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Optimal Bracing Type of Reinforced Concrete Buildings with Soil-Structure Interaction Taken into Consideration

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Abstract

This study aims to investigate the impact of soil-structure interaction (SSI) on the seismic behavior of reinforced concrete buildings. An advanced numerical model for SSI was developed and verified using ABAQUS software. The seismic response of a 12-story building on four types of soil (rock, dense soil, stiff soil, and soft soil) was examined using a Normalized Response Spectra based on the Moroccan paraseismic regulation RPS 2011. The global lateral displacement, inter-story drift, and period were compared for two types of bracing (column and shear wall). The results show that SSI has a significant impact on the seismic behavior of buildings, and the seismic responses of soil-structure systems with column and shear wall bracing are quite different. The research contributions of this paper include developing an advanced numerical model for SSI, examining the impact of SSI on the choice of bracing for reinforced concrete buildings, and providing guidance on the most reliable bracing method for structures of various heights and soil types. The study's findings have important implications for seismic design and can help improve the safety and reliability of buildings in earthquake-prone regions. The study also highlights the importance of considering SSI in seismic design and the need for guidelines that describe the bracing systems to be used based on the structure's height and type of soil.

Keywords: Bracing System; Reinforced Concrete; Soil-Structure Interaction; Seismic Response; ABAQUS.

1. Introduction

To ensure the overall stability of a building, it is necessary to provide bracing. The most commonly used types of bracing for reinforced concrete buildings are columns and shear walls, which enable the transmission of loads to the ground and contribute to the good behavior of buildings during earthquakes. Several standards and regulations address this issue and enable engineers to choose the most optimal seismic design. However, in most cases, soil-structure interaction is neglected, and buildings are assumed to be embedded in the ground. Additionally, several software tools used by engineers do not effectively account for the influence of the soil. This can result in uncontrollable material and human damage during seismic stresses, highlighting the importance of conducting further scientific research in this area [1]. While there have been numerous studies on the behavior of buildings considering the soil-structure interaction, further research is needed to accurately represent the real behavior of buildings. Some researchers have demonstrated the effect of increasing the thickness of shear walls on the building's performance by reducing displacement under seismic loads [2]. Additionally, the location of the shear walls can significantly reduce displacement due to seismic loads [3]. One study presented the effect of the position of steel bracing in L-shaped reinforced concrete buildings under lateral loads [4]. Another study was conducted using ETABS software to present the effect of seismic loads on various criteria such as story drift, base shear, and displacement [5]. Others have studied the effects of seismic loads on reinforced concrete frame buildings with shear walls as bracing systems [6]. This study showed that shear walls affect

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the lateral strength of high-rise buildings but have less effect on lateral stiffness. On the other hand, shear walls for low-rise buildings have a strong effect on lateral stiffness but a lesser effect on lateral strength. A study on the effect of the position and size of shear walls on the attracted forces revealed that increasing the upper dimension of the shear walls will increase the horizontal forces resisted by that wall.

It is evident from the literature review that very little work has been done to study and analyze the effect of seismic loads on reinforced concrete buildings, considering the soil-structure interaction and comparing the types of bracing systems used. Most research has focused on analyzing buildings using a single bracing system, either columns or shear walls. The present study aims to investigate and analyze the effect of seismic loads on reinforced concrete buildings using the two most common bracing systems (columns and shear walls) while considering the soil-structure interaction. The objective of this work is to evaluate the effect of different bracing systems on a structure with soil-structure interaction subjected to seismic loads and identify the most suitable bracing system to resist seismic loads.

There are several methods for analyzing soil-structure interaction (SSI), which is a field of applied mechanics focused on developing and investigating theoretical and practical approaches for structure analysis that consider soil and foundation behavior [7, 8]. Before the 1971 San Fernando earthquake and the start of nuclear construction in California, the effects of SSI on seismic response were not given much attention. However, recent catastrophic earthquakes in various parts of the world have raised concerns among engineers [8, 9]. A comparative review of various SSI analysis methods can be found in Mohammadioun & Pecker [10] and Wolf et al. [11]. Guéguen et al. [12] and Bard et al. [13] have confirmed the influence of soil on a structure's response as well as the significance of certain structural configurations such as burial, mass, and geometry. Impedance functions [14, 15] have been used to account for SSI. The research has also demonstrated that the movement of a structure generates reaction forces at the interface between the soil and the structure, resulting in a secondary wave field backscattered in the soil from the foundation, known as the Structure-Soil Interaction. A simplified two-dimensional anti-planar motion model [16] has confirmed that the presence of a structure can modify the ground motion recorded in the free field, even at significant distances of kilometers. Additionally, Jennings [14] has recorded the movements created by the forced vibration of a structure at a distance of several hundred meters. A recent experiment [12] has quantified the wave field radiated into the ground from the base of a structure that was artificially excited by release tests. This study showed that the motion transmitted to the ground from the structure is not negligible.

The soil's deformability can result in Davidovici [17]:

- An increase in the first mode's vibration period, leading to a variation in acceleration values depending on the zone.
- Considerable damping (including radiative damping and specific damping of the soil material).
- Rotation of the foundation, which can significantly alter the calculation of modal deformation and, in turn, the distribution of accelerations across the building's height [18].
- In most cases, the ground motion at the building's base is assumed to be the same as that of the free field, and this approximation is usually deemed acceptable [19, 20].

There is a general tendency for SSI to have beneficial effects on most typical building structures, as it can reduce bending moments and shear forces in individual structural elements [21]. When SSI is not required by codes such as Eurocode 8 [22] or Eurocode 7 [23], considering it can often lead to reduced loads through ground-level dissipation and a more favorable spectral response. There are several reasons why it is important to consider soil-structure interaction [24]:

- To include the movements at the base of the structure in the analysis of deformation modes by considering a coupled soil-structure system.
- To obtain a better understanding of the vibration frequency of the coupled system, which has implications for the design and assessment of the structure.
- To fully evaluate the behavior of critical structures.

An analysis was performed to investigate the impact of soil-structure interaction under various conditions, including different soil types (soft, medium, and hard) and the use of an embedded foundation. The structures were subjected to a normalized response spectrum based on Moroccan seismic code RPS 2011, specifically for the Al Hoceima region, which is one of the most seismically active areas in the north of Morocco, as shown in Figures 1 and 2. To achieve this, 10 models were created using ABAQUS finite element software to simulate dynamic soil-structure interactions accurately and realistically. Infinite soil elements were used to avoid seismic wave reflection. The two most common types of bracing (columns and shear walls [25]) were also extensively studied to contribute to the creation of a design guide.

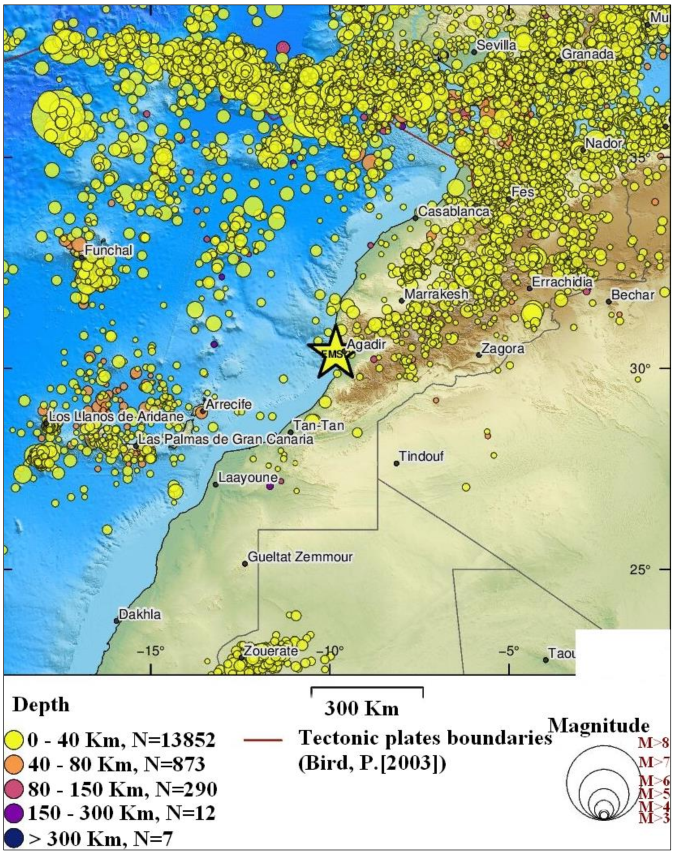


Figure 1. Seismicity map of Morocco [26]

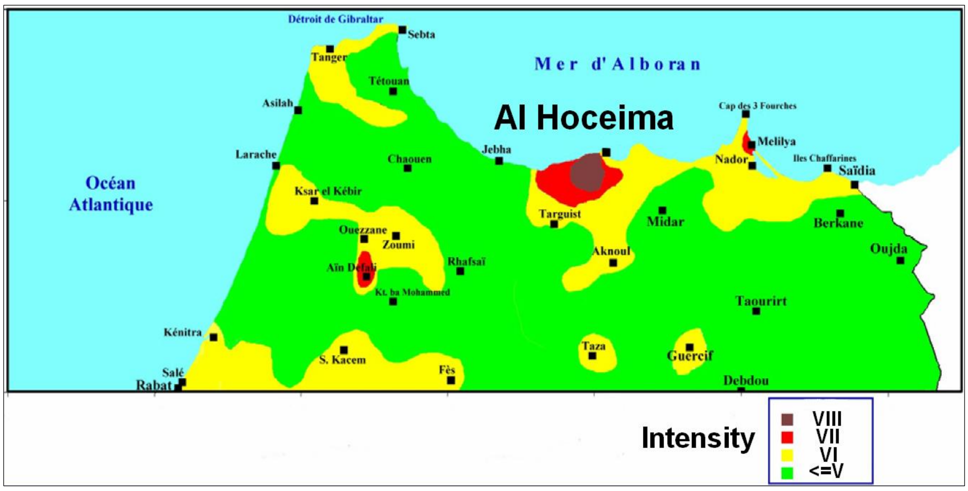


Figure 2. Map of maximum felt intensities in northern Morocco between 1901 and 2000 [27]

2. Research Methodology

The major goal of this study is to determine how bracing affects structures of various heights with various types of soils when subjected to seismic loads and to identify the best bracing strategy in each situation. In order to thoroughly examine the subject, we followed the methodology presented in Figure 3. The methodology of this study, was carefully planned and executed to achieve the research goals. It started with a comprehensive literature review to identify the different types of bracing and soil-structure interaction phenomena. This information was used to gather data on the different types of soils and materials mandated by Moroccan regulations. The next step was to design and model a 12-story building with different types of bracing on the four soil types specified by Moroccan regulations. The model was validated using the ABAQUS software, which is a powerful tool for analyzing complex structural systems under seismic loading. Data analysis was performed by comparing the amplitude of displacements and time periods of the buildings with different types of bracing and soil types. The impact of soil-structure interaction on the choice of bracing type for RC buildings was highlighted, and the results were discussed in terms of global lateral displacement, inter-story drift, and period.

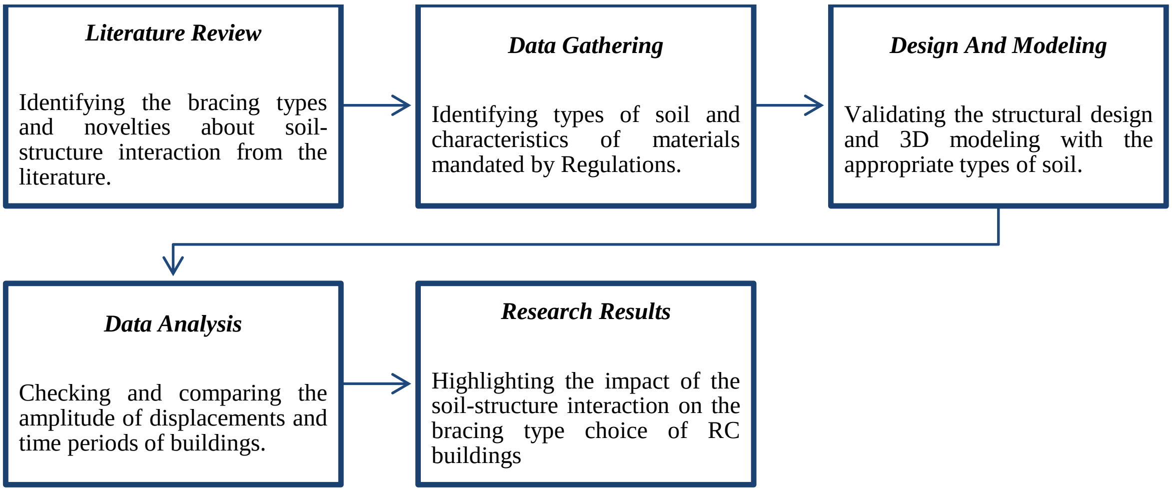


Figure 3. General research methodology flowchart

Figure 4 shows the approach followed in the study to investigate the effects of soil-structure interaction on different types of bracing for a 12-story building. The study focused on two types of bracing, columns, and shear walls, which are commonly used in reinforced concrete (RC) buildings. To determine the impact of soil type on the performance of these two types of bracing, the study considered five different soil types: rock, dense soil, stiff soil, soft soil, and fixed base. Simulations were carried out for each soil type, and for each simulation, an analysis of the amplitude of displacement and time period of the building was performed. By changing the soil type for each building, the study was able to establish results that can contribute to the improvement of seismic regulations, which do not address the soil-structure interaction for each type of bracing. Overall, the methodology used in the study was rigorous and comprehensive, and the results obtained can be used to improve the seismic design of RC buildings in Morocco, and potentially in other regions with similar geological conditions.

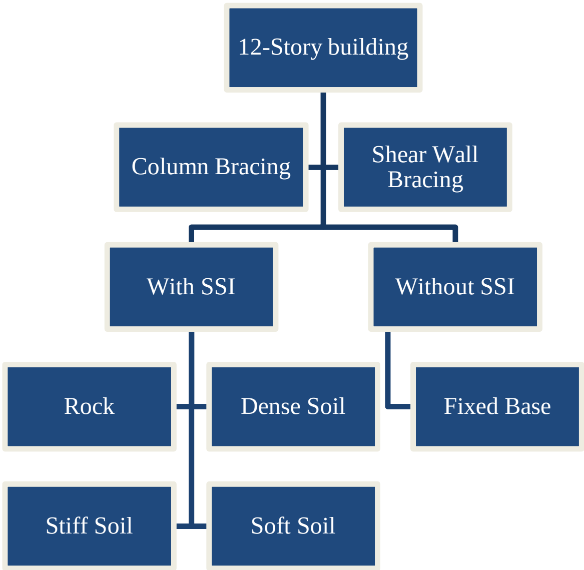


Figure 4. Technical flowchart explaining subject processing

3. Study Data

3.1. Seismic Area

In a previous study, it was demonstrated that the seismic zone plays a significant role in the seismic response of a building and in determining the type of bracing required [28]. The 2011 RPS earthquake regulations divide Morocco into five different zones and provide two seismic zoning maps, one based on acceleration and the other on velocity [29]. Due to its history [26], especially the city of El Hoceima [30, 31], the northern seismic zone of Morocco is the least favorable zone in the country, as shown in Figure 5. The seismic hazard is characterized by using 5% damped elastic response spectra from a probabilistic perspective, which represents a 475-year recurrence interval. For our study, a response spectrum derived from the national seismic code is suggested.

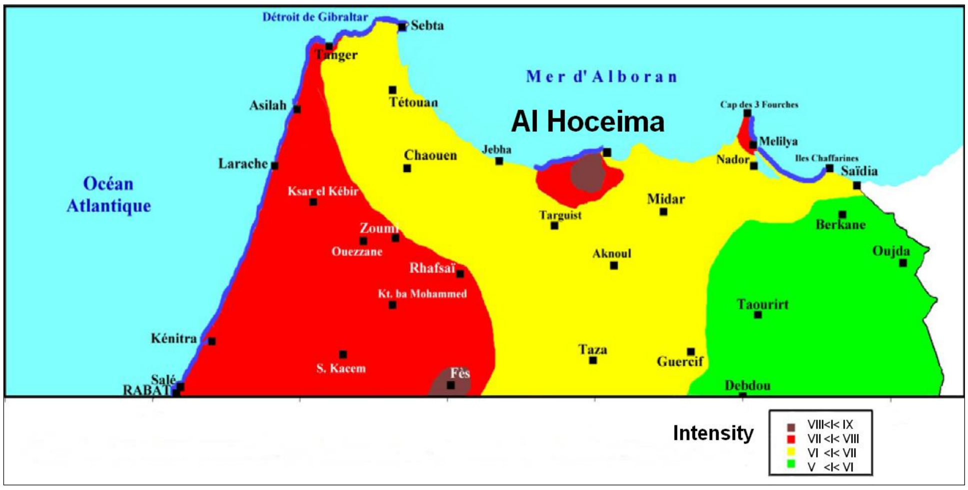


Figure 5. Map of maximum felt intensities taking historical data into account [27]

The elastic response spectrum Se(T) is given in Table 1.

Table 1. Seismic acceleration values based on the national seismic code RPS 2011 [29]

Z_a/Z_v Ratio *	$0 \leq T \leq 0.25$	$0.25 \leq T \leq 0.5$	$0.5 \leq T$
$Z_a/Z_v > 1$	1.9.S.ag**	1.9.S.ag	
$Z_a/Z_v = 1$	2.5.S.ag	(-2.4.T + 3,1).S.ag	1.20.ag.S / $(T)^{2/3}$
$Z_a/Z_v < 1$	3.5.S.ag	(-6.4.T + 5,1).S.ag	

where Za and Zv are respectively the acceleration and the velocity values corresponding to the seismic zone, ag is the acceleration value which ranges between 0.04 g and 0.18 g, S is the soil factor having values displayed in the Table 2.

Table 2. Site classification according to the national seismic code RPS 2011 [29]

Site Class	Shear Wave Velocity Vs (m/s)	Standard Penetration Resistance N60	Undrained Shear Strength Su (kPa)	Soil Factor (RPS2011)
S1	Vs > 760	Not Applicable	Not Applicable	1
S2	360 < Vs < 760	Ns > 50	Su > 100	1.2
S3	180 < Vs < 360	15 < Ns < 50	50 < Su < 100	1.4
S4	180 < Vs	Ns < 15	Su < 50	1.8

Figure 6 displays the resulting 5% damped elastic response spectra for several types of soil using matching values from the seismic area chosen, Al Hoceima (S1: Rock – S2: Dense Soil – S3: Stiff Soil – S4: Soft Soil).

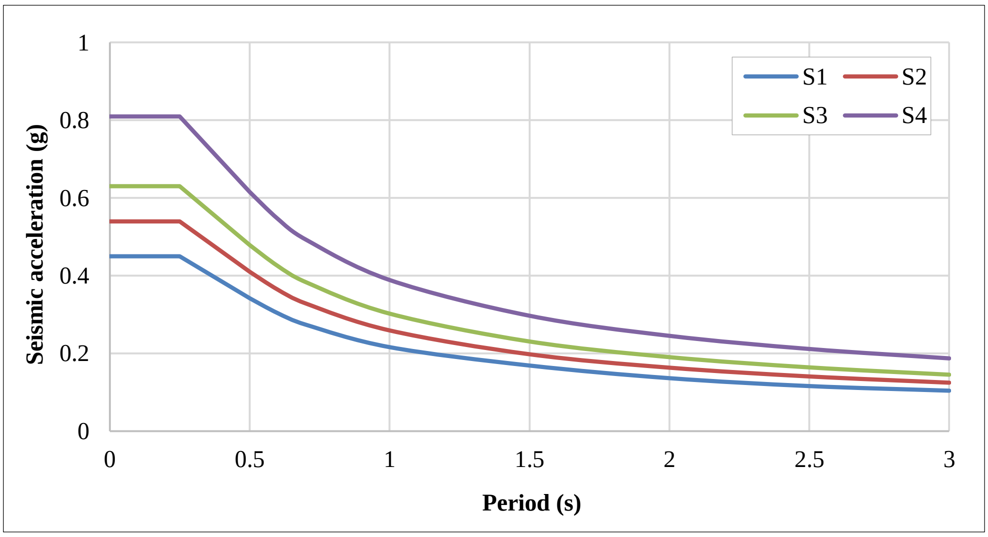


Figure 6. Normalized Response Spectra of the Moroccan paraseismic regulation RPS 2011 [29] For Al Hoceima

In order to match the response spectra to a historical earthquake event, we used the software SeismoMatch [32]. The software utilizes a matching algorithm to compare the recorded ground motion with a database of ground motions from historical earthquakes. It is capable of adjusting earthquake accelerograms to achieve a specific target response using the wavelet algorithm [33]. To achieve this, data from real earthquakes "ghiss" [30] and "zeghanghane" [31] was used to match the specified target response spectra, considering a minimum and maximum time period of 0.02 sec and 4 sec, respectively, with a tolerance of 0.02. Figure 7 shows the normalized response spectra for soil S1 with its matched response spectra, and Figure 8 shows the matched historical earthquakes obtained for all 4 types of soils. Figure 9 illustrates a comparison between the seed/input and seismically matched time histories for soil type 1 over a time span of 10 to 20 seconds.

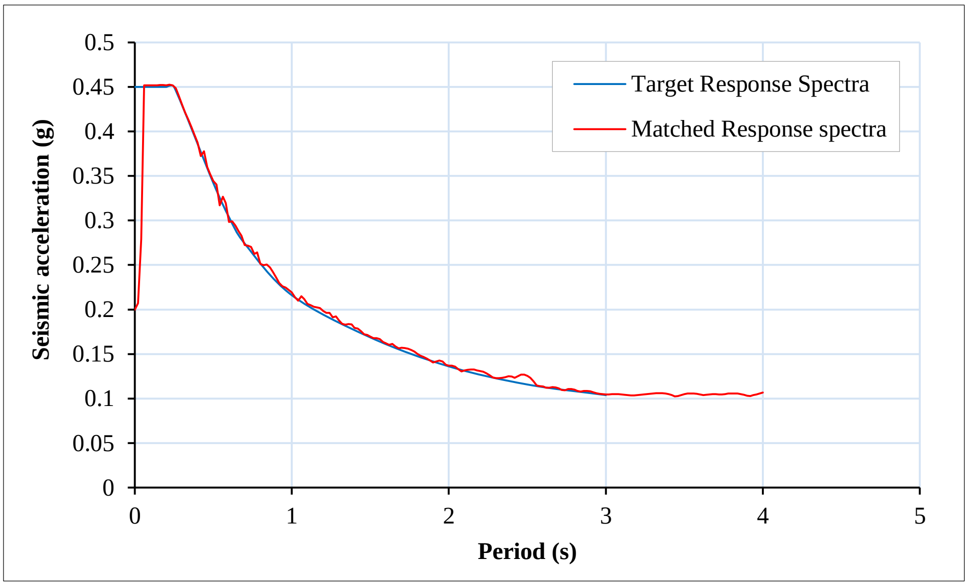


Figure 7. Normalized Response Spectra of the Moroccan paraseismic regulation RPS 2011 For Soil S1 and its Matched Response Spectra

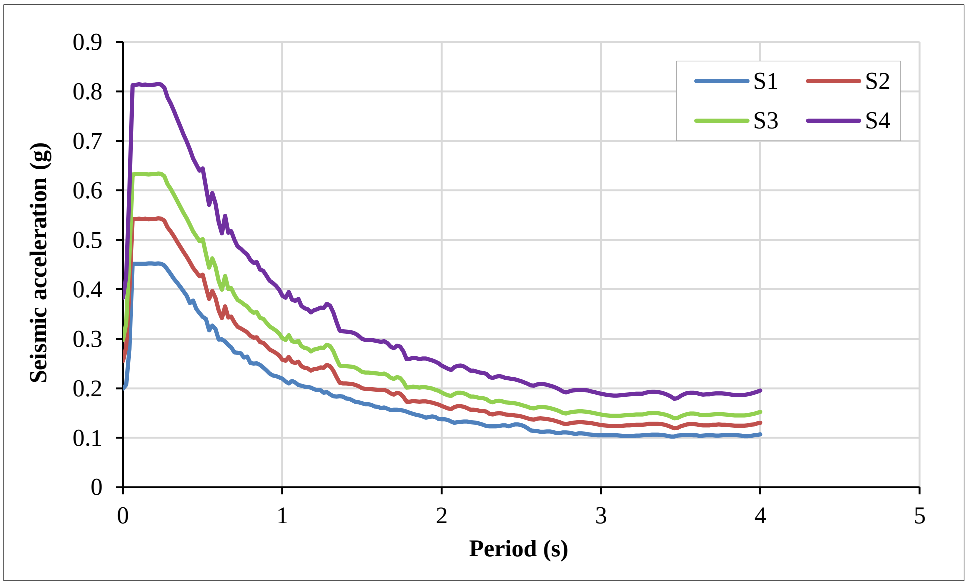


Figure 8. The Matched Response Spectra for the four soil types

3.2. Soil Data

The classification of sites is based on the soils that comprise them, in accordance with Moroccan seismic rules. RPS 2011 [29] specifies four types of sites, which are listed in Table 2. All soil types can be described as follows:

- S1: Rock.
- S2: Very Dense soil and Soft Rock.
- S3: Stiff Soil.
- S4: Soft Soil

The intensity of an earthquake at a given location depends significantly on the type of soils through which the seismic wave travels, as well as the local geological and geotechnical conditions [34]. Consequently, RPS 2011 defines a Soil Factor S for each type of site.

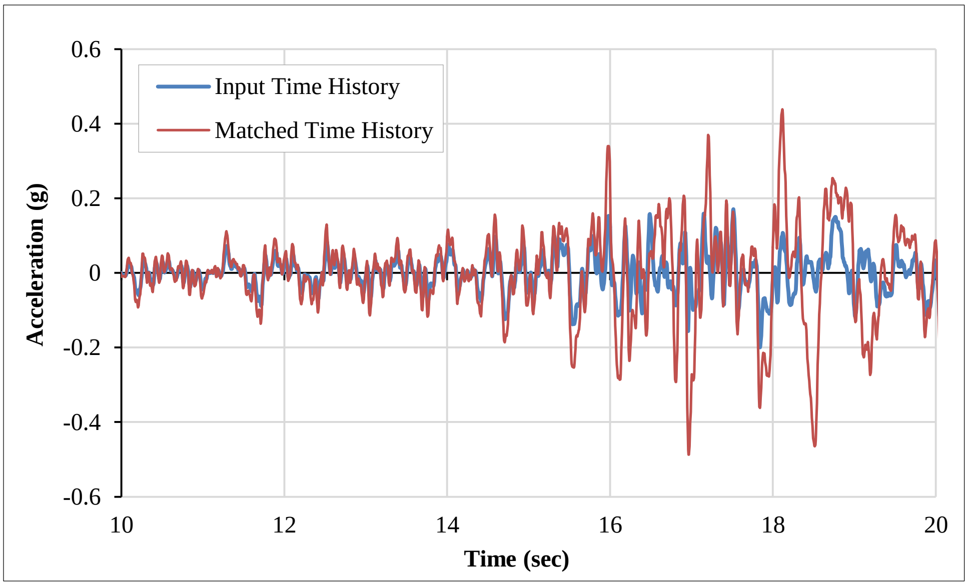


Figure 9. The seed/input and seismic matched time histories for soil S1 over a time span of 10 to 20 sec

3.3. Building Design and Materials

To ensure a fair comparison between different types of bracing, we selected the designs presented in Figure 10. These designs feature simple and regular structural configurations while adhering to the minimum section requirements outlined by Moroccan regulations [34, 35].

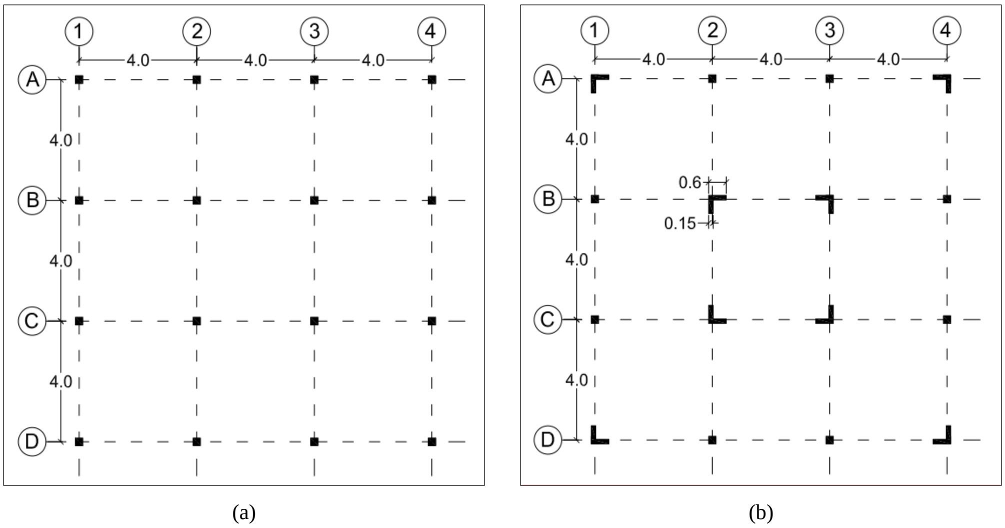


Figure 10. Structural plan of (a) column bracing (b) shear wall bracing

The concrete buildings modeled in this study exhibit the following characteristics:

- Cross-section of a column: (25×25) cm.
- 15 cm is the shear wall thickness.
- Cross-section of a beam: (25×45) cm.
- The solid slab is 20 centimeters thick.
- Story height is 3 meters.
- E = 32000Mpa, the concrete rigidity value.
- The calculations incorporate a 0.2 Poisson coefficient.
- 2.5 T/m^3 specific weight.

3.4. Finite Element Model

The interaction between the soil and the structure can be represented by a simple model in which the structure is modeled as a cantilever beam with equivalent stiffness to the shear-loaded walls or columns that contain masses mainly corresponding to those of the floors. This model is a multi-degree-of-freedom system. To simulate the interaction with the ground, springs can be used to represent the translation or rotation, and they are connected to a mobile base that moves according to the imposed seismic motion [36].

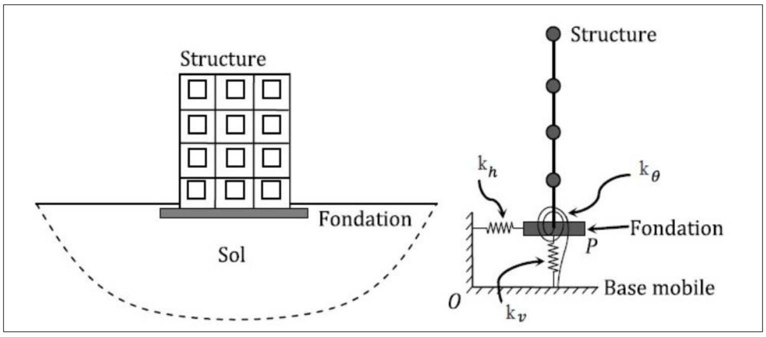
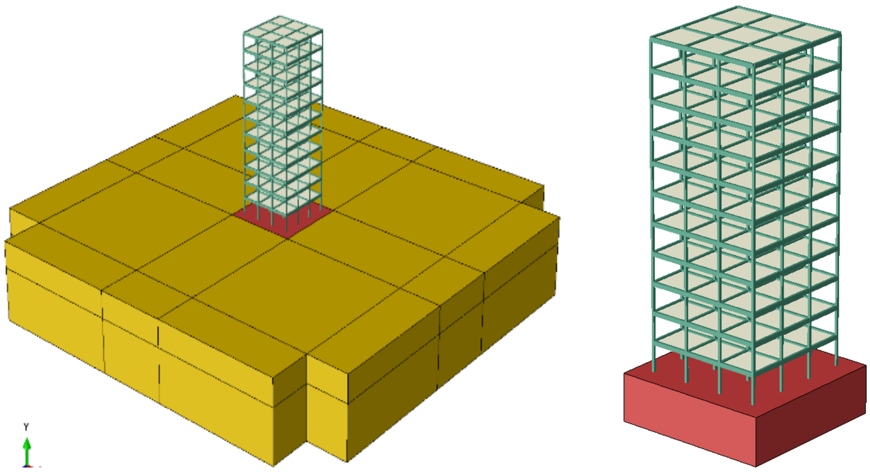


Figure 11. Schematic of soil-structure interaction [36]

The finite element software Abaqus is a widely used tool for modeling soil-structure interaction, as highlighted in recent studies [37, 38]. Abaqus offers several techniques for modeling soil-structure interaction, including the Coupled Eulerian-Lagrangian (CEL) method [31], Discrete Element Method (DEM) [39], and Pile-soil interaction. The latter can be modeled using techniques such as the Winkler foundation model, p-y curve model, and Extended Finite Element Method (XFEM) [40]. The software can also simulate the dynamic behavior of soil-structure systems under seismic loading using techniques such as frequency-domain analysis, time-history analysis, and hybrid methods [41].

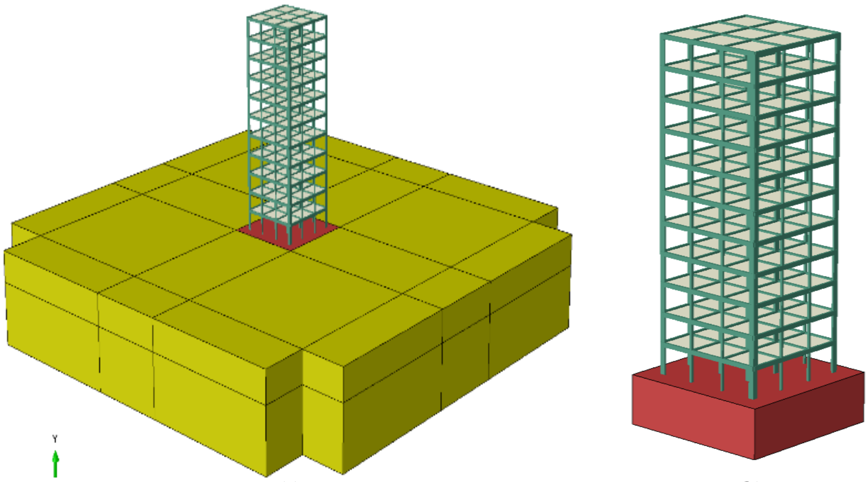
To analyze the soil-structure interaction, a 3D finite element model of a 12-story building was developed using Abaqus. To reduce the size of the problem, beam and columns were modeled using the 'B31' beam element, roof slabs were modeled using the 'S4R' shell element, and the raft foundation was modeled using the 'C3D8R' solid element, with all material and sectional properties attributed according to specifications. The model consisted of 202,140 elements and 218,215 nodes. The columns/beams and roof slabs were attached via tied connections, while the columns were attached to the concrete foundation using kinematic coupling to determine the base shear force of the building structure due to lateral seismic loads.

The analysis was performed using Abaqus dynamic implicit analysis with geometric nonlinearity (nlgeom=on). The total simulation time was 40 seconds, adequately covering the earthquake strong motion zone. Due to the high non-linearity of the system (soil and structure), the minimum step size was 4x10-05 seconds and the maximum time step was 0.01 seconds, which was also the time step of the applied time history. To ease convergence issues, 'line-search' was used, and solution control parameters were enhanced without compromising solution quality. The solution was performed in three steps: in the first static step, gravitational load was used, in the second static step, dead loads were applied according to specified conditions, and in the third step, full transient analysis was performed against seismic conditions. As the analysis was performed with base excitation, the seismic load was applied at the soil base in terms of time-displacement obtained from the time-acceleration data with base correction. The displacement loads were used to aid convergence of the solution and ensure that the system performed vibratory motion about the mean position instead of drifting in any one direction. Figures 12 and 13 show some of the models created using Abaqus software.



(a) (b)

Figure 12. Abaqus 3D Modeling for building with column bracing (a) with SSI (b) with fixed base



(a) (b)

Figure 13. Abaqus 3D Modeling for building with shear wall bracing (a) with SSI (b) with fixed base

3.5. Soil Modeling

In the current study, the Mohr-Coulomb model has been adopted as the constitutive model to simulate the nonlinear behavior of the soil medium, which is an elastic-perfectly plastic model. The use of advanced soil plasticity models may create complexity and convergence issues in implicit dynamic analysis with base excitation, as well as increase simulation time. Therefore, the Mohr-Coulomb model is used to optimize analysis accuracy and cost. The boundary conditions of the soil in dynamic problems are developed by using infinite elements ('CIN3D8') in Abaqus to avoid the reflection of outward propagating waves back into the model and to allow necessary energy radiation. This is achieved by defining a soil domain large enough so that waves reflected from the boundary take too much time to return to the region of interest. However, this is practically not possible because the speed of waves is very high in most soils, and consequently requires a large area. Therefore, infinite elements are used to impose the boundary conditions that produce the necessary energy radiation.

In static problems, fixed boundary conditions can be used to represent the lateral boundary conditions of the soil domain. However, this assumption is not adequate in dynamic problems because fixed boundary conditions may lead to the reflection of outward propagating waves back into the model and do not allow necessary energy radiation, trapping energy inside the model. The simplest solution to this problem is to define a domain large enough so that waves reflected from the boundary do not have time to return to the region of interest. However, this is not a practical solution due to the relatively high wave speeds of most soils. Therefore, it is desirable to have boundary conditions that allow the necessary energy radiation. This can be achieved using infinite elements in ABAQUS ('CIN3D8') at the corner of the soil area while the rest of the soil medium is developed using elements 'C3D8R,' as shown in Figure 14. The total height of the soil medium is 15 m, while the concrete foundation of the building is 5 m, and the horizontal distance between the soil lateral boundaries is more than 70 m. The interaction between the soil and concrete base is surface-to-surface friction contact.

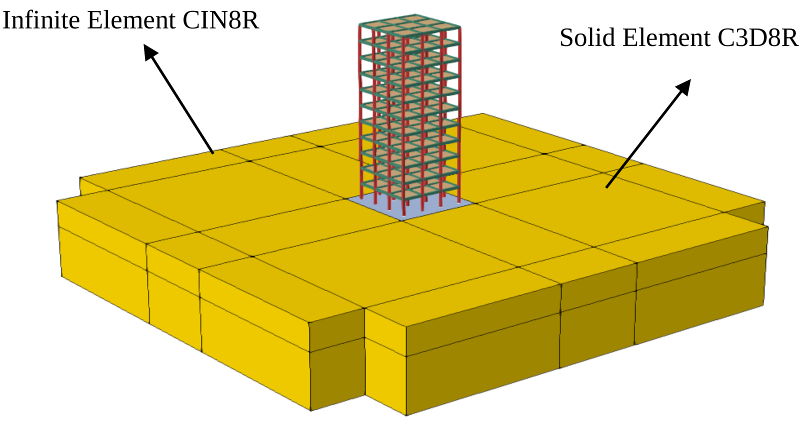


Figure 14. Soil Modeling

3.6. Damping of System

Damping is a dissipation of energy in a vibration system. In SSI analysis, the total damping of the system is sum of 1) structural damping and 2) soil foundation damping. Foundation damping includes combined effects of energy dissipated from radiation damping and hysteretic action in soil medium (material damping). While the structural damping introduced due to material nonlinearity (inelastic dissipation) and internal and external friction. Total damping of SSI system is determined according to the following equation:

$$\eta = \frac{1}{(T_{ssi}/T_{fixed})^2}\beta_i + \beta_f \tag{1}$$

where β_i is Structural damping, β_f is Foundation damping, T_{ssi} is Fundamental time period of SSI system, and T_{fixed}: Fundamental time period of fixed base system.

Damping is defined in ABAQUS in the form of Rayleigh damping coefficients. The damping matrix in Rayleigh damping is a linear combination of mass-proportional (α) and stiffness-proportional (β) terms and it provides a convenient abstraction to damp lower (mass-dependent) and higher (stiffness-dependent) frequency range behavior, as shown in Figure 15. In Abaqus under linear perturbation analysis, natural frequencies of the system are determined and considering the significant modes of vibration, 5% damping is introduced by determining the values of α and β.

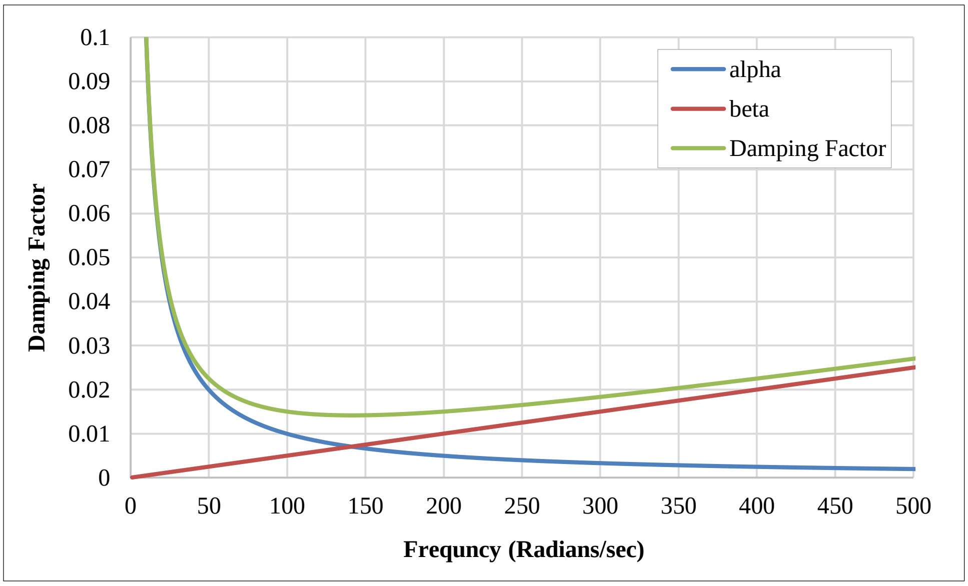


Figure 15. Structural damping curve

4. Results and Discussions

4.1. Lateral Displacement

The lateral displacement is a crucial parameter for structural calculation and stability verification, as shown in Figures 16 and 17 for various types of soils with column bracing and shear wall bracing. Careful consideration of a building's drift and lateral deformation during the design process is crucial to prevent excessive deformation, as emphasized by a recent study that highlighted the importance of analyzing the displacement of the top stories to understand the level of damage to buildings [4]. It is affected by many factors, including the type of soil and the type of bracing used in the building. However, the interaction between the soil and structure is also a critical factor that affects the overall lateral displacement of the building. It is observed that buildings with column bracing have greater displacement than those with shear wall bracing. Displacements increase significantly depending on the soil, with S1 being the safest soil and S4 resulting in the greatest deformations. Considering soil-structure interaction, there is a 3.9% increase for S1 and a 24.6% increase for S2 soils, while S3 and S4 soils exceed 50%. Column bracing gives satisfactory results for S1 and S2 soils, but for S3 and S4, shear wall bracing is preferable. Only S1 is safe for column bracing when considering soil-structure interaction, but with shear wall bracing, S2 becomes admissible.

Overall, the study shows that the soil-structure interaction has a significant impact on the behavior of buildings during earthquakes, and the type of soil and bracing system used can greatly affect the safety of the structure. Furthermore, a recent study focused on soil-structure interaction of adjacent buildings has shown that by considering soil-structure interaction, there is an increase of 90 to 95% in the maximum lateral roof displacement values, which is consistent with our findings [42]. It is essential to consider the inter-story drift ratio and lateral displacement in structural design and stability verification, and to account for the effects of soil-structure interaction in seismic design. The findings of this study can provide valuable insights for engineers and architects in Morocco and other seismic-prone regions, helping them to design safer and more resilient structures.

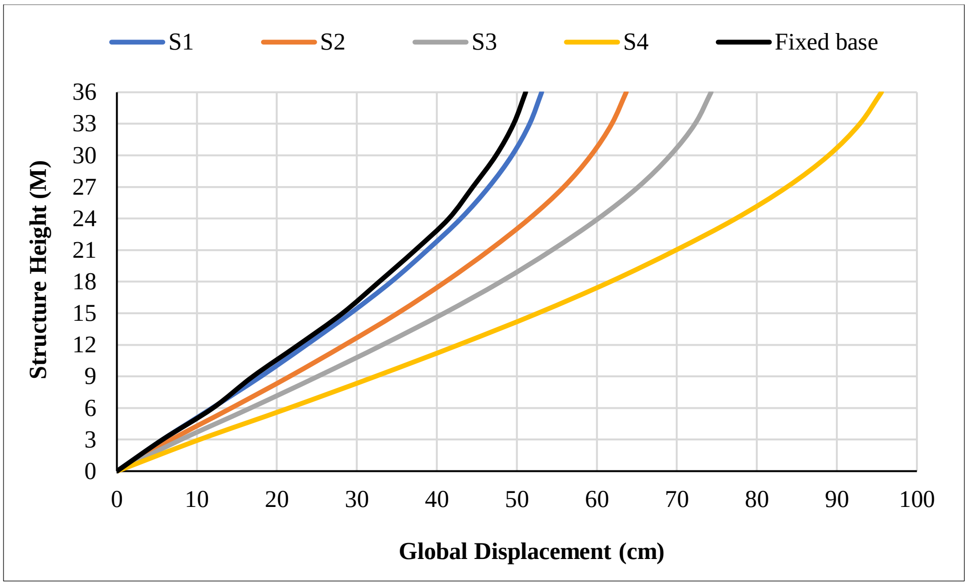


Figure 16. Plot of global displacement and structure height with various types of soils with column bracing

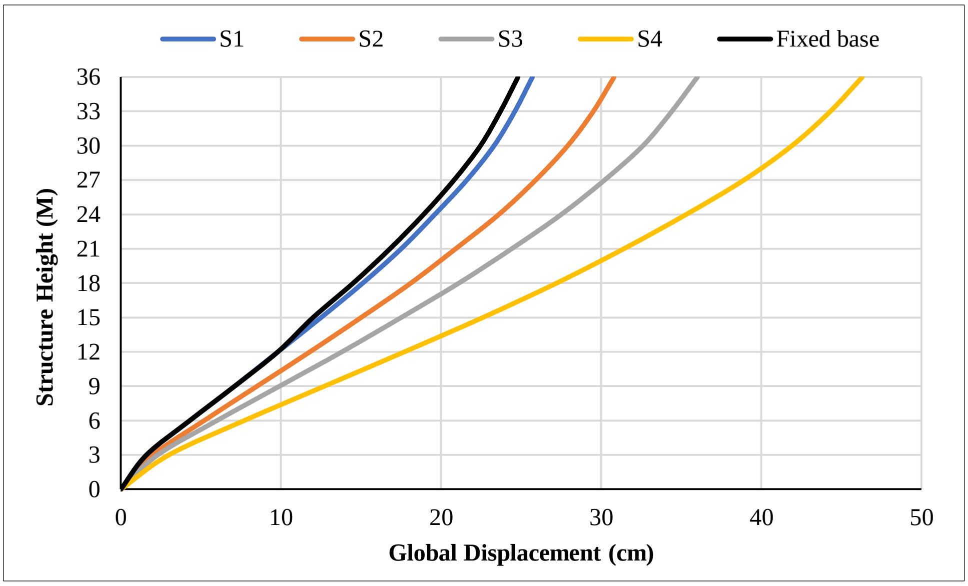


Figure 17. Plot of global displacement and structure height with various types of soils with shear wall bracing.

Therefore, it is clear that the interaction between the soil and the structure, as well as the choice of bracing system, are significant factors that must be considered in the design and construction of buildings. A recent study has shown that bracing with shear walls reduces displacement, which is not contradictory to our findings [43]. Neglecting these factors can lead to significant increases in lateral displacement, potentially compromising the stability and safety of the building.

4.2. Inter-story drift ratio

The inter-story drift ratio is a critical design criterion. A recent study has demonstrated the importance of considering inter-story drift, as this research investigated the damages of structures [44]. The Moroccan Paraseismic Regulation RPS 2011 provides the following equation for calculating the inter-story drift ratio [29]:

$$\text{Inter-story Drift} = ((Di+1 - Di) / h) \quad (2)$$

where h represents the story height, Di+1 denotes the displacement of the upper level, and Di denotes the displacement of the lower level.

The inter-story drift ratios of buildings with column bracing and shear wall bracing in various types of soil in Morocco were analyzed in Figures 18 and 19. The effect of soil-structure interaction was found to have a significant impact on the increase in inter-story drift ratios, which was also supported by a recent study [45]. The study also revealed that inter-story drift ratios increase with the type of soil, from soil S1 to soil S4, with the second story having the highest inter-story drift ratio. For buildings with shear wall bracing in soils S1 and S2, the displacement limit set by the Moroccan regulation was deemed safe, while soils S3 and S4 were found to be at risk. However, for buildings with column bracing, only soil S1 was found to be safe, while buildings in soils S2, S3, and S4 were found to be unsafe.

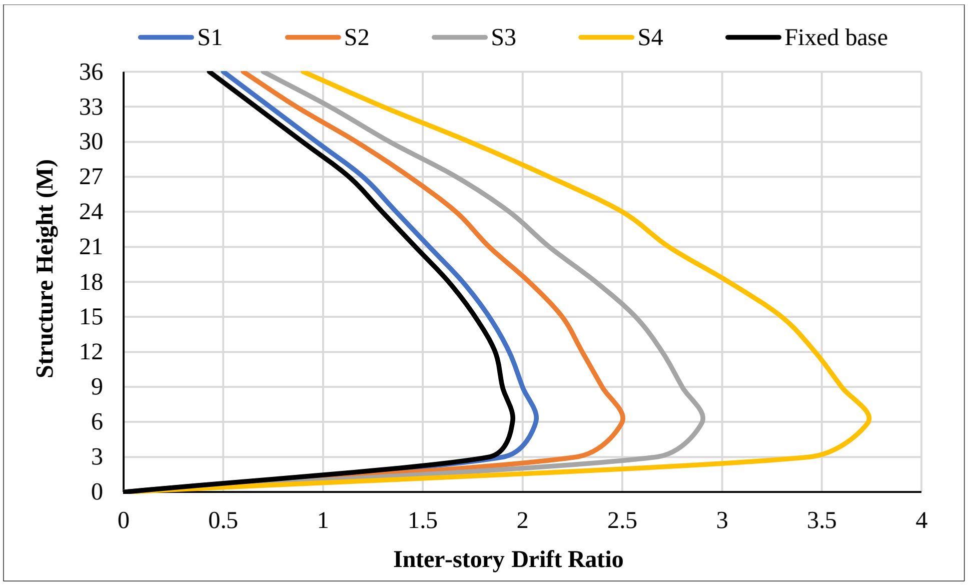


Figure 18. Plot of Inter-story drift and structure height with various types of soils with column bracing

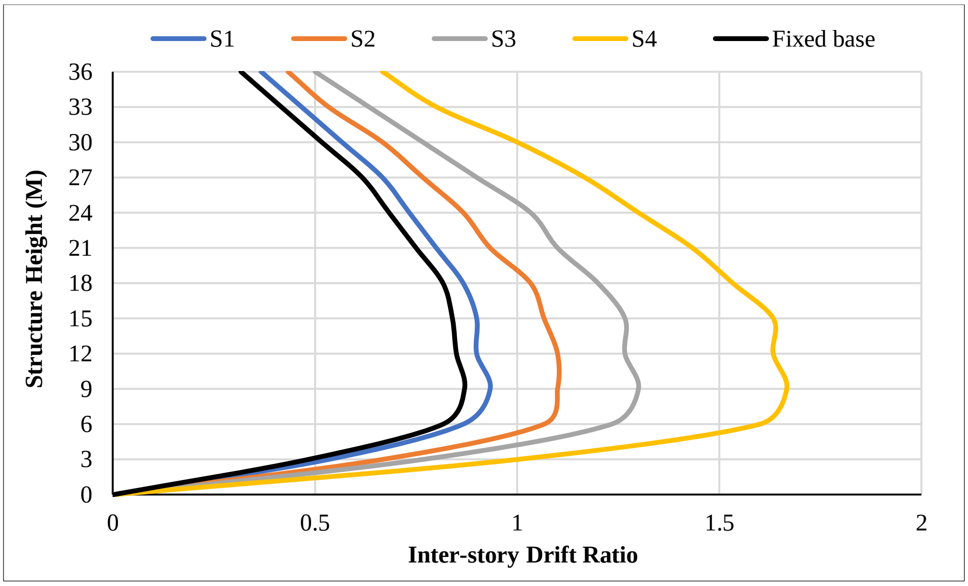


Figure 19. Plot of Inter-story drift and structure height with various types of soils with shear wall bracing

The findings suggest that the type of bracing also plays a crucial role in the inter-story drift ratios. Buildings with shear wall bracing showed lower inter-story drift values compared to those with column bracing. Moreover, the results indicate that the need for structural ductility increases as the soil type becomes softer

Therefore, it is recommended to use shear wall bracing for buildings located in seismically active regions with soft soil, such as soils S3 and S4 in the north of Morocco. On the other hand, for buildings located in soils S1 and S2, either column bracing or shear wall bracing can be used, as both types of bracing showed safe inter-story drift ratios, with shear wall bracing being slightly more efficient.

4.3. Time Period

The fundamental natural period of a structure is a crucial parameter that represents the time (in seconds) taken by the structure to complete one cycle of oscillation. Modal forms of buildings with column bracing are depicted in Figure 20, where it is evident that the time period decreases as the mode increases. However, it was found that the time period increased when the effect of soil-structure interaction (SSI) was considered, and also when the bracing type was changed from column bracing to shear wall bracing. These findings were also demonstrated in a recent study, where the consideration of SSI effect resulted in a 15-25% increase in time period [42]. Consequently, it has become imperative to incorporate structural ductility in the design to cater to the increased time period. The study conducted by Singh & Mala on a G+9 building also confirms that time period increases due to soil flexibility caused by SSI impact [46].

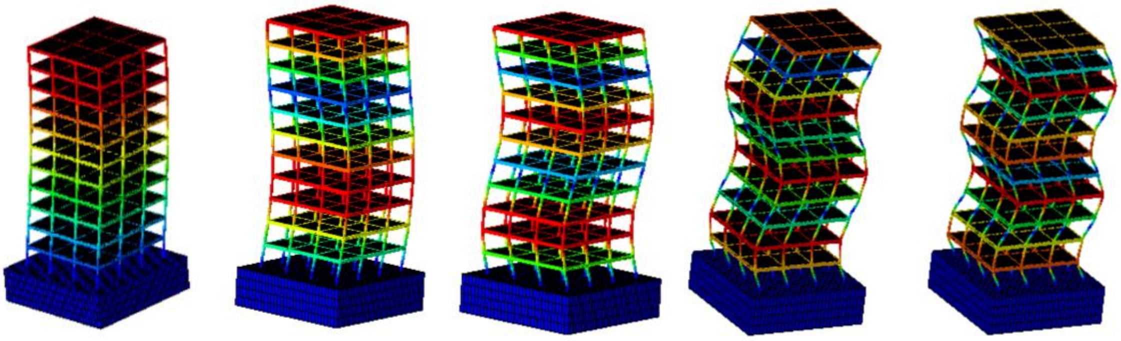


Figure 20. Modal forms of the building with SSI (column bracing)

Modal analysis was performed on both structures—columns and shear wall bracing—using the Abaqus Linear Perturbation procedure. This analysis is helpful in understanding the dynamic response of the system and determining the important modes of vibration by comparing them with the corresponding effective mass/mass participation factor. The mass participation factors are given in Table 3. It is evident that the natural frequency of the structure with shear walls is larger than that of the structure with columns due to the addition of walls, which makes it stiffer and results in an increased natural frequency. The mass participation factors show that the first two modes of vibration are more important, especially the first mode, due to its significant mass participation factor.

Table 3. The mass participation factors for both type of bracing

Mode No.	Mass participation factor %	
	Shear walls	Columns
1	0.83	0.824
2	0.11	.102
3	0.03	3.38E-05
4	0.02	1.63E-02
5	0.01	9.22E-03
6	2.35E-14	5.61E-03

Furthermore, the impact of building bracing type on the time period has been shown in Figure 21. It can be observed that for buildings with column bracing, the time period is relatively higher than for those with shear wall bracing. This indicates that shear wall bracing is more effective in reducing the time period of the structure. This was demonstrated in another recent study, which showed that the use of shear wall bracing leads to a reduction in fundamental time period values by between 22.29% and 24.93% for the various levels of the models studied [43]. Hence, it is crucial to consider the bracing type during the design phase to ensure that the structure can withstand seismic forces efficiently.

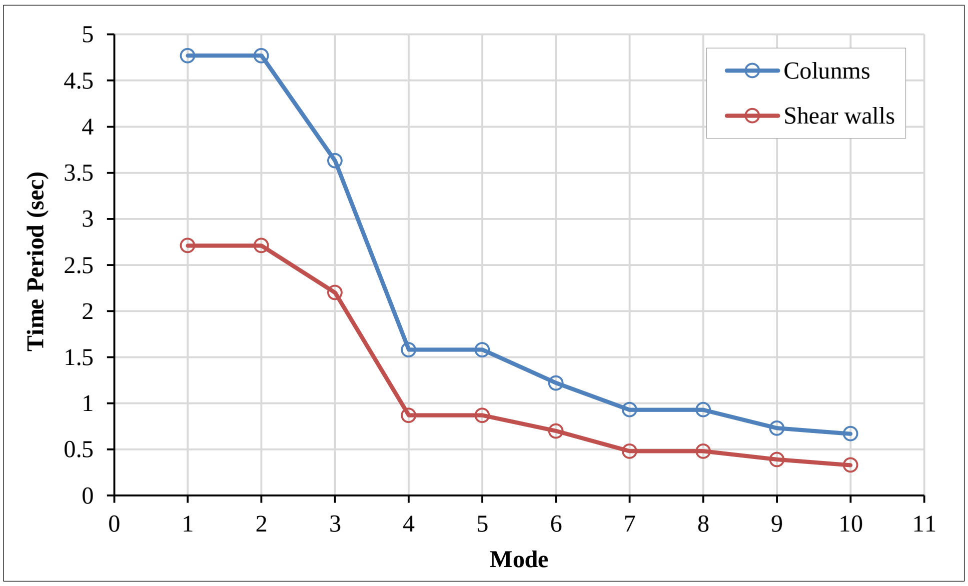


Figure 21. Time period (sec) indifferent modes with columns and shear walls bracing

4.4. Mass Structural Comparison

To aid our study, we changed the load-bearing elements' dimensions so that the global displacements of the structures could be compared to the RPS 2011 limit of displacement, which is equivalent to 0.4% of the entire height. This analysis compares the various structures based on increased mass in order to ensure that the lateral displacements of all structures remain within the seismic code's permitted range.

The graphs in Figures 22 to 25 provide the following observations:

- When constructed on rocky soil (type S1), buildings with column bracing show a mass increase of less than 20% for 27-meter-high buildings, and up to 33.8% for 12-story buildings. Shear-wall braced buildings show a maximum increase of 7%, even for 12-story buildings.
- For buildings constructed on S2-type soil, column-braced structures exhibit a percentage increase ranging from 30% for nine-story buildings to 97% for 12-story buildings. In contrast, shear wall bracing structures have a maximum percentage increase of 12% for 12-story buildings.
- In the case of S3 type soil (stiff soil), there is a significant difference between column bracing and shear wall structures for buildings above 9 stories. Buildings with column bracing show an increase ranging from 72% to 173% for 9- and 12-story buildings, respectively, compared to 11.5% and 55% for shear wall bracing structures. Therefore, there is a difference of 97.9% between the two types of bracing at 12 levels.
- For buildings constructed on S4-type soil (soft soil), column bracing structures have a mass increase that exceeds 55% for buildings with six levels or more. On the other hand, shear walls show much smaller percentage increases, resulting in a difference of 118% between the two types of bracing. Therefore, structures with shear wall bracing are preferable for buildings with six levels or more in the presence of soft soil.
- For buildings built on a S4-type soil (soft soil), with column bracing we have a mass increase that exceeds 55% from 6 level buildings, while shear walls have much smaller percentages, and we find a difference of 118% between the two types of bracing. Therefore, it is preferable to choose buildings with shear wall bracing over structures with six stories when there is soft soil present.

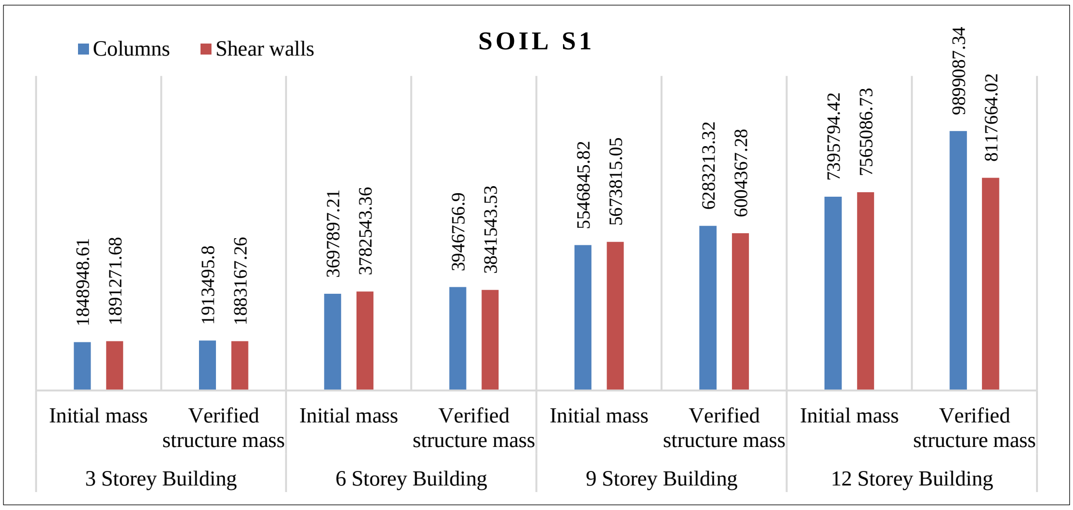


Figure 22. Summary of mass before and after verification for all levels with soil S1

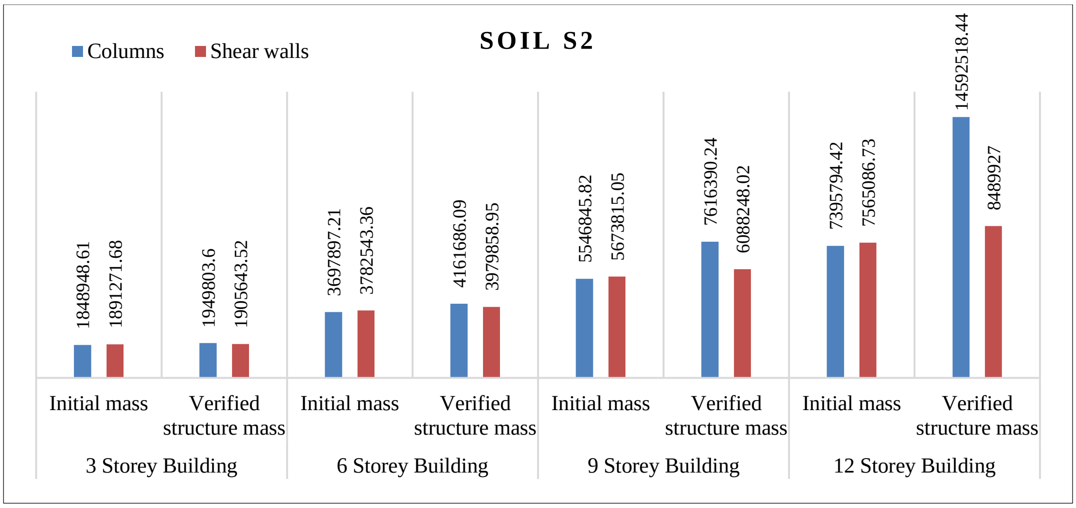


Figure 23. Summary of mass before and after verification for all levels with soil S2

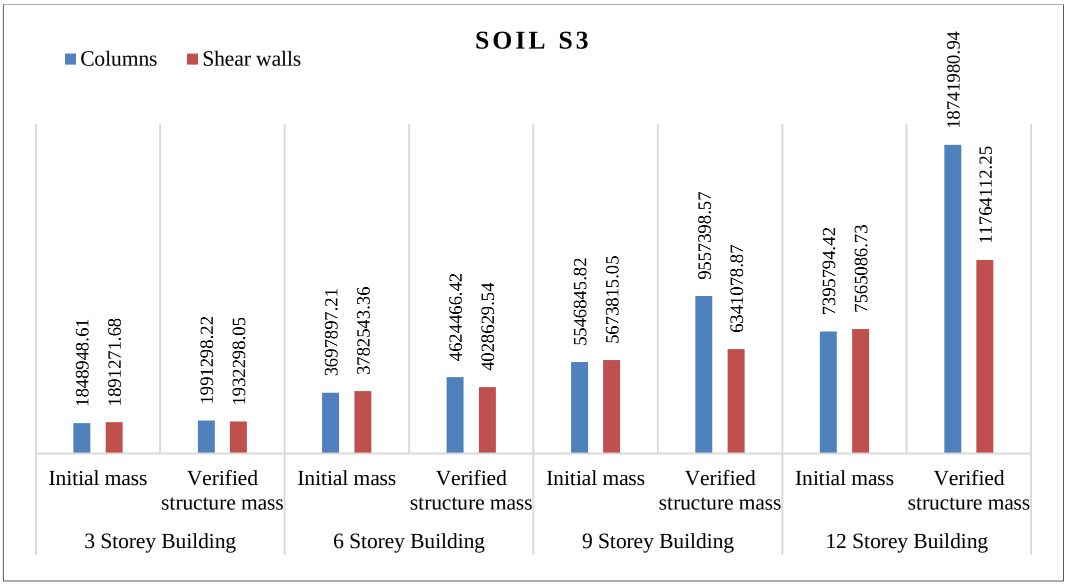


Figure 24. Summary of mass before and after verification for all levels with soil S3

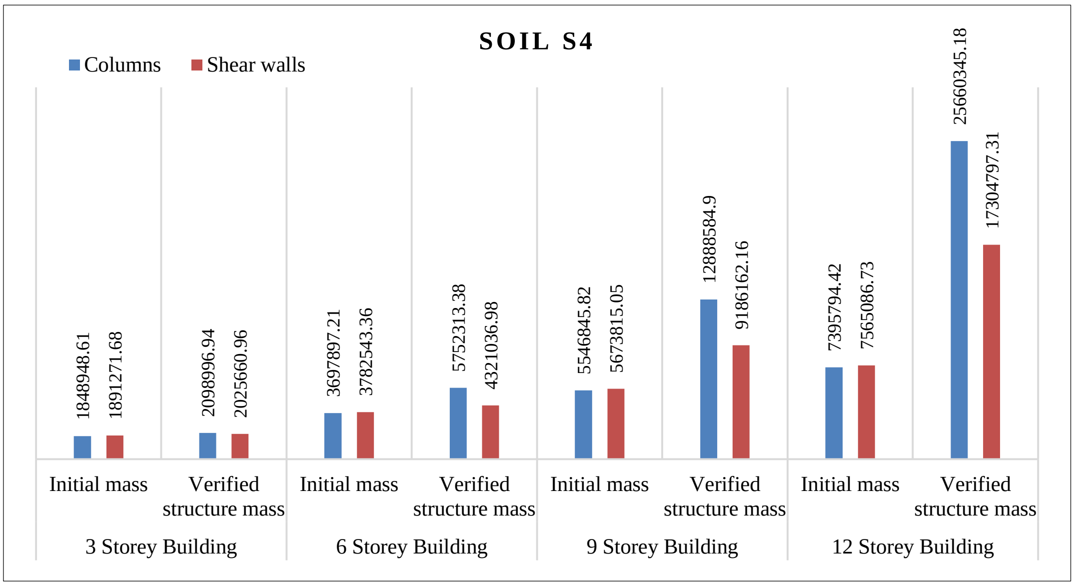


Figure 25. Summary of mass before and after verification for all levels with soil S4

In summary, the results of the study show that the choice of bracing type for a building depends on the type of soil it will be constructed on. For buildings constructed on rocky soil (S1), column bracing can be used without significantly increasing the mass of the building, while shear-wall bracing may cause a larger increase in mass. On S2-type soil, column bracing results in a greater mass increase, while shear-wall bracing is more effective for limiting mass increase. For S3-type soil, column bracing results in a much larger mass increase than shear-wall bracing, particularly for buildings with nine or more stories. Finally, on soft soil (S4), shear-wall bracing is the preferred choice for buildings with six stories or more due to the significantly lower mass increase compared to column bracing. Overall, these findings can assist engineers and architects in selecting the appropriate bracing strategy for buildings depending on the soil conditions of the construction site, helping to optimize both safety and cost-effectiveness.

5. Conclusions

Any load-bearing structure, including shear walls and column bracing, can be used in earthquake-resistant buildings if proper construction methods are employed. However, their reactions to an earthquake differ greatly. Seismic regulations do not take into account soil-structure interaction or specify when it should be considered. They also do not specify the type of bracing to use based on the structure's specifications, such as height and soil type. This allows us to continue our research and select the most reliable bracing method for structures of various heights and soil types. We looked at numerous models with two types of bracing (column and shear wall) using the four soil types specified by Moroccan regulations, a height constraint of 36 meters, and a traditional architectural design. The findings of our study are discussed below:

- The lateral displacement showed that the case of soil type S1 does not differ in displacement value from the fixed base, which proves that the fixed base is only valid with non-cohesive soil. Furthermore, we observed that in all cases, we exceeded the code's limit value, which is amplified with the increase in the story of the structure and the decrease in the stiffness of the ground. Taking into account the SSI effect, only S1 seems to be the most secure one for structures with column bracing; however, if we use shear wall bracing, S2 will also be permitted.
- When considering the effects of SSI, the values of inter-story drift increase dramatically. We found that buildings with shear wall bracing are more secure with both types of soil, S1 and S2. However, only the building in soil S1 was found to be safe when using column bracing. Due to the flexibility of the construction, it has also been shown that the type of bracing and SSI increased the time period.
- After calculating structural masses, we assumed that all bracing types could be used for construction shorter than 18 meters in soils S1 and S2 (6 stories). Only buildings with five stories or less can be considered for column bracing in soil S3. Higher constructions need shear walls, which are safer and preferable to the latter. Lastly, we point out that column bracing is only suitable for buildings with three stories or less on S4 soil.

To sum up, the study found that fixed bases are only suitable for structures built on non-cohesive soil, and all cases exceeded the code's limit value. SSI significantly increases inter-story drift values, and shear wall bracing is more secure in both S1 and S2 soil types. Buildings with column bracing are safe only in S1 soil. The type of bracing and SSI also increase the time period. All bracing types can be used for buildings shorter than 18 meters in S1 and S2 soils, while buildings with five stories or less can only have column bracing in S3 soil. Column bracing is only suitable for buildings with three stories or less in S4 soil.

This study has significantly contributed to the understanding of the impact of soil-structure interaction on the seismic behavior of reinforced concrete buildings. The advanced numerical model for SSI developed and verified using ABAQUS software has provided valuable insights into the choice of bracing for structures of various heights and soil types. The findings of this study indicate that SSI has a significant impact on the seismic response of buildings and that the seismic responses of soil-structure systems with column and shear wall bracing are quite different.

The study's contributions include developing an advanced numerical model for SSI, examining the impact of SSI on the choice of bracing for reinforced concrete buildings, and providing guidance on the most reliable bracing method for structures of various heights and soil types. The study's findings have important implications for seismic design and can help improve the safety and reliability of buildings in earthquake-prone regions. The study also highlights the importance of considering SSI in seismic design and the need for guidelines that describe the bracing systems to be used based on the structure's height and type of soil. However, the study has some limitations, such as not considering the irregularity of buildings and the influence of p-delta. Further research is needed to address these limitations and extend the study to other seismic zones to provide a comprehensive guide for seismic design.

In summary, this study has demonstrated the importance of considering SSI in seismic design and has provided valuable insights into the choice of bracing for structures of various heights and soil types. The study's findings have important implications for seismic design and can help improve the safety and reliability of buildings in earthquake-prone regions. By contributing new theoretical knowledge to the field, this study provides a foundation for further research and the development of guidelines for seismic design.

6. Declarations

6.1. Author Contributions

Conceptualization, Y.R.; methodology, Y.R. and M.A.; software, Y.R. and A.E.M.; validation, K.B.; formal analysis, Y.R.; investigation, Y.R. and K.B.; resources, Y.R., K.B., and M.A.; data curation, Y.R. and M.A.; writing—original draft preparation, Y.R.; writing—review and editing, M.A., K.B., and A.E.M.; visualization, M.A. and K.B.; supervision, K.B.; project administration, Y.R., and K.B.; funding acquisition, Y.R., K.B., and M.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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