APPLICATIONS OF
MODELLING AND SIMULATION

http://arqiipubl.com/ams eISSN 2600-8084 VOL 7, 2023, 122-131

Numerical Investigation of Wall Packing Effects on Geotechnical Behavior of Infilled Frames under Lateral Loads

Maher Taha EL-Nemr[1], Waseim Ragab Azzam[2], Mohammed Mohammed Abu-Raia[1] and Moataz Ahmed Wahba[1*]

[1]Department of Civil Engineering, Menoufia University, Egypt
[2]Department of Civil Engineering, Tanta University, Egypt

[*]Corresponding author: moataz.wahba@sh-eng.menofia.edu.eg

Submitted 03 August 2023, Revised 09 September 2023, Accepted 20 September 2023; Available online 02 October 2023.

Abstract: Structures are affected by additional forces due to the different lateral loads that may cause foundation failure. Many studies of infilled frames' behavior under lateral loads were performed, but the effect of walls' existence on the foundation's behavior was ignored. In this work, PLAXIS 3D software was used to study the various factors affecting the foundation of reinforced concrete infilled frames under lateral load. Two specimens of single-story frames consisting of one bay of 3.10 m, width of 0.50 m, and 2.10 m in height, with and without masonry walls were adopted in this study. The effect of walls on the stability of the foundation soil system over sandy soil is investigated to show the improvement of the structure response under lateral loads. The wall stiffness is also investigated in the case of increasing the wall's inertia. Numerical results indicated that the fully infilled frame has better performance than the bare frame, thus the infilled frame interacts with the surrounding infill walls as a single unit. Results demonstrated that the wall's existence reduced the soil horizontal acceleration and shear strain by 35% and 37%, respectively, compared to the bare frame. As indicated throughout the tests' findings, the wall's existence has a great impact on minimizing settlement and reducing the stress of the foundation. Walls' existence significantly reduced the foundation settlement and stresses by as much as 18.5% and 33%, respectively, from its initial values. Results showed that the utilization of walls has promising outcomes and improves structural stability against the devastating effects of earthquakes.

Keywords: Brick walls; Foundation; Infilled Frames; Lateral Loads; PLAXIS 3D; Sand.

---

1. INTRODUCTION

Masonry walls are commonly used and found in most reinforced concrete (RC) buildings and steel structures. Masonry infill causes major hazards and typically fails in case of strong earthquakes. This is due to several reasons, such as the large weight, the very low tensile strength, and the weakness between the structural elements [1]. This inhomogeneous material is widely used for interior and exterior separations as it is an economical material that is reachable to all cities and provides the structure with both acoustic and thermal insulation [2]. Masonry infill is considered a nonstructural element, which interacts with the surrounding frame columns when the structures are under the effect of strong earthquake loads or wind loads. Also, masonry infill panels are widely used to increase the existing moment-resisting frames and improve the performance of different structures under the effect of earthquake loads [3].

On the other hand, masonry infill contribution to the effect of frames foundation and subsoil behavior is mainly neglected during earthquakes. During the earthquake, a huge amount of energy is firstly received by the foundation, then it is distributed to the superstructure [4]. The effect of infill on different structural foundation performances has been controversial, and there are no seismic code requirements or any available guidelines for the safety design and utilization of walls' existence on foundation behavior. In light of the aforementioned information, it is rigorous work to evaluate the existence of the wall on the dynamic behavior during earthquakes. Besides, a major important issue is that in the numerical modeling of infilled frames, the soil mass with its real interaction was ignored. This study is motivated to investigate the effect of masonry infill walls on the frames, foundation, and subsoil behavior during earthquakes by using the finite element method. Findings pointed out that walls' existence decreased the system settlement, displacement, and stresses.

It can be clearly seen that the majority of experimental studies have shown that masonry infills increase the frame stiffness and strength by as much as 50% compared to the case of bare frames [5-9]. Also, the walls' existence reduced the lateral displacement of the frames under cyclic loads compared to the bare once [10]. Previous experimental investigations confirmed that the existence of masonry increased the frame lateral capacity due to the increase in the elastic stiffness and improved the frame seismic response throughout both the lateral displacement and the base shear in comparison to the bare frame [11]. An experimental study on infill walls with behavior with variable thicknesses and materials on the frame subjected to cyclic loads was conducted [12]. Results confirmed that walls with thicknesses of 12 cm and 6 cm increased the frame lateral resistance by 184% and 61%, respectively, compared to the case of a bare frame. A numerical study by finite element analyses program conducted to study the effect of infill walls on the frame's failure under lateral loads. The results demonstrated that decreased the frame displacement and increased the frame's lateral loads capacity [13]. Both experimental and numerical studies of the effect of adding walls on the frame behavior under seismic loads were conducted. The results demonstrated that walls reduced the inner displacement and enhanced the dissipation energy capacity of infilled frames and avoid damage to the system [14].

In summary, most previous experimental investigations or numerical analyses have been focused on the effect of walls on the superstructure behavior under the effect of lateral loads with no consideration of the foundation. Moreover, the literature ignored the effect of walls' existence on the soil mass, which has a major role in altering the structural system behavior during earthquakes. Also, analysis of any structure without considering the real effect and behavior of the soil leads to either unnecessarily costly or unsafe designs. Consequently, this paper's main goal is to model and simulate the real interaction between the structure and the soil, then investigate the effect of adding walls on the structure system behavior by using the PLAXIS 3D program [15] to capture the utilization of walls to improve the structure, foundation, and soil stability under the effect of lateral load condition. The derived results from the numerical analyses are presented in various charts and comparisons.

Therefore, in this current study, an attempt has been made to take into consideration the effect of walls' existence on the subsoil response. Also, the walls' influence in improving the subsoil performance and the foundation dynamic behavior was investigated. A numerical representation model has been created of the interface between both the soil mass and the foundation to estimate the influence of walls' existence to improve the behavior of structures subjected to lateral loads. This paper discovers and analyse such a problem to relieve the system deformation and safeguard the foundation from collapse. In addition, this research studies the utilization of walls as an attractive choice to control the lateral displacement of the structure and decreases foundation stresses, displacement, and settlement by using the PLAXIS 3D finite element program.

2. NUMERICAL MODELLING AND RESEARCH STRATEGY

In this work, the soil domain consisted of sand strata with thickness of 30 m, and 40 × 4 m for length and width, respectively. These dimensions were enough to satisfy the soil failure mechanism under the effect of both static and dynamic loads [16]. The investigated reinforced concrete frame consists of one story of one bay of 3.10 m, 0.50 m and 2.10 m for width and height respectively. The ratio of frame height to length (H/L) was 1/1.5 as presented in Figure 1. The layout of the model including the supporting soil is illustrated in Figure 2. For the generation of the mesh, it was selected as a 'coarse' mesh, while the clusters surrounding the structure were refined twice because of the high expected stresses under the structure elements and to get a more accurate analysis.

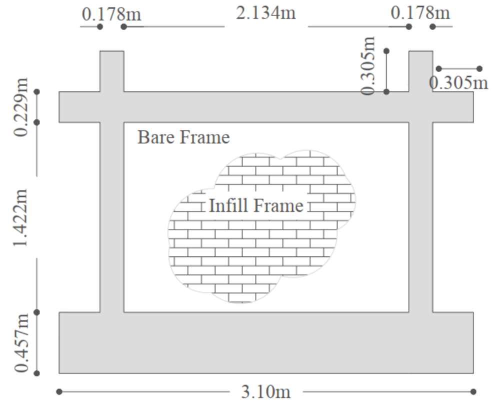
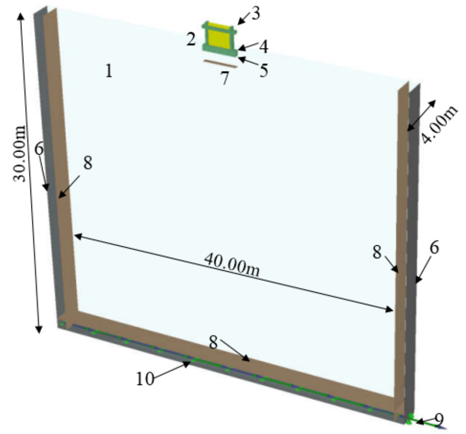


Figure 1. Schematic diagram of the bare / infilled frame dimensions [3]



1. Subsoil, 2. Frame model, 3. Node A, 4. Node B, 5. Node C, 6. Absorbent boundaries, 7. Negative interface, 8. Positive interface, 9. Prescribed displacement, 10. Standard fixation.

Figure 2. Layout of the numerical model (by PLAXIS 3D)

Raleigh damping was considered at vertical boundaries by considering α and β = 0.2320 and 0.008, respectively to overcome the effect of the Raleigh waves [17-18]. The soil plastic material properties (viscous properties) are the material damping coefficients as described in PLAXIS by the Rayleigh coefficients (α and β). They were used to include the soil plastic properties under the effect of dynamic loads and were automatically defined by the program. The damping terms are assumed which is relative to both the mass and stiffness of the system (Rayleigh damping) as presented in Equation (1) where C is the damping coefficient, M is the mass, K is stiffness and α and β determine the effect of the mass and the stiffness in the damping system, respectively.

$$C = \alpha M + \beta K \tag{1}$$

Three monitoring nodes A, B, and C were selected at the top of the frame, the foundation base level, and the subsoil beneath the foundation, respectively, to investigate the performance of the structure, the foundation, and the subsoil under the effect of lateral loads. The interface was set to 1 for the real soil, while the different structure elements embedded in the soil were modified to 0.67 to realize the compatibility deformation between the structure element and the surrounding soil. The seismic activity is modeled by assigning a prescribed horizontal displacement at the boundary bottom in contrast to the standard unit length ($U_x = 1.0$ m, $U_y = 0$ and $U_z = 0$) [17-18].

3. BOUNDARY CONDITIONS AND MODEL CONSTITUTIVE

Numerical modeling and simulation are commonly applied to study the seismic response of different structures during earthquakes. For simulating the model within acceptable limits and to model and define a domain large enough to represent the dynamic condition, it is recommended to only model the soil region of interest surrounding the investigated model in the range of five to ten times the structure width, while modeling the rest of the soil as artificial fixed boundaries [19].

3.1 Lateral Boundary and Bedrock Conditions

In this work, the horizontal distance between the structure and the soil domain boundaries was set to be five to ten times the dimensions of the structure that has a small effect on the model seismic response. Therefore, the horizontal distance between the soil lateral boundary and the model was to be 18 meters (six times the structure width in this study). These dimensions are enough to prevent soil failure under both seismic and static conditions [20-21]. Also, the bedrock depth was about 30 m in the case of numerical analysis, which complies well with most seismic codes [22-23] that highlighted the characteristics of the first 30 m of the soil stratigraphy to assess local site effects.

3.2 Dynamic Boundary Conditions

According to the constraint of finite element methods (FEM), the propagating waves are reflected and refracted from the boundaries that waves return back into the model and do not allow the required energy radiation and trapping energy in the model. So, the major objective of dynamic models is to investigate the effect of radiation conditions in overcoming the reflection of false waves (avoid waves to return back to the model and region of interest) from the soil domain boundaries [24-25].

4. CALCULATION METHOD

The following FEM analysis procedure was adopted:

The case of wind load calculation procedure involves three phases: (1) The initial phase includes the generation of the initial conditions; (2) The second phase is the frame construction; (3) The third phase is applying the frame to lateral load. In the case of the bare frame, a concentrated load was applied to the frame center starting from 10 kN and was increased gradually up to 100 kN. For the infilled frame, a lateral load was applied starting from 40 kN and was increased gradually up to 180 kN.

In the case of earthquakes, the numerical process consists of four phases: (1) The initial conditions phase; (2) The simulation of the frame construction phase; (3) The free vibration analysis phase; (4) The dynamic phase. In phase 4, the earthquake force was modeled, the displacement was set to zero and the seismic time interval was set to 10 sec. The earthquake ground acceleration was set according to the PLAXIS default acceleration input file (225 SMC) (SMC, Strong Motion CD is a format used by the U.S. Geological Survey National Strong-Motion Project). The used acceleration time history was the program default with the maximum horizontal acceleration (0.3 g = 2.94 m/sec^2 at a time of 2.53 sec). Pore water was started before generating the mesh.

5. VERIFICATION EXAMPLE

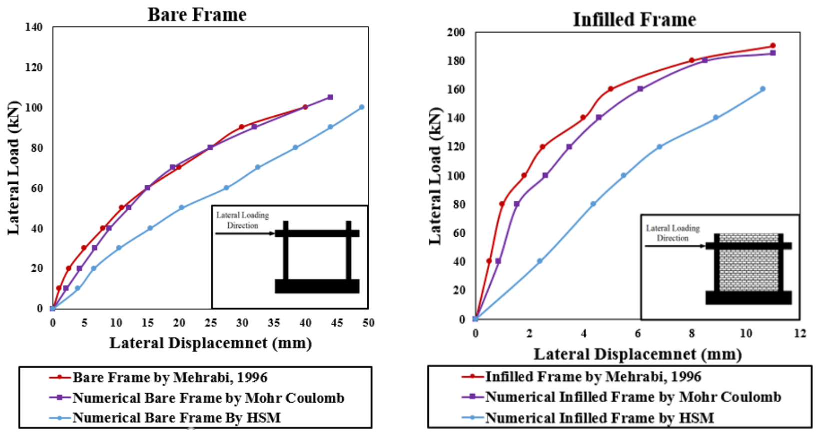
The model test presented by [3] was used to verify the finite element program accuracy in solving such problems. The soil domain had a thickness of 30 m, and 40 × 4 m for length and width, respectively, to overcome the boundary effect. The bare and the infilled frame were modeled by PLAXIS with the dimension in Figure 1. The verification processes were created by both Mohr-Coulomb and hardening soil constitutive models. Table 1 presents the geotechnical properties of the sand soil. The level of the underground water was assumed at 2.0 m beneath the earth's surface. The soil undrained conditions were considered to assess the pore water excess pressure. The frame, foundation, and walls properties are listed in Table 2.

Table 1. Details of soil geotechnical and mechanical parameters for Mohr Coulomb (M.C) parameters [18] and for Hardening Soil Model (H.S.M) [26]

Soil Parameter	Units	Dense Sand Soil	
Material Model	--	M.C	H.S.M
Relative Density(D_r)	--	85%	85%
Unsaturated unit weight (γ)	kN/m^3	18	17.65
Saturated unit weight (γ)	kN/m^3	19.5	19.5
Poisson's Ratio	--	0.3	0.3
Angle of Friction (φ)	°	38	39
Dilatancy Angle(Ψ)	°	8	9
Modulus of Elasticity	kN/m^2	50000	--
E_{50}^{ref}	kN/m^2	--	50000
E_{oed}^{ref}	kN/m^2	--	50000
E_{ur}^{ref}	kN/m^2	--	62000
P_{ref}	kN	--	100
Power (M)	--	--	1

Table 2. Material properties of frame and walls [2]

Parameter	Unit	Frame and Foundation	Masonry Walls
Set Type	--	Soil Properties	Plate Properties
Material weight (γ)	kN/m^3	33.33	17.5
Young's modulus (E)	kN/m^2	30E6	1.5E4
Poisson's ratio (υ)	--	0.15	0.15
Rayleigh damping (α and β)	--	0.2320 & 0.008	--



(a) (b)

Figure 3. Verification of the PLAXIS results with the load displacement for (a) bare frame and (b) infilled frame by [3]

Results in Figure 3 showed that the H.S.M has a significant difference compared to both experimental and Mohr-Coulomb results as presented. However, there is a good agreement and strong reproducibility between both the experimental study that was discussed by [3] and the numerical results by (M.C) criteria model. Also, Mohr-Coulomb was recommended to model the real dynamic soil behavior under the effect of seismic load conditions [20]. Therefore, this model was adopted in this present study.

6. RESULTS AND DISCUSSIONS

The following subsections present the effectiveness of walls on the behavior of the subsoil, the foundation, and the frame.

6.1 Effect of Walls on the Frame Displacement under Wind Load

The numerical results demonstrate that the existence of walls decreased the lateral displacement for each corresponding load at least eight times for infilled frame compared to the same load at the bare frame. Also, as presented in Figure 3, infill walls increased the frame capacity to resist the lateral loads by two times more than the bare once. These results indicate the effectiveness of the walls in reducing the lateral displacement and improving the frame lateral load capacity [27].

6.2 Effect of Walls on the Performance of the Subsoil

The results show an improvement in the soil horizontal displacement beneath the foundation. Figure 4 illustrates (orange circled points) which refers to the maximum horizontal displacement at point *C* in the bare frame was 0.01 m, which was reduced to 0.0085 m in the case of the infilled frame. Also, by increasing the inertia, *I* of the infilled walls to 2*I*, the displacement decreased to 0.0075 m with a reduction of 25%. As a main conclusion, the existence of the walls increases the frame stability and mass besides decreasing the soil lateral displacement under the frame and avoids the soil particles from moving and flowing in the horizontal position of the free displacement [28]. Also, the soil acceleration was reduced at the peak point (orange circled points) by nearly 35%, from 0.242 m/s^2 in the case of the bare frame to 0.157 m/s^2 for the infilled frame, as shown in Figure 5. This reduction has occurred as the addition of such walls represents an additional coherent mass that increases the stability of the foundation under seismic effects. As shown in Figures 6 and 7, the maximum horizontal velocity was 2.00 m/s, while after adding the walls the velocity was reduced by 25% to 1.5 m/s. So, adding walls improves the subsoil seismic response as a result of the densification of the mass over the soil layers which leads to increasing the foundation stability. Figures 8 and 9 present the shear strain of soil particles before and after adding walls respectively. According to the numerical results, the existence of walls reduced the shear strain by 37% along the foundation subsoil. The results confirmed that the effect of adding walls on the reduction of shear strain is due to the additional coherent mass of the walls over the soil which reduces the soil particles movement. The walls and the subsoil behaved as one block which has an excessive effect on resisting the induced shear strength during the earthquakes.

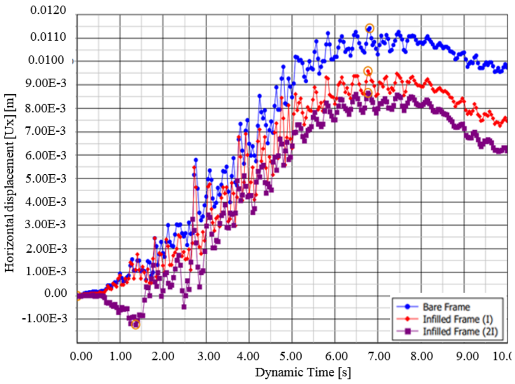


Figure 4. Relation between the horizontal displacement and earthquake dynamic time under the foundation level (Point *C*)

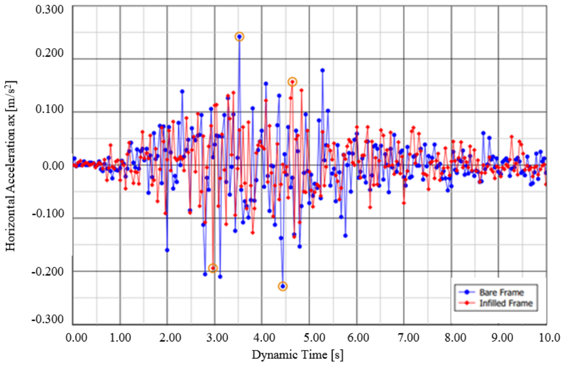


Figure 5. Relation between the horizontal acceleration and earthquake dynamic time under the foundation level (Point *C*)

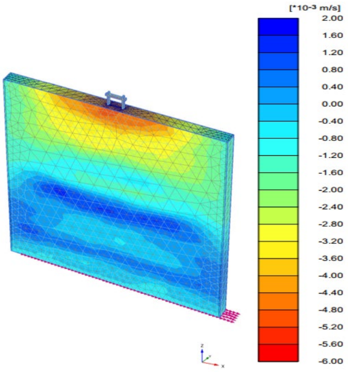


Figure 6. The horizontal velocity shading for the bare frame (maximum velocity 2.00 m/s)

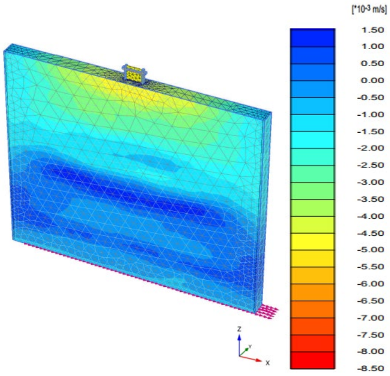


Figure 7. The horizontal velocity shading for the infilled frame (maximum velocity 1.50 m/s)

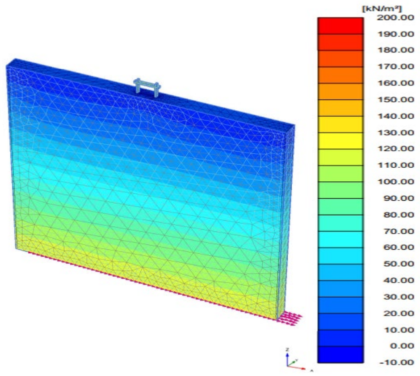


Figure 8. The horizontal shear shading for the bare frame (maximum shear 191 kN/m^2)

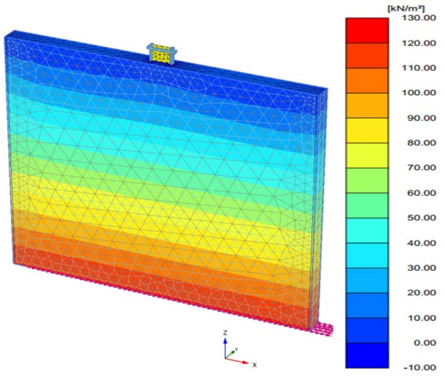


Figure 9. The horizontal shear shading for the infilled frame (maximum shear 124.5 kN/m^2)

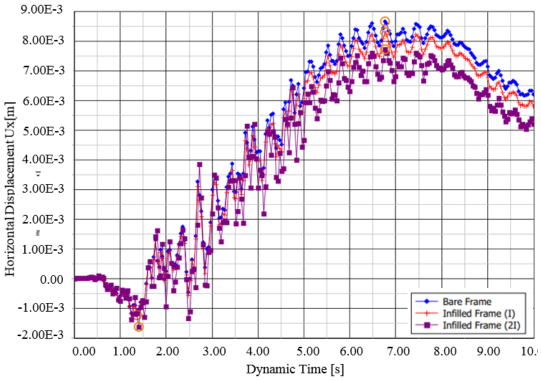


Figure 10. Relation between the horizontal displacement and earthquake dynamic time at the foundation level (Point *B*)

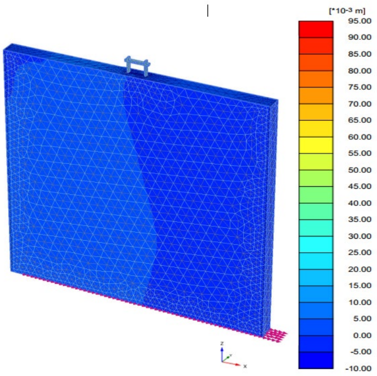


Figure 11. Total displacement contours under horizontal loading in case of bare frame (maximum displacement = 81 mm)

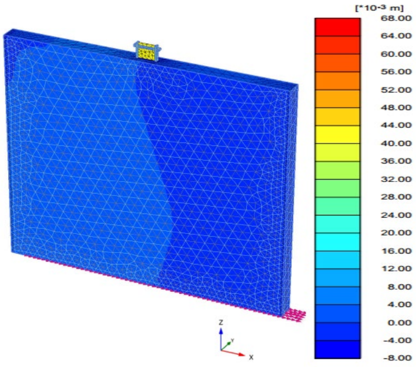


Figure 12. Total displacement contours under horizontal loading in case of infilled frame (maximum displacement = 66 mm)

6.3 Effect of Walls on the Foundation

The effect of applying different wall stiffnesses was also studied at the monitoring point (point *B*). Results confirmed that increases in the wall stiffness improved the foundation lateral displacement behavior as shown in Figure 10 (orange circled points). A major point included was to investigate the existence of walls on the vertical settlement of the frames during the earthquake loads. Results illustrated that the total settlement of the bare frame was 81 mm, but in the case of the infilled frame, the final settlement was only 66 mm as presented in Figures 11 and 12. The existence of walls leads to a reduction in the total vertical settlement by as much as 18.5% compared to the bare frames. This reduction due to the wall's weight reduced the soil voids and improved the soil particles' stability.

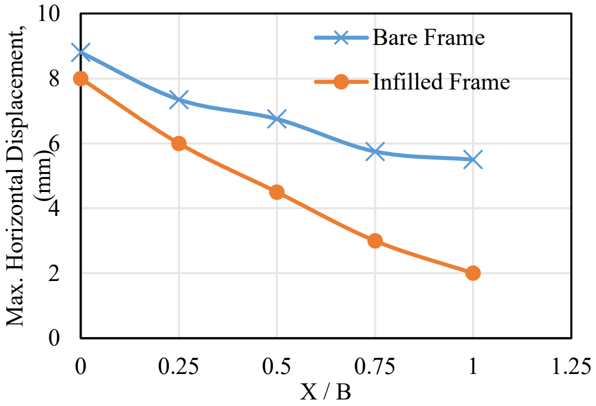


Figure 13. Variation of horizontal displacement at foundation level for bare and infilled frames

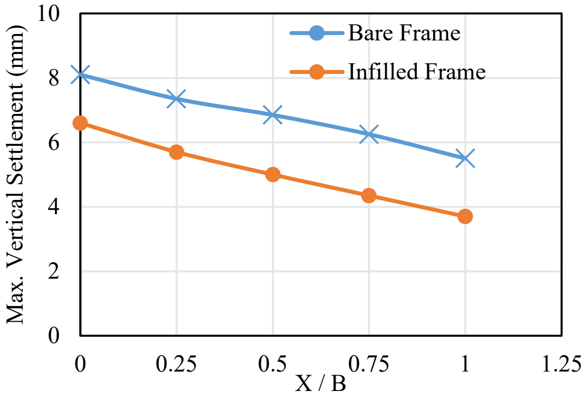


Figure 14. Variation of vertical settlement at foundation level for bare and infilled frames

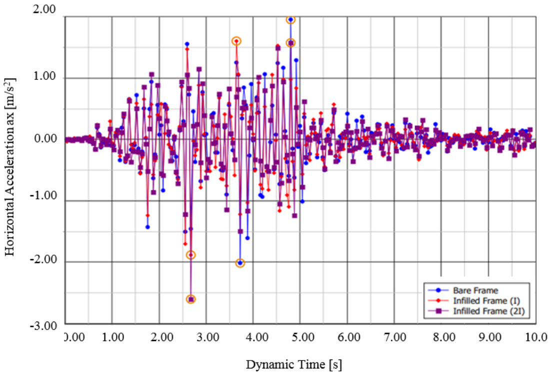


Figure 15. Decrease in the horizontal acceleration at the foundation level of the bare / infilled frame (Point B)

Values of the different measures were taken from the numerical analysis and plotted against the (X/B) ratio, where X is variable distance from the model center and B is distance from the model center to the edge. Figure 13 presents the effect of walls to reduce the horizontal displacement along the foundation. Walls existence significantly increased the foundation stability during the earthquake and the reduction in the horizontal settlement at $X/B = 1$ was about 63% in comparison with the bare frame. Moreover, the walls reduced the foundation's vertical settlement as presented in Figure 14, which shows the variation in vertical settlement between the bare and infilled frame, the existence of walls can mitigate the frame models vertical settlement.

Walls' existence has a main role in the tuning of the foundation acceleration behavior (orange circled points), as presented in Figure 15. The numerical results have shown that the walls decreased the maximum acceleration by 17% in comparison to the maximum acceleration of the bare frame at point B. Moreover, increasing the wall's stiffness leads to a remarkable decrease in acceleration by 22% compared to the bare frame acceleration. It has been found that adding walls enlarged the foundation and the subgrade stiffness and increased the foundation stability during earthquake loads.

Also, the existence of the wall has a major role in the tuning of the foundation stresses, as presented in Figures 16 and 17 for bare and infilled frames. It has been found that using walls decreased the stresses from 161 kN/m^2 to 108 kN/m^2 with a reduction factor of 33%. Numerical results confirmed that the existence of walls contributed effectively to mitigating and reducing the effect of the horizontal loads during the earthquake which causes a reduction in the transmit stress to the beneath soil. As presented in Figure 18, the walls reduced the stresses along the path of the infilled frame foundation in comparison to the case of bare once. This tendency in stress improvement is due to the dynamic interconnection between both the frame elements and the walls; thus, walls increased the structure strength and contributed in the dissipation and distraction of seismic energy during the earthquake loading [1].

6.4 Effect of Walls on the Frame Response

Walls existence causes a significant decrease in the frame lateral displacement (orange circled points) as illustrated in Figure 19. Numerical results demonstrated that the existence of the wall decreased the displacement by 10% compared to the case of bare frame. Moreover, the numerical results confirmed that the walls adjusted the frame's horizontal acceleration. At the top monitoring node of the frame (point A), the maximum horizontal acceleration at the peak point (orange circled points) as presented in Figure 20 was significantly reduced by 16% in comparison to the case without walls. In addition, doubling the wall's stiffness has reduced the acceleration by 28%. As a main conclusion, it has been found that the horizontal displacement is inversely proportional to the wall's stiffness, thus because the existence of walls increases frame stiffness and improves both the flexure and shear demands of different frame elements [29]. Walls behave similarly to a diagonal strut and a bracing member to increase the frame strength and improve the initial elastic stiffness to behave as monolithic shear walls through the earthquake loads.

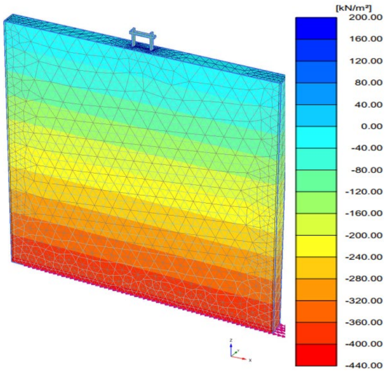


Figure 16. Shading of stresses in case of bare frame (maximum stresses = 161 kN/m^2)

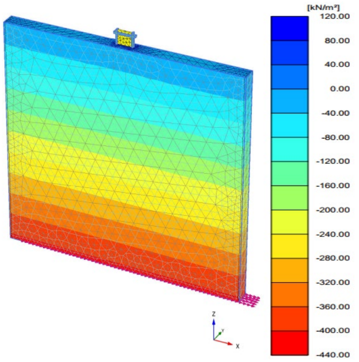


Figure 17. Shading of stresses in case of infilled frame (maximum stresses = 108 kN/m^2)

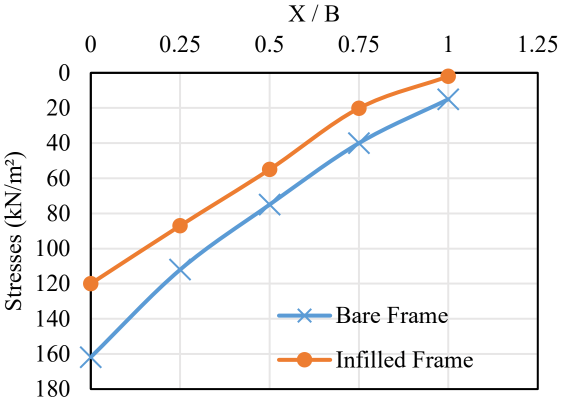


Figure 18. Variation of stresses of bare and infilled frame for different foundation distance

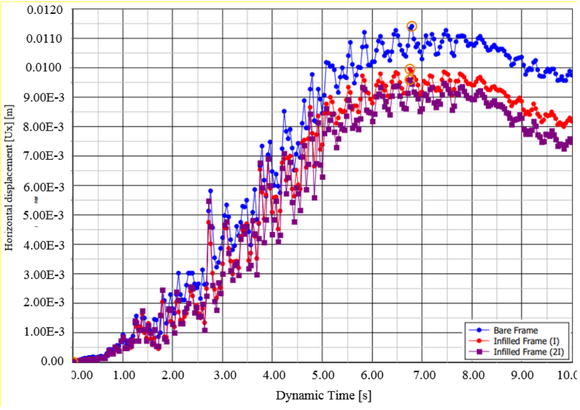


Figure 19. Relation between the horizontal displacement and earthquake dynamic time at the top of the frame (Point *A*)

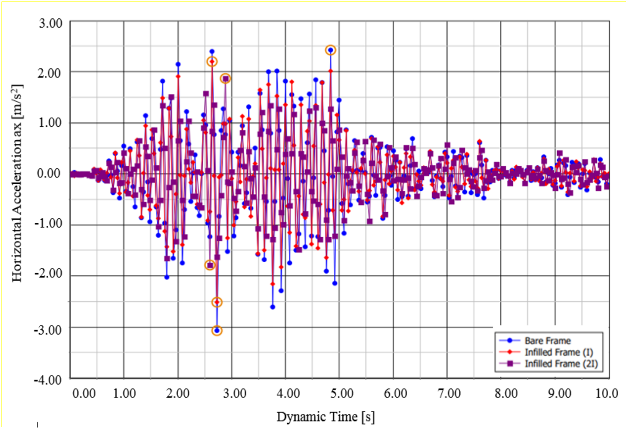


Figure 20. Decrease in the horizontal acceleration at the top of the bare / infilled frame (Point *A*)

7. CONCLUSION

Previous studies neglect the vital role of walls' existence to increase the lateral load resistance and consider the infilled frames as bare once. Therefore, this study investigates the advantages of existing walls to decrease the lateral displacement and increase the overall stability of the frames during earthquakes. These results are valid for a small scale one-bay single-story reinforced concrete frame of H/L is $1/1.5$ and rested over dense sandy soil of relative density of 85% and internal angle friction of 38°, with fully masonry walls and without walls. This was investigated numerically under the effect of seismic loads. According to numerical results, the following remarks were drawn from this study:

a) Walls existence decreased the infilled frame lateral displacement and increased the infilled frame lateral load resistance by nearly two times more than the bare frame.
b) Results show that adding walls leads to a reduction in the subsoil horizontal displacement by 15% from the initial value. Besides, increasing the wall's stiffness reduced the horizontal displacement by as much as 25% in comparison to the case of bare frame.
c) Walls existence reduced the soil horizontal acceleration and soil velocity by as much as 35% and 25% respectively, in comparison to the case of bare frame.
d) Soil shear strain was reduced by as much as 37% along the foundation subsoil.
e) Walls’ existence reduced the foundation's horizontal displacement and the vertical settlement by as much as 17% and 18.5% respectively from it is initial value. Also, increasing wall stiffness reduced the acceleration by about 22% compared to the case of bare frames which leads to more stability of foundation during earthquakes.
f) The stresses at the infilled frame foundation caused a 33% reduction compared with the corresponding values of the bare frame which walls increase the structure strength and contribute to dissipation and distraction of seismic energy during the earthquake loading.
g) Results showed that the existence of walls reduced the frame horizontal displacement and acceleration by as much as 10% and 16% respectively, thus because walls behave as a strut and increases the structure confinement and bracing during earthquakes.

FUNDING

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

DECLARATION OF CONFLICTING INTERESTS

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

REFERENCES

[1] M. N. M. Elsiragy, Effect of existing building walls on the geotechnical behavior of foundation under earthquake loading, *European Journal of Engineering and Technology Research*, 6(4), 2021, 100-104.
[2] M. A. Bouarroudj and Z. Boudaoud, Comparison between numerical modeling approaches of infilled frames under in-plane load, *Frontiers in Built Environment,* 7, 2022, 783051.
[3] A. B. Mehrabi, P. B. Shing, M. P. Schuller and J. L. Noland, Experimental evaluation of masonry-infilled RC frames, *Journal of Structural Engineering*, 122(3), 1996, 228-237.
[4] A. T. Akyildiz, A. K. Koczwara and L. Hojdys, Seismic protection of RC buildings by polymeric infill wall-frame interface, *Polymers,* 13(10), 2021, 1577.
[5] R. J. Mainstone, On the stiffness and strength of infilled frames, *Proceedings of the Institution of Civil Engineers,* 49(2), 1971, 57-90.
[6] A. Parducci and M. Mezzi, Repeated horizontal displacements of infilled frames having different stiffness and connecting systems-experimental analysis, *Proceedings of The Seventh World Conference on Earthquake Engineering,* Istanbul, 1980, 193-196
[7] T. Schmidt, Experiments on the nonlinear behaviour of masonry infilled reinforced concrete frames, *Annual Journal on Concrete and Concrete Structures*, 4, 1989, 185-194.
[8] M. N. Abdel-Mooty, S. Abdel-Gawad, H. H. Shaheen and M. E. Issa, Experimental evaluation of cyclic behavior of masonry infilled R.C frames with and without openings, *Journal of Engineering and Applied Science*, 46, 1999, 217-236.
[9] H. A. Moghaddam, Lateral load behavior of masonry infilled steel frames with repair and retrofit, *Journal of Structural Engineering,* 130(1), 2004, 56-63.
[10] C. G. Karayannis, D. J. Kakaletsis and M. J. Favvata, Behavior of bare and masonry infilled RC frames under cyclic loading, experiments and analysis. *WIT(Wessex Institute of Technology) Transactions on The Built Environment*, 81, 2005, 429-438
[11] Ö. Anil and S. Altin, An experimental study on reinforced concrete partially infilled frames, *Engineering Structures,* 29(3), 2007, 449-460.
[12] T. Essa, A. S. Ahmed, M. R. K. Badr and A. H. El-Zanaty, Effect of infill wall on the ductility and behavior of high strength reinforced concrete frames, *HBRC Journal, Housing and Building National Research Center,* 10(3), 2014, 258-264.
[13] A. Brodsky and E. Bentz, Failure of reinforced concrete infilled frames under extreme loads, *Symposium of Concrete Structures: New Trends for Eco-Efficiency and Performance*, Lisbon, 2021, 968-977.

[14] C. Zhang, T. Yu, Z. Chen, W. Huang, S. Zhang, Y. Zhou, D. Lu and Z. Lin., Seismic behavior of novel low-damage precast infill walls with sliding joints for reinforced concrete frame, *Earthquake Engineering & Structural Dynamics,* 51(15), 2022, 3730-3754.

[15] R. B. J. Brinkgreve, E. Engin and W. M. Swolfs, *PLAXIS 3D 2013 User Manual*, Plaxis bv Delft, 2013.

[16] P. Fazeli and S. Ghareh, A numerical study of bearing capacity coefficients of soil beneath foundation under earthquake load, *Electronic Journal of Geotechnical Engineering*, 17(A), 2012, 13-22.

[17] W. R. Azzam and A. Z. Elwakil, Performance of axially loaded-piled retaining wall: experimental and numerical analysis, *International Journal of Geomechanics,* 17(2), 2017, 04016049.

[18] W. R. Azzam, M. Ayeldeen and M. El Siragy, Improving the structural stability during earthquakes using in-filled trench with EPS geofoam-numerical study, *Arabian Journal of Geosciences,* 11, 2018, 395.

[19] K. E. El-Hoseiny, M. A. Tayel and A. B. Abdel Lateef, Influence of soil-structure interaction on seismic response of multi-storey buildings, *Engineering Research Journal*, 44(1), 2021, 33-41.

[20] M. H. Rayhani and M. H. El Naggar, Numerical modeling of seismic response of rigid foundation on soft soil, *International Journal of Geomechanics,* 8(6), 2008, 336-346.

[21] S. H. R. Tabatabaiefar, B. Fatahi and B. Samali, Seismic behavior of building frames considering dynamic soil-structure interaction, *International Journal of Geomechanics,* 13(4), 2013, 409-420.

[22] P. Anbazhagan, M. N. Sheikh and A. Parihar, Influence of rock depth on seismic site classification for shallow bedrock regions, *Natural Hazards Review,* 14(2), 2013, 108-121.

[23] C. D. Comartin, R. W. Niewiarowski, S. A. Freeman and F. M. Turner, Seismic evaluation and retrofit of concrete buildings: a practical overview of the ATC (The Applied Technology Council) 40 Document, *Earthquake Spectra,* 16(1), 2000, 241-261.

[24] J. F. Semblat, Modeling seismic wave propagation and amplification in 1D/2D/3D linear and nonlinear unbounded media, *International Journal of Geomechanics,* 11(6), 2011, 440-448.

[25] V. Galavi, A. Petalas and R. B. J. Brinkgreve, Finite element modelling of seismic liquefaction in soils, *Geotechnical Engineering Journal of the Southeast Asian Geotechnical Society (SEAGS) & Association of Geotechnical Societies in Southeast Asia (AGSSEA),* 44(3), 2013, 55-64.

[26] N. K. Lwti, D. A. Al-Hamdani, M. F. Abbas and B. S. Albusoda, Numerical studies of shallow footing subjected to earthquake loading, *American Institute of Physics Conference Series*, 2404(1), 2021, 080019.

[27] Y. M. Hashem, A. A. Mahmoud, M. Adam and A. S. Shanour, Behavior of reinforced concrete infilled frames under cyclic loading, *Ain Shams Journal of Civil Engineering*, 2, 2010, 169-182.

[28] D. Boldini, A. Franza, N. Losacco and S. Miraei, Tunnelling-induced displacements and damage on framed structures: comparison between numerical models, *Lecture Notes in Civil Engineering: Proceedings of the 16th International Conference of the International Association for Computer Methods and Advances in Geomechanics (IACMAG)*, 126, 2021, 148-155.

[29] A. Brodsky and X. Huang, Multi-platform modelling of masonry infilled frames, *Journal of Building Engineering,* 43, 2021, 102561.