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Response Reduction Factor for Structures with Significant Irregularities on Different Soil Stratum

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Abstract

The ability of a structure to dissipate energy through inelastic behavior is reflected in the response reduction factor (R), which is influenced by redundancy, ductility, and overstrength. Accurate determination of R is crucial for seismic design. This study focuses on determining the response factor for reinforced concrete (RC) structures with various irregularities. Non-linear static pushover analysis using SAP2000 was employed for numerical simulations to assess the impact of soil-structure interaction (SSI). The analysis included elevational and in-plan irregularities, revealing that buildings with irregular vertical geometries have lower inelastic seismic capacities compared to regular buildings. Consequently, R should be reduced by 15–40% from the ECP 2020 standard before the design phase for such structures. Irregularity was found to have a significant impact on weak soil conditions (C), leading to a reduction in R of 20.3% and 13.1% for fixed and isolated supports, respectively, on loose soil. Additionally, stiffer base soils were associated with higher R values for the same structure.

Keywords: Irregular RC Buildings; Elevation Irregularity; Plan Irregularity; Nonlinear Static Pushover Analysis; Response Reduction Factor; Soil Structure Interaction.

1. Introduction

A structure must be able to withstand intense seismic events without collapsing suddenly, even though it may suffer some structural and nonstructural damage. This is the core principle of earthquake-resistant design, which involves constructing a structure to withstand seismic forces by dissipating energy and exhibiting inelastic behavior [1-3]. Recent earthquakes have shown that elastic analysis is inadequate for assessing the true seismic performance of reinforced concrete buildings. Nonlinear time history analysis (NTHA), although challenging and dependent on ground motion data, can predict the likely inelastic response of structures [4]. To ensure safe and cost-effective designs, elastic analysis techniques are used to account for a structure's inelastic response by amplifying deformations and reducing seismic forces. Therefore, seismic design response elements are essential for both safety and cost-effectiveness [5]. Many seismic codes include response reduction or behavior factor (R) in their seismic analysis studies. NTHA is being replaced by other performance-based seismic evaluation techniques, such as nonlinear pushover analysis (NPA).

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Several methods, including the FEMA440 displacement coefficient technique [6], the capacity spectrum technique of ATC-40 [7], the N2 method by Fajfar & Fischinger [8], and modal pushover analysis (MPA) [9], are considered as part of nonlinear pushover analysis (NPA) to determine a structure's inelastic performance. The response factor (R) is a crucial element in earthquake design, representing a structure's ability to dissipate energy through inelastic deformations [2]. Most structures use reduction factors to reduce seismic loads and bring the building closer to the inelastic range. Therefore, more deformation is required to dissipate energy from the structure. It is essential to consider both the economy and the performance and safety of constructions during earthquakes, highlighting the significance of the behavior factor in the seismic design process. The behavior factor (R) is a key component in the seismic design of new construction materials and is also used in equivalent static analysis as a seismic design parameter. It determines the nonlinear behavior of structural buildings during intense earthquakes. R is determined by engineering judgment and experimental testing; however, there is no standard method to calculate this value under various circumstances. Building response characteristics, which significantly impact the rates assigned to R, must be systematically assessed to enhance the reliability of modern earthquake-resistant buildings [10].

Accurate estimation of R is essential for assessing a structure's seismic response effectively. If the modification factor is overestimated, it can lead to a reduction in base shear and potentially result in more economical design solutions. However, precautions should be taken to ensure the structure's ductility performance [2-4]. Conversely, underestimating R could lead to uneconomical structural designs. Design codes implicitly account for structural non-linearity by reducing the seismic base shear of structures by the value of R.

The structural systems of buildings often need to incorporate various geometric irregularities, either in the horizontal or vertical plane, as specified by architectural requirements. Many existing structures exhibit severe irregularities that may not be addressed by current design codes, necessitating thorough research for their proper design [3]. Past experiences have shown that irregular constructions are more prone to catastrophic damage during earthquakes compared to regular structures [11]. In reality, most existing structures are asymmetrical, some intentionally designed that way for reasons such as creating commercial basements by removing central columns. Moreover, smaller beams and columns were added to the upper stories to meet functional requirements and for additional commercial purposes, such as storing large mechanical appliances. This variation in usage along a floor's length compared to neighboring floors results in irregularities in mass, stiffness, and strength distribution. Other structures may unintentionally become irregular due to factors like inconsistent building techniques and materials. The irregular distribution of mass, strength, and stiffness along a building's height can also occur [2]. Previous experiences demonstrate that structures with vertical irregularities perform poorly inelastically when located in seismically active areas. Hence, reliable design requirements are crucial for earthquake-prone areas. Regarding the impact of these irregularities [12], Brahmavrathan & Arunkumar [2] noted that the number of stories greatly influences the reduction of R for non-regular structures. Their research showed that the R factor value decreased by 37.53% and 31.04% for ordinary moment resisting frames (OMRF) and stiff moment resisting frames (SMRF) structures, respectively.

ECP-201 (2012) [13] sets values for R ranging from 3 to 5 for framed structures with sufficient to limited ductility. These values need to be adjusted to accommodate severe irregularities. Fayed et al. [3] calculated behavior factor values at failure for idealized multistory frame systems with moment resistance made of RC and developed in compliance with ECP-201 (2012) [13]. A decrease in the stated R values was observed. The structure's fundamental TP and seismic zone significantly impact the reduction factor. It decreases as the seismic zone becomes larger and increases with a longer basic TP. Hussein et al. [1] assessed how irregularities in floor heights and span lengths affect the behavior factor for common RC frames used in various structures. The outcomes showed inconsistent R values compared to structures with uniform bay length and floor height. El-Mahdy et al. [14] noted that R values differ in the X- and Y-directions for the cases covered in their research, which is more realistic than the design code-specified constant value. The lowest R values were determined for constructions with a loose ground story and a coupled asymmetric setback. Additionally, R's sensitivity to the vertical irregularity index (Vtm) was found to have an R-squared value of 80%, as demonstrated by Ahmed et al. [15].

Moreover, this article addresses the impact of SSI. The interaction between soil and foundation significantly affects the structure's response [16, 17]. The behavior of a structure during an earthquake is influenced by three interconnected systems: the construction, the foundation, and the soil surrounding the foundation. SSI is the process through which the soil's response affects the structure's motion, and the motion of the structure affects the soil's response [16, 18]. Design codes do not provide sufficient guidance on incorporating SSI effects on structures. A well-defined computational technique is necessary to encourage practical engineers to include SSI in the design process [19]. For ensuring the safety and earthquake resilience of non-regular RC buildings, it is important to conduct a thorough seismic risk evaluation considering both site selection and geometric irregularity. Proper consideration of these issues during design and strengthening stages will result in safer structures and more effective mitigation measures [20]. According to some studies, the flexible base condition affects the building's response differently than the fixed base condition, reducing the structure's stiffness and altering the response spectrum [21].

The structure's response is dependent on various factors, including the stiffness of the soil, the structure's dynamic characteristics, damping factor, natural period, mass, and stiffness [22-25]. In the United States, the amount of scientific investigation considering SSI increased towards the end of the 2000s, with some studies summarized in the FEMA-440 report [6], which considered nonlinear analysis. The findings of this research were incorporated into US code requirements [26]. However, the provisions in FEMA-440 and ASCE 2013 standards are not recommended for NLT assessments, highlighting the need for new studies. In 2012, additional research on SSI in performance-based seismic engineering was compiled, suggesting an approach that could be applied to NLT analysis [27, 18]. Research investigated the impact of soil-structure interaction and found a significant decrease in R due to SSI for 3, 6, and 9-story buildings, with a 16% reduction in loose soils (R fixed support vs. R isolated footing type D). ECP-201 (2012) suggests a value of 3.9 for the response reduction factor R for limited ductility reinforced concrete moment frame buildings in multi-story multi-bay frames. Building on soft soil increases displacement, while increasing soil rigidity decreases lateral displacement [28]. The natural period becomes longer when considering the soil's flexibility, and the characteristics of the footings affect the building's performance [22, 7]. Many researchers have studied the influence of irregularities on RC structures' seismic performance, finding that regular buildings have larger roof displacement values than irregular buildings, while non-regular buildings were the first to achieve life safety and collapse prevention [23].

The influence of plan irregularity, specifically L-shaped structures, was illustrated by determining the actual overturning moment response from seismic analysis of L-shaped models. Improper layout of building elements could compromise the building's stability [29]. The increased total mass and rigidity of the building caused more displacement in the structure. Top displacement is greater in irregular building models than in standard frames. Additionally, the model of vertical irregularities included in the bottom story displayed the maximum value of the story drift ratio [24]. Allena & Chowdary [25] investigated how irregularities affected the seismic performance of high-rise buildings. They found that when the center of gravity and center of mass were aligned, mass irregularity did not significantly affect the reduction in frequency. The model with lumped mass at lower stories was substantially stiffer and showed more resistance [30]. It is evident that base shear and lateral displacement increase as seismic energy rises, indicating greater seismic demand for the structure. Nonlinear static pushover analysis (POA) has gained significant attention among researchers in recent years, providing a review of various pushover analysis approaches for vertical and horizontal irregularities of structures [31]. The factor R is affected by the hysteresis loop's shape, ductility, natural period, structural system, and construction materials. Only 8% of previous research attempts were dedicated to assessing the seismic response of irregular buildings [5].

This study focused on three main branches: evaluating the modification factor for irregular RC structures, employing nonlinear seismic analysis using the pushover analysis (POA) method to assess the seismic performance of irregular buildings, and incorporating soil-structure interaction (SSI) to evaluate the influence of soil and foundation type on assessing R. Nonlinear POA was used to evaluate the modification factor R for three RC structures with structural plan and elevation irregularities. Changes in floor plan geometry were made for each structure, which had different areas and heights. The study also considered the influence of various soil types on various subgrade response moduli (ks), as well as various seismic regions with ground accelerations of 0.15g, 0.20g, and 0.25g. Finally, the two response spectra identified by ECP were considered and investigated.

2. Response Modification Factor

The concept behind the response factor is to integrate nonlinearity with the overstrength, redundancy, and ductility of a structure to accurately assess the seismic force. Figure 1 illustrates the relationship between a structure's base shear (total horizontal load) and its roof displacement, as described by [1-3] for nonlinear static analysis. The reduction factor is typically expressed as a function of various structural system factors, including strength, ductility, damping, and redundancy. This factor is referred to as the response modification factor (R-factor) in the Egyptian code (ECP 2020), the behavior factor in the Eurocode, and the response modification coefficient in ASCE/SEI 7-22 [26, 32-34]. Therefore, the response factor (R) is calculated as follows:

$$R = R_S \cdot R_\mu \cdot R_\xi \cdot R_R \tag{1}$$

where, R_s is the over strength that is defined as the ratio of the base shear at yielding to the design lateral strength.

$$Rs = Vy/Vd \tag{2}$$

where R_R intended to quantify the improved reliability of seismic framing system that uses multiple lines of vertical seismic framing in each principal direction of the building. The higher of the redundancy factor R_R Cannot be larger than one. Therefore, R_R was taken equal to unity, R_ξ is the damping factor used to account for the influence of additional viscous damping in constructions that have additional energy dissipation devices. If such devices are not provided, the damping factor is normally set at 1.0, and R_μ of the displacement at yield to the allowable displacement or maximum considered displacement.

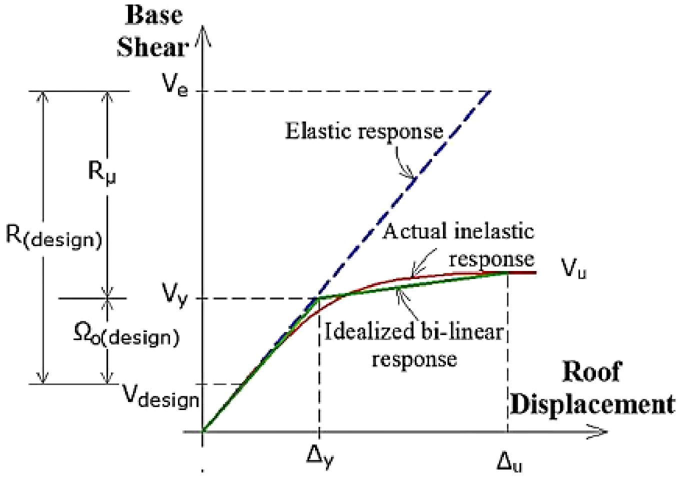


Figure 1. Relationship between applied base shear and roof horizontal deformation for regular buildings [3]

Factor that reduces ductility $R\mu$ based on the properties of earthquake ground motion additionally features of structure including ductility and basic period of vibration (T) [11, 35-42]. In this study, the formulation recommended by Priestley & Paulay (1992) [38] is used:

$R\mu = 1.0$	for zero-period structures	(3-a)
$R\mu = \sqrt{2\mu - 1}$	for short-period structure	(3-b)
$R\mu = \mu$	for long-period structure	(3-c)
$R\mu = 1 + (\mu - 1)\ T/0.70$	$(0.70 < T < 0.30)$	(3-d)

where, $R\mu$ is the ductility reduction factor and μ is the displacement ductility.

Many codes and standards had addressed ranges for R, UBC97 has set values for (R) ranges between 3.5–8.5 while IBC (2012) [43] and ASCE7 uses near values ranges from 3.0–8.0 for ordinary to special moment resisting frames, respectively. ECP 2012 and IS 1893 have set values ranges from 5.0–7.0 and 3.0–5.0 for limited (ordinary) to Sufficient ductility frames, respectively. Moreover, Eurocode related the value of (R) to the ratio (Vu/Vy) based on the structure configuration.

3. Nonlinear Static Analysis (Pushover Analysis (POA))

Nonlinear Dynamic Time History (NDTH) analysis is widely recognized as the most accurate method for seismic evaluation in structural nonlinear analysis. However, due to its extensive computational requirements and the complexity of interpreting the responses for design purposes, it is considered impractical for routine use in structural design. Another significant challenge is the selection of suitable acceleration records for the numerical analysis, along with the need to account for torsional effects in the nonlinear static responses of irregular buildings.

The findings of nonlinear static analyses on irregular multi-story RC buildings were deemed appropriate [10]. Previous studies [44-47] have developed a 3D pushover approach for investigating non-regular building structures. So, it can be concluded that nonlinear static pushover analysis (POA) yields satisfactory results when applied to the analysis of irregular buildings. Consequently, nonlinear static POA has been utilized to compute the response factor for a building model.

Pushover Analysis (POA) is a method used for conducting non-linear static structural analysis. It determines the capacity curve by comparing base shear with displacement and evaluates the formation of plastic hinges at different stages beyond the elastic limit. In this analysis, the increasing load is represented by horizontal forces or displacements applied to a mathematical model of the building. The analysis concludes when it reaches a critical condition or target displacement. This target displacement or drift represents the maximum displacement or drift experienced by the building during the earthquake.

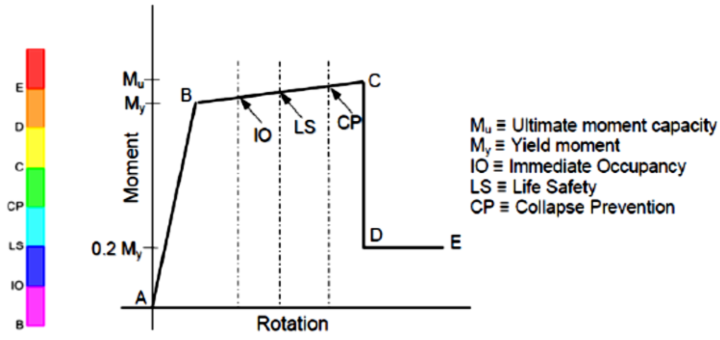


Figure 2. Moment - rotation graph for pushover analysis

4. Research Methodology

In this comparative analysis, we employed the equivalent static approach to seismic analysis for buildings with 6, 7, and 10 stories. Finite Element Models were created using the widely used software SAP2000 [46], with frame elements used to model beams and columns, and shell elements for simulating slabs. A parametric study was conducted, varying soil type, seismic zone, building irregularity, and using different spectra (I and II) as the main parameters. The design and comparison were guided by ECP-203. Figure 3 outlines the test procedures and estimates the number of trials needed for the study. Initially, the focus was on three models of structures with irregularities, labeled A, B, and C, with irregularity percentages of 28.6%, 30%, and 21%, respectively. Irregularity percentage was calculated as the total surface area of the cut floors of a building compared to the total surface area of all floors of the corresponding regular building. Corresponding regular models, named A', B', and C', were also created for control. These six models were constructed on different soil strata, categorized as per ECP-203 classification. This resulted in twelve models subjected to two types of response spectrum, each simulated at different seismic zones, totaling 144 models. Nonlinear pushover static analysis was utilized to determine the status of plastic hinges at yield and ultimate states. The structures were horizontally displaced until reaching predetermined failure conditions.

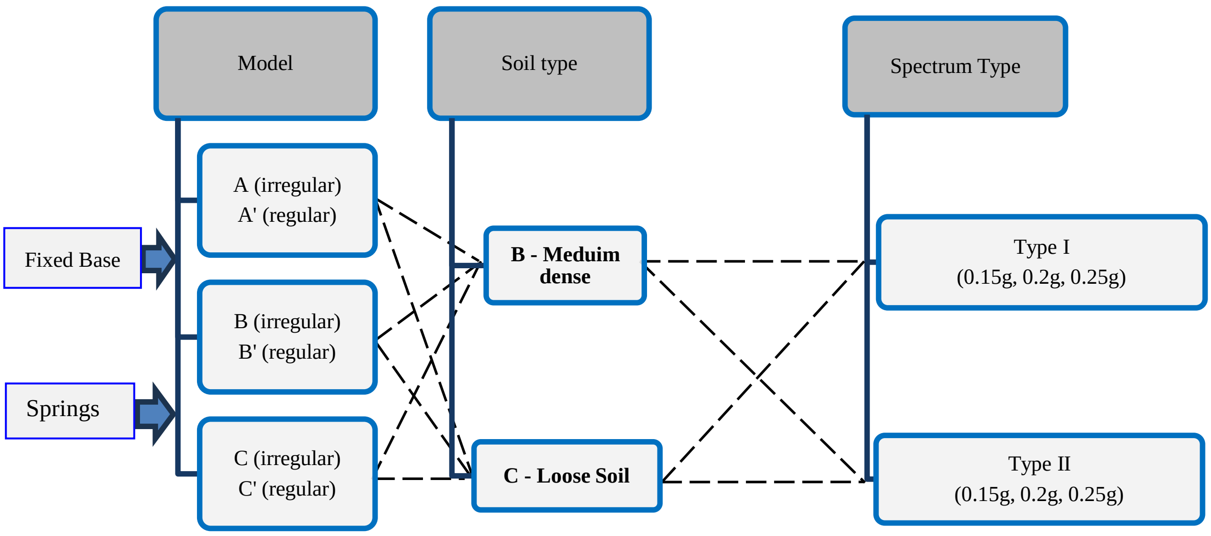
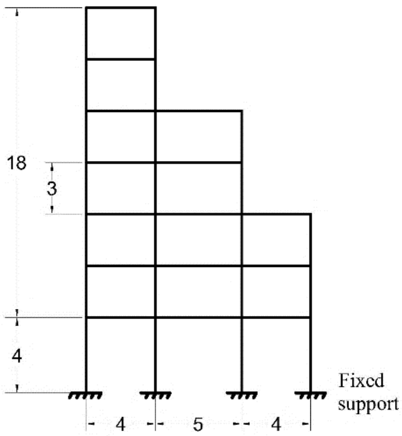


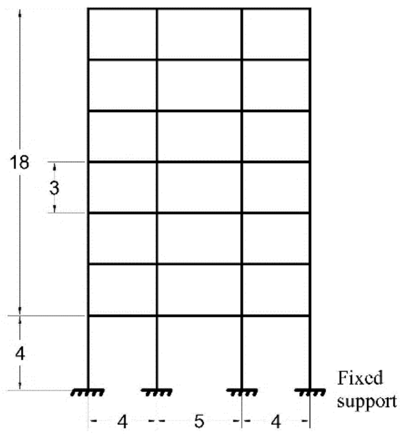
Figure 3. Sequence of numerical trails

5. Models Description

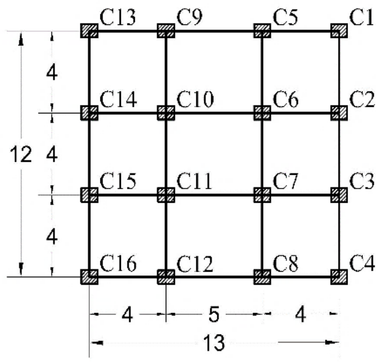
In this section, three different categories of structures were numerically simulated. The first category was denoted as Model (A) and Model (A'), representing relatively short buildings with 7 floors and a stepped reduction in floor area in one direction only. The second category was denoted as Model (B) and Model (B'), representing relatively taller buildings with 10 stories. The third category, named Model (C) and Model (C'), represented buildings with a random reduction in floor areas, each with 6 stories. Figure 4 illustrates different cross-sectional views for the three models, while Figure 5 shows 3D views of all structures. The irregularity percentage of each structure was determined by calculating the total surface area of the regular structure and subtracting the missing area until the irregularity percentage of buildings A, B, and C reached 28.6%, 30%, and 21%, respectively.



Model A

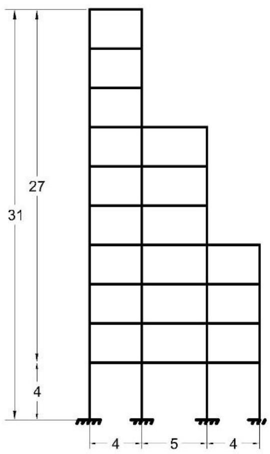


Model A’

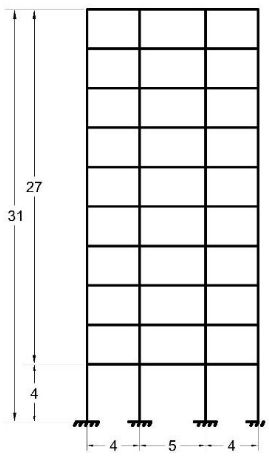


Plan View

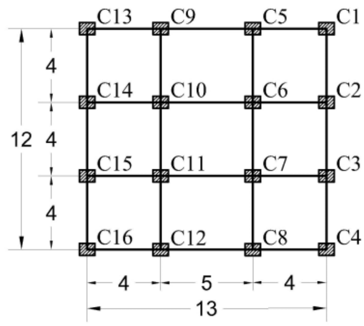
Typical Floor Elevation View -irregularity percentage (28.6%)



Model B

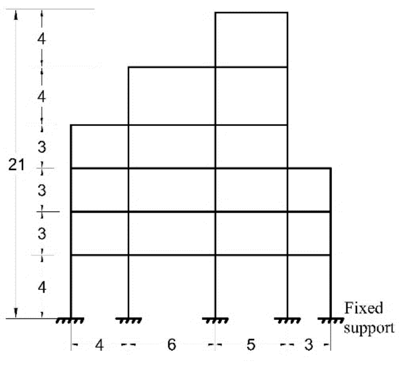


Model B’

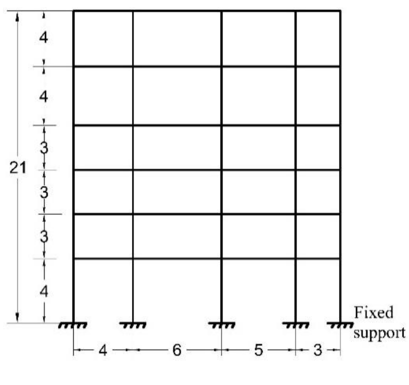


Plan View

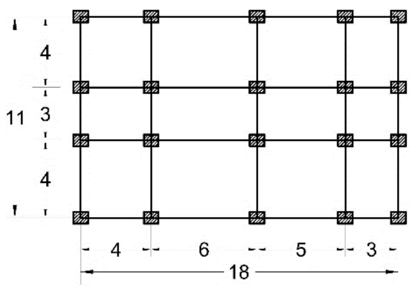
Typical Floor Elevation View- irregularity percentage (30%)



Model C



Model C’



Plan View

Typical Floor Elevation View - irregularity percentage (21%)

Figure 4. Description of Models

Nonlinear static analysis was conducted using SAP2000 [46]. Various parameters were taken into account during modeling, including material properties with different stress-strain relationships, expected locations and lengths of plastic hinges, and their types. The moment-curvature relationship is essential for nonlinear static analysis. Factors such as geometry, material properties, longitudinal reinforcement, shear reinforcement, and applied loads on a specific member all influence the values derived from an element's moment-curvature relationship.

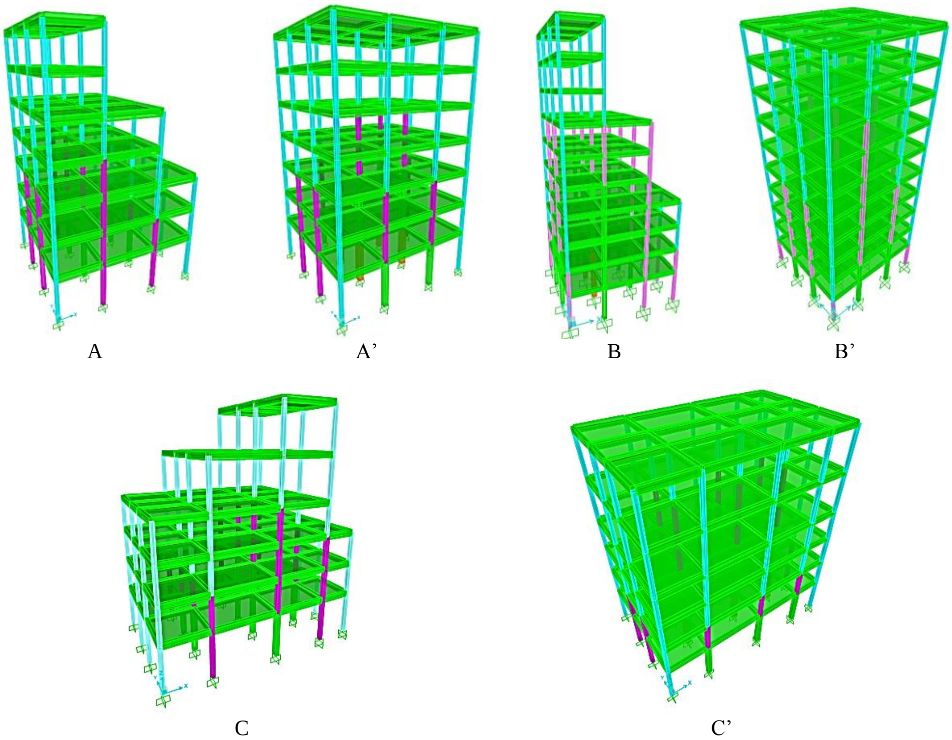
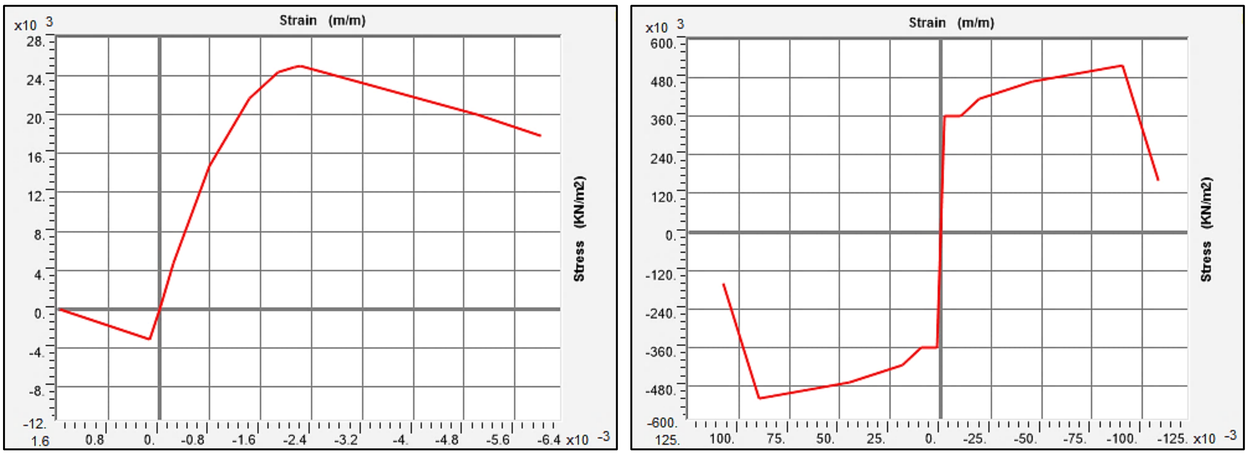


Figure 5. 3D simulation of all Multistory Buildings

Table 1. Material Properties used in simulation

Material Properties	Value
Concrete characteristic strength (F_C)	25000 kN/m^2
Rebar yield strength (F_Y)	36709780 kN/m^2
Modulus of elasticity of rebar (E_S)	360000 kN/m^2
Modulus of elasticity of concrete (E_C)	22433756 kN/m^2
Shear modulus – CONCRETE (G)	93473980 kN/m^2
Poisson’s ratio for concrete (Yc)	0.2
Poisson’s ratio for steel (Ys)	0.3

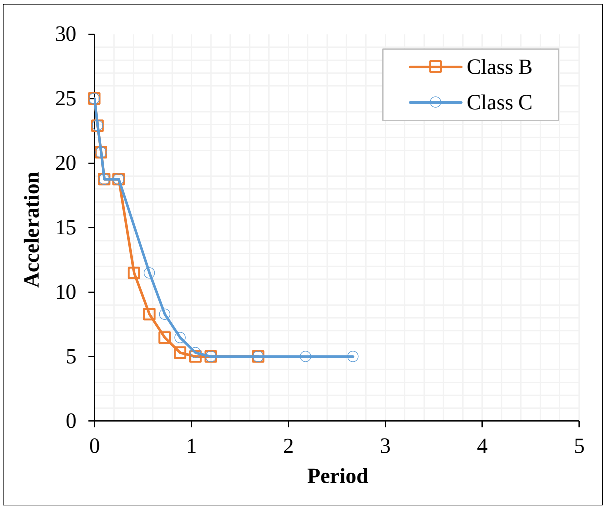


(a) Stress-strain curve for concrete (b) Stress-strain curve for steel bare

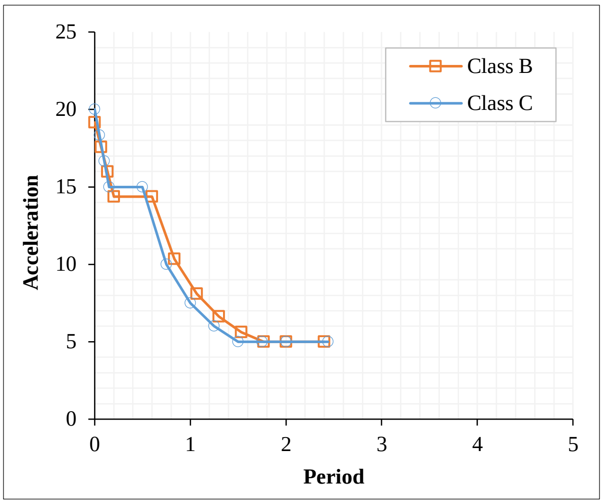
Figure 6. Stress-strain curves for used materials

RC frame structures with 6, 7, and 10 stories were designed according to ECP-203 (2020) to withstand both gravity and seismic loads (spectrum types I and II) at various seismic zones (0.15g, 0.2g, and 0.25g) as shown in Figure 7. The soil was classified as Type B and Type C according to ECP-203. For each soil type, the models were simulated using both fixed support, considering a rigid foundation, and an isolated footing system based on design outcomes. Initially, the models were simulated assuming a limited ductility moment-resisting frame with R equal to 5. Throughout the design process, the following factors were considered:

- To ensure that the standards for damage limitation are met, the inter-story drift should not be greater than 0.005 of the story height.
- Stirrups were assumed to carry shearing forces in columns as well as to enhance their ductility.



SP1



SP2

Figure 7. Applied Response Spectrum at seismic zone (0.25g)

For all models, the beams were designed with the same cross-sectional area (250 mm × 500 mm). The top and bottom reinforcement were also kept constant at (8T16) for top and bottom reinforcement.

It was noticed that the capacity/demand ratios for most columns are at lower levels in all the analyzed buildings, and within the range of 0.75 to 0.90, the reinforcement ratio of sections is shown in Table 2.

Table 2. Column sections with corresponding reinforcement ratio

Reinforcement Ratio	Column Section			
	25×25	30×30	40×40	50×50
μ %	1.44: 2.5	1: 1.79	1.5	1.287

6. Modelling Soil-Structure Interaction

A theory regarding the vibration of the foundation soil suggests that because buildings are more flexible than corresponding fixed-base structures, inertial interaction effects cause the natural period of the soil-structure system to lengthen. Additionally, it states that an increase in damping of the soil-structure system is caused by energy dissipation, and radiated waves from the building back into the ground. This theory distinguishes the case of flexible foundation motion used in an FB model and proposes a direct approach for SSI studies that resolves the dynamic equilibrium equation of the soil-structure assembly [46, 47].

In section 6.3 of FEMA 356, two approaches for modeling SSI are described [6]. The first approach utilizes flexible soil and a stiff foundation, with the foundation's modeling based on six formulas for each of the six degrees of freedom. The second approach involves linear flexible soil and flexible foundations, where the soil support is represented by distributed springs with homogeneous spring values dispersed throughout the footing's length. This approach is most suitable when the foundation's structural elements are flexible (refer to Figures 8 and 9).

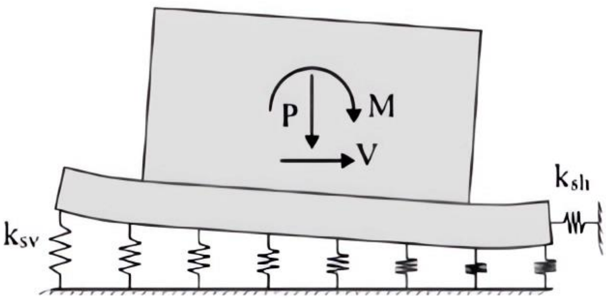


Figure 8. Foundation modeling approaches with vertical springs presented in FEMA (2020)

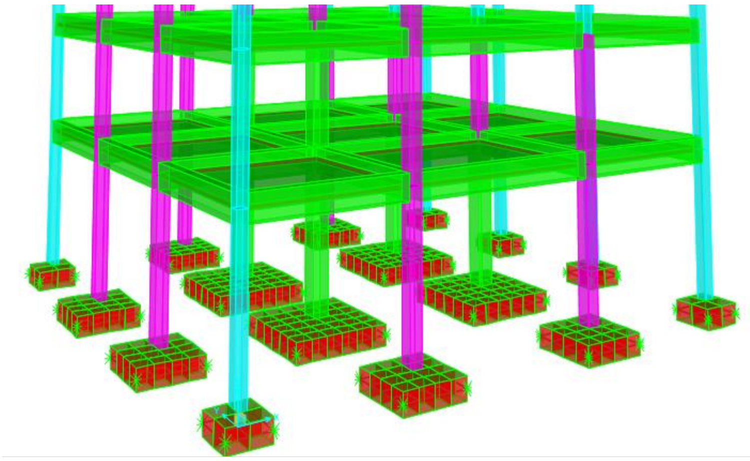


Figure 9. Typical foundation modeling with vertical soil springs is based on ASCE/SEI 41-17 in SAP2000

6.1. Flexible-base Analysis

For SSI calculations, understanding the behavior of a building with a flexible base is crucial. This can be approached in two ways. Firstly, to compute radiation damping reductions, which depend on the ratio of fixed-base to flexible-base periods, it is necessary to consider the change in dynamic behavior between the fixed-base and flexible-base conditions. Secondly, to properly account for soil-structure interaction, ASCE/SEI 7-16 Section 19.1 recommends considering all aspects of foundation flexibility, including soil flexibility and the foundation's rotational, vertical, and horizontal orientations.

For analysis, ASCE/SEI 7-16 Section 12.13.3 specifies a 50% increase and decrease in soil spring values. This involves multiplying the best estimations by 1.5 and 0.5 to determine the maximum and minimum spring values.

Equation 4 for vertical soil springs is based on ASCE/SEI 41-17 Section 8.4.2.5, Technique 3, which uses a uniform spring along the footing's length (refer to Figure 9). This method leverages the relative flexibility of the concrete foundation element to the soil. Since the continuous footings extend as cantilevers beyond the frame columns, creating flexibility in the foundation structure, and because the model explicitly considers the footings' flexibility, this method appears to be suitable.

$$K_{SV} = \frac{1.3G}{B_F(1-V)} \tag{4}$$

The spring values are depending on the shear modulus of the soil, G, and Poisson's ratio, ν, B is width of footing, and the modules of subgrade reaction, (K_S) is the value in this study according to soil type shown in Table 3.

Table 3. The modules of subgrade reaction, (K_S) value

Vertical soil springs is based on ASCE/SEI 41-17 Area Spring at the bottom of footing (Stiffness/length^2)	Soil Type
K_S= 9806.6502 kN/m^2	Soil type B
K_S= 19613.3 kN/m^2	Soil type C

7. Results and Discussion

The results of the simulation, including contributing mode shapes, the effects of different soils, and seismic zones, are introduced in the next sections. The effect of different irregularities was discussed. The obtained R was compared with the corresponding value of regular buildings.

7.1. Mode Shapes

A structure's modes are its intrinsic characteristics, independent of applied loads or forces. Changes in the structure's boundary conditions (mountings) or material properties (mass, stiffness, damping) will also change the modes. Mode shapes, on the other hand, are unique. They represent the unique motion of a point to another at resonance. Therefore, the structure's irregularity percentage significantly influences the mode shape, as higher irregularity percentages result in higher torsional moments on the structure. The fundamental natural periods for all regular and non-regular buildings were determined. Figure 10 displays the first four periods for irregular structures. During analysis, these modes exhibit a modal participation factor over 95%. It was observed that the first two modes corresponded to global structural bending motions, while torsional modes appeared in the third mode. Significant bending modes for the higher floors in irregular buildings were observed in the fourth mode. The natural period is provided under each mode. Generally, a greater number of modes are required for accurate assessment of the dynamic response of irregular structures [24, 25]. Thus, it is important to consider torsion effects in the nonlinear static responses of irregular buildings.

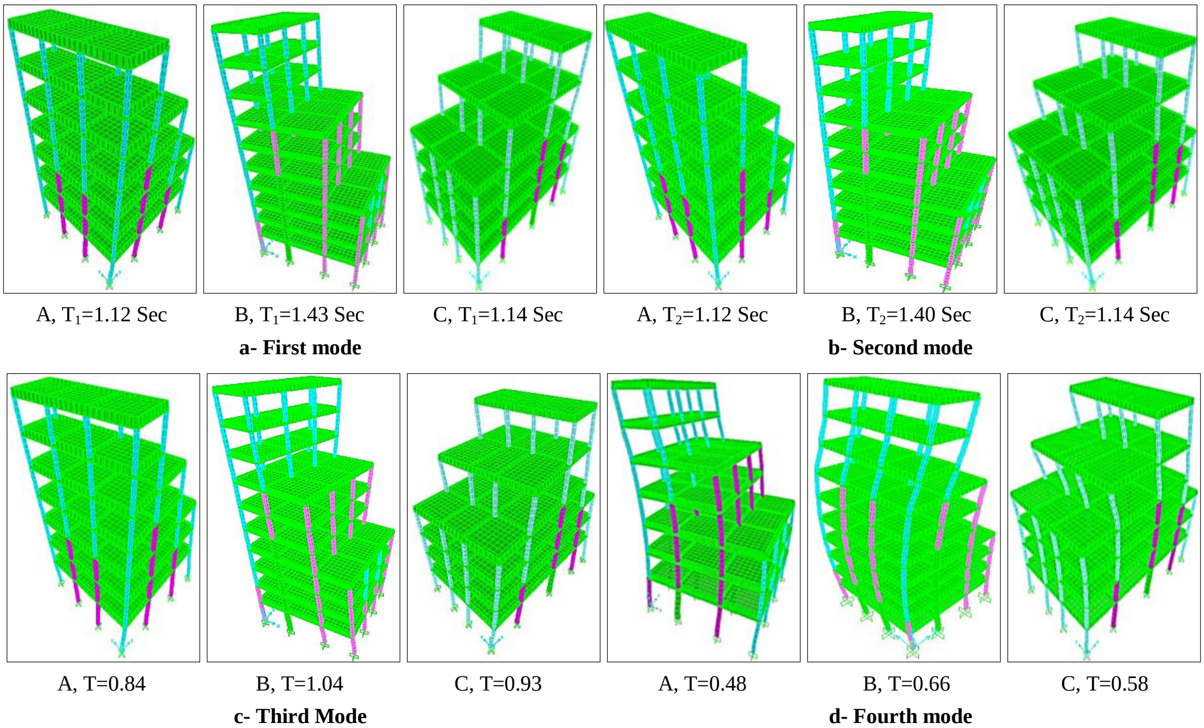


Figure 10. 3D view of vibration mode shapes of studied building models. a 1st vibration mode shape, b) 2nd vibration mode shape, c) 3rd vibration mode shape, and d) 4th vibration mode shape

The fundamental natural periods for all regular and non-regular buildings were obtained. Figure 10 shows the first four periods for irregular periods. During analysis, these modes have a modal participation factor of over 95%. It was also noted that the first two modes represented global structural bending motions. Torsional modes appeared on the third mode. Whereas significant bending modes for the higher floors in irregular buildings appeared in the fourth mode. The natural period is written under each mode. Generally, for an accurate assessment of the dynamic response of the structure, a greater number of modes are required for irregular structures [38]. So, we need to take into account the torsion effects in irregular buildings' nonlinear static responses.

7.2. Pushover Curves

The pushover curves listed in Figures 11 to 16, which draw the relationship between the top displacement and the ultimate base shear.

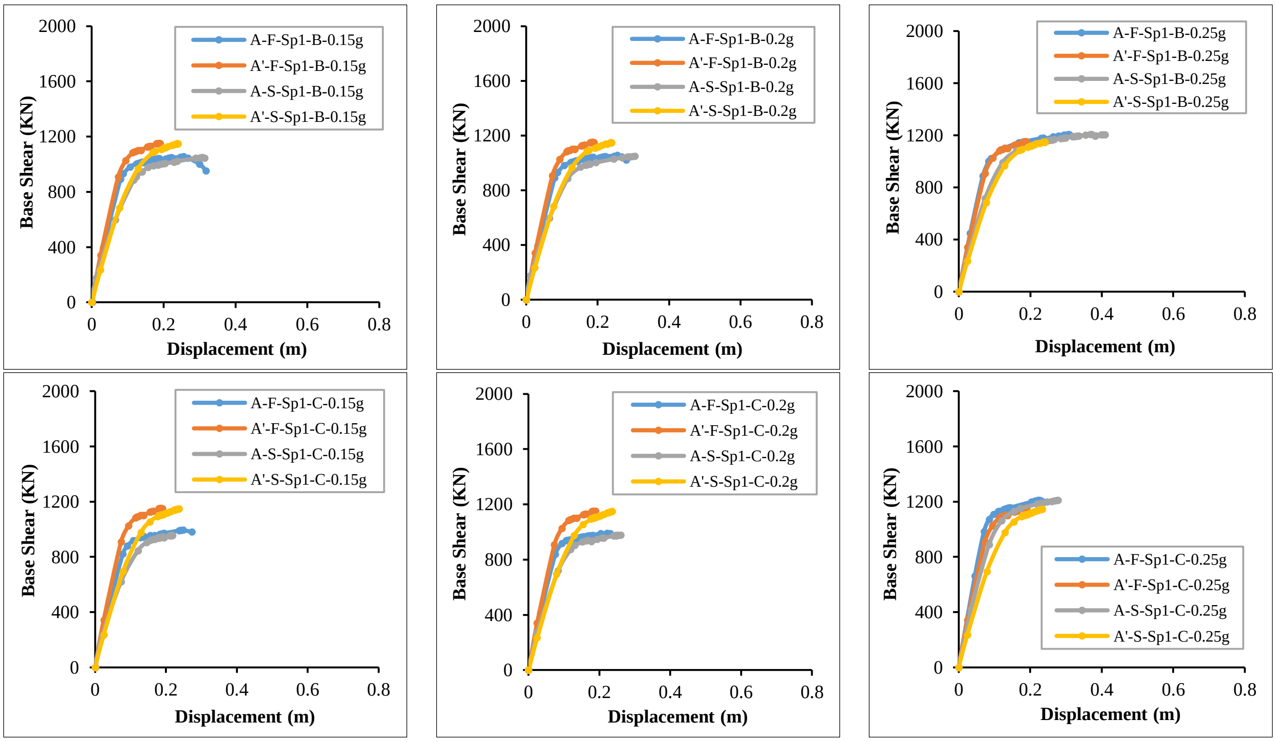


Figure 11. Pushover curves (P.O.C.) for the spectrum type I for models A, A'

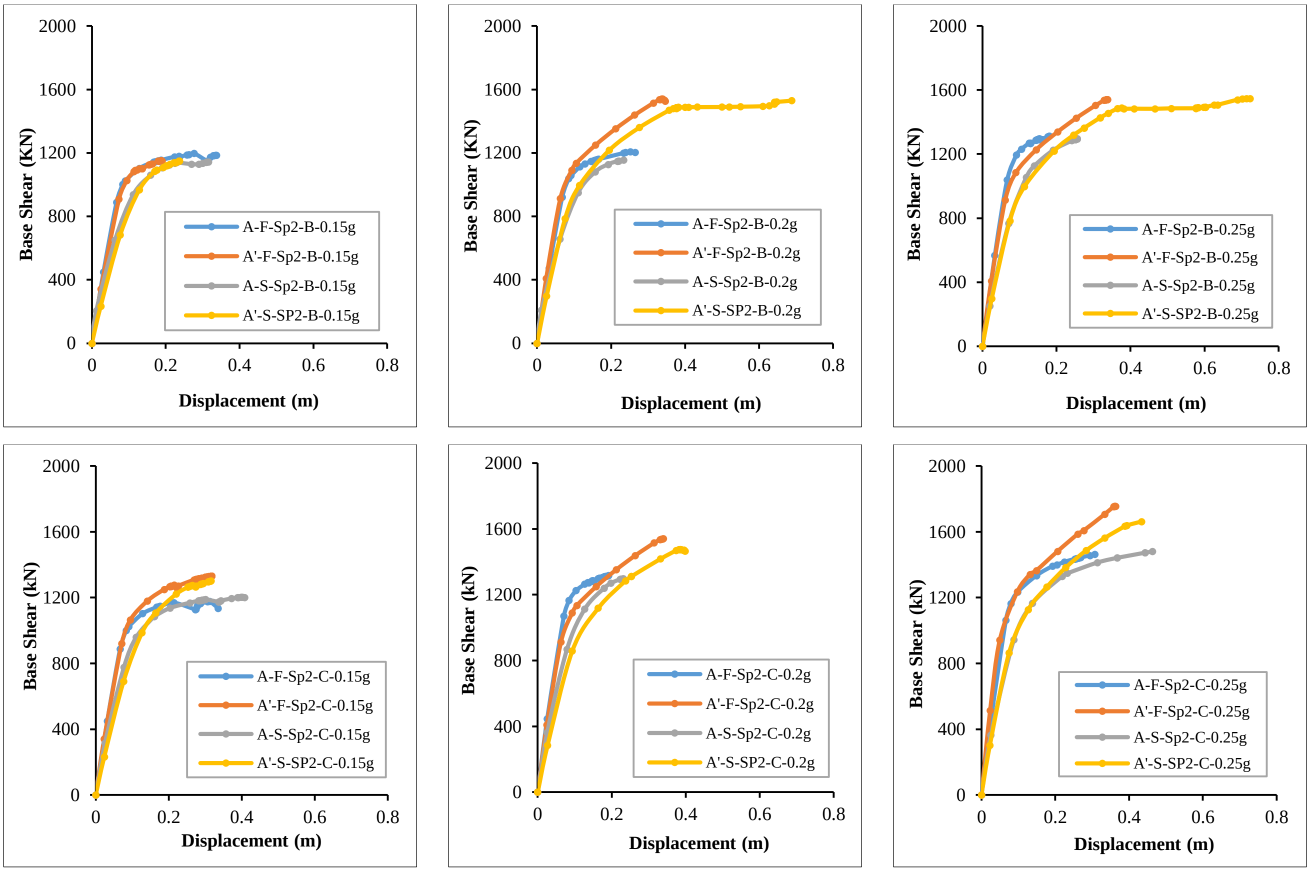


Figure 12. Pushover curves (P.O.C.) for the spectrum type II for models A, A'

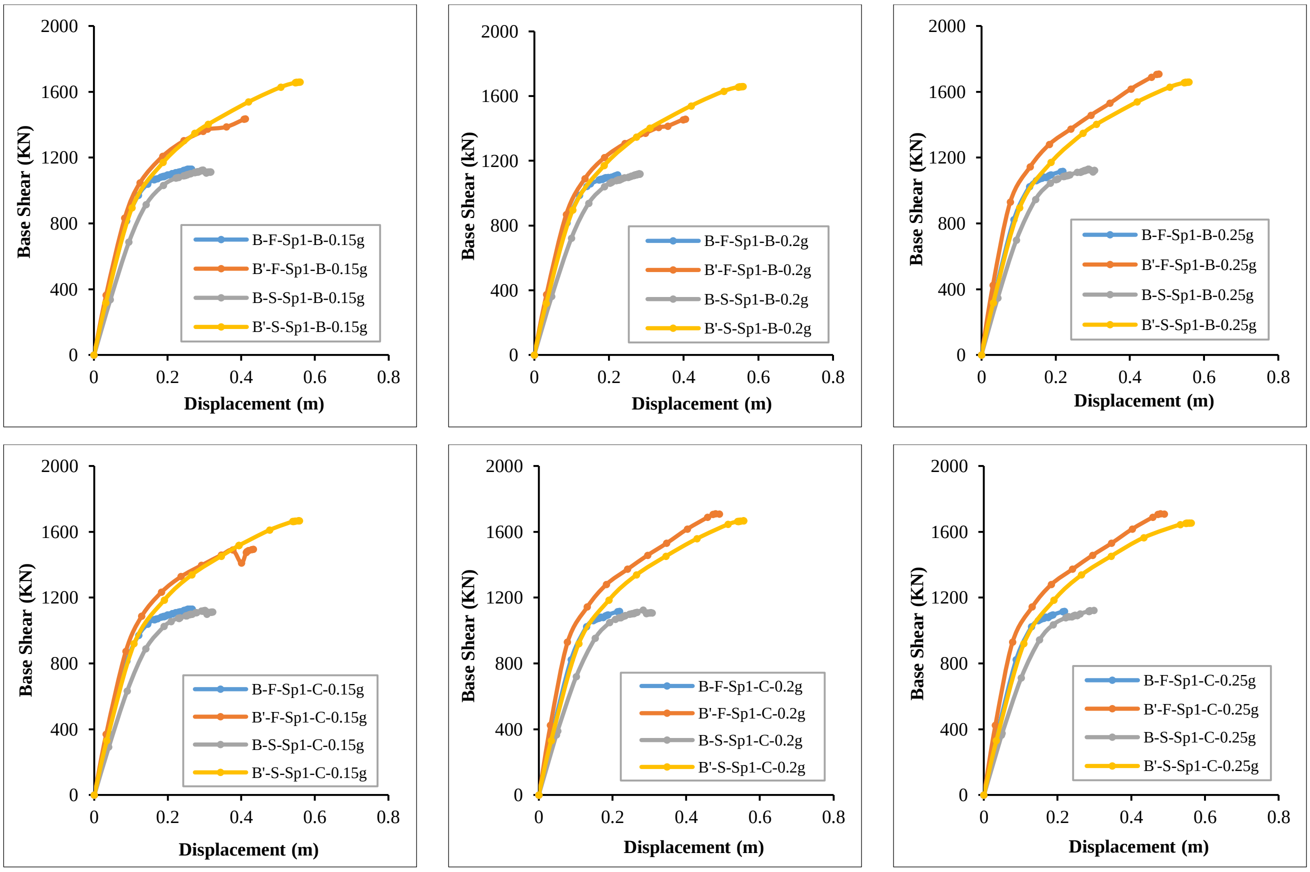


Figure 13. Pushover curves (P.O.C.) for the spectrum type I for models B, B'

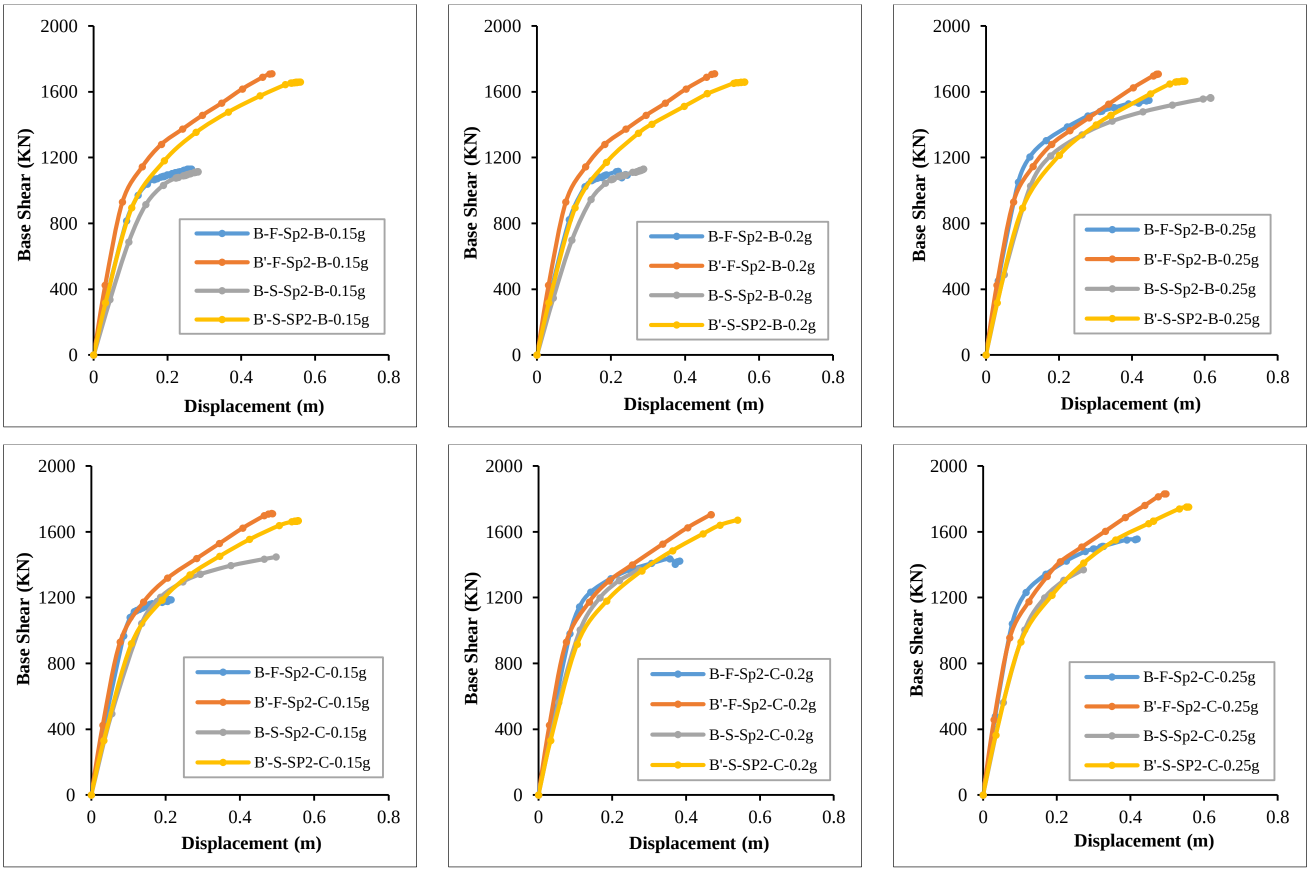


Figure 14. Pushover curves (P.O.C.) for the spectrum type II for models B, B'

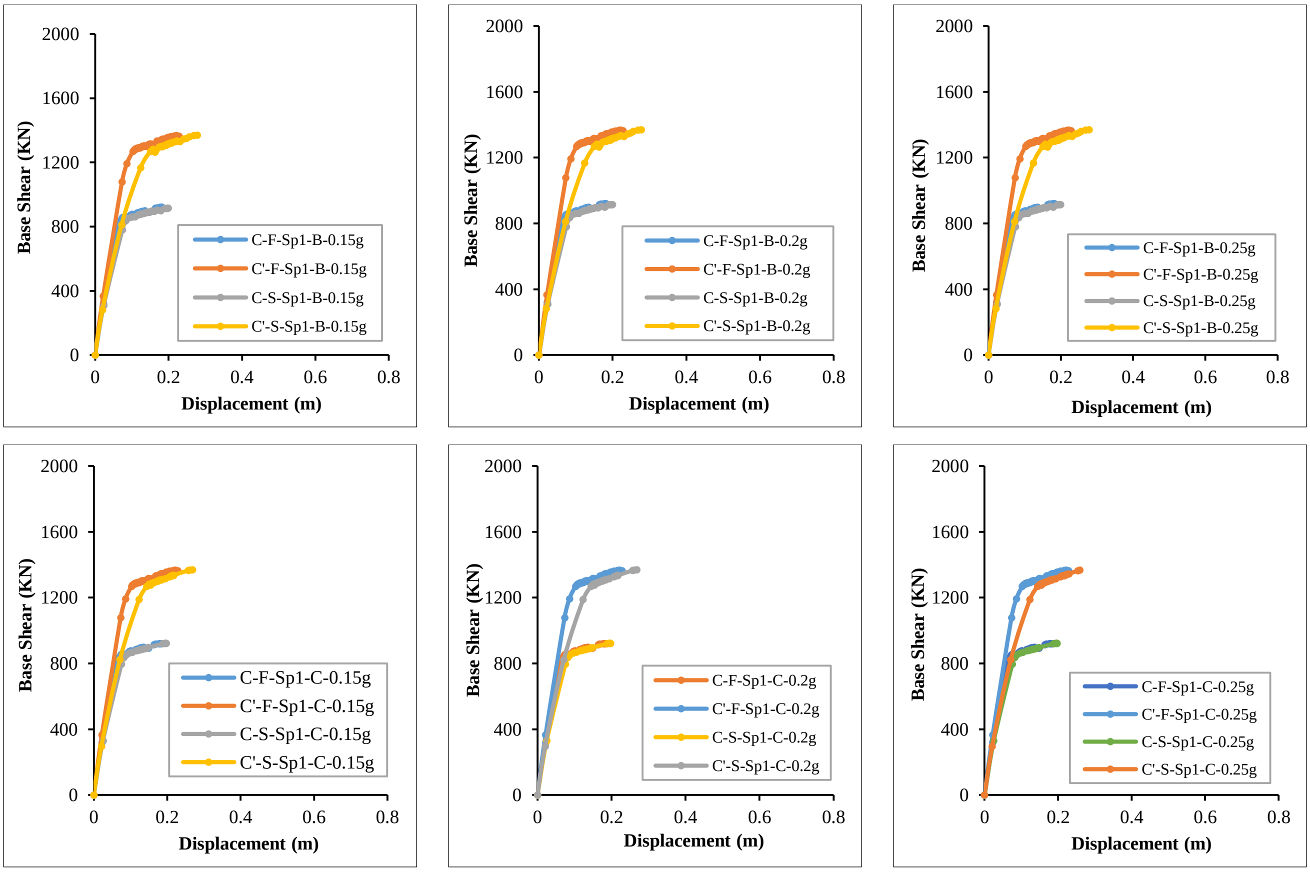


Figure 15. Pushover curves (P.O.C.) for the spectrum type I for models C, C'

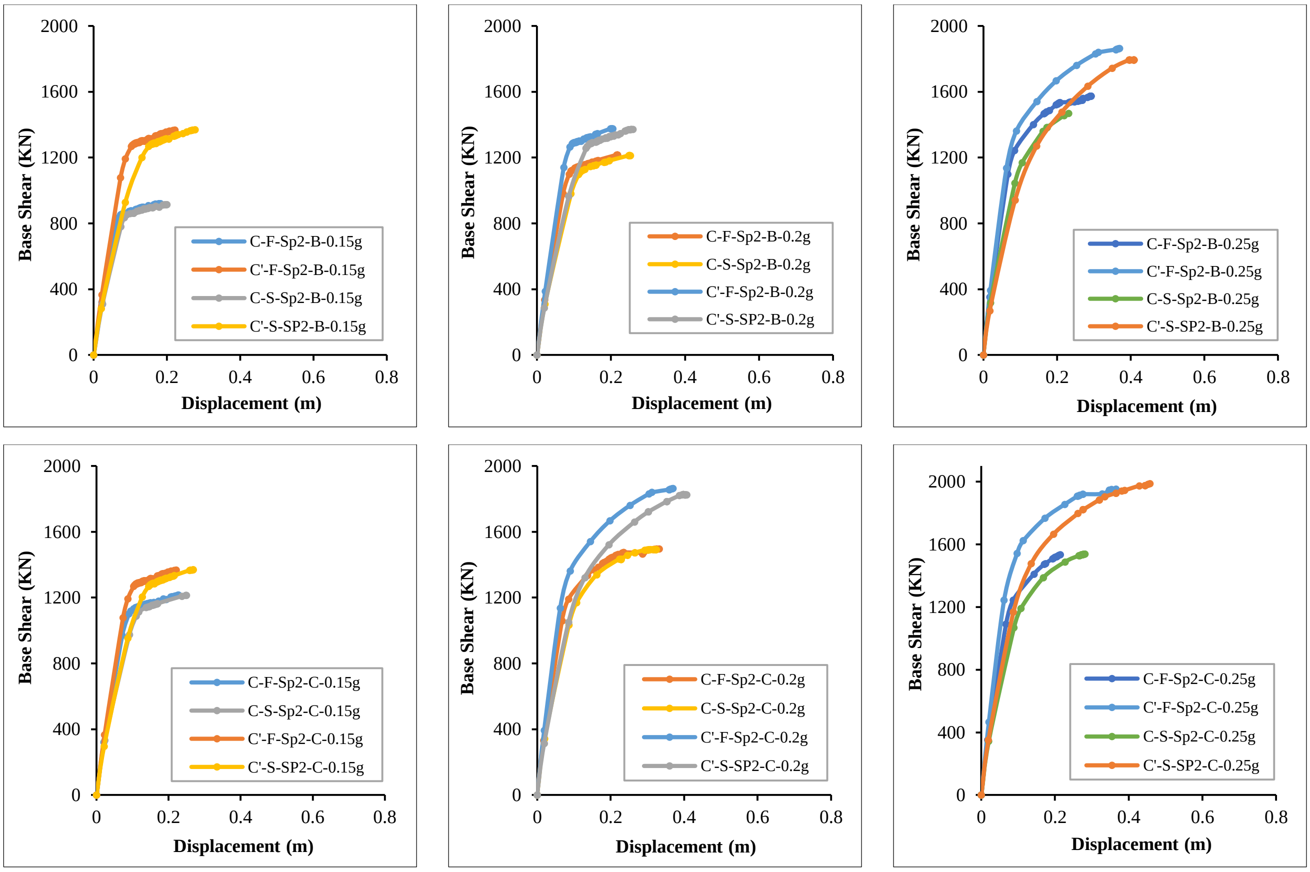


Figure 16. Pushover curves (P.O.C.) for the spectrum type II for models C, C'

Structural behavior during a weak earthquake tends to be similar across different structures, despite varying geometries and characteristics. However, at higher seismic intensities, the mass, stiffness, and geometry of a building significantly affect the shape of the pushover curve (POC). Buildings with more floors and higher irregularity percentages exhibit greater areas under the curve, resulting in higher displacement ratios, particularly when considering the effects of soil-structure interaction (SSI). This phenomenon allows all structural elements to reach their maximum deformation capacity, leading to higher displacement values.

7.3. Effect of SSI

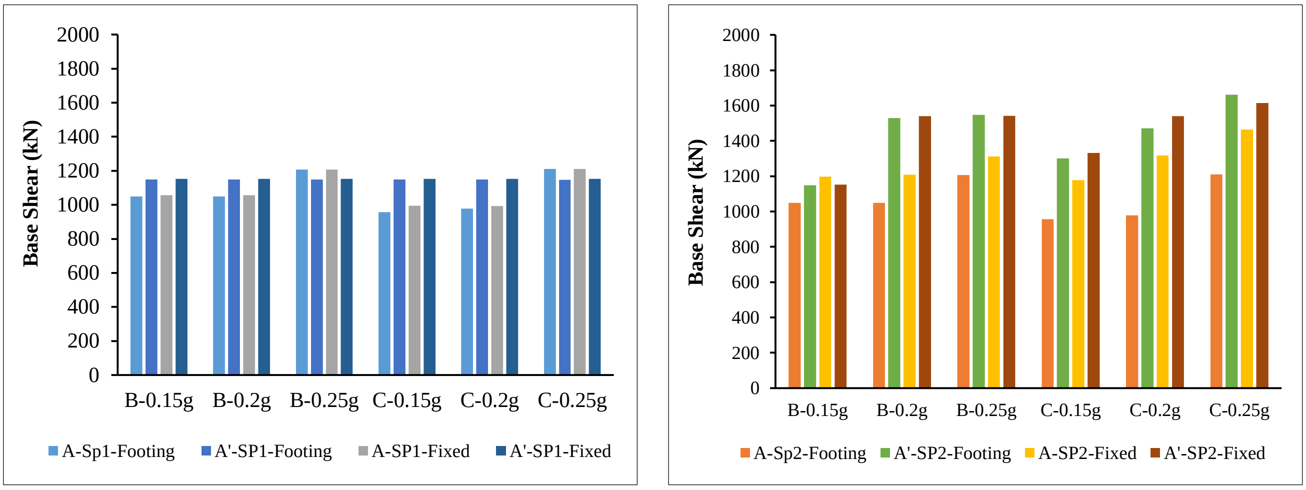
In this section, the effect of different soil types on the structures was investigated. The obtained charts are labeled with a specific code format. For example, "A-F-Sp1-B-0.15g" represents building (A) with fixed support (F), subjected to response spectrum type I (Sp1), founded on soil type (B), in seismic zone with intensity (0.15g). In the case of isolated footing, "S" was used instead of "F". Each pair of successive rows in the upcoming graphs represents one building. Each row contains a family of curves where the seismic intensity was increased from 0.15g to 0.25g (see Table 4). The first row corresponds to spectrum type I, while the second row corresponds to spectrum type II.

The base shear value and the natural time period (NTP) were both impacted by soil-structure interaction, as illustrated in Figures 17 and 18. For the A, B, and C models, the base shear decreased by 1%, 10.5%, and 1%, respectively, when SSI was considered, especially in soft soil (type C) for SP1. Additionally, for SP2, the base shear decreased by 17%, 12%, and 1% for the A, B, and C models, respectively. Furthermore, the NTP increased by 14%, 12%, and 13% in the A, B, and C models, respectively, as seen in Figure 18. Due to the SSI effect, the structure's natural period becomes longer, with a more pronounced effect in soft soil. The natural time period is a key factor controlling the building's lateral seismic response. Therefore, evaluating this value without considering seismic design could lead to significant errors. It has been observed that the NTP increases with soil flexibility. The structure's characteristics cause the rate of increase in NTP to be higher when the soil is represented by springs, showing a higher time period than the fixed base model. This difference is less for low-rise buildings and increases with the building's height. Additionally, high-rise structures on weak soil are more affected by SSI than low-rise ones, as indicated by a parametric analysis varying the height and geometry of the building with and without SSI [45]. The influence of SSI was evident in the push-over curve, where irregular Model B (soil type C - zone 0.25g) had a maximum lateral displacement of 0.32 m, increasing by 31.5% compared to a fixed base, and 14% for regular Model B. Thus, the impact of soil representing SSI's effect on seismic design, especially for irregular structures, needs to be considered.

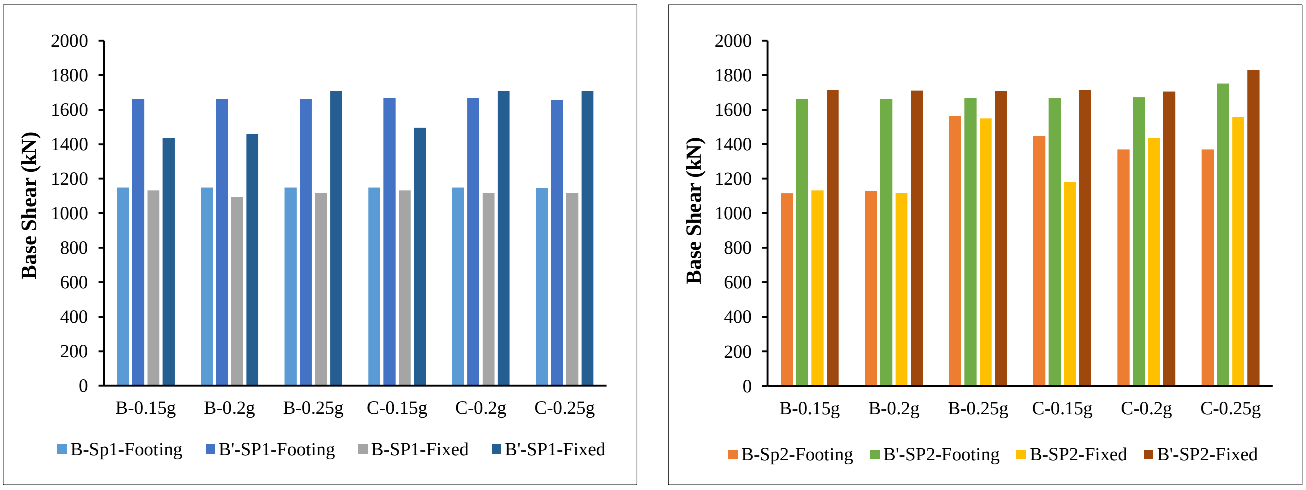
Table 4. Response modification factor value for fixed base (F) and isolated footing (S), for models

Soil Type		Models	A F	A S	A' F	A' S	B F	B S	B' F	B' S	C F	C S	C' F	C' S
Spectrum (I)														
	B	0.15g	6.72	7.10	7.35	7.65	5.893	6.55	6.41	6.8٦	7.123	7.34	7.52	7.96
		0.2g	6.52	7.07	6.87	7.25	5.297	6.08	5.82	6.43	6.857	7.28	7.37	7.90
		0.25g	5.42	6.14	5.87	6.32	4.060	5.18	5.00	5.92	6.126	6.60	6.65	7.32
	C	0.15g	5.40	6.00	5.72	6.25	4.590	5.41	4.89	5.53	5.827	6.18	6.12	6.51
		0.2g	4.67	5.35	4.94	5.57	3.489	4.76	4.11	5.31	5.126	5.79	5.55	6.10
		0.25g	3.79	4.56	4.18	5.13	2.523	3.48	3.29	4.20	4.495	5.30	5.14	5.83
Spectrum (II)														
	B	0.15g	5.24	5.69	5.44	5.78	4.800	5.24	4.98	5.56	5.723	6.07	5.78	6.30
		0.2g	4.81	5.27	5.11	5.69	4.401	4.80	4.72	5.35	5.312	5.88	5.58	6.31
		0.25g	4.64	5.12	5.05	5.70	4.139	4.37	4.45	5.12	4.895	5.49	5.27	6.03
	C	0.15g	4.26	4.51	4.67	5.17	3.997	4.20	4.35	4.82	4.533	5.13	4.91	5.35
		0.2g	3.75	4.19	4.16	5.06	3.193	3.70	3.64	4.27	4.170	4.73	4.66	5.45
		0.25g	3.26	4.01	3.72	4.79	2.597	3.39	3.46	4.70	3.816	4.47	4.39	5.28

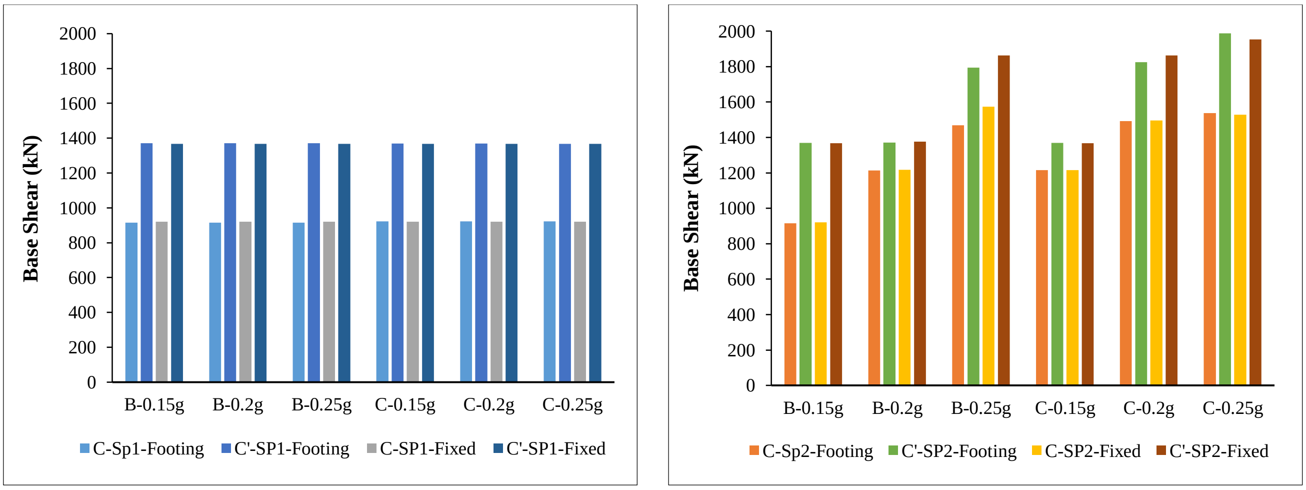
Response Modification Factor (R)



Model A,A'



Model B,B'



Model C,C'

Figure 17. Base shear values for models

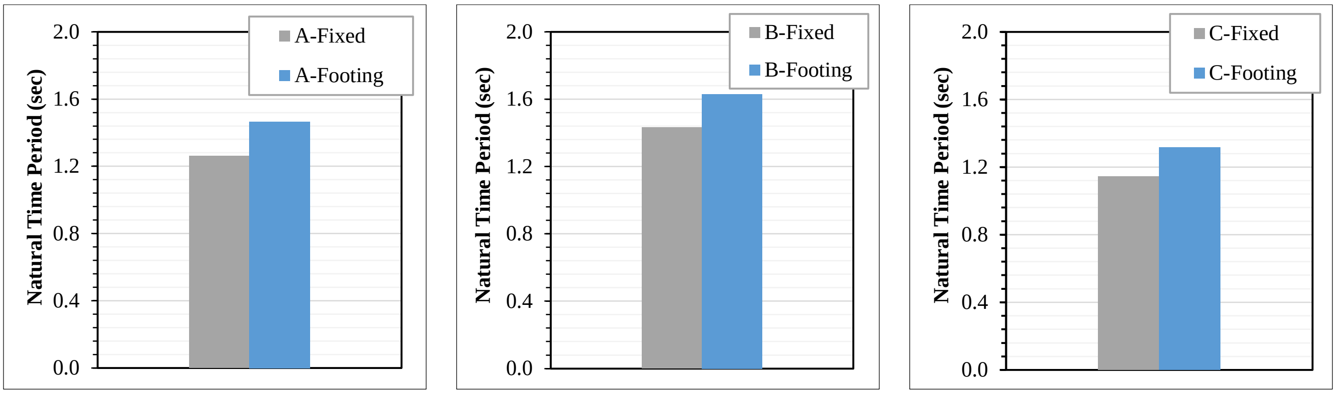


Figure 18. Natural Time Period (Sec) for models

There is an observed improvement in the natural period, roof displacement, base shear, and structure's deformation, along with an improvement in the flexibility of the soil; essentially, the conclusion will affect the response factor.

7.4. Effect of Irregularity

It was clear how the structure's irregularity on the pushover curve affected the structure's strength and how it behaved during the earthquake. The deducted area from the structure, or the degree of irregularity of the structure.

The impact of irregularity appears more pronounced in flexible structures, such as model B, highlighting that the effect is more noticeable in more flexible models. Regular and non-regular structures exhibit similar behavior in response to a weak earthquake. Figures 9 to 14 show that structures (models A, B, and C) demonstrate low ductility. However, models (A', B', and C') exhibit good ductility, with irregularity causing a decrease in maximum displacement of 0%, 54%, and 18% respectively for Sp I compared to regular models. This decreased by 22.5%, 16%, and 23% respectively for Sp II (for fixed base).

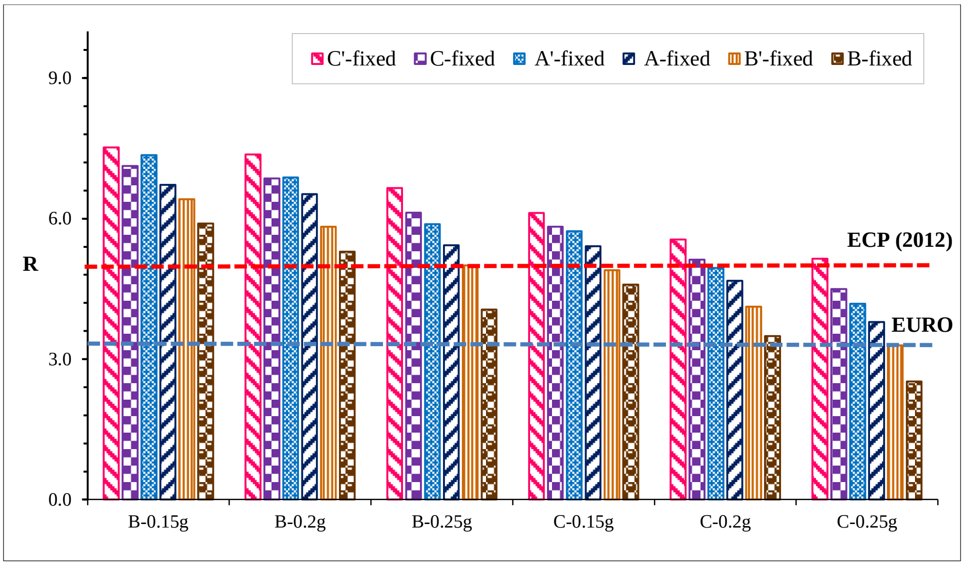
With fixed base: In both regular and irregular buildings, as the seismic zone's intensity increases, the value of R decreases, approaching the values specified in the ECP (2012) code for soil type B. For soil type C, the values were 9.3%, 23.4%, and 12.61% for models A, B, and C respectively for SP1. For SP II, the values were 12.4%, 25%, and 13.12% for models A, B, and C respectively. When representing soil with springs: Similar to the fixed base scenario, in both regular and irregular buildings, as the seismic zone's intensity increases, the value of R decreases, approaching the values specified in the ECP (2012) code for soil type B. For soil type C, the values were 11.13%, 16.5%, and 9.1% for models A, B, and C respectively for SP1. For SP II, the values were 16.2%, 28%, and 15% for models A, B, and C respectively. In tall buildings with many floors, the percentage decrease in the structure's response was higher as the seismic zone increased, particularly in weak soil (type C).

The seismic load significantly affected the structure's response, especially due to the varying percentage irregularity in the study's models. Design requirements and code standards need to consider the irregularity percentage to ensure more stable and secure seismic load designs. For instance, a 30% irregularity rate caused the reduction factor to decrease to 23.4% for soil type C and 18% for type B (for SP1). Similarly, it decreased to 25% for soil type C and 7% for type B (for SP II).

Model C has a 21% irregularity percentage. For SP1, the reduction percentage varied from 7% to 6% in weak soil (type C) and from 5% to 4.5% in soil type B in the same seismic zone. The reduction percentage varied between 4.5% and 3.8% in soil type B. Conversely, the decrease for models B, A, and C was around 17%, 11%, and 9%, respectively, when the soil was represented by springs.

Because structures have a large reserve strength and the ability to dissipate energy—properties known as overstrength and ductility, respectively—seismic design regulations take these into account and reduce design loads using a reduction factor. This study shows that structural irregularity impacts the value of R, especially in weak soil subjected to strong seismic intensity. For instance, model B, with a 30% irregularity rate, shows a more pronounced effect. As the seismic zone becomes more intense, the decrease in the value of R is significantly less than the values listed in the ECP, approaching the values of the Euro Code. Therefore, it is necessary to review the ECP values and reduce them, especially for irregular buildings. Using the Egyptian Code values for irregular buildings, particularly after considering soil representation, is considered an unsafe design practice (see Figures 19, 20, and Table 5).

The value of R decreased as the seismic zone increased for all models. The shape or irregularity of the structure had a clear impact on the values of R with the same soil type and seismic zone, indicating that the value of R was close to the values of the Euro Code, especially in poor soil in SP2. It is indirectly impacted by the structure's shape and irregularity. The reduction in the modification factor is clearly influenced by the number of floors, and the percentage of irregularity also had an impact, with the maximum decrease in the modification factor reaching 23% in model B in loose soil (type C) for spectrum I. For springs, the maximum decrease reached 17.7% in model B for spectrum I. The decrease reached 16.2% in model A, 28% in model B, and 15.4% in model C for spectrum II in loose soil (type C).



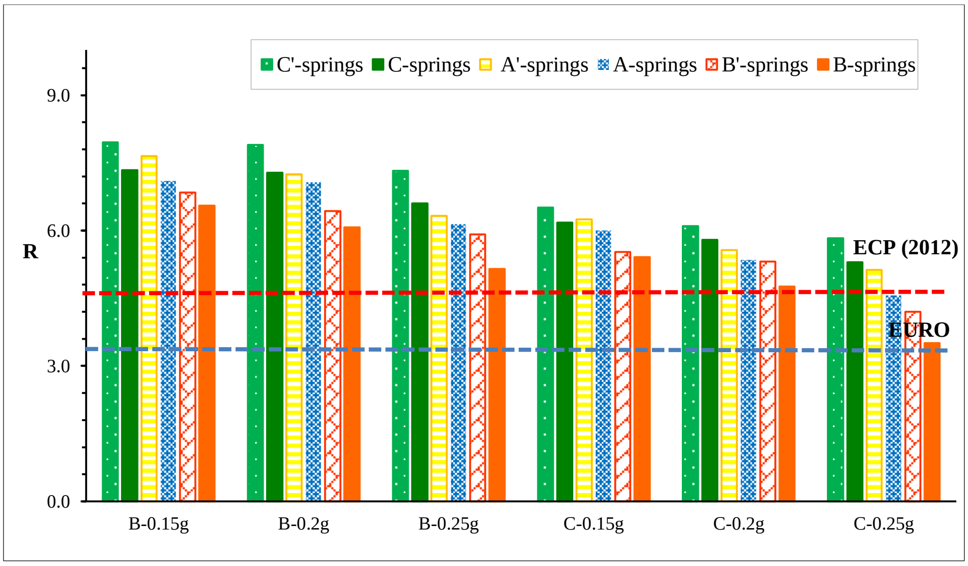


Figure 19. Response Modification factor (R) for models, (spectrum type I)

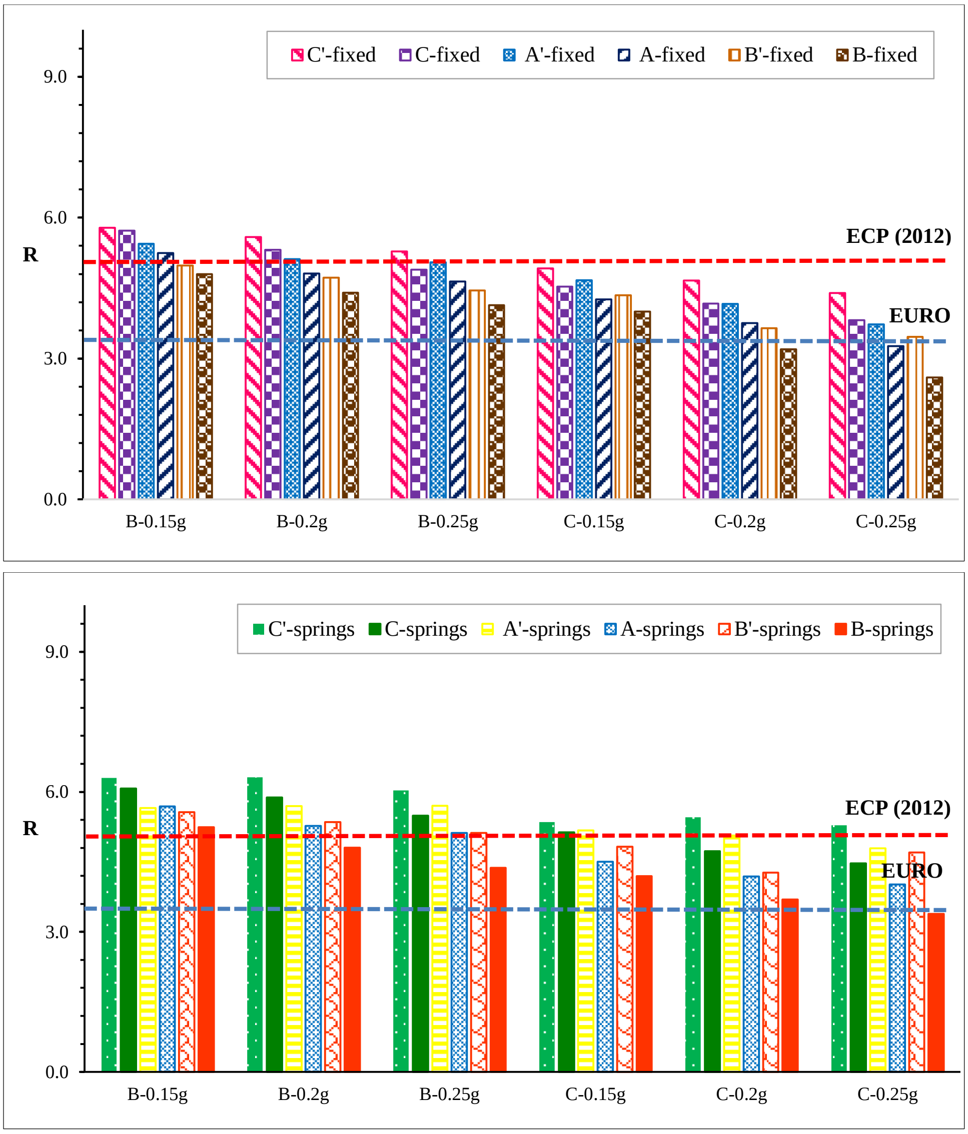


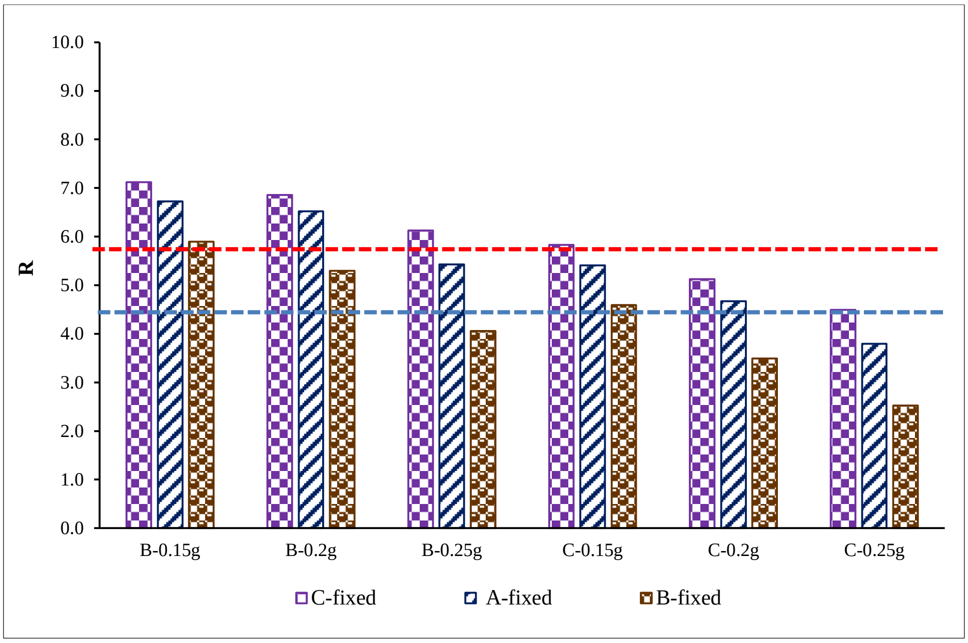
Figure 20. Response Modification factor (R) for models, (spectrum type II)

Table 5. Response factor value for fixed base (F) and isolated footing (S), for models

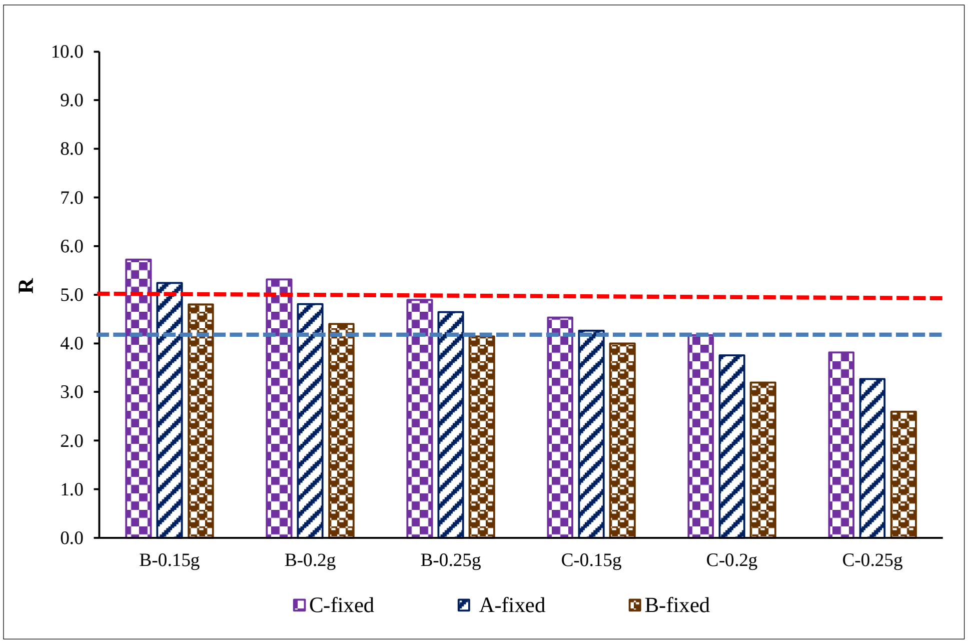
Decrease in Response Modification Factor (R) due to irregularity %								
MODELS			**A (28.6%)**		**B (30%)**		**C (21%)**	
			F	**S**	**F**	**S**	**F**	**S**
Spectrum I								
Soil Type	**B**	0.15g	8.61	7.16	8.12	4.46	5.28	7.78
		0.2g	5.22	2.47	9.08	5.42	6.96	7.78
		0.25g	7.67	2.91	18.83	12.42	7.92	9.83
	C	0.15g	5.56	3.98	6.32	2.13	4.84	5.02
		0.2g	5.53	3.94	15.25	10.34	7.69	5.02
		0.25g	9.30	11.14	23.39	17.17	12.61	9.09
Spectrum II								
	B	0.15g	3.60	1.64	3.67	5.81	1.06	3.58
		0.2g	6.03	7.46	6.78	10.29	4.87	6.78
		0.25g	8.11	10.14	7.03	14.54	7.26	8.99
	C	0.15g	8.76	12.86	8.13	12.97	7.82	4.09
		0.2g	9.79	17.31	12.49	13.50	10.56	13.32
		0.25g	12.39	16.23	24.96	28.05	13.12	15.42

7.5. Effect of Seismic Zone

Figure 21 shows that as the zone increases Displacement also increases [40], and Base shear and lateral displacement increase with increase in the seismic intensity.



Spectrum Type II



Spectrum Type II

Figure 21. Response Modification factor (R) for models

The Figure 22 illustrates how SSI affects the strength reduction factors for weak soils. Because of this, applying fixed-base strength reduction factors for interacting systems results in non-conservative design forces, hence interaction effects for weak soils cannot be ignored [39].

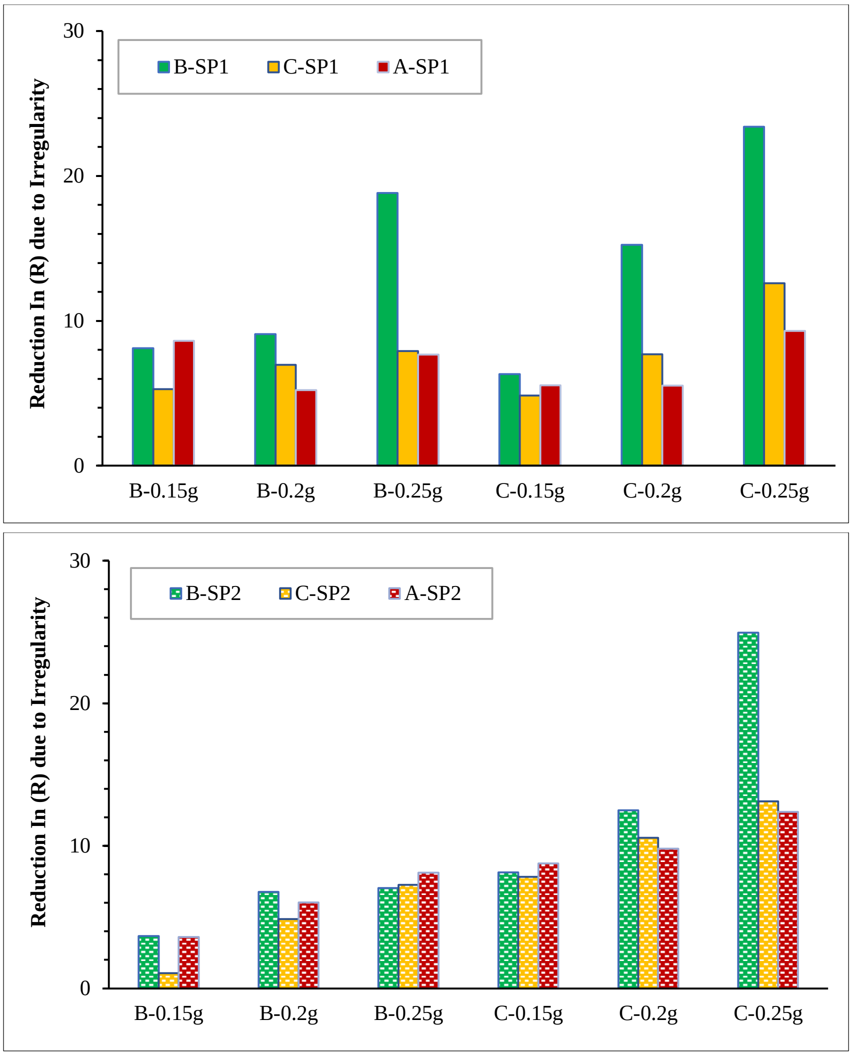


Figure 22. Reduction in Response factor due to irregularities% (R), for SP I and SP II

8. Conclusions

The present study aims to determine the effectiveness of plan and elevation irregularities in relation to seismic response within seismic zones I, II, and III, on medium and poor soil (types B & C), for both types of design response spectra given in ECP-201 (2012). The study also seeks to understand the significance of SSI or representing soil interaction with the footing (using isolated footing with springs) on R-value, base shear, lateral displacement of buildings, and the fundamental natural period of regular and irregular models. The investigation reveals the following main conclusions:

There is an observed enhancement in the natural period, roof displacement, base shear, and structure's deformation with an improvement in soil flexibility. Essentially, this conclusion will impact the response factor. If the SSI approach is not appropriately included in the investigation and design, it may be difficult to determine how safe a structure is from earthquakes accurately. When the seismic zone increases, the basic time period (TP) increases, and therefore, the response factor decreases. The natural period of the structure becomes longer due to the SSI influence, with the effect being more pronounced in soft soil. One of the main factors controlling the building's lateral seismic reaction is the NTP. Therefore, if this value is evaluated without considering seismic design, significant errors could occur. It has been demonstrated that as soil flexibility increases, so does the NTP. The irregularity resulting from increased structural rigidity seems insignificant for buildings supported by isolated footings. Regular and non-regular buildings that rely on weak soil deposits may not have sufficient structural safety guaranteed by standard design techniques if the SSI method is not used. Regular and non-regular structures behave similarly in response to weak earthquakes. The seismic zone has a significant impact on the reduction factor. As the seismic zone increases, the decrease in R's value is significantly less than the values listed in the ECP and is considered close to the Euro Code values. Therefore, it must be considered that the ECP values need to be reviewed and this percentage reduced, especially in irregular buildings. Taking the ECP Code values for irregular buildings, specifically after representing the soil and considering it, is considered an unsafe design.

9. Declarations

9.1. Author Contributions

Conceptualization, S.M.E. and N.E.N.; methodology, N.E.N. and M.N.E.F.; software, T.M.S.; vformal analysis, N.E.N. and M.N.E.F.; investigation, M.N.E.F.; resources, T.M.S.; writing—original draft preparation, S.M.E. and A.M.A.; writing—review and editing, A.M.A.; visualization, A.M.A.; supervision, S.M.E. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available in the article.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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