Analysis of the Influence of Soil Conditions on the Dynamic Characteristics of a Selected Building Structure

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Abstract

The supporting soil is one of the key factors affecting the behavior of building structures. The mechanical properties of soil can significantly modify the dynamic characteristics of a structure, in particular its natural frequencies and the corresponding mode shapes. The aim of this study is to analyze the influence of selected soil conditions on the dynamic characteristics of a selected building structure using a numerical model developed in Autodesk Robot Structural Analysis. Three variants of foundation conditions were considered: a model with fixed supports, a model founded on weak soil and a model founded on good soil. For each case, modal analysis was carried out and the natural frequencies, periods and mass participation factors were determined. The obtained results show that the foundation condition has a clear influence on the dynamic characteristics of the structure. The weak-soil variant produced the lowest natural frequencies, while the good-soil variant resulted in higher values but still lower than the fixed-support reference model. The results confirm that the representation of soil-structure interaction is important when assessing the dynamic behavior of residential building structures.

Keywords: soil-structure interaction; modal analysis; natural frequency; finite element model; foundation stiffness; Robot Structural Analysis

1. Introduction

The dynamic characteristics of a building are governed not only by the mass and stiffness of its superstructure, but also by the mechanical properties of the subsoil and the flexibility of the foundation system. Although the fixed-base assumption is commonly adopted in engineering models, it may lead to an unrealistic representation of the actual boundary conditions. Based on empirical data from instrumented buildings, Stewart et al. [1] demonstrated that foundation flexibility may significantly affect the natural period and damping of a structural system. Mylonakis and Gazetas [2] further emphasised that the period elongation and additional damping associated with soil–structure interaction do not necessarily result in a favourable structural response.

The influence of soil–structure interaction can be particularly important for relatively stiff, low-rise buildings, for which foundation deformability may constitute a substantial part of the overall system flexibility. Dutta et al. [3] showed that accounting for soil flexibility may noticeably increase the natural periods and modify the seismic response of low-rise buildings founded on shallow foundations. Öz et al. [4] obtained similar observations for existing low- and medium-rise reinforced-concrete buildings analysed under different soil conditions. Caycı et al. [5] demonstrated that the effects of soil–structure interaction depend on both the height of the building and the adopted soil model. More recently, Jang et al. [6] confirmed that the influence of soil flexibility is especially relevant for structures whose dynamic characteristics correspond to the dominant frequency range of the excitation.

The reliability of soil–structure interaction analyses is strongly dependent on the adopted modelling approach. Zangeneh et al. [7] showed that modal analysis of coupled soil–structure systems requires a careful distinction between structural modes and modes associated predominantly with the soil domain. Ayala et al. [8] demonstrated that numerical models calibrated using micro-vibration measurements can reproduce both the natural frequencies and mode shapes of actual buildings more accurately. Experimental shaking-table studies conducted by Ahn et al. [9] also confirmed that structural dynamic properties directly influence the observed interaction between the structure and the supporting ground. Tests performed by Du et al. [10] indicated that changes in ground conditions may substantially modify the dynamic response of foundation–structure systems.

In buildings with an irregular plan, the flexibility of the foundation may additionally influence the relationship between translational and torsional modes. Bhattacharjee et al. [11] found that plan asymmetry, combined with soil flexibility, can alter modal periods and the contribution of higher modes. Field investigations provide further evidence that building frequencies depend on local soil conditions. Based on a database covering reinforced-concrete and unreinforced masonry buildings, Gallipoli et al. [12] observed a systematic increase in structural periods for buildings located on softer soils. Gangone et al. [13] demonstrated that the proximity of soil and building frequencies may also produce soil–building resonance effects. Moreover, Auersch [14] showed that the dynamic stiffness and damping of foundations are frequency-dependent and may be inadequately represented by simplified static soil parameters.

Despite extensive research on soil–structure interaction, many studies focus primarily on seismic response, medium- or high-rise structures, or advanced coupled soil–foundation models. Comparatively less attention has been given to the influence of simplified representations of foundation flexibility on the complete modal characteristics of irregular low-rise masonry buildings founded on strip foundations. In particular, changes in the sequence and character of translational and torsional modes are rarely discussed together with modal mass participation factors.

The aim of this study is therefore to evaluate the influence of subsoil conditions on the dynamic characteristics of a selected irregular residential building. Three finite-element models are compared: a fixed-base model and two models incorporating foundation flexibility corresponding to weak and good soil conditions. The first twenty natural modes are examined in terms of natural frequencies, vibration periods, mode shapes and modal mass participation factors in the principal directions. Particular attention is paid to the identification of modes dominated by translation along the X- and Y-axes and by torsional motion. The

analysis is intended to determine whether the fixed-base assumption provides a sufficiently accurate representation of the building or may lead to a distorted assessment of its actual dynamic behaviour.

2. Description of the Investigated Building

The investigated structure is a detached residential building with an irregular plan and a multi-slope roof. The building consists of a foundation level, a ground floor, an upper storey and an attic part. The load-bearing system is composed mainly of masonry walls, reinforced concrete strip foundations and horizontal reinforced concrete elements such as slabs, beams and stair flights. The roof structure was represented by timber bar elements forming rafters, purlins and secondary members. The structural layout is not fully symmetric, which is important for the interpretation of torsional mode shapes.

Fig. 1. General views of the investigated building: (a) garden-side elevation, (b) front elevation from the entrance side.

The foundations were modelled according to the available foundation drawing. The strip foundations have variable widths, including approximately 0.60 m, 0.70 m and 0.90 m. This variability was taken into account while defining the elastic support of the soil in the models with deformable subsoil. In the fixed-support model, the foundation system was restrained in order to reproduce the idealized case of very stiff ground.

Fig. 2. Numerical model of the investigated building after finite element discretization.

3. Numerical Model and Analysis Procedure

The numerical model was prepared in Autodesk Robot Structural Analysis Professional 2026. Walls and slabs were represented by shell finite elements, while roof members, beams and strip foundations were represented by bar elements. Openings in walls were included in the shell geometry. The mesh was generated for shell elements with local adjustments near openings, corners and contact zones between walls, slabs and beams. The shell mesh is important especially in dynamic calculations [15]. Particular attention was paid to the compatibility of nodes between bars and shell elements, because disconnected nodes may produce local mechanisms or incorrect modal forms.

Three support variants were analyzed. The first variant was a reference model with fixed foundation conditions. The second variant represented weak soil. The third variant represented good soil. In the deformable-soil variants, the foundation strips were modelled as bars supported by elastic subgrade parameters. The modal analysis was performed for the first 20 natural modes. The results were compared using natural frequencies, periods and mass participation factors in the global directions UX, UY and UZ.

In Table 1 the material properties of the analyzed building model are listed according to procedure established in [16].

Tab. 1. Main material parameters adopted in the numerical model.

Structural element	Material	E [MPa]	ν [–]	G [MPa]	γ [kN/m³]
Foundation walls / strip foundations	B25	30,000	0.20	12 500	24.53
Reinforced-concrete slab	C30	33,000	0.20	13 750	25.00
Masonry wall	MAX clay blocks with M5 mortar	3,000	0.20	1250	11.00
Timber roof members	C24	11,000	0.00	690	3.43

4. Results of Modal Analysis

The selected modal results are summarized in Tab. 2. The fixed-support variant produced the highest natural frequencies among the considered models. The X-dominated form was identified as mode 3 with a frequency of 6.70 Hz. The Y-dominated form was identified as mode 12 with a frequency of 14.93 Hz, while the torsional form was identified as mode 7 with a frequency of 12.40 Hz. For the weak-soil model, the corresponding characteristic frequencies decreased considerably. In the good-soil model, the frequencies increased in comparison with the weak-soil model and reached intermediate values between the weak-soil and fixed-support cases.

Tab. 2. Characteristic modal forms selected for comparison of foundation variants.

Variant	Type	Mode	Case/Form	f [Hz]	T [s]	Running UX [%]	Running UY [%]	Running UZ [%]
Fixed support	X	3	1/3	6.70	0.15	7.23	0.01	0.00
Fixed support	Y	12	1/12	14.93	0.07	4.26	6.30	0.01
Fixed support	Torsional	7	1/7	12.40	0.08	0.00	0.39	0.00
Weak soil	X	3	1/3	3.65	0.27	71.88	0.16	0.00
Weak soil	Y	1	1/1	3.23	0.31	0.29	78.83	0.00
Weak soil	Torsional	4	1/4	4.03	0.25	3.47	0.00	0.01
Good soil	X	1	1/1	5.11	0.20	23.23	0.67	0.00
Good soil	Y	6	1/6	7.06	0.14	4.96	38.06	0.00
Good soil	Torsional	7	1/7	7.69	0.13	0.50	1.11	0.01

Tab. 3. Frequency changes of the selected modal forms.

Type	Fixed f [Hz]	Weak f [Hz]	Good f [Hz]	Weak vs fixed [%]	Good vs fixed [%]	Good vs weak [%]
X	6.70	3.65	5.11	-45.5	-23.7	40.0
Y	14.93	3.23	7.06	-78.4	-52.7	118.6
Torsional	12.40	4.03	7.69	-67.5	-38.0	90.8

The weak-soil model shows the greatest reduction of dynamic stiffness. The X-dominated frequency decreased by about 45.5% in relation to the fixed-support model. The reduction was even stronger for the Y-dominated and torsional forms, where the decrease reached about 78.4% and 67.5%, respectively. The good-soil model provided intermediate results: the characteristic frequencies were higher than in the weak-soil model but still lower than in the fixed-support reference model.

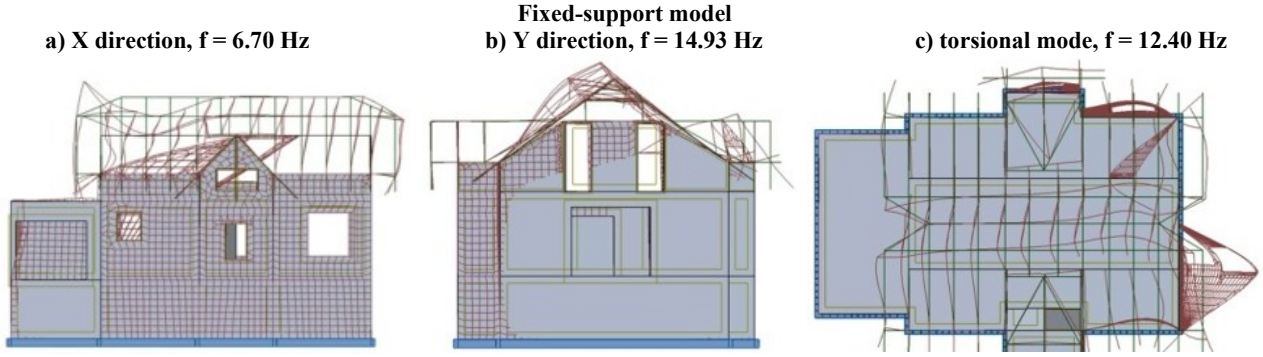

Fig. 3. Selected mode shapes of the fixed-support model.

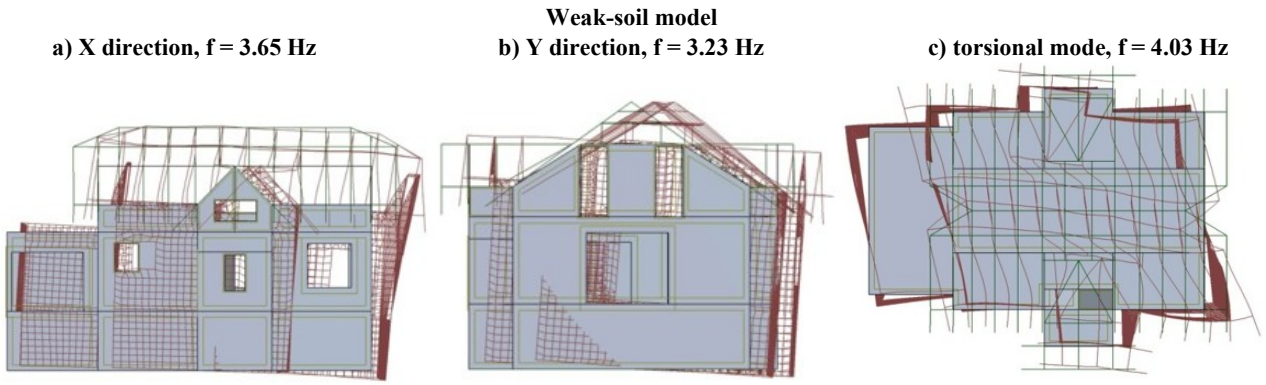

Fig. 4. Selected mode shapes of the weak-soil model.

Good-soil model

a) X direction, f = 5.11 Hz b) Y direction, f = 7.06 Hz c) torsional mode, f = 7.69 Hz

Fig. 5. Selected mode shapes of the good-soil model.

5. Complete Modal Tables

The complete modal sets are presented in Tabs. 4-6. The tables contain the first 20 calculated natural modes together with the periods and mass participation factors. They make it possible to compare both the frequency range and the cumulative participation of global translational components for the three foundation variants.

Tab. 4. Complete modal results for the fixed-support model.

Mode	f [Hz]	T [s]	Rel. UX [%]	Rel. UY [%]	Rel. UZ [%]	Run. UX [%]	Run. UY [%]	Run. UZ [%]	Mass [kg]
1	5.65	0.18	6.25	0.00	0.00	6.25	0.00	0.00	503 594.62
2	6.57	0.15	9.23	0.01	0.00	2.98	0.01	0.00	503 594.62
3	6.70	0.15	16.46	0.02	0.00	7.23	0.01	0.00	503 594.62
4	7.80	0.13	16.61	0.02	0.00	0.14	0.00	0.00	503 594.62
5	8.35	0.12	21.91	0.02	0.00	5.30	0.00	0.00	503 594.62
6	9.85	0.10	27.62	0.03	0.00	5.71	0.01	0.00	503 594.62
7	12.40	0.08	27.62	0.41	0.00	0.00	0.39	0.00	503 594.62
8	12.91	0.08	27.62	0.42	0.00	0.00	0.00	0.00	503 594.62
9	13.95	0.07	29.01	1.28	0.00	1.38	0.87	0.00	503 594.62
10	14.24	0.07	29.52	1.66	0.00	0.51	0.37	0.00	503 594.62
11	14.77	0.07	31.02	3.26	0.00	1.51	1.60	0.00	503 594.62
12	14.93	0.07	35.29	9.56	0.01	4.26	6.30	0.01	503 594.62
13	15.69	0.06	35.65	9.66	0.01	0.37	0.10	0.00	503 594.62
14	17.74	0.06	37.08	10.06	0.01	1.43	0.40	0.00	503 594.62
15	18.77	0.05	37.08	10.07	0.01	0.00	0.01	0.00	503 594.62
16	19.10	0.05	37.08	11.07	0.02	0.00	1.00	0.00	503 594.62
17	21.62	0.05	37.20	13.06	0.02	0.12	1.99	0.00	503 594.62
18	22.00	0.05	37.27	14.42	0.02	0.07	1.36	0.00	503 594.62
19	22.87	0.04	37.95	16.69	0.02	0.68	2.28	0.00	503 594.62
20	23.01	0.04	41.78	17.20	0.02	3.83	0.51	0.00	503 594.62

Tab. 5. Complete modal results for the weak-soil model.

Mode	f [Hz]	T [s]	Rel. UX [%]	Rel. UY [%]	Rel. UZ [%]	Run. UX [%]	Run. UY [%]	Run. UZ [%]	Mass [kg]
1	3.23	0.31	0.29	78.83	0.00	0.29	78.83	0.00	545 356.28
2	3.56	0.28	7.33	90.51	0.01	7.04	11.67	0.01	545 356.28
3	3.65	0.27	79.21	90.66	0.02	71.88	0.16	0.00	545 356.28
4	4.03	0.25	82.68	90.66	0.03	3.47	0.00	0.01	545 356.28
5	5.02	0.20	85.00	90.83	0.05	2.33	0.16	0.02	545 356.28
6	5.44	0.18	85.45	90.87	0.06	0.45	0.04	0.00	545 356.28
7	6.07	0.16	85.70	90.94	0.13	0.25	0.08	0.08	545 356.28
8	6.50	0.15	87.23	90.95	0.14	1.53	0.01	0.01	545 356.28
9	7.43	0.13	87.86	95.56	5.71	0.63	4.61	5.57	545 356.28
10	7.54	0.13	87.87	95.71	53.22	0.02	0.15	47.51	545 356.28
11	7.62	0.13	87.87	97.42	99.03	0.00	1.71	45.80	545 356.28
12	7.92	0.13	88.02	99.73	99.51	0.14	2.31	0.49	545 356.28
13	8.16	0.12	98.25	99.76	99.74	10.23	0.02	0.23	545 356.28
14	9.24	0.11	99.10	99.87	99.75	0.85	0.11	0.01	545 356.28
15	9.94	0.10	99.19	99.93	99.83	0.09	0.07	0.08	545 356.28
16	10.44	0.10	99.25	99.94	99.85	0.06	0.00	0.02	545 356.28
17	10.55	0.09	99.31	99.94	99.86	0.05	0.00	0.01	545 356.28
18	11.78	0.08	99.32	99.94	99.87	0.01	0.01	0.00	545 356.28
19	11.98	0.08	99.32	99.97	99.87	0.00	0.02	0.00	545 356.28
20	12.43	0.08	99.32	99.97	99.92	0.00	0.00	0.05	545 356.28

Tab. 6. Complete modal results for the good-soil model.

Mode	f [Hz]	T [s]	Rel. UX [%]	Rel. UY [%]	Rel. UZ [%]	Run. UX [%]	Run. UY [%]	Run. UZ [%]	Mass [kg]
1	5.11	0.20	23.23	0.67	0.00	23.23	0.67	0.00	545 356.28
2	5.53	0.18	23.86	1.94	0.00	0.63	1.28	0.00	545 356.28
3	5.93	0.17	46.87	1.96	0.01	23.01	0.02	0.01	545 356.28
4	6.35	0.16	48.34	19.98	0.01	1.47	18.02	0.00	545 356.28
5	6.77	0.15	52.44	43.06	0.01	4.10	23.08	0.00	545 356.28
6	7.06	0.14	57.40	81.13	0.01	4.96	38.06	0.00	545 356.28
7	7.69	0.13	57.90	82.24	0.02	0.50	1.11	0.01	545 356.28
8	8.00	0.12	61.81	90.51	0.03	3.91	8.27	0.01	545 356.28
9	8.60	0.12	72.29	90.51	0.03	10.48	0.00	0.00	545 356.28
10	9.58	0.10	78.60	90.51	0.06	6.31	0.00	0.03	545 356.28
11	10.15	0.10	83.56	90.64	0.07	4.95	0.12	0.01	545 356.28
12	10.73	0.09	87.49	90.67	0.07	3.93	0.03	0.00	545 356.28
13	11.77	0.08	88.85	90.68	0.07	1.36	0.02	0.00	545 356.28
14	12.62	0.08	88.93	90.94	0.20	0.08	0.26	0.12	545 356.28
15	12.88	0.08	88.94	90.95	0.36	0.00	0.01	0.17	545 356.28
16	13.06	0.08	89.53	91.01	0.38	0.60	0.06	0.02	545 356.28
17	13.61	0.07	89.57	91.02	0.49	0.04	0.01	0.12	545 356.28
18	13.96	0.07	89.67	91.33	1.89	0.10	0.31	1.40	545 356.28
19	14.76	0.07	89.78	91.37	2.20	0.11	0.04	0.31	545 356.28
20	14.91	0.07	89.99	91.54	2.54	0.21	0.17	0.33	545 356.28

6. Comparative Evaluation of the Complete Modal Set

The summary comparison in Tab. 7 confirms the tendency observed for the selected characteristic forms. In the fixed-support model the first frequency was 5.65 Hz and the twentieth frequency was 23.01 Hz. In the weak-soil variant, the corresponding frequency range was 3.23-12.43 Hz. In the good-soil variant, the range increased to 5.11-14.91 Hz. Therefore, increasing soil stiffness shifts the modal spectrum toward higher frequencies, although the values remain below the idealized fixed-support case.

Tab. 7. Comparison of modal frequencies and cumulative mass participation factors for the first 20 modes. UX and UY values are cumulative percentages.

Mode	f fix	UX fix	UY fix	f weak	UX weak	UY weak	f good	UX good	UY good
1	5.65	6.25	0.00	3.23	0.29	78.83	5.11	23.23	0.67
2	6.57	9.23	0.01	3.56	7.33	90.51	5.53	23.86	1.94
3	6.70	16.46	0.02	3.65	79.21	90.66	5.93	46.87	1.96
4	7.80	16.61	0.02	4.03	82.68	90.66	6.35	48.34	19.98
5	8.35	21.91	0.02	5.02	85.00	90.83	6.77	52.44	43.06
6	9.85	27.62	0.03	5.44	85.45	90.87	7.06	57.40	81.13
7	12.40	27.62	0.41	6.07	85.70	90.94	7.69	57.90	82.24
8	12.91	27.62	0.42	6.50	87.23	90.95	8.00	61.81	90.51
9	13.95	29.01	1.28	7.43	87.86	95.56	8.60	72.29	90.51
10	14.24	29.52	1.66	7.54	87.87	95.71	9.58	78.60	90.51
11	14.77	31.02	3.26	7.62	87.87	97.42	10.15	83.56	90.64
12	14.93	35.29	9.56	7.92	88.02	99.73	10.73	87.49	90.67
13	15.69	35.65	9.66	8.16	98.25	99.76	11.77	88.85	90.68
14	17.74	37.08	10.06	9.24	99.10	99.87	12.62	88.93	90.94
15	18.77	37.08	10.07	9.94	99.19	99.93	12.88	88.94	90.95
16	19.10	37.08	11.07	10.44	99.25	99.94	13.06	89.53	91.01
17	21.62	37.20	13.06	10.55	99.31	99.94	13.61	89.57	91.02
18	22.00	37.27	14.42	11.78	99.32	99.94	13.96	89.67	91.33
19	22.87	37.95	16.69	11.98	99.32	99.97	14.76	89.78	91.37
20	23.01	41.78	17.20	12.43	99.32	99.97	14.91	89.99	91.54

7. Discussion of Soil Influence

The comparison of the three variants shows that the support model modifies not only the numerical value of natural frequencies but also the order of the corresponding modal forms. This is especially visible in the Y-dominated form. In the fixed-support case it occurred as the twelfth mode, whereas in the weak-soil model it became the first mode. This change indicates that the flexible support allowed a global deformation mechanism that was restrained in the reference model. Therefore, the modal forms were compared according to deformation shape and mass participation, not only according to mode number.

The weak-soil model gave the most pronounced global translations. The cumulative mass participation factors reached high values already within the first few modes, which means that the dominant dynamic behavior was represented by low-frequency global forms. In contrast, in the fixed-support model the cumulative mass participation increased more gradually, especially in the UY direction. This confirms that idealized restraint at the foundation level increases the dynamic stiffness and shifts important vibration forms to higher frequencies.

The good-soil model showed an intermediate response. Its first frequency was close to the first frequency of the fixed-support model, but the Y and torsional modes were still substantially lower than in the fixed case. This suggests that even relatively stiff deformable support may noticeably influence the dynamic behavior of a structure with an irregular plan and non-uniform stiffness distribution. The irregular geometry also explains why torsional forms are relevant in the interpretation of the results.

Tab. 8. Identification of corresponding modal forms in the analyzed variants.

Mode type	Fixed support	Weak soil	Good soil	Comment
X-dominated	Mode 3 / 6.70 Hz	Mode 3 / 3.65 Hz	Mode 1 / 5.11 Hz	Translation in global X direction
Y-dominated	Mode 12 / 14.93 Hz	Mode 1 / 3.23 Hz	Mode 6 / 7.06 Hz	Translation in global Y direction
Torsional	Mode 7 / 12.40 Hz	Mode 4 / 4.03 Hz	Mode 7 / 7.69 Hz	Rotation of the plan around vertical axis

The presented model is an engineering simplification of the real structure. Local details of timber joints, exact stiffness of connections, local eccentricities of roof members and non-linear contact between the foundation and subsoil were simplified. These assumptions are acceptable for the objective of the study, which is a comparison of global modal characteristics under different support conditions. The same structural geometry was used in all variants, which makes the observed differences primarily related to the change in foundation and soil stiffness.

8. Conclusions

The numerical analyses demonstrated that the representation of foundation conditions has a substantial influence on the modal characteristics of the investigated building. For the first 20 modes, the natural frequency range decreased from 5.65–23.01 Hz in the fixed-base model to 3.23–12.43 Hz in the weak-soil model. The good-soil model produced intermediate values of 5.11–14.91 Hz. The influence of foundation flexibility is therefore not limited to a uniform shift in frequency but affects the distribution of the entire modal spectrum.

The magnitude of the frequency reduction depended strongly on the direction and type of vibration. Relative to the fixed-base model, the weak-soil variant reduced the frequencies of the selected X-dominated, Y-dominated and torsional modes by 45.5%, 78.4% and 67.5%, respectively. For the good-soil model, the corresponding reductions were 23.7%, 52.7% and 38.0%. The particularly large changes obtained for the Y-dominated and torsional modes indicate that the effect of soil flexibility is influenced by the irregular plan and non-uniform stiffness distribution of the building.

Foundation flexibility also changed the sequence and relative importance of the characteristic mode shapes. The Y-dominated mode occurred as mode 12 in the fixed-base model but became mode 1 in the weak-soil model and mode 6 in the good-soil model. Similar reordering was observed for the X-dominated and torsional modes. Consequently, corresponding modes in different numerical variants should be identified from their deformation patterns and modal mass participation factors rather than from their ordinal numbers alone.

In the weak-soil model, cumulative mass participation reached 79.21% in the X direction and 90.66% in the Y direction within the first three modes. In contrast, the corresponding values in the fixed-base model reached only 41.78% and 17.20%, respectively, after 20 modes. This shows that flexible support shifts the dominant global translational response towards the lowest-frequency modes, whereas in the fixed-base model the effective modal mass is distributed over a larger number of higher modes. Therefore, analyses based on a fixed support model may require considerably more modes to obtain adequate modal mass participation.

From an engineering perspective, the fixed-base assumption may be treated as an upper-bound estimate of the natural frequencies, but it should not automatically be regarded as a conservative representation of structural behaviour. Overestimating the frequencies may lead to an incorrect identification of the frequency ranges in which resonance or increased dynamic response can occur. Even for relatively good soil conditions, foundation flexibility should therefore be considered when analysing low-rise buildings with irregular geometry.

The conclusions are limited to the adopted linear-elastic model and the investigated structure. Further research should include a sensitivity analysis of the subgrade stiffness, consideration of foundation–soil coupling and nonlinear contact effects, and comparison with a three-dimensional soil-continuum model. Experimental identification of the natural frequencies and mode shapes using ambient-vibration measurements would enable calibration of the numerical model and verification of the assumed soil parameters. The calibrated model could subsequently be used to investigate the building response to seismic, traffic-induced or other dynamic excitation.

References

1. Stewart, J.P., Seed, R.B., Fenves, G.L. Seismic soil–structure interaction in buildings. II: Empirical findings. *Journal of Geotechnical and Geoenvironmental Engineering*, 125(1), 38–48, 1999. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:1(38)
2. Mylonakis, G., Gazetas, G. Seismic soil–structure interaction: Beneficial or detrimental? *Journal of Earthquake Engineering*, 4(3), 277–301, 2000. https://doi.org/10.1080/13632460009350372
3. Dutta, S.C., Bhattacharya, K., Roy, R. Response of low-rise buildings under seismic ground excitation incorporating soil–structure interaction. *Soil Dynamics and Earthquake Engineering*, 24(12), 893–914, 2004. https://doi.org/10.1016/j.soildyn.2004.07.001
4. Öz, I., Şenel, S.M., Palancı, M., Kalkan, A. Effect of soil–structure interaction on the seismic response of existing low and mid-rise RC buildings. *Applied Sciences*, 10(23), 8357, 2020. https://doi.org/10.3390/app10238357
5. Caycı, B.T., İnel, M., Özer, E. Effect of soil–structure interaction on seismic behavior of mid- and low-rise buildings. *International Journal of Geomechanics*, 21(3), 04021009, 2021. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001944
6. Jang, H., Yoon, J., Cho, W., Lee, J. Effects of structural dynamic characteristics on soil–structure interaction analysis of high-frequency-dominant seismic excitation. *Applied Sciences*, 15(7), 3679, 2025. https://doi.org/10.3390/app15073679

References

7. Zangeneh, A., François, S., Lombaert, G., Pacoste, C. Modal analysis of coupled soil–structure systems. *Soil Dynamics and Earthquake Engineering*, 144, 106645, 2021. https://doi.org/10.1016/j.soildyn.2021.106645
8. Ayala, F., Sáez, E., Magna-Verdugo, C. Computational modelling of dynamic soil–structure interaction in shear wall buildings with basements in medium stiffness sandy soils using a subdomain spectral element approach calibrated by micro-vibrations. *Engineering Structures*, 252, 113668, 2022. https://doi.org/10.1016/j.engstruct.2021.113668
9. Ahn, S., Park, G., Yoon, H., Han, J.-H., Jung, J. Evaluation of soil–structure interaction in structure models via shaking table test. *Sustainability*, 13(9), 4995, 2021. https://doi.org/10.3390/su13094995
10. Du, X., Dou, P., Xu, C., Miyajima, M., El Naggar, M.H., Chen, S. Large shaking table tests of pile-supported structures in different ground conditions. *Soil Dynamics and Earthquake Engineering*, 139, 106307, 2020. https://doi.org/10.1016/j.soildyn.2020.106307
11. Bhattacharjee, T., Chanda, D., Saha, R. Influence of soil flexibility and plan asymmetry on seismic behaviour of soil-piled raft-structure system. *Structures*, 33, 1775–1788, 2021. https://doi.org/10.1016/j.istruc.2021.05.045
12. Gallipoli, M.R., Petrovic, B., Calamita, G., Tragni, N., Scaini, C., Barnaba, C., Vona, M., Parolai, S. Towards specific T–H relationships: FRIBAS database for better characterization of RC and URM buildings. *Bulletin of Earthquake Engineering*, 21, 2281–2307, 2023. https://doi.org/10.1007/s10518-022-01594-7
13. Gangone, G., Gallipoli, M.R., Tragni, N., Vignola, L., Caputo, R. Soil–building resonance effect in the urban area of Villa d'Agri (Southern Italy). *Bulletin of Earthquake Engineering*, 21, 3273–3296, 2023. https://doi.org/10.1007/s10518-023-01644-8
14. Auersch, L. Soil–structure interaction and damping by the soil—Effects of foundation groups, foundation flexibility, soil stiffness and layers. *Vibration*, 8(1), 5, 2025. https://doi.org/10.3390/vibration8010005
15. Boroń, P.; Dulińska, J.M. Dynamic response analysis of multi-storey building to a non-uniform excitation, MATEC Web Conf., 107 (2017) 00064, DOI: https://doi.org/10.1051/matecconf/201710700064
16. Boroń, P.; Dulińska, J.M.; Jasińska, D. Two-Step Finite Element Model Tuning Strategy of a Bridge Subjected to Mining-Triggered Tremors of Various Intensities Based on Experimental Modal Identification. *Energies* **2021**, *14*, 2062. https://doi.org/10.3390/en14082062