

Improving the Structure and Foundation Response Under Seismic Loads Considering Wall Packing Effects – Numerical Study

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Abstract: During earthquakes structures in active seismic areas are affected by different random ground motions that cause different forces in the structure such as displacement, acceleration, and stresses. These structures consist of a skeleton of reinforced concrete and masonry walls. The behavior of these composite structures is very complex and complicated to model. Furthermore, there is an observation lack in the regulation's guidelines and seismic codes for the infill design process and behavior through the earthquakes. In practice, infill walls are considered a non-structure component, and so it is neglected in the design process. However, eliminating the infill leads to negative consequences. This paper investigates and evaluates the infill walls effect on the structure behavior during earthquakes. Four structural models consisting of basement with seven, nine, and eleven stories, without and with walls in different locations were idealised. The 3D analysis program PLAXIS was adopted in this study. A series of investigated models under the effect of lateral loads were conducted to discuss the infill walls effects on the model's response. Results confirmed that infill walls take a place in increasing the structure's resistance to horizontal actions and improve the structure's lateral response. The infill walls reduced both the soil acceleration and strain by 56% and 16.7% respectively from their initial values. Also, walls' presence reduced both the foundation displacement and acceleration by 49% and 28% respectively compared to bare structures. Finally, the wall existence has a vital role in the modification of the superstructure lateral performance against displacement and story drift. It may be considered as an alternative technique to construct foundation resistance structures.

Keywords: Foundation; Infill walls; Jointed rock; Numerical modelling; Sand; Seismic loads; Structure.

1. INTRODUCTION

The reinforced concrete structures with infill walls are common structural systems which are widely utilised in seismicity areas [1]. Walls are defined as inhomogeneous, non-elastic, and anisotropic material which are created from two different materials, bricks and cement [2]. The masonry walls utilisation was limited to buildings' external walls and used to divide the building's internal sectors. Masonry infill is one of the most preferred materials for many reasons such as simple construction practice, durability, low cost, and providing the building with both thermal insulation and acoustic [3]. On the other hand, the infill walls are mainly defined as a non-structural material, despite their significant role in improving the lateral response of reinforced structures [5-8]. Different construction codes did not consider the usage and influence of infill walls in the different design processes, thus there is a lack of sufficient information about their design. Also, the seismic codes neglected and disregarded the infill walls' impact on the different structures during the earthquakes, due to the result of deficiency in both the guidelines and regulations in their design practice. According to the Eurocode V.8 (EC8) [9] the masonry infill walls in the earthquakes resistant structures is considered as "The second life of defense" which increase the structural lateral resistance, even though the code did not consider decreasing the structure seismic resistance demands during the design process due to the infill walls presence. Therefore, the infill walls additional seismic resistance is considered as "stocks of resistance".

From another point of view, the Eurocode confirmed that the infill walls are necessary for the construction of low-load capacity and stiffness structures [10]. As a fact, the infill walls are not simulated or modelled in the different structure analysis programs throughout the design criteria, even though they are constructed in the building [11-12]. Previous studies demonstrated that simulating and modelling reinforced concrete structures while considering the existence of infill walls leads to a remarkable improvement in both the structure stiffness and strength. Results showed that infill walls improved structures stiffness and strength by more than 50% compared to bare structures. Also, walls existence has a vital role in the reduction of

structures lateral displacement estimates to 60% [2,3]. Besides, an experimental study confirmed that walls improved the structures lateral response by 64% and the infilled structure ductility was less than bare structure by 51% [13]. Thus, infill walls combine and interlock with the reinforced concrete skeleton and work as one block against horizontal actions. Moreover, the results showed a considerable improvement in the structure response such as, the lateral load resistance and energy dissipation during the earthquakes [13]. Therefore, it is necessary to take into consideration the consequence of the infill walls during the different processes of structure design as a novel and low economic technique [1]. In practice, the different approaches to resist the reinforced concrete structures' lateral loads such as mass dampers, bracing members, shear walls, core walls, or combined system of shear and core walls were wide range studied and investigated by different researchers and modelled with many finite element programs [14-15].

Previous research focused on the influence of masonry walls on the superstructure stability without any consideration to the foundation or the soil [3]. Therefore, this paper aims to investigate and represent the real interaction between structure, foundation, and supporting soil, then evaluate the effect of infill walls in different locations on the structure's lateral behavior. To overcome the effect of both the shaking table problems and scale effect, full-scale numerical modelling and analyses were adopted by the utilisation of the PLAXIS 3D program to represent a real soil structure interaction [16]. An advanced constitutive model named Hardening Soil Model (HSM) was adopted for the soil profile. The structure is modelled in detail for all the structure elements, with the consideration of the infill walls effects. In this current work, a 3D constitutive model namely Jointed Rock Model (JRM) was adopted to the infill panels simulation. The outcome of this work investigates and presents the effect of existence walls to improve the soil subgrade and the structure during the lateral loads.

There is a dire requirement to investigate and evaluate the effect of the infill walls role on the structure, foundation, and soil lateral performance. This paper also investigates the geotechnical performance of a structure and foundation under the effect of lateral loads in the case of without walls, case of full infilled and with walls in different locations between columns. In addition, the influence of infill walls on the soil subgrade geotechnical behavior is also evaluated. The numerical results were presented in terms of displacement, acceleration, straining actions, and the effect on the soil properties in different charts and comparisons. These results may be used to assess the effect of walls on the structure's dynamic response and to address the gap in the lack of knowledge of the seismic design codes. Based on these results, special consideration is demanded to generate suitable data and information to be utilised in engineering practice and to improve the current seismic codes.

2. METHODOLOGY

2.1 The Soil Profile Constitutive Model

In this work, the subsoil consists of sand layers with a depth of 40 m and 172 x 30 m for the soil domain dimensions length and width respectively. It is worth mentioning that these dimensions are enough to give up the effect of the dynamic loads to satisfy the subsoil failure mechanism [17]. The soil was modelled according to the HSM criteria which is preferred for the simulation of the dynamic soil structure interaction to represent the actual subsoil behavior under the effect of lateral loads and to achieve higher accuracy in both the analysis and output results [18-19]. The soil geotechnical properties are listed in Table 1. The Rayleigh damping factors at the soil domain vertical boundaries were taken as α and $\beta = 0.2320$ and 0.008 , respectively. These values are enough to overcome the effect of Rayleigh waves. The plastic material properties of the soil during the effect of lateral loads through the dynamic processes are defined automatically by the Rayleigh coefficients in the PLAXIS program. These damping coefficients are expressed by the following equation:

$$C = \alpha M + \beta K \quad (1)$$

where C refers to the damping coefficient, M is the mass and K is the stiffness. α and β are the Rayleigh coefficients [2].

2.2 The Superstructure Constitutive Model

An administration building with different walls location and glass finishing was adopted in this current research. The model consists of three equal bays and a basement with seven, nine, and eleven stories with total heights of 21, 27, and 33 meters, respectively. The total width and length of the structure is 12 m. It must be pointed out that only one strip of the investigated model was modelled due to the symmetric situations of the investigated model [22-24]. The investigated structure's main elements were modelled as the following:

- The columns and beams were defined as beam elements.
- The floor slabs and foundation were defined as plate elements.

The previous structure elements were modelled as linear elastic with the following reinforced concrete material properties as presented in Table 2. In addition to the structure self-weight, a superimposed static surface uniform load was assigned on the building stories. According to the design approaches, the slabs were applied to Dead Load (DL) (floor covering weight) and Live Load (LL). The DL and LL were assumed as 1.5 kN/m^2 and 2.0 kN/m^2 respectively [25]. With the factor of safety, which is a crucial engineering concept, the slabs are applied to static load, $W = 1.4DL + 1.6LL$. Therefore, the final load on the slabs was $w = 5.3 \text{ kN/m}^2$ [25].

Table 1. Details of soil geotechnical and mechanical parameters for HSM [20,21].

Soil Parameter	Unit	Dense Sand Soil	Soil Parameter	Unit	Dense Sand Soil
Material Type	-	Drained Soil	Cohesion (C)	kN/m ²	1
Relative Density (D_r)	%	85	Angle of Friction (ϕ)	deg	40
Unsaturated unit weight (γ)	kN/m ³	17.7	Dilatancy Angle (Ψ) ($\phi - 30$)	deg	10
Saturated unit weight (γ)	kN/m ³	18.2	γ 0.722	-	0.0001
E_{50}^{ref}	kN/m ²	60000	G_0^{ref}	kN/m ²	250000
E_{oed}^{ref}	kN/m ²	60000	Poisson's Ratio	-	0.3
E_{ur}^{ref}	kN/m ²	180000	P_{ref}	kN/m ²	100
M	-	0.5	R_f	-	0.9

Table 2. Structure material properties.

Parameter	Symbol	Unit	Structure material properties
Material type	-	--	Elastic Linear Isotropic
Unit weight	γ	kN/m ³	24
Young modulus	E	kN/m ²	3×10^7
Poisson ratio	ν	--	0.2
Raleigh damping	α, β	--	0.2320 and 0.008

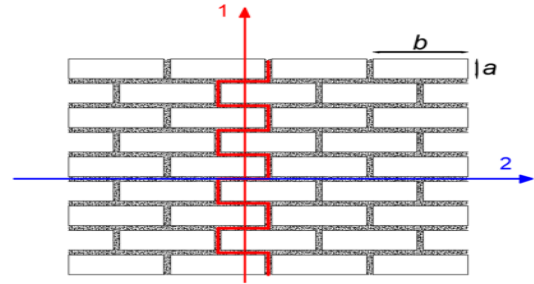


Figure 1. Head (1-1') and bed (2-2') joints direction for the walls in the jointed rock model [18-19].

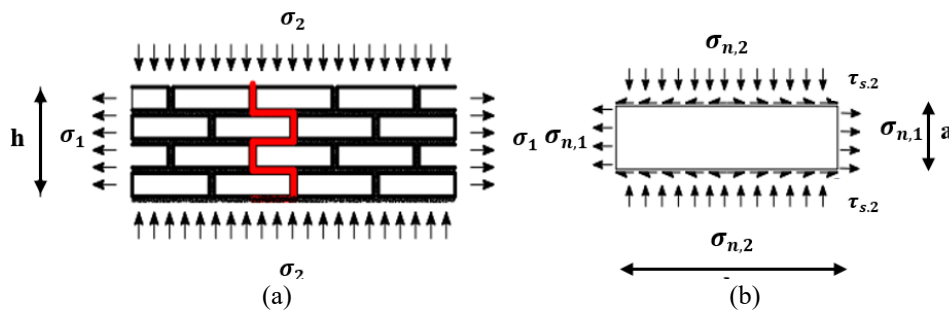


Figure 2. Stress state acting on: (a) a portion of the masonry wall, (b) the single block [18-19].

2.3 The Masonry Constitutive Model

The infill walls were simulated by the utilisation of the JRM. This model can be used to represent both the macroscopic and anisotropic response of masonry walls. In this model, two plane sides were used to represent the vertical and horizontal masonry wall joints [18]. In practice, the infill is constructed in horizontal deposits, therefore, shear and tensile stresses laterally by the head joints are defined as (direction 1-1) is improved by the influence of the bed joints which is defined as (direction 2-2). That leads to a significant increase in the vertical stresses as presented in Figures 1 and 2 and the infill properties are presented in Table 3.

Interface elements were adopted between both the subsoil and the raft foundation. On the other hand, the interface value was modified to 0.67 for different structure components embedded in soil. The earthquake was simulated by the assignment of the horizontal displacement function at the bedrock of the soil domain ($U_x = 1.0$ m, $U_y = 0$, and $U_z = 0$) [2-4]. Also, viscous boundary properties were generated at the soil vertical boundaries to take in any returned waves to both the model and the region of interest [3]. The earthquake was loaded by the program default earthquake. The water pressure was activated before generating the mesh to take into consideration the excess water pressure to obtain the subsoil liquefaction. Three monitoring points along the structure, foundation, and soil level were selected to investigate the effect of the infill walls on the dynamic response of the structure, foundation, and soil under the effect of lateral loads. These points (A , B , and C) were selected at the top of the building, the foundation level, and the soil layer beneath the foundation level respectively.

The mesh generation was chosen as coarse, while the cluster surrounding the foundation was refined twice, thus of the high stresses under the raft and to achieve more accuracy in the analysis and results. The general layout of the investigated model and the supporting soil is presented in Figure 3. Also, the plan configurations and sectional elevations of the studied structures are demonstrated in Figure 4.

Table 3. Material properties of walls [18-19].

Parameter	Symbol	Unit	Value	Parameter	Symbol	Unit	Value
Unit weight	γ	kN/m ³	19.2	Friction angle	$\Phi_{1,2}$	degree	37.0
Young's modulus (horizontal direction)	E_1	kN/m ²	2.91×10^6	Dilatancy	$\psi_{1,2}$	degree	0.0
Young's modulus (vertical direction)	E_2	kN/m ²	2.78×10^6	Tensile strength (horizontal direction)	$f_{tens,1}$	kN/m ²	80.0
Stiffness	G	kN/m ²	0.89×10^5	Tensile strength (vertical direction)	$f_{tens,2}$	kN/m ²	50.0
Number of planes	N	-	2	Rayleigh damping coefficients	α	-	0.5712
Cohesion	$C_{1.2}$	kN/m ²	50.0		β	-	1.447×10^{-3}

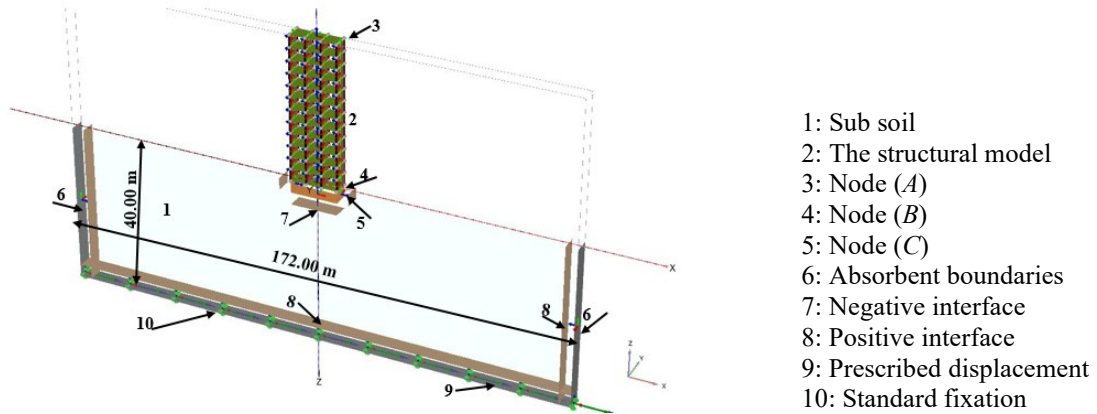


Figure 3. General layout of the numerical model by PLAXIS 3D.

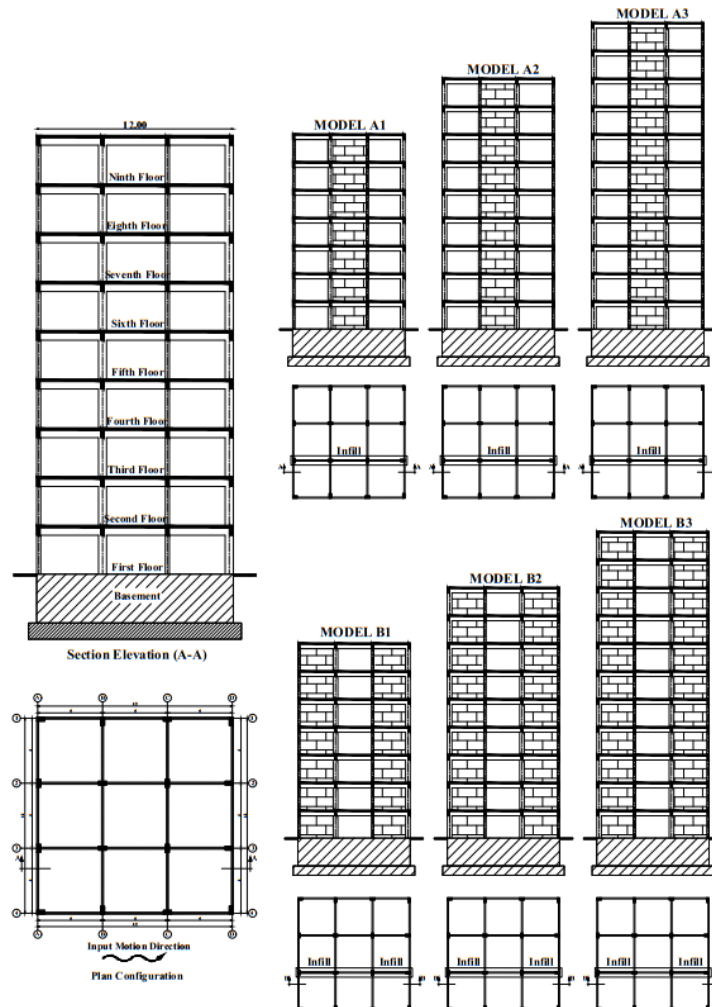


Figure 4. Models of investigated structures, identifying the different infill position.

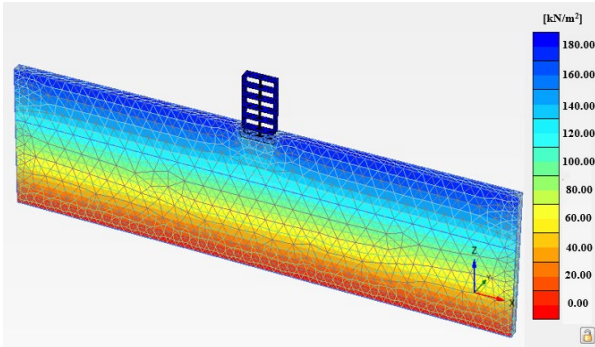


Figure 5. Shading of stress obtained by PLAXIS 3D.

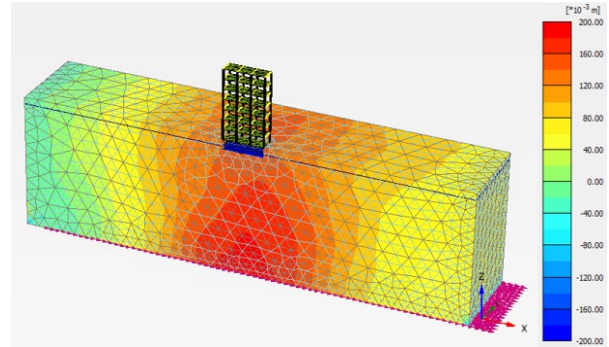


Figure 6. The horizontal displacement shading for without walls model (maximum displacement = 0.18 m).

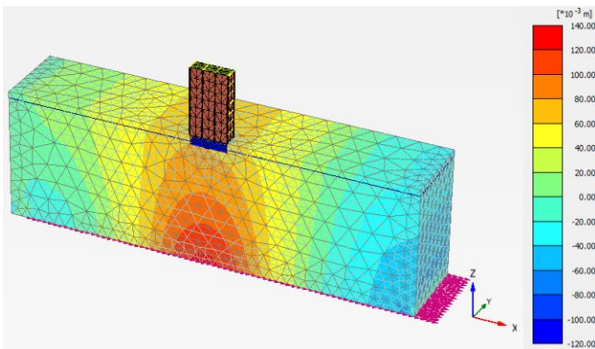


Figure 7. The horizontal displacement shading for full infill walls model (maximum displacement = 0.08 m).

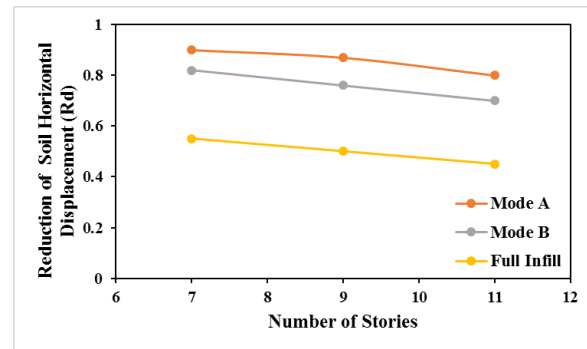


Figure 8. Reduction of soil horizontal acceleration for different modes with increasing the number of stories.

3. ANALYSIS PROCEDURES

A series of dynamic numerical models were adopted to evaluate the effect of infill walls on the system dynamic behavior using different parameters. These parameters are case of no walls, full infill, different wall locations (Model *A* and *B*), and different number of stories. The numerical process is composed of four phases: (1) The normal plastic condition; (2) The construction of the investigated structure where the input solution step is modified to 250 steps for more accuracy in the results; (3) Generating the free vibration condition; (4) The dynamic phase where the earthquake is run.

It shall be noticed that in the dynamic phase, the value of the displacement is reset to zero, the time interval is set to 10 s and the sub-step is modified to 1. The earthquake acceleration was taken from the default program file acceleration data (225 SMC) (SMC refers to the Strong Motion CD-ROM, which refers to a format used by the U.S. Geological Survey National Strong-Motion Project). The default acceleration time history of the program is the Loma Prieta earthquake (1990) with the maximum horizontal acceleration of 0.3 g (2.94 m/sec² at a time of 2.53).

To confirm and verify the program accuracy, a solved dynamic example in the PLAXIS was resolved manually by the Equivalent Static Load (Simplified Modal Response Spectrum method) as stated by the Egyptian Code of Practice 2020 [26]. The manual and the numerical results were compared to each other. Numerical output results showed that the stresses were 190 kN/m² as presented in Figure 5 and the stresses by the manual solution of the example were 183 kN/m². Therefore, there is a good agreement and compatibility between the two methods.

4. RESULTS AND ANALYSIS

The aim of this current research is to investigate and evaluate the infill walls effects on the lateral response of the subsoil, foundation, and structure behavior. These results are presented in detail in the following subsections.

4.1 Effect of Existence of Infill Walls on the Soil Subgrade Behavior

One of major objectives of this study is to evaluate the influence of walls existence on the subgrade soil dynamic behavior through different soil dynamic parameters.

4.1.1 Soil Displacement

The seismic waves that are induced during an earthquake will cause soil particles to disperse and spread in both directions. The numerical results confirmed that infill walls' existence can improve the soil subgrade stiffness and restrict the soil particles from flowing and moving. From Figure 6, the maximum horizontal displacement of the soil beneath the foundation was 0.18 m, while after the existence of the infill walls the soil displacement decreased to 0.08 m with a reduction percentage of 55.5% as in Figure 7. The effect of the infill walls in different positions to decrease the peak soil displacement (d_{max}) with increasing the stories number and compared to the case of bare structure ($d_{max,0}$) is presented as $R_d = (d_{max}/d_{max,0})$ in Figure 8.

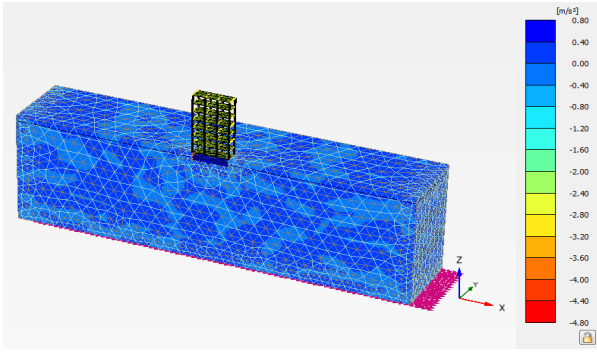


Figure 9. The horizontal acceleration shading for without walls model (maximum acceleration = 0.75 m/s^2).

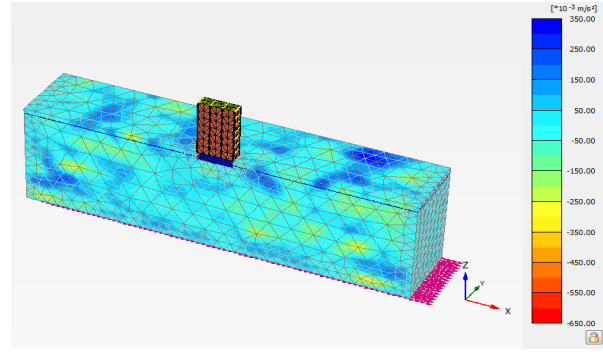


Figure 10. The horizontal acceleration shading for full infill walls model (maximum acceleration = 0.33 m/s^2).

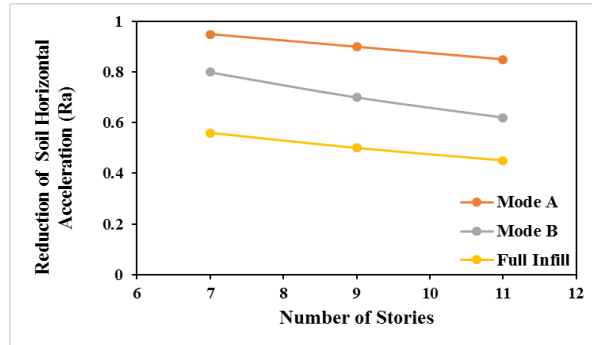


Figure 11. Reduction of soil horizontal acceleration for different modes with increasing the number of stories.

For the load transfer mechanism during earthquakes, firstly the induced earthquake waves will spread the soil particles then the induced waves effect on the superstructure. Walls existence will redistribute the vibration waves on the structure and offer relief to different structure elements and decrease the vibration loads to the soil layers [27]. The walls can be considered as a novel method to enhance the subgrade soil stiffness during earthquakes. Walls will increase and improve soil stabilisation which will restrict the soil from flowing and moving beneath the foundation [2,3].

4.1.2 Soil Acceleration

Soil acceleration is considered as the main characteristic of the soil dynamic properties during earthquakes. The numerical results showed the importance of infill walls' existence to justify the soil subgrade acceleration. It shall be noted that the soil acceleration was decreased remarkably compared to the case of the bare structure. As seen in Figures 9 and 10 the soil maximum horizontal acceleration was 0.75 m/s^2 for the bare structure, while after infilling the walls this value decreased gradually until it was the maximum reduction in the case of full infill to reach 0.33 m/s^2 with a reduction percentage of 56%. The maximum subgrade soil horizontal acceleration history was recorded (a_{\max}), and the effect of the infill walls in different positions with increasing the stories number then compare the results with bare structure ($a_{\max,0}$) is presented in the ratio of $R_a = (a_{\max} / a_{\max,0})$ in Figure 11.

This reduction in the acceleration is referred to as infill walls perform as a consequential mass that improves the structure's lateral stiffness and improve the foundation stabilisation through the effect of seismic loads by decreasing the structure lateral displacement during the earthquake [2,3].

4.1.3 Soil Velocity

There is a close relationship between both soil velocity and soil acceleration, such the soil acceleration is increased the soil velocity is increased, and vice versa. Numerical results illustrated that infill walls adjusted and modified the soil velocity. The velocity was significantly decreased with increasing the infill bays. As seen in Figures 12 and 13, the soil subgrade velocity decreased from 6.75 m/s in the bare structure model to 2.5 m/s in the full infill structure with a reduction percentage of 63%. The maximum subgrade soil horizontal velocity with dynamic time was recorded (v_{\max}), and the effect of the infill walls in different positions with increasing the stories number in the form of $R_v = (v_{\max} / v_{\max,0})$ where ($v_{\max,0}$) is the soil velocity in the case of bare structure is presented in Figure 14. Based on the output findings, it is observed that the infill walls improve the foundation stability by increasing the foundation mass which restricts the soil particles from movement and flow under the effect of lateral loads [2,3].

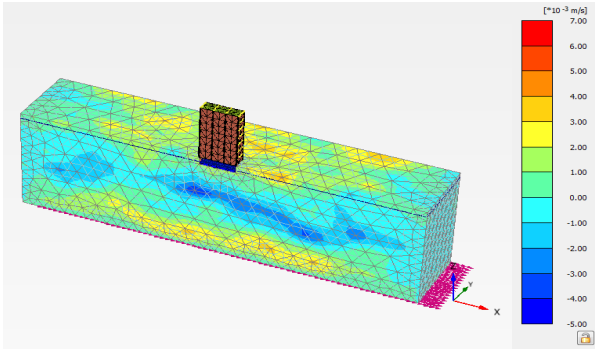


Figure 12. The horizontal velocity shading for without walls model (maximum velocity = 6.75 m/s).

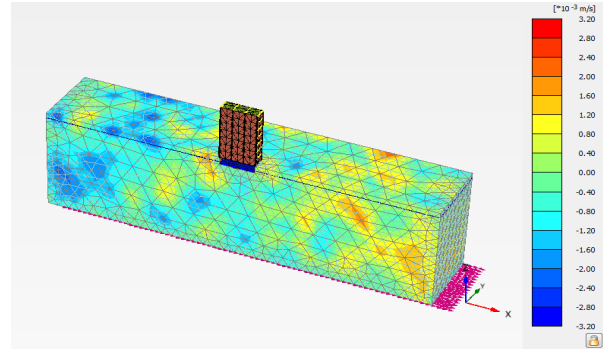


Figure 13. The horizontal velocity shading for full infill walls model (maximum velocity = 2.5 m/s).

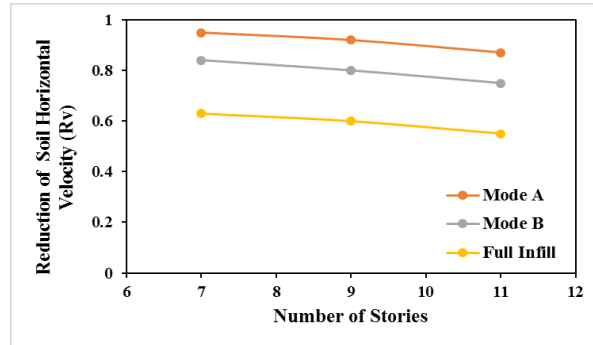


Figure 14. Reduction of soil horizontal velocity for different modes with increasing the number of stories.

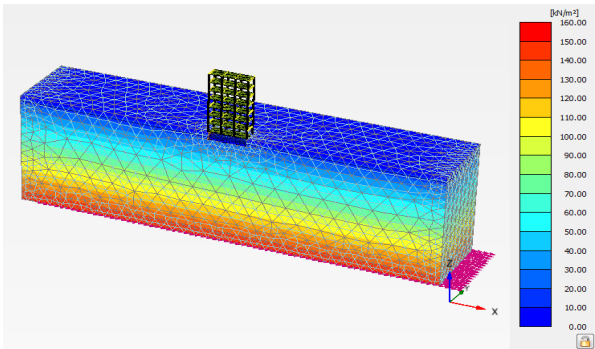


Figure 15. The shear shading for without walls model (maximum shear 152.6 kN/m²).

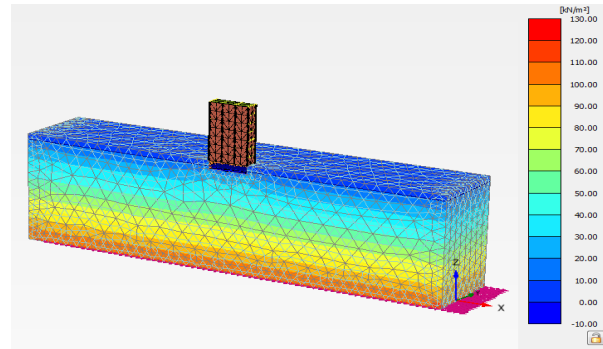


Figure 16. The shear shading for the full infill walls model (maximum shear 127 kN/m²).

4.1.4 Soil Shear Strain

The impact of shear waves on the soil subgrade, which distributes the soil particles, particularly beneath the foundation level, is one of the most significant earthquake dangers. This work aimed to evaluate the impact of infill walls existence to control and decrease the soil shear strain during the earthquakes. The different models were investigated, and the results confirmed that the presence of the infill has a remarkable role in reducing the induced soil shear strain along the foundation subsoil. As seen in both Figures 15 and 16, the maximum shear strain was 152.6 kN/m² in the case of the bare structure and this value decreased gradually with the existence of infill walls until it reached the maximum reduction to be 127 kN/m² in the case of the full infill structure with a reduction percentage of 16.7%. The reduction of the soil shear strain with the variation of walls location and different stories number is presented in Figure 17.

The behavior of the infill walls is comparable to a mass damper and behaves as a vertical obstacle block that resists and dissipates the induced shear stresses during earthquakes, which leads to a remarkable reduction in soil shear strain [2,3]. Besides, the walls will contribute with the structure columns to change the mechanism of load transfer from frame action to hybrid mechanism of both frame and truss action as a result of walls owing, besides walls increase the overall structure strength, stiffness and improve the energy degeneracy capacity [28].

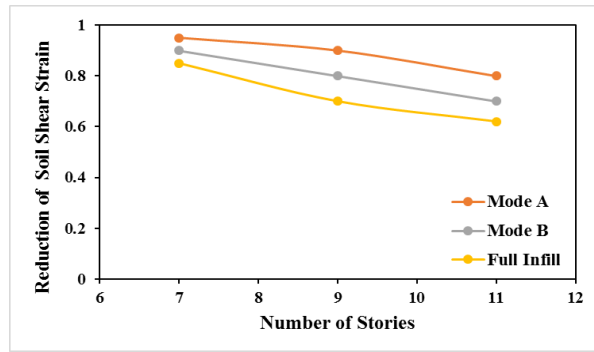


Figure 17. Reduction of soil shear strain with different walls location.

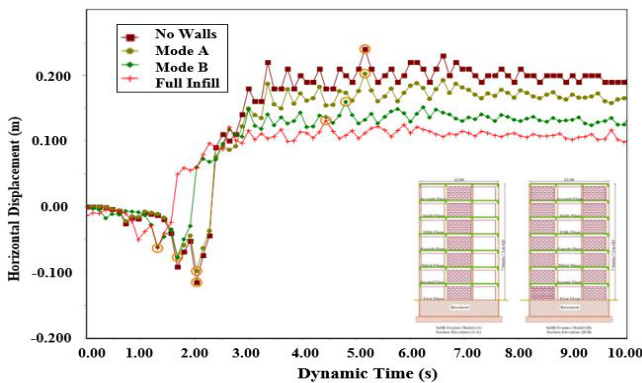


Figure 18. Reduction of the foundation horizontal displacement with different investigated models of basement + 7 stories.

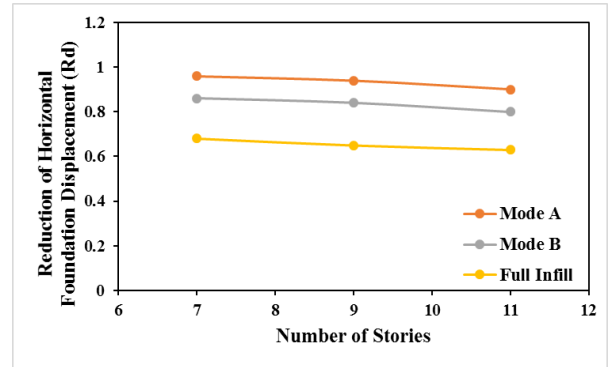


Figure 19: Reduction of horizontal displacement for different modes with increasing the number of stories.

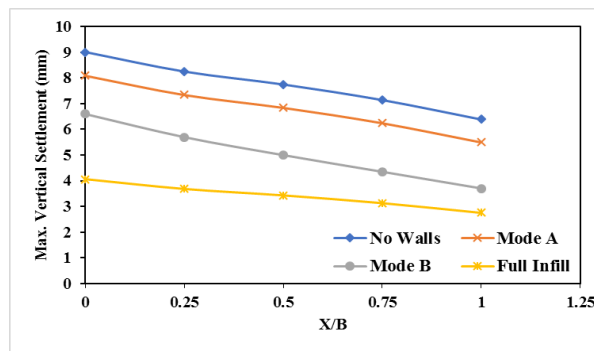


Figure 20. Reduction of foundation vertical settlement for different modes.

4.2 Effect of the Existence of Infill Walls on the Foundation Behavior

This part demonstrates the effect of existence of infill walls to adjust and modify the foundation behavior during the earthquake for different investigated parameters.

4.2.1 Foundation Displacement

The induced waves by the earthquakes have a high quantity of energy which affects firstly the foundation stability. The numerical results illustrated that infill walls have a significant role in adjustment and reduced the foundation movement during the earthquake. As presented in the results in Figure 18, the infill walls modified the foundation's horizontal displacement through dynamic time. Wall decreased the foundation peak horizontal displacement by as much as 49% from the initial value. Also, infill wall location in the external bays has a remarkable role in the adjustment of the foundation stabilisation and decreases the horizontal displacement with a reduction percentage of 22% compared to the wall's existence in center bays.

The variation value of the foundation horizontal reduction and the location of infill walls is presented in Figure 19. Also, the results confirmed that the infill walls decreased the vertical settlement of the foundation during the earthquake. Different vertical settlement values were chosen from the numerical analysis and illustrated as (X/B) ratio, where X is different spaces from the raft center, while B is distance between the raft center to the edge. Results showed that wall existence can mitigate and decrease the raft vertical settlement along the foundation length as seen in Figure 20. Results confirmed that the maximum vertical settlement reduction was in the case of full infill with a percentage of 57% compared to the bare structure.

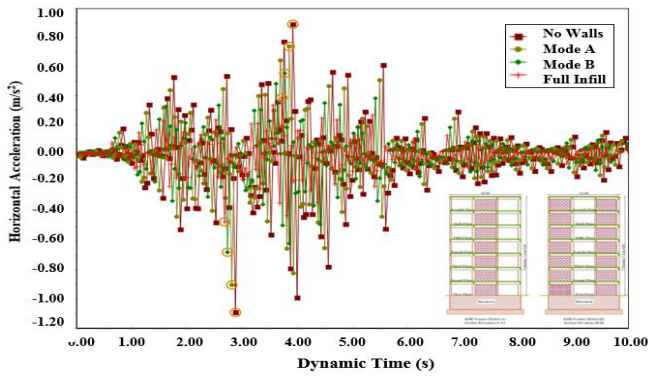


Figure 21. Reduction in the foundation horizontal acceleration with the different investigated models of basement + 7 stories.

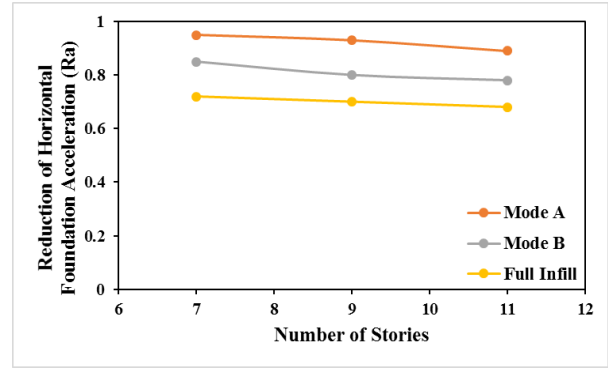


Figure 22: Reduction of foundation horizontal acceleration for different modes with increasing the number of stories.

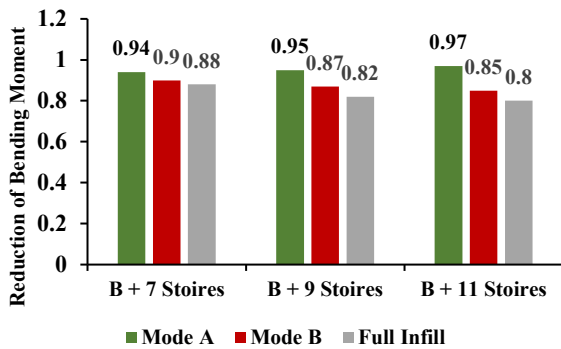


Figure 23. Reduction of the bending moment values at the foundation with different walls location modes.

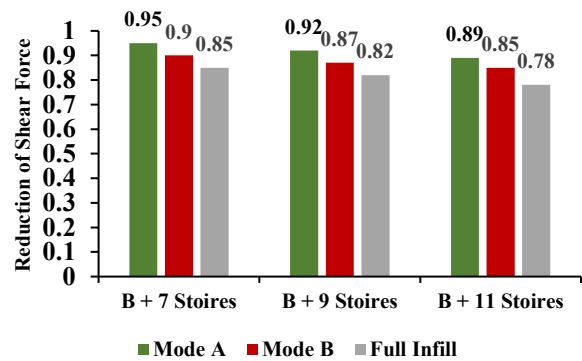


Figure 24. Reduction of the shear force values at the foundation with different walls location modes.

As a main conclusion, the infill walls' existence enlarged the soil subgrade stiffness and behaved as a resilient system to limit the lateral earthquake loads. Walls existence increase the interaction and interlock between the walls bays and columns that leads to improve the structure stability [26]. Also, the wall's weight decreases the soil voids and restricts the soil particles from flow and movement during earthquakes [2,3].

4.2.2 Foundation Acceleration

Results showed that infill walls existence has a remarkable role in the tuning of the foundation acceleration as seen in Figure 21. The results confirmed that full infill walls mode decreased the foundation acceleration by as much as 28% from its peak acceleration. Moreover, infill wall location has a major role in adjustment and modifying the acceleration values. Results confirmed that walls in the external bays have a major role in decreasing acceleration compared to the case of walls in internal bays. This reduction in acceleration is related to the existence of walls that improve the foundation stability and enlarge both the foundation and subsoil stiffness [2,3]. The foundation horizontal acceleration history was recorded, and the effect of the infill walls in different positions is presented as $Ra = (a_{max}/a_{max,0})$ in Figure 22.

4.2.3 Foundation Straining Actions

In addition, the infill walls existence reduced the straining action on the foundation. Results showed that full infill walls decreased the different straining actions. In the case of (Mode A), there was a little bit of reduction in straining actions compared to the case of (Mode B). Results showed that infill walls have a significant role in dissipating the induced moment and shear force. Thus, the wall's existence decreases and limits the earthquake intensity and shear waves. The effectiveness of the walls will be beneficial to mitigate the foundation shear force, but it would not mitigate the applied moment, such that the vertical loads cause a bending moment in the first place. The reduction of the different straining actions for different wall locations compared to the no walls case is presented in Figures 23 and 24.

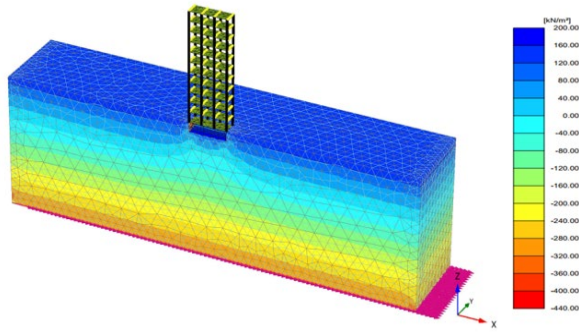


Figure 25. Shading of stresses in case of bare structure (Max. stresses = 161 kN/m²).

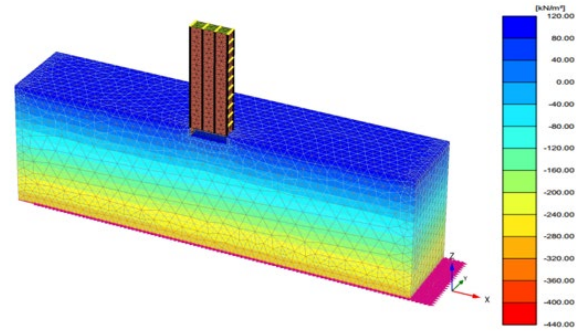


Figure 26. Shading of stresses in case of full infill structure (Max. stresses = 120 kN/m²).

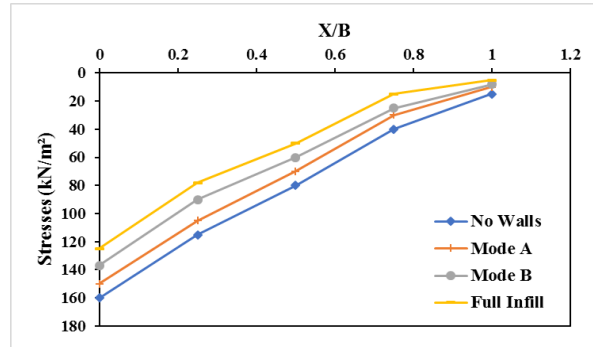


Figure 27. Variation of stresses of different models for different foundation distance.

4.2.4 Foundation Stresses

In engineering practice, one of the main issues in the high-rise design processes is to control and mitigate the stresses under the foundation. The infill walls have a remarkable role in the tuning of the stresses as presented in Figures 25 and 26. It shall be noticed that the existence of infill walls gradually decreased the stresses from 160 kN/m² to 150 kN/m² then to 140 kN/m² for the infill models (*A* and *B*) respectively. While the maximum reduction was in the case of full infill where the stresses reached 120 kN/m² with a reduction percentage of 25%. As seen in Figure 27, the existence of walls with different locations reduced the stresses beneath and along the foundation path. This improvement is backed by the dynamic interlock between the different structural elements and the existing walls. Therefore, the walls improve the structure stiffness and strength. Also, walls have a vital role in the dissipating and distracting of the seismic energy [2,3].

4.3 Effect of the Existence of Infill Walls on the Structure Response

This section evaluates the infill walls existence on the structure lateral response during earthquakes under different studied parameters.

4.3.1 Structure Displacement

To investigate the effect of infill walls on the structure lateral response a monitoring point (*A*) was chosen at the top of investigated models. The relationship between both the horizontal displacement and the corresponding dynamic time was recorded. Based on the numerical results as presented in Figure 28, utilisation of infill walls in all stories for all investigated models leads to a significant reduction in the horizontal displacement compared to other structure counterparts. The results demonstrated that the infill position has a major role to modify the structure horizontal displacement by as much as 50% from its initial value as shown in Figure 28. The infill walls in the external bays reduced the horizontal displacement by 23% more than the infill walls in the center bays. Besides, eliminating infill walls led to maximum horizontal displacement in all the investigated models. Moreover, by increasing the structure stories number the full infill mode and case of mode (*B*) exhibits more reduction in the structure stability in comparison to other modes. The value of the maximum horizontal displacement (Rd_{max}) at the top of building was determined and compared with the case of bare building horizontal displacement (Rd_0) and presented in Figure 29 in the form of $Rd = (Rd_{max}/Rd_0)$.

This reduction in the lateral displacement is related to infill walls improving and increasing the structure's lateral stiffness and improving the structure stability. Infill walls behave similarly to a diagonal strut and as a bracing member between the structure bays which decreases the lateral displacement as seen in Figure 30.

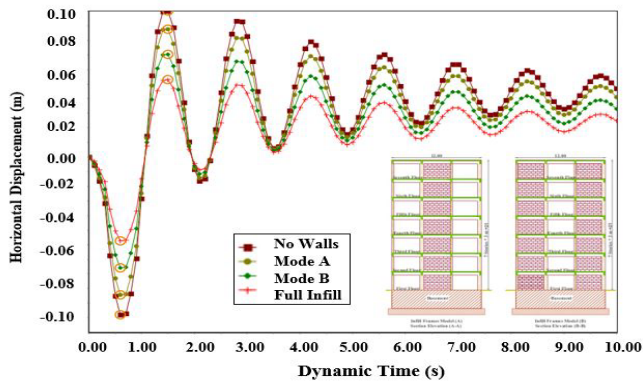


Figure 28. Reduction in the building horizontal displacement (Point A) with different investigated models of basement + 7 stories.

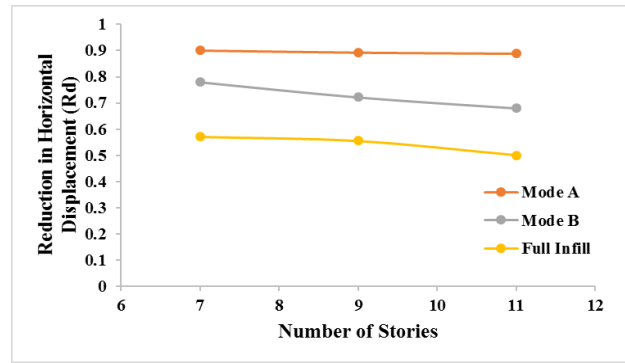


Figure 29. Reduction of horizontal displacement for different modes with increasing the stories number.

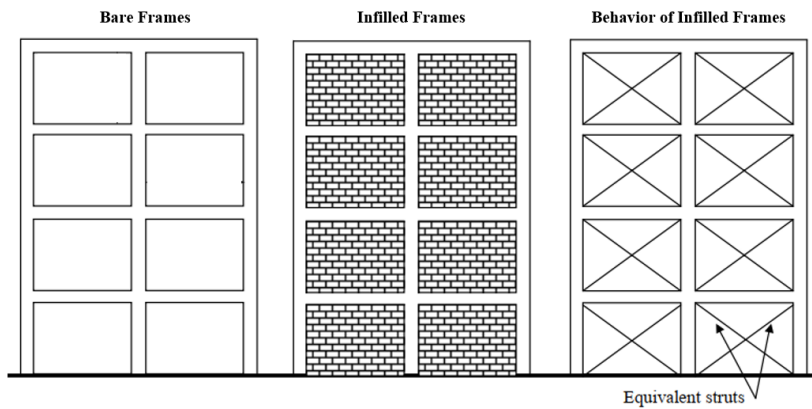


Figure 30. Schematic diagram of the bare, infilled and the behavior of infilled frame during earthquakes [29].

4.3.2 Structure Stories Drift

The structures' response through the lateral loads is sway and forth. Through the earthquake, different structure elements are deformed and stressed, which leads to the appearance of cracks in the different structure members and may lead to structure damage or even failure under extreme ground motions. Therefore, structures' drift control and limitation are one of the main survivability conditions. Structure drift ratio is given by the difference in drift between two consecutive floors divided by the storey height. The numerical results demonstrated the effect of the existence of the infill walls to control the drift values as seen through Figures 31 to 33. Based on the results, the bare structures have the maximum drift ratios in all investigated cases which represent a clear representation of structure deformation. Also, in the case of infill walls in the center bay only, the values vary slightly and no significant reduction in the stories drift ratio was achieved compared to the bare structure.

The results showed a remarkable reduction in the drift values in both cases of walls at the external bays and the case of full infill walls, thus the infill walls behave similarly as a bracing member between structural columns to restrict structures' excessive sway and decrease structures' lateral deformation during earthquakes as presented in Figure 30. Therefore, structures with suitable infill walls will not affect from inter-story drift during earthquakes [30].

4.3.3. Structure Acceleration

The relationship between the structure horizontal acceleration at the investigated point (a_{max}) and the corresponding dynamic time was recorded. Then, a different comparison was conducted with different infill modes and with the bare case mode ($a_{max,0}$). Results showed that the maximum reduction in the horizontal acceleration was in the case of full infill mode with a reduction of 50% as seen in Figure 34. The effect of the infill walls in different position modes to reduce the horizontal acceleration in the ratio of $Ra = (a_{max}/a_{max,0})$ is presented in Figure 35. As a main conclusion, the infill walls increased the structure stability and improved the structures' resistance to lateral loads. Thus, walls existence enhances the structure stiffness and behave similar as a monolithic shear wall through during the earthquakes [2,3].

4.3.4 Structure Straining Actions

The results showed that the maximum straining actions such as moment and shear have their maximum values when the infill is omitted from the structure. Also, in the case of the infill in the center bay only, there was an insignificant reduction in the straining actions. It shall be noticed that the presence of infill walls in the center bay is similar to the case of the bare one. Results showed that the maximum reduction in the induced straining action in the case of the full infill walls, and then in the case of the infill walls in the external bays. The reduction of the different straining actions for different wall locations compared to the no walls case is presented in both Figures 36 and 37.

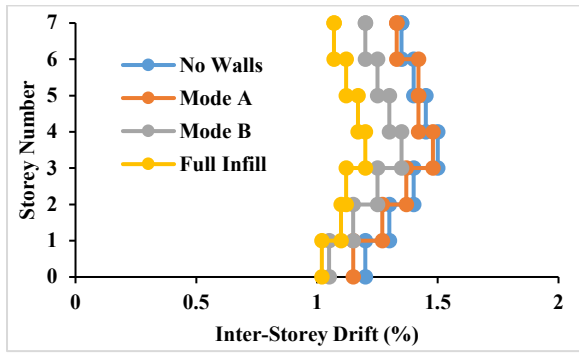


Figure 31. Inter-stories drift of different investigated structural (Basement + 7 Stories).

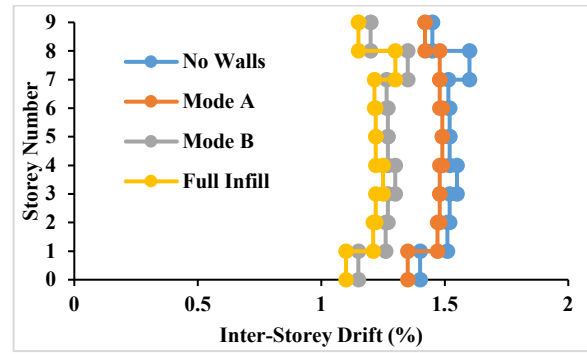


Figure 32: Inter-stories drift of different investigated structural (Basement + 9 Stories).

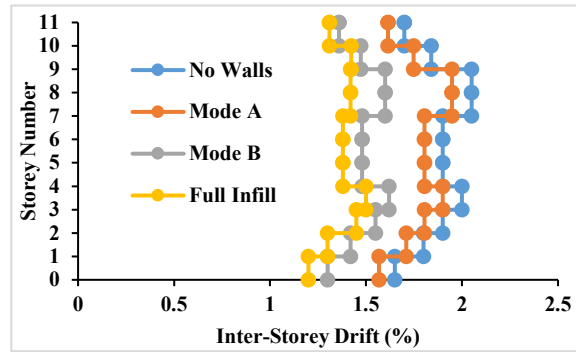


Figure 33: Inter-stories drift of different investigated structural (Basement + 11 Stories).

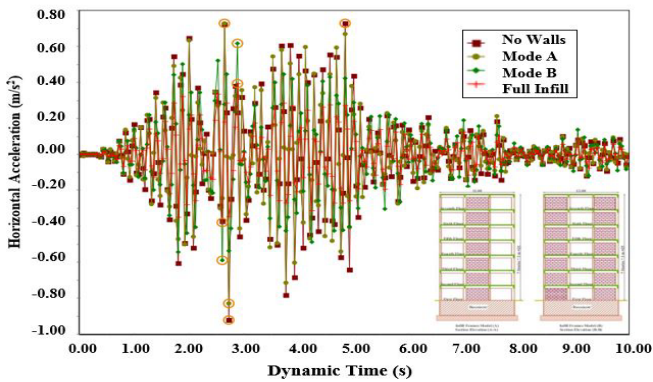


Figure 34. Reduction in the building horizontal acceleration (Point A) with different investigated models of basement + 7 stories.

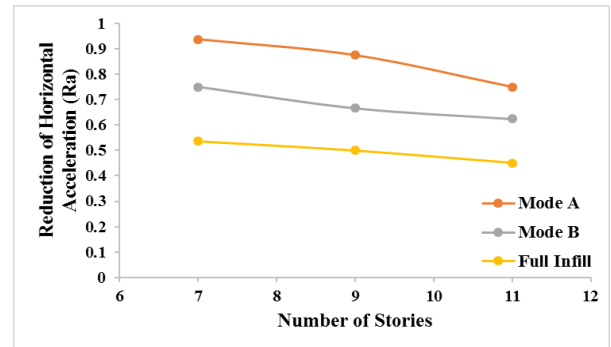


Figure 35. Reduction of horizontal acceleration for different modes with increasing the stories number.

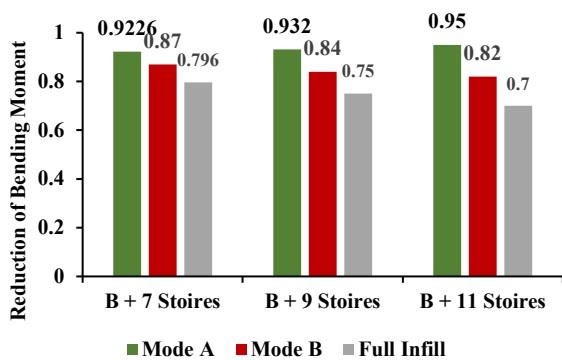


Figure 36. Reduction of the bending moment values at the building top point (Point A) with different walls location modes.

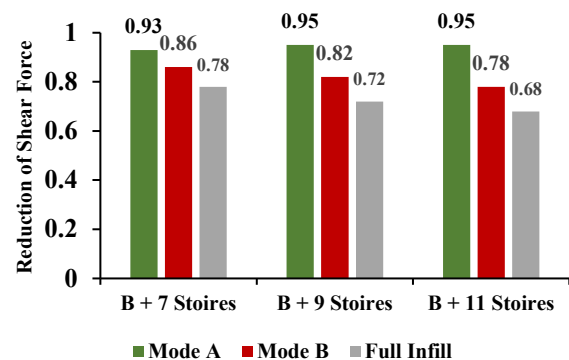


Figure 37. Reduction of the shear force values at the building top point (Point A) with different walls location modes.

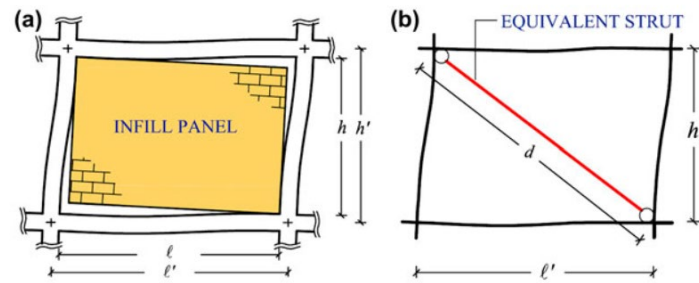


Figure 38. Schematic diagram: (a) actual infill panel system; (b) equivalent diagonal braced system [30].

This reduction is due to infill walls interacting with the surrounding different structure elements and behaving with the surrounding columns and beams as a single unit which reduces the induced vibrations by the earthquakes. Also, the infill walls presence plays a major role in changing the structure performance from frame behavior in the case of bare structure to truss behavior due to walls existence. The methodology of the truss action that truss members perform and work as an equivalent strut to decrease the different induced straining actions to the columns as seen in Figure 38.

5. CONCLUSIONS

This research analyzed the influence of infill walls' existence on the superstructure, foundation, and soil under the effect of earthquakes. In this study, four buildings rested over dense sand soil were numerically modelled, with different story numbers and different infill wall configurations. This research presents a novel technique that can be used to increase structure stability and improve both the foundation and soil lateral response by mitigating the effects of earthquakes. The main output findings of this research are:

- Results demonstrated that infill walls' existence improved the soil, foundation, and structure against horizontal actions and lateral deformation. Based on the numerical results the infill walls positions have a major role in the modification of structure and soil dynamic characteristics during seismic actions. The results showed that a greater effect when the structure is full of infill than in the case of external walls position.
- It was observed that the full infill walls model decreased the soil horizontal displacement by 55.5% from its initial value. The results of this study revealed that infill walls existence reduced both the subsoil acceleration and velocity by as much as 56% and 63% respectively compared to the bare structure. Also, the existing walls reduced the subsoil shear strain by 25% along the foundation path.
- The full infill walls decreased the foundation peak horizontal displacement by as much as 49% from its initial values, while this reduction was achieved by 22% in the case of the external infill walls. In addition to, the foundation acceleration decreased by as much as 28% from its maximum value after the existence of infill walls. Finally, a considerable reduction in the stresses beneath the foundation and the straining action were achieved, which is estimated to be 25%, and average of 80% for bending moment and shear force respectively.
- The walls existence location has a significant role in the displacement reduction, full infill walls reduced the horizontal displacement by 50% from its initial value, while this reduction achieved to 23% in the case of external infill walls.

As a main finding in all infill models, wall existence decreased the inter-story drift compared to the bare model. Results illustrated the walls decreased the structure's horizontal acceleration by as much as 50% compared to the bare structure. Finally, it can be shown that walls' existence has a considerable effect on decreasing the structure-straining actions, which leads to a significant economic gain in the design processes.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare no potential conflicts of interest with respect to the research and publication of this article.

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