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An Investigation on the Effect of Infill Walls on the Fundamental Period of Moment-Resisting Steel Frames with Consideration of Soil-Structure Interaction

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ABSTRACT

One of the most critical parameters in process of analysis and design of structures is determination of the fundamental period of vibration. The fundamental period depends on the distribution of the mass and stiffness of the structure. Therefore, the building codes propose some empirical equations based on the observed period of real buildings during an earthquake as well as ambient vibration tests. These equations are usually a function of type and height of the buildings. Differences in the fundamental period of buildings determined by the code equation and analytical methods are due to elimination of the effects of non-structural elements in the analytical methods. For this reason, the presence of non-structural elements such as infill panels, which may produce a variation in these properties, should be carefully considered. Another effective parameter on the fundamental period is the influence of Soil-Structure Interaction (SSI). It is obvious that soil flexibility increases the fundamental period of the structure. The current research deals with the effect of infill panels on the fundamental period of moment resisting frames considering the influence of soil-structure interaction (SSI). For this purpose, 3, 6, 9, 12, 15 and 18 stores 2-D frames were investigated with different configuration of infill panel in the plan and also various percentage of infill openings. The studied frames were modelled and analyzed in Seismo Struct software. The calculated values of the fundamental period are compared with those of obtained from proposed equation in the seismic code. From the analysis of the results it has been found that the number of stores, the infill opening percentage, the stiffness of the infill panels and the soil type are crucial parameters that influence the fundamental period of steel building frames.

Keywords:

Fundamental period, Infill wall, Moment-resisting steel, Soil-structure interaction.

1. Introduction

One of the most important parameters in the seismic design of a building is its fundamental period of vibration, which controls the seismic demand on the building and subsequently its structural elements sizes. The fundamental period of a building depends on the lateral stiffness and seismic mass and it cannot be precisely calculated for a building yet to be designed. In reality, it is very difficult to predict the actual period of vibration of a building under real earthquake shaking because of many uncertain parameters (i.e. non-structural elements, seismic mass of a building during earthquakes, soil condition, etc.). Therefore, it is common practice to use approximate empirical, analytical and experimental methods to estimate the fundamental period for the design of a new building or an existing building. Some studies in the literature focus on the determination of fundamental period of structures which will be described in the next section.

2. A review on Building Codes and Fundamental Period

The fundamental period of a structure depends on distribution of the mass and the stiffness along the height of the building. Building codes provide simplified empirical relations to estimate the fundamental period of buildings. Being often based on observations of real response of buildings to earthquake, such relations usually depend on both frame type and building height. In reality, additional structural stiffness imposed by such infill walls results in reduced fundamental period. Accordingly, building codes usually set an upper limit for the fundamental period values obtained from finite element models and eigenvalues methods so that the period values calculated from numerical methods may not exceed the period value obtained from empirical relations multiplied by a certain coefficient which is not identically set by different building codes. In UBC97 [1] , for example, the coefficients are set to 1.3 and 1.4 for seismic and non-seismic areas, respectively (UBC-97). The corresponding coefficient to the upper limit on the calculated period in the ASCE-2010 depends on design the spectral response acceleration parameter and varies within 1.4–1.7. Eurocode8, however, has not provided such an upper limit. Such limitation is intended to prevent the use of unreasonable values obtained from numerical methods wherein non-structural elements are not taken into account. Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800, 4th edition) [2] not only limits the fundamental period value obtained using the numerical method to a maximum of 1.25 times as much as the period obtained by the empirical formula (T = 0.08H0.75) but also requires that in cases where infill walls cause any hindrance to the frame movement, empirical fundamental period be further multiplied at a coefficient of 0.8 (T = 0.064H0.75). Table 1 lists some of the relations provided in National Building Code of Canada (NBC) [3] and other codes for estimating fundamental period of moment-resisting steel structures. The relation provided by Iranian Standard No. 2800 is similar to those provided by UBC97 and Eurocode8 [5]. This relation has been updated in FEMA450 [4], based on the works of Goel and Chopra [6]. These relations are derived from studies on behaviors exhibited by buildings in different earthquakes. Chopra and Goel [7] carried out the regression analysis of measured data to develop formulas to estimate fundamental periods of the buildings. Hong and Hwang [8] experimentally determined the fundamental time period of 21 reinforced concrete moment resisting frame buildings, located in Taiwan through vibration measuring instruments. Based on the experimental results, an empirical relationship between building period and height was derived. Paolo et al. [9] carried out modal analyses on 3D numerical RC MRF building models, varying structure morphology (height, surface area and ratio between plan dimensions) and infill characteristics. Simplified formulas based on regression analysis of obtained numerical data were presented and discussed. Elgohary [10] carried out a parametric study using finite element analysis to study the effect of the major parameters influencing in the fundamental period. He concluded that the code's formulae, in most cases, underestimate the fundamental period with a large deviation from finite element results. This large deviation is a result of considering only the effect of frame height and neglecting of remaining major parameters in the codes formulae. Asteris et al. [11] investigated the fundamental period of vibration of reinforced concrete buildings by means of finite element macro-modelling and modal eigenvalue analysis. They studied various parameters including the number of spans, the span length in the direction of motion, the stiffness of the in fills, the percentage openings of the infills, the location of the soft stores and the soil type. Asteris et al. [12-15] proposed an empirical expression that takes into account the number of stores, the number of spans, the span length, the infill wall panel stiffness and the percentage of openings within the infill panel. More than 700 analyses were performed and from regression analysis an equation was proposed. This equation was shown to fit better the data than others available in the literature, having a high correlation factor R2 and a low Mean Square Error and can adequately estimate the fundamental period of masonry infilled RC buildings. Varadharajan et al. proposed an equation, based on the results of time history analysis of 305 different building frames, for the estimation of the fundamental period of buildings with setback irregularity [15].

Table 1. Experimental formula provided in different building codes for estimating fundamental period of moment resisting steel frames.

Code	T (s)	Description
Iranian St. No. 2800 (without infill)	$0.08H^{0.75}$	H is expressed in meter
Iranian St. No. 2800 (with infill)	$0.064H^{0.75}$	H is expressed in meter
UBC97 Code	$0.0853H^{0.75}$	H is expressed in meter
FEMA450	$0.0724H^{0.8}$	H is expressed in meter
Eurocode8	$0.085H^{0.75}$	H is expressed in meter
NBC	0.1N	N denotes number of stories

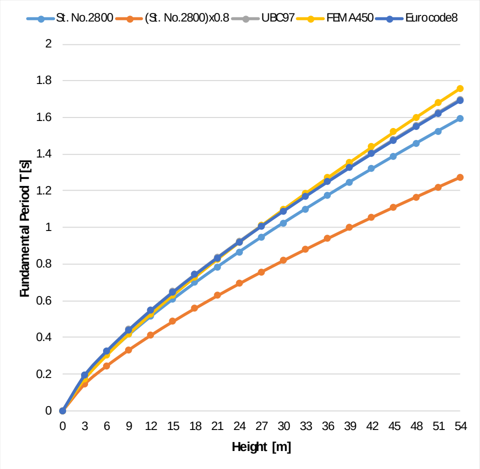

Figure 1. Results of comparison of code expressions for the estimation of fundamental period of steel frame structures.

3. Description of the Structures

The current research deals with the effect of infill panels on the fundamental period of moment resisting and eccentrically braced frames considering the influence of soil-structure interaction (SSI). For this purpose, 3, 6, 9, 12, 15 and 18 storeys 2-D frames were investigated with different configuration of infill panel in the plan and also various percentage of infill openings. The storey height for all buildings is kept constant and equal to 3.0 m. The number of spans varied 3. Both bare frame structures as well as structures with fully or partially unreinforced masonry infilled frames with or without openings are analysed, in order to examine the influence of infill walls. Various parameters are considered for each case. Infill panels are either 50, 70, 100, 150 or 200 mm thick. The influence of infill wall openings is also examined. Infill wall openings are given as a percentage of the panel area. Six different cases for infill wall openings are studied. These are: fully infilled walls (0% openings), infill walls with small and large openings (20%, 40%, 60% and 80% openings) and bare frames (100% openings). The building parameters used for the development of the model are listed in Table 2. Three-dimensional finite element models of the structure were prepared using ETABS software (ETABS ver. 16.0.3-2016). All the frames were of steel moment-resisting type considered as symmetric squares of equal spans along both directions in the plan. Moreover, a fixed connection type was used at the column base. The steel yield was assumed to be 240 MPa. The floors were also considered to be of rigid type with their slabs presumed in the modelling. The corresponding dead load to external infill walls was considered as a linear load, while those of other partition walls, namely, internal infill walls, and floor finishing were accounted as distributed loads. The frames were designed according to AISC 360-10, including the use of the Direct Analysis Method in LRFD provision.

Table 2. Building parameters.

Steel yield strength	240 MPa
Number of floors	3, 6, 9, 12, 15, 18
Building height	9.0 m, 18 m, 27 m, 36 m, 45 m, 54 m
Number of span	3
Span length	5.0 m
Size of columns	400×400×24, 240×240×25(corners)
Size of beams	IPE300, IPE360, IPE450
Storeys dead loads	5.5 kN/m^2
Storeys live loads	2 kN/m^2 + 1 kN/m^2
Roof dead loads	6 kN/m^2
Roof live loads	1.5 kN/m^2
Slab thickness	150 mm
Modulus of elasticity of masonry, E_m	0.5GPa, 0.7GPa, 1GPa, 1.5GPa, 2GPa, 2.5GPa, 3GPa, 4GPa, 6GPa, 8GPa, 10GPa
Thickness of infill panel, t_w	50 mm, 70 mm, 100 mm, 150 mm, 200 mm
Infill wall opening percentage	0% (fully infilled), 20%, 40%, 60%, 80%, 100% (bare frame)

4. Modelling of Infill Walls

For interaction between masonry infill walls and building frames, all buildings were modelled as plane frames using SeismoStruct (Seismosoft 2018) [16]. The equivalent diagonal compression strut method has become the most popular approach for analysing infilled frame systems. A bracing action, affecting both the strength and stiffness, originates by this mechanism, as demonstrated by a large number of experimental investigations. From the comparison of experimental and numerical results, it was shown that the double-strut model proposed by Crisafulli (1997) [17] provided a very good fit to the experimental results, while the single-strut model could not adequately represent the experimental behaviour. In this study, masonry is modelled using an equivalent strut nonlinear cyclic model proposed by Crisafulli (1997) for the modelling of the nonlinear response of infill panels in moment-resisting steel frames from 3 to 18 stories. Each panel is represented by six strut members. Each diagonal direction features two parallel struts to carry axial loads across two opposite diagonal corners and a third one to carry the shear from the top to the bottom of the panel (Figure 2). The struts act only across the diagonal that is on compression.

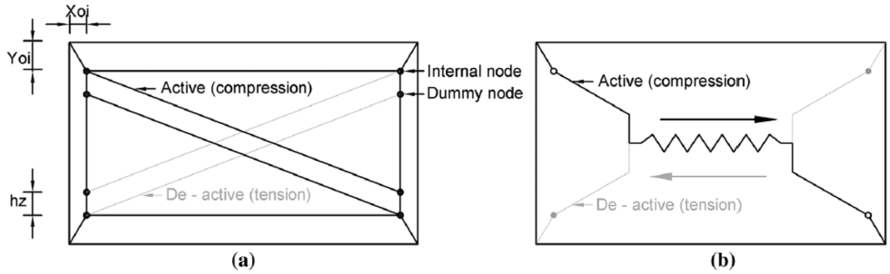

Figure 2. Infill panel element proposed by Crisafulli (1997). (a) Compression Struts, (b) Shear Strut

4.1. Influence of infill masonry panel stiffness on the fundamental period

The mechanical characteristics of the masonry infill panels are shown in Table 3. The same Table and Fig. 3 show the determined fundamental period versus the infill masonry panel stiffness Et (E: modulus of elasticity, t: thickness of the masonry panel) for all the stores infilled steel frames for 3 spans with 5 meters length From Fig. 3, it can be seen that the period is highly sensitive to the infill wall panel stiffness. Infills act as diagonal bracing and resist lateral deflection. So, if the infill wall panel stiffness increases, the lateral deflection decreases and the fundamental period decreases. Finally, from Fig. 3, it can be seen that the fundamental period of all frames (3, 6, 9, 12, 15 and 18-storey) decreases by about 65% for a change in infill wall stiffness from each 0.5×105 to 10×105 kN/m.

Table 3. Fundamental period of a three-span (3, 6, 9, 12, 15 and 18-storey) fully infilled steel frame with 5 meters span length.

Modulus of Elasticity *E* (MPa)	**Thickness *t* (m)**	**Stiffness Et (×10^5 kN/m)**	**3-story**	**6-story**	**9-story**	**12-story**	**15-story**	**18-story**
Bare	0.00	0.0	0.597	1.23	1.76	2.332	2.71	2.96
1,000	0.05	0.5	0.383	0.752	1.114	1.492	1.79	2.064
1,000	0.07	0.7	0.347	0.68	1.011	1.354	1.642	1.903
2,000	0.05	1.0	0.313	0.606	0.902	1.209	1.478	1.728
3,000	0.05	1.5	0.271	0.526	0.784	1.052	1.297	1.531
4,000	0.05	2.0	0.244	0.472	0.705	0.948	1.176	1.397
5,000	0.05	2.5	0.225	0.434	0.649	0.873	1.088	1.3
6,000	0.05	3.0	0.211	0.405	0.604	0.814	1.019	1.221
4,000	0.1	4.0	0.188	0.361	0.541	0.73	0.919	1.107
6,000	0.1	6.0	0.159	0.306	0.461	0.625	0.794	0.963
8,000	0.1	8.0	0.141	0.272	0.411	0.56	0.716	0.872
10,000	0.1	10	0.129	0.25	0.377	0.515	0.662	0.808

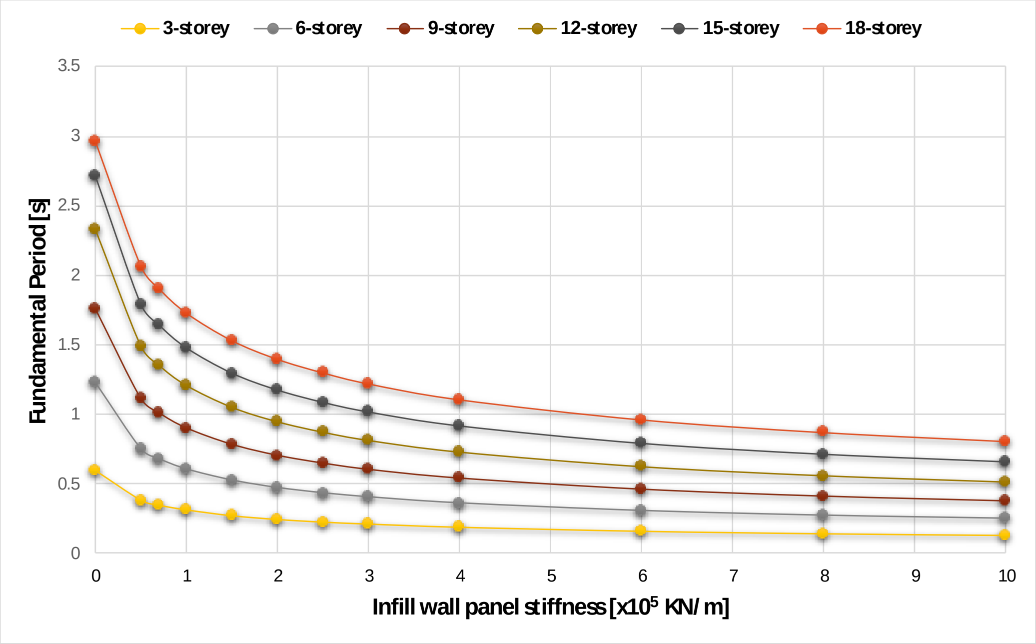

Figure 3. Influence of masonry stiffness on the fundamental period of 3, 6, 9, 12, 15 and 18-storey fully infilled

4.2. Influence of infill masonry panel stiffness on the fundamental period

Under lateral in-plane loading, the lateral stiffness of the infilled frame with openings, i.e. door and window, depends on the size of the opening. For the effect of openings a reduction factor according to Eq. (1) was proposed by Asteris (2003) [18].

$$R_F = 0.6\left(\frac{A_O}{A_P}\right)^2 - 1.6\left(\frac{A_O}{A_P}\right) + 1 \tag{1}$$

Where AO and AP are area of the opening and infill panel, respectively. In this study, this coefficient is used to modify the equations of the Crisafulli model. All of the infill walls with openings in the selected buildings have been analyzed. Fig. 4 shows the influence of infill on the fundamental period of a 3, 6, 9, 12, 15 and 18-storey fully infilled steel frame with three spans with five meters length. The values of the fundamental period of these infilled frames with openings are shown in Table 4. It can be seen that as the infill opening percentage increases from full infill (no opening) to 75-80% infill opening, the fundamental period increases almost linearly.

Table 4. Fundamental period of the models with opening in infill panels.

Case	**Stiffness Et (×10^5 kN/m)**			**Opening percentage**				**Reduction**
		0.00%	**20%**	**40%**	**60%**	**80%**	**100%(Bare)**	
3-storey	0.5	0.383	0.406	0.445	0.496	0.549	0.597	**35.85%**
	0.7	0.347	0.373	0.415	0.471	0.535	0.597	**41.88%**
	1.0	0.313	0.338	0.381	0.441	0.518	0.597	**47.57%**
	1.5	0.271	0.298	0.342	0.406	0.491	0.597	**54.61%**
	2.0	0.244	0.271	0.314	0.377	0.47	0.597	**59.13%**
	2.5	0.225	0.251	0.292	0.356	0.452	0.597	**62.31%**
	3.0	0.211	0.235	0.275	0.338	0.437	0.597	**64.66%**
	4.0	0.188	0.211	0.25	0.311	0.41	0.597	**68.51%**
	6.0	0.159	0.181	0.216	0.272	0.372	0.597	**73.37%**
	8.0	0.141	0.161	0.194	0.247	0.344	0.597	**76.38%**
	10	0.129	0.148	0.178	0.228	0.323	0.597	**78.39%**
	Reduction	**66.32%**	**63.55%**	**60.00%**	**54.03%**	**41.17%**	**0.00%**	
6-storey	0.5	0.752	0.802	0.884	0.992	1.114	1.23	**38.86%**
	0.7	0.68	0.733	0.82	0.938	1.082	1.23	**44.72%**
	1.0	0.606	0.661	0.749	0.874	1.042	1.23	**50.73%**
	1.5	0.526	0.58	0.667	0.799	0.982	1.23	**57.24%**
	2.0	0.472	0.525	0.611	0.74	0.934	1.23	**61.63%**
	2.5	0.434	0.485	0.568	0.697	0.895	1.23	**64.72%**
	3.0	0.405	0.454	0.534	0.66	0.863	1.23	**67.07%**
	4.0	0.361	0.407	0.483	0.604	0.808	1.23	**70.65%**
	6.0	0.306	0.348	0.417	0.527	0.728	1.23	**75.12%**
	8.0	0.272	0.311	0.374	0.477	0.67	1.23	**77.89%**
	10	0.25	0.285	0.343	0.441	0.628	1.23	**79.67%**
	Reduction	**66.76%**	**64.46%**	**61.20%**	**55.54%**	**43.63%**	**0.00%**	
9-storey	0.5	1.114	1.186	1.301	1.45	1.612	1.76	**36.70%**
	0.7	1.011	1.088	1.212	1.376	1.569	1.76	**42.56%**
	1.0	0.902	0.983	1.111	1.288	1.516	1.76	**48.75%**
	1.5	0.784	0.864	0.993	1.182	1.436	1.76	**55.45%**
	2.0	0.705	0.784	0.91	1.097	1.371	1.76	**59.94%**
	2.5	0.649	0.725	0.847	1.036	1.318	1.76	**63.13%**
	3.0	0.604	0.678	0.797	0.981	1.273	1.76	**65.68%**
	4.0	0.541	0.61	0.722	0.9	1.195	1.76	**69.26%**
	6.0	0.461	0.523	0.624	0.788	1.081	1.76	**73.81%**
	8.0	0.411	0.469	0.562	0.714	0.998	1.76	**76.65%**
	10	0.377	0.43	0.516	0.66	0.936	1.76	**78.58%**

	Reduction	**66.16%**	**63.74%**	**60.34%**	**54.48%**	**41.94%**	**0.00%**	
12-storey	0.5	1.492	1.589	1.741	1.937	2.145	2.32	**35.69%**
	0.7	1.354	1.458	1.623	1.841	2.091	2.32	**41.64%**
	1.0	1.209	1.316	1.49	1.725	2.023	2.32	**47.89%**
	1.5	1.052	1.16	1.332	1.584	1.918	2.32	**54.66%**
	2.0	0.948	1.053	1.221	1.472	1.834	2.32	**59.14%**
	2.5	0.873	0.975	1.138	1.391	1.764	2.32	**62.37%**
	3.0	0.814	0.913	1.072	1.317	1.705	2.32	**64.91%**
	4.0	0.73	0.823	0.973	1.21	1.602	2.32	**68.53%**
	6.0	0.625	0.709	0.844	1.062	1.451	2.32	**73.06%**
	8.0	0.56	0.638	0.761	0.963	1.34	2.32	**75.86%**
	10	0.515	0.587	0.702	0.892	1.258	2.32	**77.80%**
	Reduction	**65.48%**	**63.06%**	**59.68%**	**53.95%**	**41.35%**	**0.00%**	
15-storey	0.5	1.79	1.906	2.075	2.29	2.512	2.71	**33.95%**
	0.7	1.642	1.761	1.946	2.185	2.454	2.71	**39.41%**
	1.0	1.478	1.602	1.798	2.059	2.382	2.71	**45.46%**
	1.5	1.297	1.424	1.622	1.904	2.27	2.71	**52.14%**
	2.0	1.176	1.302	1.497	1.781	2.179	2.71	**56.61%**
	2.5	1.088	1.211	1.402	1.69	2.103	2.71	**59.85%**
	3.0	1.019	1.138	1.326	1.607	2.04	2.71	**62.40%**
	4.0	0.919	1.033	1.211	1.485	1.926	2.71	**66.09%**
	6.0	0.794	0.897	1.06	1.316	1.758	2.71	**70.70%**
	8.0	0.716	0.813	0.963	1.202	1.634	2.71	**73.58%**
	10	0.662	0.752	0.892	1.12	1.542	2.71	**75.57%**
	Reduction	**63.02%**	**60.55%**	**57.01%**	**51.09%**	**38.61%**	**0.00%**	
18-storey	0.5	2.064	2.18	2.351	2.561	2.77	2.96	**30.27%**
	0.7	1.903	2.03	2.22	2.46	2.72	2.96	**35.71%**
	1.0	1.728	1.863	2.071	2.336	2.651	2.96	**41.62%**
	1.5	1.531	1.673	1.887	2.181	2.544	2.96	**48.28%**
	2.0	1.397	1.54	1.754	2.054	2.455	2.96	**52.80%**
	2.5	1.3	1.439	1.652	1.96	2.381	2.96	**56.08%**
	3.0	1.221	1.358	1.569	1.873	2.317	2.96	**58.75%**
	4.0	1.107	1.24	1.442	1.744	2.204	2.96	**62.60%**
	6.0	0.963	1.085	1.274	1.56	2.032	2.96	**67.47%**
	8.0	0.872	0.987	1.163	1.435	1.904	2.96	**70.54%**
	10	0.808	0.917	1.083	1.343	1.806	2.96	**72.70%**
	Reduction	**60.85%**	**57.94%**	**53.93%**	**47.56%**	**34.80%**	**0.00%**	

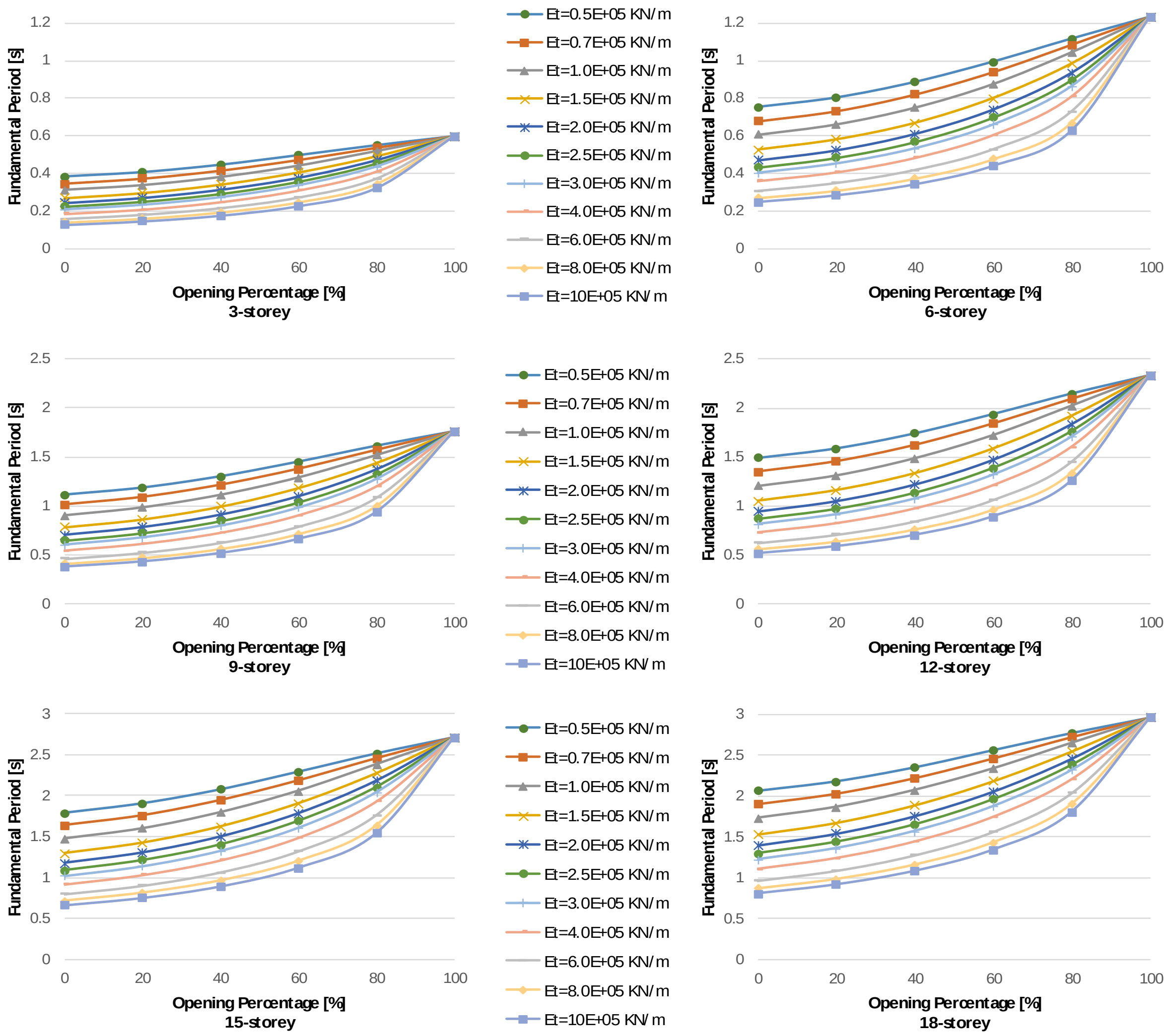

Figure 4. Influence of opening percentage on the fundamental period

4.3. Influence of soil-structure interaction on the fundamental period

It is well known that soil flexibility increases the fundamental period of the structure. In order to examine the influence of the soil conditions on the fundamental period, soil-structure interaction is taken into account in the current study. For simulate the soil-structure interaction used link element on SeismoStruct (Seismosoft 2018), especially a translational spring is introduced by using a link element and for compute the dynamic-stiffness coefficients used CONAN program (CONe ANalysis). Fig. 5 shows the influence of soil-structure interaction on the fundamental period of 3, 6, 9, 12, 15 and 18-storey fully infilled steel frame with three spans and span length equal to 5 m. As it was expected, the soil-structure interaction strongly affects the fundamental period. In general, the value of the fundamental period is higher when the soil is more flexible. Soil-structure interaction strongly influence the bare frames. From Fig. 5 it can be seen that fundamental period increases by 8% to 22% for the case of the 18-storey bare frame, if soil-structure interaction is taken into account. Infilled frames on rigid soil and soil types A and B have similar fundamental periods. Soil type C results to a higher value of the fundamental period (by 25% compared to rigid soil for masonry wall stiffness 10×10^5 kN/m of the 18-storey infilled frame) while soil type D results to a higher value by 43% compared to rigid soil for masonry wall stiffness 10×10^5 kN/m of the 18-storey infilled frame.

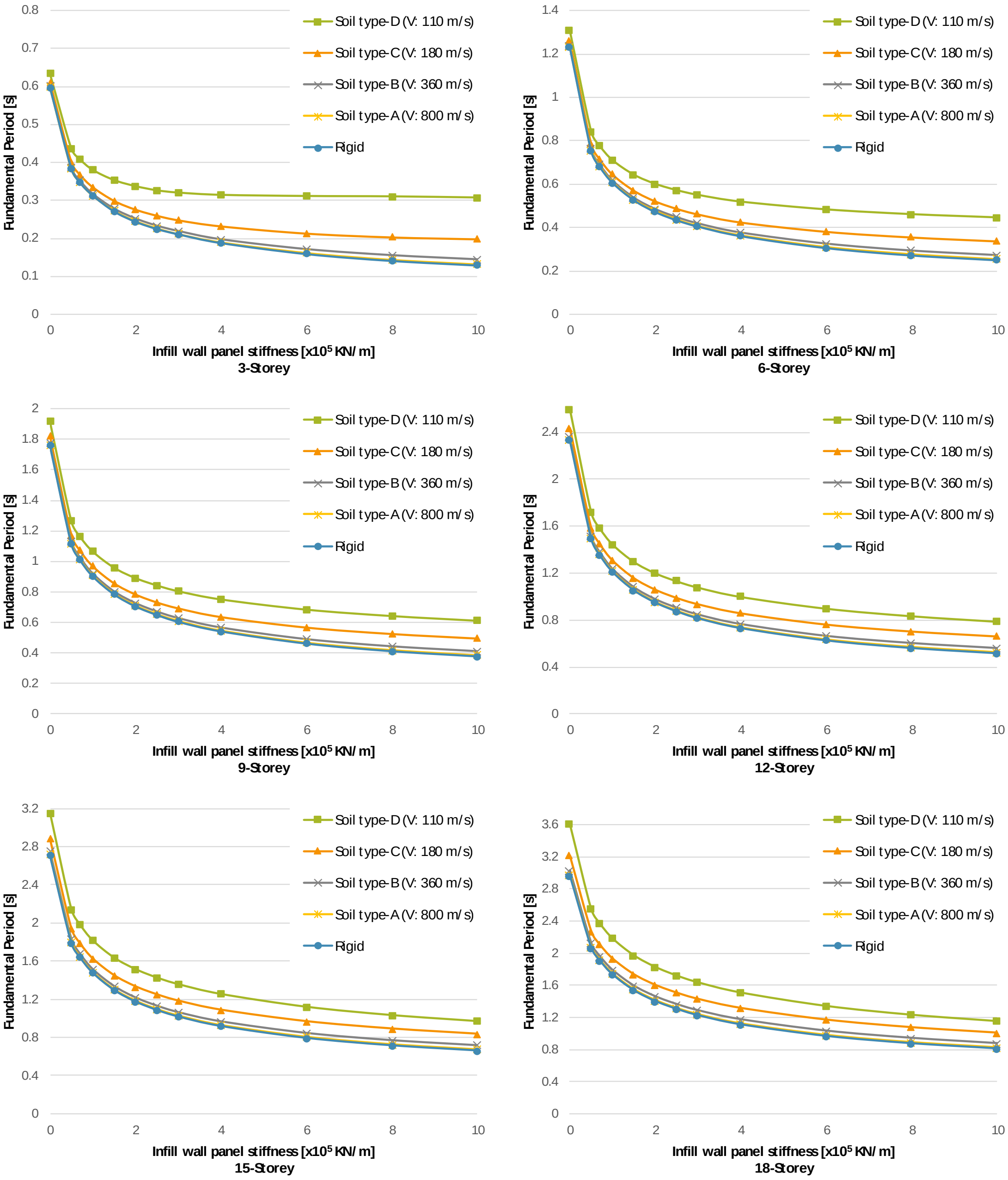

Figure 5. Influence of soil-structure interaction on the fundamental period.

5. Conclusion

From the present study the following conclusions can be drawn:

•An increase of the infill wall panel stiffness from 0.5×105 to 10×105 kN/m reduces the fundamental period by approximately 30 to 80%.

•As the opening area increases from full infill to 80% opening, the fundamental period of the structure increases almost linearly.

•For the all frames with the identical opening, the higher the masonry stiffness results in the lower fundamental period.

•The soil-structure interaction significantly affects the fundamental period. The fundamental period is higher for more flexible soil types such as the soil type C and D according to EC8. Furthermore, the influence of soil-structure interaction is higher when the infill wall stiffness is higher.

6. References

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