. For relatively regular structures, dynamic, linear static, and/or nonlinear static processes could be utilized to perform the seismic vulnerability analysis outlined above equally well; however, the nonlinear dynamic study is favoured due to its better accuracy and greater confidence [50]. Studies have been done to see if SSI has an impact on the "seismic performance" as well as vulnerability of RC ("Reinforced Concrete") buildings. Utilizing a finite-element framework, a collection of RC frames situated on various kinds of soil were designed and modelled. The soil-foundation relationship was modelled using both linear and nonlinear techniques. To examine the seismic behaviour and fragility of RC structures in the assumptions of flexible and rigid bases, nonlinear static along with incremental dynamic analyses have been conducted. The outcome then reveals that the midrise frames located on soft locations performed at a significantly higher level. Additionally, the inter-story drifts grew significantly as the number of stories within the system increased due to the "foundation flexibility" for RC frames lying on soft soil [51].

In most instances, the seismic structures design using SSI techniques is thought to be more efficient, economical, and safe than fixed-base designs. Although very common, finite element techniques that applied the direct expression to resolve SSI issues have very expensive software costs and lengthy analysis times. Despite the availability of affordable and effective software, most analyses of structures focus solely on the superstructure, ignoring the geotechnical characteristics of the earth and their interactions with the structure. Machine learning-based database techniques are dependable and yield solid outcomes. ANNs ("Artificial Neural Networks") and SVMs ("Support Vector Machines") are applied in machine learning to examine how interactions between soil and structures affect the seismic response of buildings in various earthquake situations [52]. This was on the basis of a few investigations. In this research, the investigation of four frame buildings involves changing the seismic and soil properties. Various sample sizes and optimization methods were also applied to find the optimal ML ("Machine-Learning") framework. Three engineering requirement factors are the outputs, while the input parameters include seismic and soil properties. The network is evaluated on a 3-story building along with mass irregularity as well as 4 story building after being trained on three- and five-story buildings. Additionally, the dynamic responses found with fixed-base and "ASCE 7-16 SSI" approaches are contrasted with the suggested method. With "nonlinear time history" study results as a benchmark, the proposed machine learning technique outperformed fixed-base as well as ASCE 7-16 approaches. The findings demonstrated that, when compared to fixed-base, SVM, along with ASCE 7-16 linear SSI approaches, the results of the SSI-based ANN system have been in good alignment with "nonlinear time history" analysis [53].

When SSI is included in the seismic analysis, the building often experiences less stress, which leads to a more cost-effective design [54]. Due to recently added provisions in both European and American regulations, this kind of technique is acceptable. But taking into consideration SSI might also lead to the detection of adverse consequences since the dynamic features of the structure are altered. Unfavorable outcomes include increased story drifts or global displacements increased base or story shear pressures, increased post-elastic loads on the structural components, and the collision of nearby structures that are separated by insufficient structural connections. SSI should be taken into account when designing structures for earthquakes, but the existing design codes do not provide a clear implementation strategy that engineers in the field can use. More research must be done in this area to develop methodologies that can be incorporated into the existing structural architecture [55]. Using pushover analysis, experts' work on open ground, multi-story structure frames with fixed and flexible bases were examined for various boundary conditions. Models of the earth's properties use rotational and translational springs. For comparison purposes, the analysis also comprises 2 additional boundary condition instances: fixed as well as hinged helps at the base. The lateral deflection and period of the building frames' seismic reaction are examined. Two additional boundary conditions are included in the research for comparison, namely fixed & hinged supports at the base [56]. We compare the lateral deflection and duration of the building frames' seismic responses. According to research, frames with a greater slenderness ratio show a stronger effect of SSI on lateral behavior [57]. The relationship between the sub and super-structure is examined by modelling the soil as simply as possible to reflect the system's overall reaction. The research demonstrated how taking into account different variables, such as SSI and wall placement, significantly affects the building frame's period, displacement, and base shear [58]. Therefore, it is crucial to take into account all of these factors when analyzing designs. When compared to other locations, shear walls in the middle of a multistorey structure produce baser shear and less displacement [59]. Non-linear dynamic analysis has been used in research on the SSI impacts on the "seismic performances" of two-dimensional RC "Moment-Resisting Frames" (MRFs) [60]. The study shows that SSI has a different impact on seismic demand based on the modelling approach, with respect to maximum base shear as well as maximum inter-story drift ratio[61]. Few scholars have applied thorough nonlinear dynamic study of structures with various lateral "load-bearing" systems based on flexible soil. Larger story drifts are typically the result of taking "no-tension soil springs" on the level of foundation into consideration [62]. The placement of infill walls can increase the stiffness of SMRFs and significantly reduce the fundamental periods, according to a seismic vulnerability evaluation of SMRFs ("Steel Moment-Resisting Frames") supposing various placement of infill walls that incorporate nonlinear SSI [63]. In the seismic construction of buildings, structural eccentricity is crucial. It is one of the criteria used by different seismic design codes to determine whether a structure can be regarded as regular in the plan [64]. The gap between the center of mass and rigidity is referred to as structural eccentricity. However, under the premise of fixed-based settings, the center of rigidity is precisely specified in "single-story" buildings as well as in some particular types of "multi-story" buildings, such as isotropic ones. Particularly in the case of soft soils, the applied loading pattern is crucial in determining the "twist axis" for single-story structures [65]. Therefore, it is impossible to disregard the impact of the loading that is used at the foundation [66]. The frequency content of earthquakes has a substantial impact on the seismic reaction of buildings.

3.2 SSI Impacts on Structural System

Although there is no question that the impacts of SSI could have a major influence on how structures respond to seismic loads, this system is frequently disregarded in the control of the structure [67]. The majority of buildings in metropolitan areas are made of reinforced concrete (RC) frames, either with or without RC shear walls. The installation of these walls increases the building's lateral load capacity and lateral stiffness in areas with high seismic activity [68]. Building seismic behavior has been reported to be significantly influenced by SSI in previous earthquakes, especially when the building is situated on soft soil. The shear wall affects the natural vibration properties by shortening the "natural period" and altering the RC frame's mode shape profile. In comparison to a flexible frame, the alteration is substantially greater for a stiffer frame. Additionally, the alteration for frames with SSI effects is noticeably reduced[69]. The magnitude of seismic force created during an earthquake shaking depends on the intrinsic vibration properties of the structure. The key factor that controls the magnitude of the mobilized force is the vibration's natural period. Smaller building frames have greater SSI impacts due to their smaller widths and heights [70]. This is because the shear wall contributes more to the frame's total rigidity with smaller widths. The system gets more flexible as width and height increase, showing fewer SSI impacts. SSI impacts are more pronounced in shorter frames than in taller frames [71]. A very small number of studies examined the relationship between soil flexibility and the pounding caused by earthquakes on nearby buildings. Engineers frequently treat brick infill panels as non-structural components when building various kinds of frame constructions. In the meantime, modern specifications and building standards stress the significance of considering the influence of infill panels since they might significantly affect how the structure responds to seismic excitation [72]. Since the impact of SSI is thought to be advantageous to the structure's response during seismic excitation, the conventional high-rise building design approach often supposes that the structure is fixed on the base. Recent earthquakes and research, however, suggested that SSI might have a negative impact on structural systems that are often used. Researchers are examining the seismic activity of frame-core tube constructions with a range of soil types, foundation types, height-width ratios, and structural heights. They examine and contrast the outcomes of numerical simulations that included flexible-base buildings, base shears of rigid-base, inter-story drifts, foundation rocking, and maximum lateral deflections. The findings show that when SSI is considered, base shears are not always minimized but the inter-story drifts as well as lateral displacement of the superstructure could be increased. The subsoil and foundation stiffness might typically be raised to meet a structure's higher seismic requirements [73]. To determine the impact of SSI on "high-rise frame-core tube" constructions, several researchers create and verify an upgraded soil-structure numerical model utilizing the ABAQUS program [74].

A key factor in the design and study of reinforced concrete (RCC) walls and other structures is soil-structure interaction (SSI). The way the surrounding soil interacts with the structure can have a big impact on how the structure behaves and performs overall. An RCC wall's base is essential to the interaction between the earth and the structure. The characteristics of the underlying soil must be taken into account in the construction of the foundation, regardless of whether it is shallow or deep. Important elements affecting the foundation design are soil-structure interaction, settling, and soil carrying capacity. A thorough geotechnical examination is necessary to comprehend the soil properties. Lateral earth pressure on RCC walls is frequently caused by backfill dirt or other external loads. The lateral earth pressure acting on the wall is influenced by the kind of soil and its characteristics. Different techniques, taking into account the interaction between the wall and the surrounding soil, are frequently used to estimate lateral earth pressure, such as the Rankine or Terzaghi theories. In-depth modelling and analysis of the soil-structure interaction are frequently done using numerical techniques like finite element analysis. Engineers can simulate the intricate behaviour of the earth and the structure under varied loading scenarios thanks to FEA.

3.3 Soil Structure Interaction in Bridges

Reinforced concrete bridge structures may appear to have simpler structural systems than regular buildings, however, these structures respond more complexly to earthquake loads. Bridges have cross-sectional dimensions that are orders of magnitude greater [75]. They traverse irregular soil surfaces, and connections between them are not always monolithic. Their boundary conditions cause geometrical nonlinearity concerns and higher modes of vibration frequently contribute significantly. In terms of directivity, amplitude, duration, frequency content, and approximations made when choosing an earthquake ground motion scenario have an impact on bridge structures as well [76]. The random as well as nonlinear behavior of soil could result in inadequate levels of reliability in RC bridge construction. Because of this, it is important to consider how different soil properties may influence how a bridge behaves at its ultimate and serviceability limit states [77]. Researchers looked into the likelihood of current reinforced concrete bridges failing because of how the soil and structure interact. The reliability investigation emphasizes the crucial role that SSI plays and demonstrates just how vulnerable structural safety is to variations in soil parameters, particularly when nonlinear soil behavior is taken into account [78]. Utilizing simple finite element methods, the superstructure's seismic response is assessed in the time domain while considering frequency-dependent impedances of the soil-foundation system. Soil piles, radiation damping, as well as pile-to-pile contact, are all taken into consideration during the explicit frequency domain kinematic interaction analysis. SSI has a significant impact on global bridge flexibility, particularly in the longitudinal direction, which decreases the use of higher frequencies [79]. It was discovered that in every instance of rock classes & input earth motions, the interaction between the structure, foundation, and soil couldn't be disregarded. Additionally, pier column non-linearity had a greater impact on base stress and bridge displacement than SSI did. The impact of foundation rocking on bridge response variables has also been a factor of investigation owing to the high rocking impedance of correctly built bridge foundations, [80].

4. SSI IMPACT ON STRUCTURES' PROGRESSIVE COLLAPSE

Since the early 1970s, the occurrence of buildings collapsing gradually has been thoroughly studied. The phenomenon may be caused by a variety of abnormal loading situations that most civil engineering buildings were not intended to withstand. Although the bomb blast is one of the main reasons for this occurrence, other accidents can also result in progressive collapse [81]. Now more than ever, it is significant to consider the impacts of SSI due to the pervasive usage of performance-based design methods. A probabilistic formulation is used for these studies because there are uncertainties in the performance assessment of structures [82]. The circumstances will be better for averting progressive collapse if SSI were taken into account since the soil density and level of groundwater should increase [83]. Evaluation of the structural resistance of RC frames to progressive failure usually uses nonlinear static analysis. The benefit of this method is that it can consider nonlinear impacts [83]. The soil environment is more difficult to describe than a structure because it is semi-infinite and inhomogeneous. In SSI analysis, selecting an appropriate modelling approach and exact computational approach is a difficult and crucial problem. The "seismic response" obtained from the soil structure's dynamic study is realistic when the soil environment is studied using an appropriate modelling approach [84].

To assess the final collapse state's disproportionality, current practice primarily considers direct and pure structural damage; however, a consequence-based method in which "indirect structural" damages. Including costs and repairability in the evaluation process can result in a structure for evaluation that is more thorough [85]. It is crucial to determine a structure's susceptibility to progressive collapse events to prevent "catastrophic structural" failure of high-risk buildings under blast loads. The progressive collapse of buildings is not currently addressed by any suggestions or provisions in the existing guidelines of several nations [86].

5. SSI IMPACT ON THE STRUCTURES' TORSIONAL RESPONSE

Recent reports have noted that torsional response failures in structures were frequent during earlier earthquakes. Researchers discovered that the structures of asymmetric have been more vulnerable to harm than symmetric structures via the numerical study of the structure in seismic excitation. Building structures may exhibit a false torsional reaction if SSI is ignored during the seismic response analysis. Fixed-base analyses frequently fail to correctly forecast the building structures' torsional response. There will be a torsional reaction of the roof floor during horizontal seismic excitation if the structure is assisted with an embedded-pile foundation with nonunique pile lengths, as the rigidity and mass center of the "soil foundation system" will not coincide. The induced torsional response also grows as the difference between the pile lengths widens [87]. The majority of seismic codes include design advice for strength distribution depending on the popular wisdom that element strength and stiffness is an independent characteristic to lessen the impact of torsion during earthquakes [88]. A wall-type system's lateral stiffness distribution cannot be established before the components' strengths have been assigned. As a result, both stiffness and strength eccentricity play significant roles in determining how asymmetric wall-type structures respond to earthquakes. The lateral displacement generally rises and the rotational response generally decreases under flexibility conditions [89]. Studies have shown that the interaction between structure and soil can increase the nonlinear reactions of lower stories. The bulk of research has paid more attention to the resulting dynamic responses than the specific distribution of "nonlinear responses" in SSI along the height of the analyzed structures [90]. The story plans of real structures exhibit some eccentricity between stiffness and mass (or/and strength) centers. Therefore, the effects of such eccentricities should be considered in realistic SSI research [91].

6. SSI IN PERFORMANCE-BASED DESIGN

Structures must be designed using performance-based criteria (PBD). philosophy has been used to fulfill a structure's seismic requirements and lessen harm from various seismic motions. Given that structures behave nonlinearly in the presence of significant seismic movements, nonlinear response history, as well as a nonlinear static pushover analysis, are 2 fundamental methodologies for the PBD of buildings [92]. Due to its high processing complexity, the cost of analysis, "high sensitivity" to specific ground motions, and the necessity to specify the hysteretic behaviour of parts, nonlinear dynamic analysis—one of these two approaches—is less often utilized. "Nonlinear static pushover analysis" is therefore widely employed in the PBD method [93]. Several research has employed elastoplastic oscillators supported by soil springs to examine the impacts of SSI on the seismic response of SDOF ("Single-Degree-of-Freedom") structures. It was discovered that structures with "natural periods" greater than the "site period" have favourable SSI impacts, but buildings with natural periods lower than the site period have adverse impacts. This suggests that using conservative design solutions does not always result in SSI effects being ignored in seismic design processes[94]. One of the most important components of the transit system that has been damaged by earthquakes in the past is bridges[95]. Seismic loading causes permanent soil displacement when the bridge superstructure shifts laterally toward the abutment, applying lateral compressive stress and activating passive resistance within the soil backfill. The abutment and the soil may become separated when the bridge travels away from it[96]. Bridges typically stay in the elastic region when they are exposed to small earthquake-induced lateral forces. However, when exposed to intense earthquake shaking, the bridge's dynamic response changes and is primarily reliant on the nonlinear effects of SSI between the abutments and the backfill soils [97]. The mobilization of passive pressure behind the abutment back wall during a seismic event principally contributes to the "nonlinear force-displacement" capability of the bridge abutment. The monotonic pushover method aims to encompass the real cyclic loading during earthquake shaking and is a practical and efficient device for performance-based design [98]. To account for SSI, the inelastic response theories that were established in practice for fixed-base structures were expanded by researchers. It was discovered that, based on the period ratio of the site and structure, the SSI effects could lead to significant increases or decreases in the spectral ordinates relative to fixed-base values [99].

7. ADVANCEMENT IN SSI

The Direct and Substructure approaches of analysis are the results of two different paths that the development of SSI has taken over the past 25 years. In terms of state-of-the-art systems, the two techniques are fairly similar, with the only difference being the dynamic boundary constraints stated along the border of the finite soil area under consideration. Thus, it is possible to develop a single formulation that applies to both strategies equally. In the context of the Substructure Method, the Boundary Element approach was demonstrated to be particularly efficient in managing geometrically irregular circumstances at the soil-structure interface [100].

Among the most contentious and difficult topics in the domain of seismic design and the requalification of various structures is the adoption of the most accurate as well as realistic modelling approach and computing methodology for the consideration of dynamic SSI impacts. Numerical techniques (such as FDM and FEM) can incorporate impacts of radiation damping, material damping, stress anisotropy, heterogeneous material conditions, material nonlinearity, and variations in the geometry of the assisting soil medium within dynamic SSI analysis, in contrast to other studied SSI modelling approaches in studies [101]. In "structural analysis" and construction, the base of the system is frequently assumed to be rigid. This is true despite the fact that the system is stiffer and the basic period is shorter when a rigid base is assumed [102]. On the SSI systems' dynamic behavior, both of the aforementioned outcomes have a significant impact. Additionally, the system's highly flexible earth component typically functions as an energy sink, which increases the damping of the entire system. Over the past few decades, there have been a lot of studies done on the influences of dynamic SSI and side effects on the seismic response of structures. Furthermore, it was revealed that the positive impact of SSI is only a conditionally true oversimplification.

To capture the nonlinear behaviour of both materials under loading, nonlinear material models are used for both the soil and the concrete. While soil may display nonlinearities in stress-strain behaviour, concrete may display nonlinearities as a result of crushing, cracking, and other reasons. Sophisticated constitutive models for soil, including hypo plasticity or critical state models, are used to depict the intricate stress-strain behaviour of soils in different scenarios. These models are able to represent characteristics such as anisotropic behaviour, dilatancy, and strain softening. Discrete element modelling and finite element analysis are two examples of advanced numerical modelling approaches that are increasingly being used. With the use of these tools, engineers may model intricate relationships between soil and structures while taking into account a variety of variables, including geometric complexity, material behaviour, and nonlinearity. Particularly in seismic engineering, dynamic SSI analysis is essential. The dynamic interaction between the soil and the structure during earthquakes is taken into account by advanced models. It is possible to use time-domain or frequency-domain analysis, and soil damping effects are frequently included. In certain circumstances, a coupled study that takes into account the interaction between the soil and the structure at the same time may yield more accurate results. In order to do this, the equations of motion for the soil and the structure must be fully connected. It becomes crucial to take fluid-structure interaction into account in situations when the structure is near a water table or comes into contact with water. Soil-Structure-Fluid Interaction (SSFI) is an expanded analysis that takes into account buoyancy and pore water pressure. To improve design techniques and validate models, real-world performance data is essential. The creation and deployment of efficient instrumentation and monitoring systems to gather information on the behaviour of structures in response to soil-structure interaction throughout time are ongoing concerns. More sophisticated models take into account realistic boundary conditions that mimic the soil-structure system's genuine behaviour. This involves taking foundation flexibility into consideration in addition to lateral and vertical limits. For a more thorough understanding of the possible variability in the system response, stochastic approaches, such as probabilistic or reliability-based methods, can be used to account for uncertainties in soil qualities, loading circumstances, and other parameters. Large deformation analysis might be required in circumstances when notable deformations are anticipated. This is particularly important when digging deep holes, tunnelling, or in other situations when the soil-structure system experiences significant geometrical changes. Uncertainties about sea level rise, temperature fluctuations, and precipitation patterns are among the environmental conditions brought about by climate change. Engineers are thinking about how these alterations could impact the characteristics of the soil and, in turn, how it interacts with structures. An important part of the relationship between soil and structure is foundation design [103]. Concerns about settlement, bearing capacity, and the general stability of foundations are constantly being addressed by developments in geotechnical engineering and foundation technology.

8. CONCLUSION

One immediate effect of SSI effects is that the seismic hazard for the neighbourhood could alter if a building or group of structures is constructed or demolished. Significant structural changes result from this, particularly with regard to seismic micro zonation analyses, insurance policies, and land-use planning. During the roughly 40 years of research, some pertinent ideas have advanced extraordinarily. Nevertheless, there will be a lot of work to be done in the ensuing years. The findings of the structural analysis with the soil included produce stresses and deformations that are most similar to the structure's actual behaviour when compared to those obtained from a study of a fixed-base structure. The traditional construction process, which excludes SSI from the analysis, is not a sufficient way to ensure the structure's safety. Design engineers need to be aware of SSI's impacts, especially in soft soils. The range of soil-structure interaction comprises tunnels, bridge abutments, subsurface pipe lines, and retaining walls, among other structures. These areas are to be explored more. Several significant facts about soil-structure interaction are revealed by a survey of contemporary research. First, it appears that there are contradictory comparisons between the lumped parameter and finite element solutions. It is important to address the dynamic interaction between soil and structures, particularly in areas that are prone to earthquakes. Scholars are consistently improving their analytical techniques and numerical models to gain a deeper comprehension and forecast of the dynamic behaviour of structures on various soil types. Soil structure fluid interaction (SSFI) is becoming a bigger problem for buildings that are in or close to bodies of water. This is the interplay of structure, fluid, and soil (typically water). Engineers are investigating methods for precisely simulating and analysing the impact of water on the behaviour of structures, taking hydrodynamic forces and buoyancy into account. The focus of engineers is shifting from just completing code requirements to attaining particular performance objectives in performance-based design techniques. This entails taking into account elements like sustainability, resilience, and a structure's capacity to tolerate a range of risks, including those arising from the interaction between soil and structure.

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