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Performance Evaluation of Irregular Structures Under Seismic Response Considering Soil-Structure Interaction: A Review

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Abstract: **The hazardous destruction observed due to previous earthquakes till date such as the 2015 Nepal earthquake, 2017 Mexico City earthquake and the recent 2023 Turkey-Syria earthquake, has indicated the extreme vulnerabilities associated with the construction of asymmetrical buildings subject to the course of failure and structural defects it poses. Presence of irregularities are inevitable in today's construction scenario subject to the dire scarcity in available land area while adapting to less favourable geotechnical and extreme seismic conditions. Albeit irregularities cause damages to buildings, the seismic codes have not prohibited them, but have instead imposed specific penalties on them. Soil-structure interaction (SSI) has been traditionally considered to be beneficial in nature. However, existing researches have justified this dissent and the necessity in formulating adequate performance-based design guidelines during structural analysis and design. Thus, the present paper attempts to provide a summarized state-of-the-art review on the recent relevant numerical and experimental contributions orienting SSI and structural irregularities and the implications associated with it. The review would aid the professional and research fraternity in guaranteeing necessary awareness on the importance of incorporating the SSI influence during structural analysis and design while ensuring a performance-based approach.**

Keywords- Soil-structure interaction; Structural irregularities; Seismic excitation; Structural analysis, Earthquake Engineering

1. INTRODUCTION

Asymmetrical structures are inevitable in today's construction scenario owing to the inadequate geographical conditions, functionality and aesthetic requirements. Presence of structural irregularities are depicted by the incorporation of discontinuities in either, both plan and elevation or individually when compared to the regular bare frame structure. Major parameters affecting the structural configuration of a building depends on various aspects such as geometry, size and shape of building, location characteristics, type and degree of irregularity and the like. Structures with irregular configuration either horizontally or vertically are more vulnerable to seismic action and wind forces resulting in strength reduction causing the detrimental collapse of structures, property loss and casualties [1,2]. Under practical scenarios, concerning infrastructure, major seismic codes distinguish between irregularity in plan and elevation separately, but it must be realized that quite often structural irregularity is the result of a combination of both single and multiple irregularities. Although a considerable number of researches are adopted on capturing the responses of irregular configuration subjected to earthquake excitation, well-accepted and relevant guidelines for multi-storey irregular configuration of structures are still yet to be framed and executed [1]. In addition to the structural collapse exhibited due to the presence of irregularities, another prime parameter responsible for structural damage is the influence of the underlying soil on the seismic response of structures. The Indian seismic design code (IS 1893 (Part 1):2002 [3]) has mentioned that the influence of SSI can be neglected when the ground is sufficiently rigid enough to resist lateral deformation due to external excitation. However, the presence of loose or soft soil beneath the foundation underestimates the structural stability by reducing the overall structural performance [4]. This aspect is clearly justified through the hazardous defects exhibited by previous earthquakes such as the recent Turkey-Syria earthquake (Magnitude 7.8) due to the major structural defects and geotechnical failure of the underlying soil mass. Extensive investigation conducted indicated the major reasons responsible for the unprecedented extent of damage as shown in figure 1 [5].

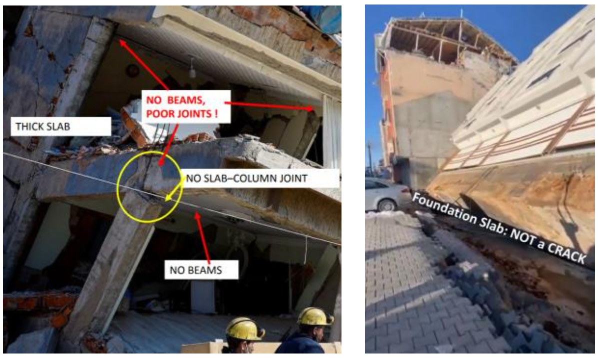

Fig. 1 Structural and geotechnical defects observed in buildings during Turkey-Syria earthquake, 2023

In addition to the extreme seismic shaking, with peak ground acceleration (PGA) in the order of at least 0.7g to 1g, major structural deficiencies such as presence of slender columns and thick slabs, inadequate steel reinforcement, transverse reinforcing bars of inadequate density and improperly tied, absence of beams with improper beam-column joints, absence of shear walls even in buildings greater than 10 stories were mainly responsible for this massive destruction under seismic response. The main geotechnical failure associated with the destructive effect depends on the overturning of a building apparently due to bearing-capacity failure on soft soil under strong seismic moment. Additionally, various responsible geotechnical reasons include liquefaction property and negligence of soil-structure interaction studies during the structural design of the building. Thus, considering the extensive impact posed by severe dynamic seismic excitation, the recent earthquake is a clear indication of the major flaws in the existing construction techniques and structural analysis methodologies. Numerous studies have critically documented the unsatisfactory performances of irregular buildings under extreme seismic action considering variations in diaphragm flexibility, re-entrant corners, soft and weak stories, presence of setbacks and the like to conclude on the atrocious influence portrayed by structural irregularities subject to dynamic seismic response [6-9]. However, to the authors knowledge, fewer efforts are undertaken in recognising the sensitivity associated in ignoring the impact of soil-structure interaction on differing structural configurations and irregularities and losses associated with the same. The issue concerning this domain is the unavailability of standard and validated analysis techniques incorporating the combination of both structural and geotechnical engineering disciplines in order to represent the non-linearity of the complex soil mass. Thus, the prime objective of the current review is to critically analyse and review exiting research outcomes orienting both, the numerical and experimental studies concerning the impact of SSI on structural irregularities by emphasizing on the various modeling techniques, proposed analysis and losses associated with the same.

2. EXISTING STUDIES ORIENTING STRUCTURAL IRREGULARITIES

According to the Indian seismic design code, IS 1893: Part 1 (2002), four main attributes are to be ensured for a structure to perform appropriately under seismic action; particularly, simple and regular configuration, adequate lateral strength, stiffness and ductility. However, rapid urbanization and numerous advancements in Civil Engineering has propelled the need for enhanced provisions in a building considering the aesthetic and functional requirements, thereby, initiating the necessity for irregular configurations. The adverse impact of structural irregularities on the response of buildings has initiated numerous relevant researches within this domain. Important research efforts have been conducted since the late 1970s by the international community considering varying geometrical configurations to understand better the impact of structural irregularities on the dynamic seismic response (linear and nonlinear) of buildings, using both experimental and analytical approaches.

Concerning the concept of seismic torsion, which is regarded as one of the most damaging conditions of structural irregularity, abundant state-of-the-art reviews orienting torsional effect on structures have been conducted including studies on base isolation strategies for torsional induced responses and several passive and active control mechanisms [11]. The sizeable literature in this area have highlighted conventional structural systems incorporating various changes in structural configurations as mentioned by Arturo Tena-Colunga (2021) [6], such as distinctive irregular plan, presence of stepped buildings, corner building configurations, torsional effect due to varying shear wall positions, torsion induced by setbacks, impact of diaphragm flexibility and the like as shown in figure 2.

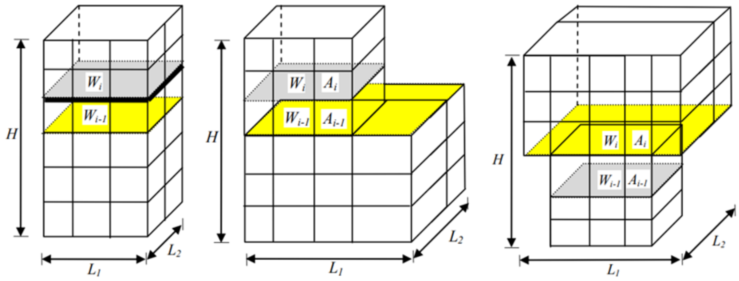

Fig. 2 Various Structural Irregularities in Buildings

A common aspect of vertical irregularity in multi-storied buildings is 'stepped building' frames represented by step-like abrupt reductions in floor area along the building height with a considerable reduction in mass, strength and stiffness. Pradip Sarkar, A. Meher Prasad and Devdas Menon (2010) [12] attempted a numerical study on stepped building frames with vertical geometric irregularity which proposed a new method of quantifying irregularity in such building frames, accounting for dynamic characteristics (mass and stiffness). The study defined that the degree of irregularity in a stepped building can be suitably assessed by considering the "regularity ratio" and also proposed an empirical formula for estimating fundamental period for regular frames as a function of the regularity index. In addition to the step-back setback buildings, floating columns is also categorized under the niche orienting vertical irregularities, which is a normal column that does not extend up to the foundation for providing larger open space. Behroz Eldar and Gagandeep Singh (2023) [13] carried out analytical studies using ETABS 2019 software to assess the seismic behaviour of G+10 irregular buildings considering with and without floating columns. Results obtained inferred the consequences created on providing floating columns in irregular buildings due to increased storey drift and storey displacement. Similarly, torsion increases in buildings when the floating columns are provided asymmetrically. Further, during earthquakes, the building with non-parallel lateral force system irregularity has higher torsion and displacement than regular building. Thus, it necessitates to increase the sections of structural members or quality of materials considering structural safety and economical aspect. Further, the common construction scenario in India involves open-ground storied structures (OGS) where the associated seismic damages are concentrated at the ground floor without any other element showing significant damages. G. V. Rama Rao, N. Gopalakrishnan and K. Sathish Kumar (2019) [14] conducted an extensive study on the presence of OGS which exhibited reduced stiffness due to absence of infill walls resulting in large seismic displacement demand at the bottom storey itself. A plastic hinge concept has been developed to assess the level of severity of OGS building which was further validated using shake table experiment conducted on a three-storey model OGS building. The plastic hinge concept is based on the assumption that the whole structure behaves as a single degree of freedom system as an inverted pendulum with a heavy mass at the top such that the entire elastic deformation of the structure is felt only by the OGS columns. The mentioned approach is a major contribution in defining a simplified procedure in terms of the plastic hinge concept for initiating the repair and rehabilitation of OGS buildings.

Referring to the number of researches orienting structural irregularities, studies related to either single irregularity, particularly, horizontal or vertical irregularity has been extensively studied. However, structures generally incorporate a combination of irregularities in varying type, location and number which should be considered to accurately conclude on the seismic response of structures. Thus, Siva Naveen E, Nimmy Mariam Abraham and Anitha Kumari S D (2019) [15] presented a numerical study on the analysis of irregular structures using ETABS under earthquake loads considering a combination of irregularities such as stiffness, mass, vertical geometric, re-entrant corner and torsional irregularity. Results obtained indicate that the

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presence of certain types of irregularities causes a negative influence on the structural response. The combination of stiffness and vertical geometric irregularities has shown maximum displacement response whereas the combination of re-entrant corner and vertical geometric irregularities has shown less displacement response. Further, Rachakonda Divya and K. Murali (2022) [1] extended the study by considering a numerical assessment of 15 storeyed reinforced concrete structures incorporating horizontal, vertical, stiffness and mass irregularity buildings with and without shear wall. Comparative analysis of the proposed configurations indicates that the presence of shear walls makes the irregular structure more economical when compared to irregular structure without shear walls, thus necessitating a reduced structure member size.

Thus, considering the detailed aforementioned researches conducted within this domain, the seismic response of structures is considerably affected by variations in structural irregularities in different conducts subject to the geometrical aspects, torsional characteristics of the building and asymmetries. In practical situations, structures incorporate multiple irregularities and studies concerning the same are in rarity. Hence, to cater this research gap, further relevant studies ought to be performed to determine the behaviour of structural irregularities under impact of ground motion.

3. STUDIES BASED ON SEISMIC SOIL-STRUCTURE INTERACTION ANALYSES ON STRUCTURAL IRREGULARITIES

The theory of soil-structure interaction has been established since the late 1960s. The novelty proposed within this field is widely attributed to both the structural configuration and foundation characteristics. Well-established notable studies conducted in the history involves researches conducted by Whitman, Roesset, Boussinesq, Steinbrenner, Reissner, Mindlin and Hanson, just to name a few. Subsequently, numerous advancements in this realm have industrialized, thus, accounting to several research innovations. The SSI studies have undergone massive progression from the historical studies conducted by Whitman orienting the inertial and kinematic effect to the developments of SSI assessment using computerized technology. The issue concerning this domain is the unavailability of standard and validated analysis techniques incorporating the combination of both structural and geotechnical engineering disciplines in order to represent the non-linearity of the complex soil mass. With the rapid advancement in technology and computational structural software applications, there has been a diverse and vast research in the present decade orienting SSI. Recent studies under soil-structure interaction influence conducted include dynamic analysis of wind turbines using substructure approach [16] , analysis of pile-grid foundations of onshore wind turbines considering seismic loading [17], seismic inelastic response of tunnels using finite element method in time domain [18], wind-induced response of tall buildings [19], dynamic SSI analysis of main telescope, dynamic analysis of tall RC chimney structures resting on pile or pile raft foundation [20] as shown in figure 3 and the like.

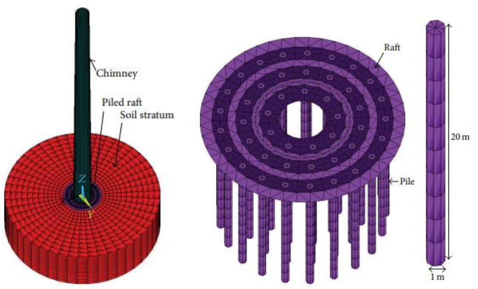

Fig. 3. Finite element model of 200 m high chimney-piled raft soil system and piled raft foundation and pile for dynamic analysis of tall RC chimney.

Other major contributions in this field include studies on SSI effects on seismic base isolation, influence of using geosynthetics on seismic performance of mid-rise buildings with different foundation types, coupling of two neighbouring SSI systems to obtain a structure-soil structure interaction (SSSI) system, effect of dynamic SSSI between adjacent buildings through nonlinear soil during earthquakes and many more. Another

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major contribution to the field of soil-structure interaction is the significant impact of pounding action between adjacent buildings. The contemporary era has initiated the presence of closely-spaced adjacent buildings with insufficient separation gap causing extreme structural damage under seismic response. Relevant researches have been extensively conducted within this domain orienting the study on the structural response of several adjacent external and internal buildings under seismic action [21], pounding response under spatial earthquake ground excitations [22], multiple collisions between three different configurations of adjacent buildings with distributed masses [23], numerical study on mid-column pounding of multi-story reinforced concrete buildings with non-equal story heights considering soil–structure interaction [24] and the like. The conclusions derived disclosed that external structures are more prone to seismic response than internal structures thereby being subjected to extreme damage. Considering the influence of ground motion spatial response indicate that a larger damping effect is required to mitigate seismic pounding effect between adjacent structures. Further, influence of SSI on pounding action also results in high over stresses and amplified displacement response in colliding buildings subject to different heights, periods or masses beyond those typically assumed in design.

Numerical studies concerning SSI influence on pounding response of buildings are also extensively investigated using Finite Element based software applications such as a study on the pounding action of two neighbouring buildings using finite-elements and boundary elements during the Montenegro earthquake conducted by Schmid and Chouw, 1992 [25]. The results obtained indicate that inclusion of SSI effect changed the dynamic characteristics of the structure–soil system; causing extreme building vibration with higher amplitude and lower frequencies and reduced internal forces leading to pounding response. In addition, research on the study of SSI on seismic response of two-adjacent 32-storied buildings for varying separation distance between buildings and soil types such as soft clay, sandy gravel and compacted gravel was also considered by Yahyai et al., 2008 [26] which defined an increase in time period, base shear, and displacement. Another addition to this relevant concept is the inclusion of structure-soil-structure interaction (SSSI) influence for two adjacent buildings carried out by researchers such as Gaonkar and Savoikar, 2016 [27], Li et al., 2017 [28], Kasai et al., 1992 [29] etc. The study based on the three-dimensional finite-element numerical simulation using ANSYS considered the influence of different types of foundation on the SSSI effect and revealed an extreme amplified response of acceleration and shear responses on adjacent buildings due to pounding and SSSI influence. Further, numerous studies have also recommended the need on enhancing the state-of-the-art and state-of-the-practice with appropriate seismic codal guidelines and seismic risk reduction practices generated by adjacent structures. Succeeding research conducted by Gong and Hao, 2005 [30] presented relevant numerical parametric studies of seismic-induced lateral-torsional-pounding responses of an asymmetric and a symmetric one-story adjacent structure which concluded that the presence of spatially varying-ground motion induces additional torsional and out-of-phase responses between adjacent structures resulting in smaller base shears, and smaller torque in an asymmetric structure, but larger torque in a symmetric structure.

Thus, in view of the recent developments within this domain in Structural Engineering, the core analysis in SSI studies have been classified into two approaches, i.e.; researches conducted to analyse the SSI effects on any structure and the other dimension being understanding the rationale behind these effects on any structural configuration subject to varying parametric conditions. Presence of various irregularities alter the dynamic properties of structures such as stiffness, time period, damping, natural period etc. considering the flexibility of the underlying soil. Hence, considering the necessary requirements in constructing structures on soft soil, well-drafted guidelines in view of SSI studies in regular design practices is of paramount importance.

4. CONCLUSIONS

This manuscript outlined a brief overview on the recent relevant studies conducted orienting the influence of soil-structure interaction and structural irregularities on the dynamic seismic response of structures. Considering the entire inventory of existing researches within this domain and the identified conditions of structural irregularity discussed within the paper, it was revealed that; the relevance of including soil-structure interaction studies in analysing the structural response is highly relevant subject to the following areas of consideration.

- Inadequately laid SSI provisions and well-framed standard SSI guidelines in existing building codes.
- Destructive implications of SSI on structural response under seismic excitation, which, if excluded results in an unconservative design.
- Detrimental effects of SSI intensified by asymmetry in geometry of superstructure and extremities in seismic action and loose or soft soil conditions.
- Response of single irregularity particularly, related to either mass, stiffness or geometry has only been considered massively and further studies incorporating the combination of irregularities is a necessity.
- Further, most of the studies have indicated a vagueness in deciding on the appropriate modeling and analysis technique considering the method adopted (Finite Element Method or Boundary Element Method) based on direct method of analysis to accurately conclude on the realistic response of the structure while ensuring less computational time without compromising on the structural reliability.

Hence, it is worth mentioning that in contrary to the conventional ideology that SSI is beneficial in nature, further studies have questioned this aspect considering relevant research conclusions. Thus, inclusion of soil-structure interaction effect is of paramount importance to conclude on the realistic response of structures. Further studies ought to be conducted to quantify the seismic damage of structures considering different structural configurations, foundation types, appropriate analysis techniques, varying soil properties and structural parameters.

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