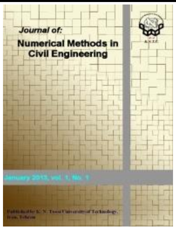
Numerical Methods in Civil Engineering, 8-1 (2023) 27-34



Numerical Methods in Civil Engineering

Journal Homepage: https://nmce.kntu.ac.ir/

Seismic Performance of Retrofitted Masonry Building Considering Soil-Foundation-Structure Interaction

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ARTICLE INFO

RESEARCH PAPER

Article history:
Received:
January 2023.
Revised:
June 2023.
Accepted:
July 2023.

Keywords:
Seismic performance;
Uunreinforced masonry building;
Squat shear wall;
Soil-structure interaction;
Nonlinear dynamic analysis

Abstract:

Around the world, many unreinforced masonry buildings have been constructed for different usages, such as schools. Studies have shown the seismic vulnerability of these buildings. Thus nonlinear analysis and seismic assessment of these buildings and improving the retrofitting methods are necessary. One of the retrofitting methods in these buildings is the use of shear walls. In most seismic rehabilitation projects of masonry buildings, piles are used in the foundations of shear walls, and the major retrofit project costs are the foundations and piles. In order to improve the accuracy of the seismic assessment of these buildings, this study investigates the effect of soil and structure interaction on the seismic behavior of these buildings. To reduce the cost of retrofitting shallow strip foundation for new shear walls were added including the effect of rocking, sliding, and settlement responses. It was shown that the interaction of soil and structure in the seismic behavior of masonry buildings retrofitted by squat concrete shear walls reduces the base shear and increases the maximum drift of the building. If this increase in the lateral drift of the building can be tolerated, it will reduce considerably the cost of retrofitting unreinforced masonry buildings.

1. Introduction

In most seismic rehabilitation projects, the buildings are modelled as the fixed base, and the reactions of this fixed base model are used to design foundation elements. Large reactions in the pier of fixed base shear walls usually lead to the use of piles as foundations. This is often costly and time-consuming. The effect of soil and structure interaction improves the accuracy of seismic analysis of structures. A very useful mechanism for dissipating energy is provided when a shallow foundation undergoes inelastic sliding, settling, and rocking movements under earthquake loading. This results in a reduction of the force demand of the building [1].

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https://doi.org/10.61186/NMCE.2022.161

Many researchers studied the analytical treatment of the soil-structure interaction, such as Pak and Saphores 1991[2] studied the rocking rotation of a rigid disc in a half-space. Pak and Saphores 1992 [3] studied the Lateral translation of a rigid disc in a semi-infinite solid. Eskandari et al. 2013[4] studied the Lateral translation of an inextensible circular membrane embedded in a transversely isotropic half-space. Ahmadi and Eskandari 2013[5] studied the vibration analysis of a rigid circular disk embedded in a transversely isotropic solid. Ahmadi and Eskandari 2014[6] studied the rocking rotation of a rigid disk embedded in a transversely isotropic half-space. Ahmadi et al. 2018[7] discussed the rocking vibration and lateral translation of a rigid disk embedded in any depth of a coupled seawater-visco-poro-elastic seabed. Different researchers worked on practical modelling of the soil-structure interaction. Harden et al. 2005[8] calibrated the model parameters for the Beam-on-nonlinear-winkler-foundation (BNWF) model. This model was subsequently updated by Raychowdhury and Hutchinson 2009[9] and later by Gajan et al. 2010[10].

Balkaya and Yuksel 2012[11] studied the soil-structure interaction effects on the fundamental periods of the shear-wall dominant buildings. Marzban et al. 2014[12] studied the seismic performance of reinforced concrete shear wall frames considering soil foundation-structure interaction.
In this study, in order to improve the retrofitting methods of a masonry building, the interaction of soil-foundation-structure was considered for squat concrete shear walls. In most of the previous studies, the soil-structure interaction was considered on only the shear walls, and the effect of the main building has been omitted. This study considered the interaction of masonry buildings and squat concrete shear walls by considering the effect of soil-foundation-structure interaction. For squat concrete shear walls, the shallow strip foundation was considered and the seismic behavior of the retrofitted masonry building was investigated, including the effect of rocking, sliding, and settlement responses. The results show a significant reduction in the force demand of the retrofitted masonry building.

2. Methodology

A statistical study was conducted for Iranian masonry schools, and based on a major survey of Iranian masonry schools, a common type of masonry building has been chosen as a representative of this building. The performance-based analysis procedures on FEMA 356 were used to model the masonry building. To retrofit the masonry building, squat concrete shear walls were added to the model in two directions. For squat concrete shear walls, a shallow strip foundation with rocking, sliding, and settlement responses were considered. The concept of "Beam-on-Nonlinear-Winkler-Foundation (BNWF)" was used for the soil-foundation-structure interaction model. The static and dynamic nonlinear analyses were used to evaluate the seismic response of the building.

3. Finite Element Modelling

FEMA 356 [13] includes the performance-based analysis procedures for unreinforced masonry buildings; In study, this method is used to model the masonry building. According to this guideline, force-deformation relations for masonry walls shall be determined based on the experimental records or the generalized force-deformation relation as shown in Figure 1. In this study, Opensees software [14] was used for finite element modelling. The masonry walls were modelled by compression diagonal members as shown in Figure 2. Truss element was used to model these diagonal members, and an axial force-deformation relationship was defined for the truss section. For each masonry wall, the behavior curve was defined, such as the generalized force-deformation relationship, presented in the FEMA 356 [13], as shown in Figure 1.

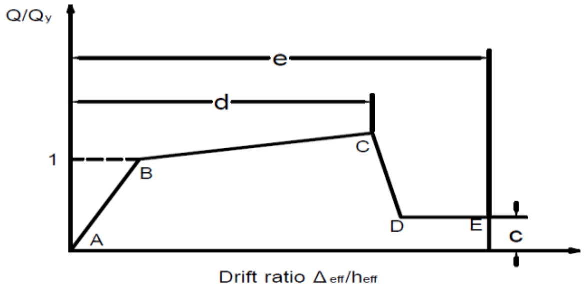


Fig. 1: Generalized force-deformation relation [13].

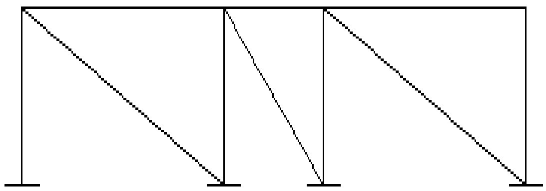


Fig. 2: Modelling of masonry walls as compression diagonal members.

The masonry building was retrofitted by four squat concrete shear walls, two walls in the east-west direction, and two walls in the north-south direction. The investigated masonry buildings are low-rise buildings and shear walls used to retrofit them are squat shear walls. For modelling squat shear walls, "Displacement_Based Beam-Column Element" and "Flexure_Shear Interaction Displacement_Based Beam-Column Element" were used. To verify the capability of modelling squat shear walls in the Opensees software [14], Kuang and Ho experiment [15] and vector2 finite element software [16] were used. The comparison results show that the "flexure-shear interaction displacement-based beam-column element" simulates the characteristics of the cyclic wall responses. However, the element model formulation has been implemented and verified for monotonic static analysis in the 2D plane, and 3D analysis is not possible with this element [14]. In this study, for 3D nonlinear dynamic analysis, "Displacement_Based Beam-Column Element" was used; this element has been identified for 3D static and dynamic analysis. This element also provides a reasonably accurate response for the squat concrete shear walls.

In order to consider soil-foundation-structure interaction, this study applied chapter 4 from FEMA 356 [13]. This guideline recommends several methods for soil-structure interaction modelling. This study was used the "Beam-on-Nonlinear-Winkler-Foundation (BNWF)" concept. If shallow foundations are flexible to the supporting soil, this method shall be used. This approach uses beam and shell elements for foundation modelling and Winkler vertical and horizontal springs for modelling soil that is concentrated at nodes of the foundation elements. The effect of moment-rotation behavior was captured via the distribution of vertical springs placed along the footing length. The distribution of these springs is uniform in flexible foundations, although in rigid foundations, the stiffer springs are placed at the two ends [13].

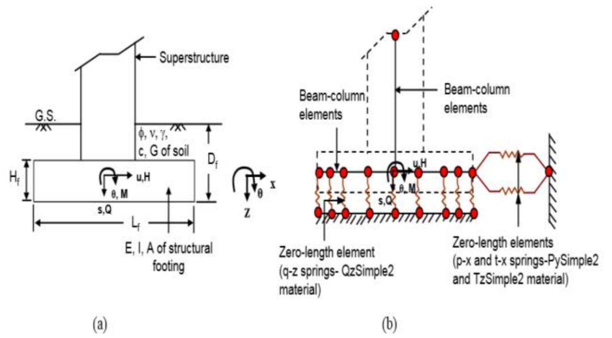


Fig. 3: Schematic represents diagram (a) superstructure-foundation system and (b) BNWF showing springs with their orientations [1].

Figure 4(a) shows mechanical springs for the non-linear behavior of the soil, a gap component (a drag and a closure spring in parallel) captures the uplift foundation behavior. Radiation damping can be captured by using a dashpot. Figure 4(b) shows the compression response for soil material. This material includes a reduced strength in tension to account for the weak soil tensile strength [1].

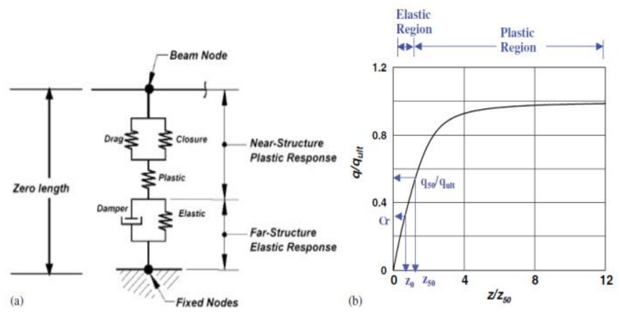


Fig. 4: (a) Conceptual construction of the mechanistic springs (b) compression response for the soil material model [17].

In this study, beam elements with inelastic behavior was used for modelling the foundation and Winkler springs which are lumped as vertical and horizontal springs at nodes of the foundation elements to model the soil. These springs are independent of each other and are considered as one-dimensional zeroLength elements in the OpenSees software [14]. For each spring, the non-linear behavior of the soil was defind, in Opensees Software by QzSimple2, PySimple2 and TzSimple2 material properties [18]. These material properties are shown in Figure 3(b). QzSimple2 was applied for vertical springs, while TzSimple2 and PySimple2 were used for horizontal springs. The constitutive material model of TzSimple2 was used for the consideration of sliding behavior and PySimple2 was used for the passive pressure of the embedded foundation.

In this study, the dimensions of strip foundations were considered as 8 m in length, 1 m in width and 0.7 m in height (Figure 5.). A control on rigidity or flexibility of strip foundations showed that the foundations of this building were flexible, so uniform distribution of the vertical springs was used. The vertical springs were lumped at a distance of 0.5 m from each other. The horizontal springs were modelled in both the x and z directions. At the short dimension of each foundation, a horizontal spring was considered at a point. However, at the long dimension of the foundation, horizontal springs were distributed at a distance of 0.5 m, similar to the vertical springs. Two horizontal springs were modelled at each node to show the passive pressure and shear strength of the soil. The assumed properties of the soil are shown in Table 1. In this study, clay was considered as the soil type. The ultimate bearing capacity of the vertical and horizontal springs and the stiffness of the springs are shown in Table 2. Radiation damping was assumed to be 5% for the dashpot on the far-field elastic component.

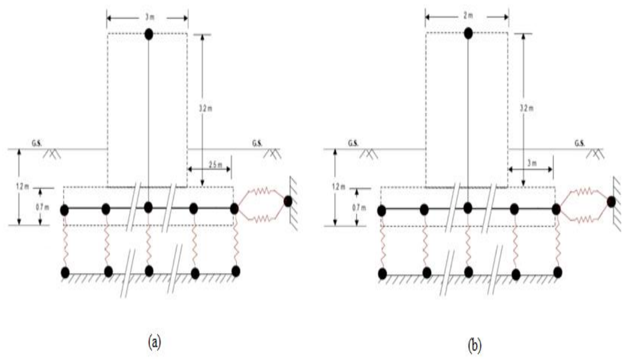


Fig. 5: Schematic diagram of superstructure-foundation system a) z direction, b) x direction.

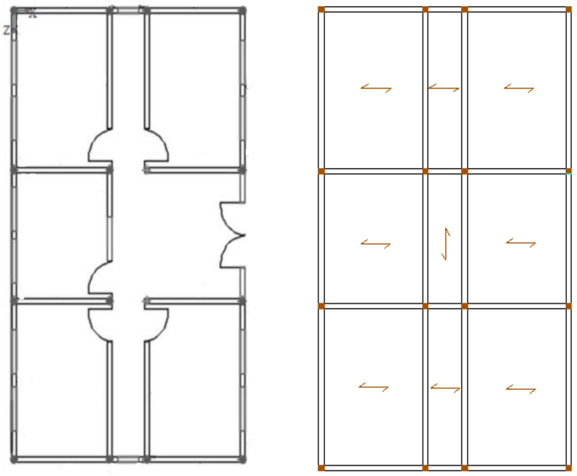
Table 1: Assumed soil properties.

γ (kN/m³)	G (Mpa)	ν	C (kPa)	ϕ°
16	20	0.4	100	0

Table 2: Ultimate bearing capacity and stiffness of vertical and horizontal springs

Q_{ult} (kPa)	p_{ult} (kN)	t_{ult} (kN)	K_x (N/m)	K_y (N/m)	K_v (N/m)
744	2012	800	179×10^6	214×10^6	272×10^6

The plan of an unreinforced masonry building as a representative building base on the most commonly built school in Iran shows in Figure 6. The building is one story, and its masonry walls have 30 cm thickness.



(a) (b)

Fig.6: Building plan and its roof beam direction

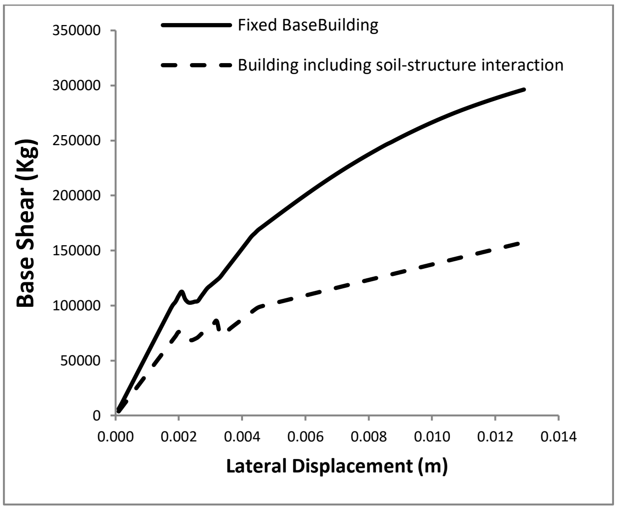


Fig. 7: Global force-deformation curve from nonlinear static analysis in the z direction.

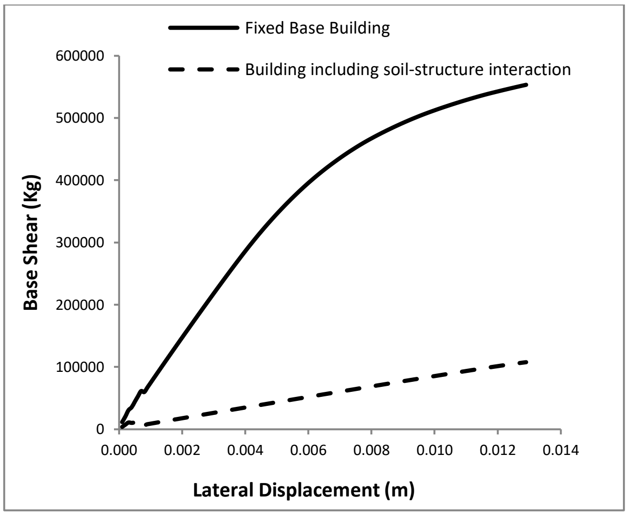


Fig. 8: Global force-deformation curve from nonlinear static analysis in the x direction.

4. Discussion of Results

4.1 Period of buildings

The building was modelled in different foundation conditions, fixed base, and flexible base (including soil and structure interaction). The interaction of soil and structure influences the period of building. A comparison was made on the period of building models. The period of building increases from 0.15 in the fixed base model building to 0.20 in the model including soil-structure interaction. This increase in this representative example building was 40% compared to fixed base model (Table 3).

Table 3: Comparison of structure periods

Model of Structure	T1	T2	T3
Model including soil-structure interaction	0.2	0.2	0.15
Fixed Base Model	0.15	0.09	0.07

4.2 Nonlinear Static Analysis

The global force-deformation curves of the building for the different base conditions were compared in x and z directions, which are shown in Figures 7 and 8.

Results of nonlinear static analysis show that, the application of soil and structure interaction reduces the amount of base shear. In the flexible base conditions, the system becomes softer, and the base shear reduces. A sudden reduction occurred in the first part of the curves. These reductions demonstrate the that the lateral strength of the existing masonry walls in the building is lost.

4.3 Nonlinear Dynamic Analysis

The span ratios of shear walls are less than 2.0, thus the drift response of the building was considered as comparison criteria. In this section, the building models were analyzed subjected to eight accelerograms of Table 4. The accelerograms were selected based on a study [19] to reduce the scattering of dynamic analysis responses.

Figures 9 and 10 show the time history drift response of buildings for the z direction. The maximum drift of buildings and the mean maximum response for eight earthquake ground motions are shown in Table 5 for the z direction.

Table 4: Property of accelerograms [19].

Event	Label	Year	Station	M	PGA Processed (g)	Distance (Km)
Bandar-e-Abas3	Bandar-e-Abas3*-C3	1975	Bandar-e-Abas3*	6.1	0.13	36
Golbaft	Qazvin*-C3	1981	Qazvin*	7.4	0.27	94
Avaj	Razan-C3	2002	Razan	6.5	0.20	35
BINGOL	Np200305010027 08_1201 N-S	2003	BAYINDIRLIK VE SKAN MUDURLUGU Beverly Hills	6.3	0.50	12
Northridge	Canyon Country-WLost cany-N90W	1994	Canyon Country-WLostcany	6.7	0.48	27
Friuli	Friuli,Italy-Tolmezzo-NSX	1976	Tolmezzo	6.5	0.34	20
Chi-Chi	Chi-Chi-CHY101-E	1999	Chi-Chi-CHY101	7.6	0.40	32
Chi-Chi	Chi-Chi-TCU045-E	1999	Chi-Chi-TCU045	7.6	0.47	76

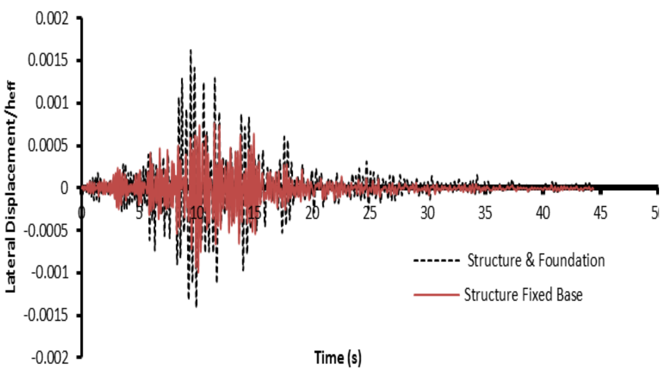


Fig. 9: Comparison of time history drift response during Bandar-e-Abas3*-C3 earthquake.

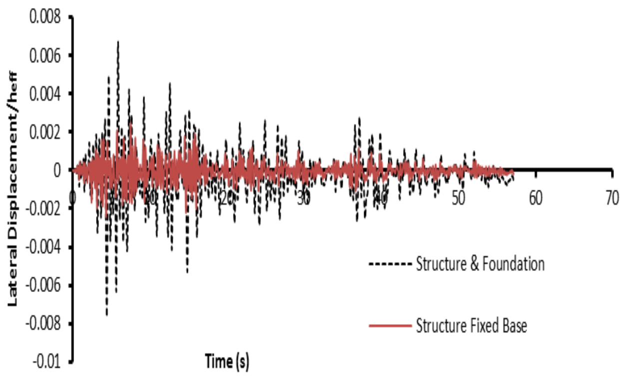


Fig. 10: Comparison of time history drift response during Qazvin*-C3 earthquake.

A Comparison of the mean maximum drift of buildings during eight earthquake ground motion records shows that the soil and structure interaction causes a 200% increase in the maximum drift of the building. In order to have more discussion on the drift response with and without soil-structure interaction effect, this response compares all ground motions:

- For Bandar-e-Abas3*-C3 ground motion, the maximum drift of building increases by 38% in the model, including soil-structure interaction, compared to the fixed base model.
- For Qazvin*-C3 ground motion, the maximum drift of building increases by 68% in the model, including soil-structure interaction, compared to the fixed base model.
- For Razan-C3 ground motion, the maximum drift of building increases by 41% in the model, including soil-structure interaction, compared to the fixed base model.
- For Np20030501002708_1201N-S ground motion, the maximum drift of building increases by 49% in the model, including soil-structure interaction, compared to the fixed base model.
- For Canyon Country-WLost cany-N90W ground motion, the maximum drift of building increases by 35% in the model, including soil-structure interaction, compared to the fixed base model.
- For Friuli,Italy-Tolmezzo-NSX ground motion, the maximum drift of building increases by 24% in the model, including soil-structure interaction, compared to the fixed base model.
- For Chi-Chi-CHY101-E ground motion, the maximum drift of building increases by 51% in the model, including soil-structure interaction, compared to the fixed base model.
- For Chi-Chi-TCU045-E ground motion the maximum drift of building increases by 61% in the model, including soil-structure interaction, compared to the fixed base model.
- In most ground motions, the time of maximum drift in the fixed base model was delayed compared to the case of the model with soil-structure interaction.

Table 5: The maximum drift of buildings and mean maximum response for eight earthquake ground motions for the z direction

	Event	Fixed Base Building	Building including soil-structure interaction
Max(Lateral Displacement	Bandar-e-Abas3*-C3	0.001	0.0016
	Qazvin*-C3	0.0025	0.0077
	Razan-C3	0.002	0.0034
	Np20030501002708_1201N-S	0.0043	0.0084

	Canyon Country-Wlost cany-N90W	0.0064	0.0099
	Friuli,Italy-Tolmezzo-NSX	0.0037	0.0049
	Chi-Chi-CHY101-E	0.002	0.0041
	Chi-Chi-TCU045-E	0.0054	0.0137
Mean(Lateral Displacement/h_{eff})		0.0034	0.0067

Figures 11 and 12 show the time history drift response of buildings for the x direction. The maximum drift of buildings and the mean maximum response for eight earthquake ground motions are shown in Table 6 for the x direction.

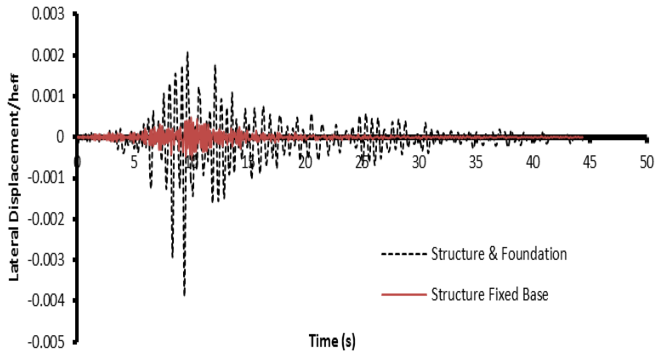


Fig. 11: Comparison of time history drift response during the Bandar-e-Abas3*-C3 earthquake.

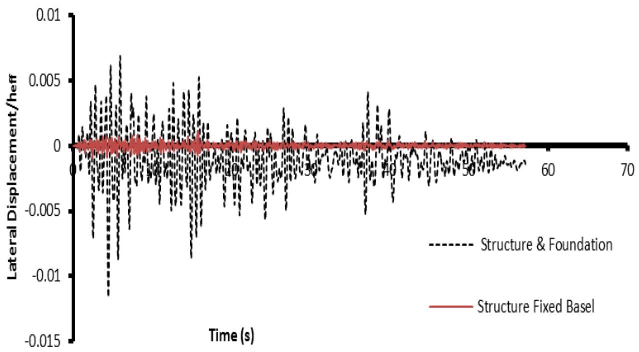


Fig. 12: Comparison of time history drift response during the Qazvin*-C3 earthquake.

Table 6: Maximum drift of buildings and mean maximum response for eight earthquake ground motions for x direction

	Event	Fixed Base Building	Building including soil-structure interaction
Max(Lateral	Bandar-e-Abas3*-C3	0.0006	0.0039
	Qazvin*-C3	0.0011	0.0116
	Razan-C3	0.0012	0.005

	Np20030501002708_1201N-S	0.0033	0.0132
	Canyon Country-Wlost cany-N90W	0.0022	0.0201
	Friuli,Italy-Tolmezzo-NSX	0.0012	0.0072
	Chi-Chi-CHY101-E	0.0015	0.0098
	Chi-Chi-TCU045-E	0.0015	0.0165
Mean(Lateral Displacement/h_{eff})		0.00157	0.0109

A Comparison of the mean maximum drift of buildings during eight earthquake ground motion records shows that the soil and structure interaction causes a 700% increase in the maximum drift of the building. In order to have more discussion on the drift response with and without soil-structure interaction effect, this response is compared to all ground motions:

- For Bandar-e-Abas3*-C3 ground motion, the maximum drift of building increases by 85% in the model, including soil-structure interaction, compared to the fixed base model.
- For Qazvin*-C3 ground motion, the maximum drift of building increases 91% in the model, including soil-structure interaction, compared to the fixed base model.
- For Razan-C3 ground motion, the maximum drift of building increases by 76% in the model, including soil-structure interaction, compared to the fixed base model.
- For Np20030501002708_1201N-S ground motion, the maximum drift of building increases by 75% in the model, including soil-structure interaction, compared to the fixed base model.
- For Canyon Country-WLost cany-N90W ground motion, the maximum drift of building increases by 89% in the model, including soil-structure interaction, compared to the fixed base model.
- For Friuli, Italy-Tolmezzo-NSX ground motion, the maximum drift of building increases by 83% in the model, including soil-structure interaction, compared to the fixed base model.
- For Chi-Chi-CHY101-E ground motion, the maximum drift of building increases by 85% in the model, including soil-structure interaction, compared to the fixed base model.
- For Chi-Chi-TCU045-E ground motion maximum drift of building increases by 91% in the model, including soil-structure interaction, compared to the fixed base model.
- In most ground motions, the time of maximum drift in the fixed base model was delayed compared to the case of a model with soil-structure interaction.

According to the roof beam direction (Figure 6 (b)), and governing mode of masonry walls, masonry walls in the z direction are more effective than masonry walls in the x direction in the lateral resistance of masonry building. Due to require shear wall dimensions for retrofitting of masonry building in each direction, the difference effect of soil-foundation-structure interaction was showen in two directions. In the direction, masonry walls are more effective, the effect of soil-foundation-structure interaction are low, however in the direction where the effect of masonry walls is low, the effect of soil- foundation-structure interaction is high.

5. Conclusions

In this research, the effect of soil-foundation-structure interaction on the seismic behavior of masonry buildings retrofitted by the squat concrete shear walls was investigated. Some of the important findings of this study are as follows:

1) The period of building increases from 0.15 in fixed base case to 0.20 in flexible base condition. This study shows that by taking into account the interaction between the soil and the structure, the construction period has increased, for the representative example building of this study, the period of building increased by 40% compared to the fixed base building. Therefore, to capture the dynamic behavior reasonably, it is important to model the base condition appropriately.

2) Global force-deformation curves of buildings in nonlinear static analysis show that soil-structure interaction reduces the base shear. In the time history analysis, the same trend was also observed.

3) The maximum drift of the building increases by considering soil-foundation-structure interaction. The lateral drift of the building increases by 700% in the direction that the effect of masonry walls is low, although in the direction that the effect of masonry walls is high, this response increases by 200%.

4) Based on time history analysis, it is observed that for all ground motions, base shear is lower for the case with soil-foundation-structure interaction. For the drift ratio, the opposite trend occurred. Drift ratio is higher for all ground motions in the state of soil-foundation-structure interaction compared to the fixed base state.

5) In most ground motions, the time of maximum drift in the fixed base model was delayed compared to the case of the model with the soil-structure effect.

6) This study proposed retrofitting masonry school by shallow strip foundations for concrete shear walls, allowing rocking, sliding, and settling motion to the building, will increase the lateral drift of the building within an acceptable range.

References

[1] Raychowdhury P., "Nonlinear Winkler-based Shallow Foundation Model for Performance Assessment of Seismically Loaded Structures", Ph.D. Thesis, University of California, San Diego, 2008.

[2] Pak R.Y.S., Saphores J.D., "Rocking rotation of a rigid disc in a half-space", International Journal of Solids and Structures, Vol. 28, 1991, p.389-401.

[3] Pak R.Y.S., Saphores J.D., "Lateral translation of a rigid disc in a semi-infinite solid", Quarterly journal of mechanics and applied mathematics, Vol. 45, 1992, p.435-449.

[4] Eskandari M., Shodja H.M., Ahmadi S.F., "Lateral translation of an inextensible circular membrane embedded in a transversely isotropic half-space", European Journal of Mechanics-A/Solids, Vol. 39, 2013, p.134-143.

[5] Ahmadi S.F., Eskandari M., "Vibration analysis of a rigid circular disk embedded in a transversely isotropic solid", Journal of Engineering Mechanics, Vol. 140, 2013, p.04014048.

[6] Ahmadi S.F. , Eskandari M., 'Rocking Rotation of a Rigid Disk Embedded in a Transversely Isotropic Half-Space", Civil Engineering Infrastructures Journal, Vol. 47, 2014, p.125-138.

[7] Ahmadi S.F., Samea P., Eskandari M., "Discussion of Rocking vibration of a rigid disk embedded in any depth of a coupled seawater-visco-poro-elastic seabed half-space by R. He [Soil Dyn. Earthq. Eng. 85(2016), 130–133]", Soil Dynamics and Earthquake Engineering, Vol. 104, 2018, 449-450.

[8] Harden C.W., Hutchinson T., Martin G.R., Kutter B.L. Numerical Modeling of the Nonlinear Cyclic Response of Shallow Foundations. Pacific Earthquake Engineering Research center, University of California, Berkeley, Report No.PEER-2005/04, 2005.

[9] Harden C.W. ,Hutchinson T.C., "Beam-on-nonlinear-Winkler-foundation modeling of shallow rocking-dominated footings", Earthquake Spectra, Vol. 25, 2009, p. 277-300.

[10] Gajan S., Raychowdhury P., Hutchinson T.C., Kutter B.L., Stewart, J.P. Application and validation of practical tools for nonlinear soil-foundation interaction analysis. Earthquake Spectra, Vol. 26, Issue 1, 2010, p. 111-129.

[11] Balkaya C., Yuksel S.B., " Soil-structure interaction effects on the fundamental periods of the shear-wall dominant buildings", The Structural Design of Tall and Special Buildings, Vol. 21, 2012, p. 416–430.

[12] Marzban S., Banazadeh M., Azarbakht A., "Seismic performance of reinforced concrete shear wall frames considering soil foundation-structure interaction", The Structural Design of Tall and Special Buildings, Vol. 23, 2014, p.302-318.

[13] FEMA 356. Prestandard And Commentary For The Seismic Rehabilitation Of Buildings, Federal Emergency Management Agency, American Society of Civil Engineers, Reston, Virginia, 2000.

[14] Mazzoni S. OpenSees Command Language Manual (Version 2.4.0), Location: Pacific Earthquake Engineering

Research Center, University of California, Berkeley,2006, http://opensees.berkeley.edu/

[15] Kuang J. S., Ho Y. B., "Seismic behavior and ductility of squat reinforced concrete shear walls with non-seismic detailing", ACI Structural Journal, Vol. 105, 2008, p. 225-231.

[16] Vecchio, F.J., Wong, P.S. Vector2 & Frameworks user's manual, 2002,
http://www.civ.utoronto.ca/vector/software.html

[17] Raychowdhury P., Hutchinson T. C., "Performance Evaluation of a Nonlinear Winkler-based Shallow Foundation Model using Centrifuge Test Results", Earthquake Engineering and Structural Dynamics, Vol. 38, 2009, p. 679-698.

[18] Raychowdhury P., Hutchinson T. C., "Nonlinear Material Models for Winkler-based Shallow Foundation Response Evaluation", ASCE Geotechnical Special Publication, No. 181, 2008, p. 686-693.

[19] Ghafory Ashtiany M., Hatefi Ardekani H., "M6.5 Strong Ground Motion Data Base Scenario", Proceeding of IASPEI-IUGG, Melbourne, Australia, June, 2011.

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