Chapter 2
Evaluation of Damage Caused by Soil Settlements in a Historical Masonry Building

Ali Fuat Genç, Ahmet Can Altunışık, and Esin Ertürk

Abstract Masonry structures, characterized by their brittle behavior, are susceptible to easy damage when subjected to external forces. Especially, soil-structure interaction problems are important factors which may cause deterioration or complete loss of structural integrity in the masonry structures. For this reason, different settlements and deformations occurred in the soil domain should be considered in numerical analyses of this type structures for a correct structural assessment. The objective of this paper is to ascertain the modal response and assess the damage condition of an authentic historical masonry building, the deterioration of which can be attributed to underlying soil issues. The structure is a historical masonry school building which is constructed in the 1870s in Samsun, Turkey. The numerical evaluation encompasses the creation of a numerical model that takes into account the soil-structure interaction. This model is then utilized to gauge the impact of soil settlements on dynamic properties, and to scrutinize the state of damage through nonlinear explicit analyses.

Keywords Soil-structure interaction · Masonry structures · Nonlinear explicit analysis · Soil settlement effect

2.1 Introduction

Concrete, steel, and other modern materials have become commonplace in construction today; however, in the past, structures predominantly arose from raw or minimally treated elements such as stone, brick, adobe, and wood. These edifices, now referred to as historical buildings, were erected using the masonry construction method. Despite their simplicity in composition, grasping the authentic behaviors

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A. S. Mosallam et al. (eds.), *Advances in Smart Materials and Innovative Buildings Construction Systems*, Sustainable Civil Infrastructures,
https://doi.org/10.1007/978-3-031-47428-6_2

of these historical masonry structures often proves intricate due to the non-uniform and anisotropic characteristics of the materials (Altunisik et al. 2017). Consequently, safeguarding these structures presents an intricate endeavor demanding expertise and profound knowledge.

Numerous historical masonry structures have withstood the test of time, with some still standing strong today. Nevertheless, a multitude of these historical marvels have succumbed to demolition or deterioration across the years, owing to both natural elements and human interventions (Parisi and Augenti 2013). Such structures are susceptible to various forces including earthquakes, floods, fires, conflicts, and vandalism, leading to damages, as well as gradual material degradation, soil settling, time-induced wear and tear, and excessive, irregular loads due to unsuitable application (Toker and Ünay 2004). Characterized by meager tensile strength, historical masonry structures were engineered primarily to counter compressive stresses (Angelillo et al. 2014; Lourenço 1998).

Therefore, they are very vulnerable to actions that lead tensile stresses on the masonry walls such as seismic and soil settlement conditions. A wall subjected to tensile stress is easily damaged by mortar joints which have low tensile strength (Bui 2013; Fathyi et al. 2009; Nasser et al. 2014). Therefore, protection measures should be taken for historical structures against such effects.

Errors of foundation design, liquefaction, soil bearing capacity problems and horizontal displacements may cause soil settlement. Furthermore, the primary factors contributing to settlement encompass fluctuations in groundwater levels, alterations in the structural loading system, excavations conducted in the vicinity of the structure, dynamic forces, and vibrations. Settlement problem leads cracks, rotations, and different damage in the structure. Masonry walls are very sensitive to the smallest foundation settlement as they exhibit a brittle behavior.

In the literature, there are different approach for the damage assessment of historical structures. Rigid base approach does not consider the soil domain in the damage assessment of historical structures (Milani and Valente 2015; Llopis-Pulido et al. 2019; Valente and Milani 2016; Lazizi and Tahghighi 2019; Altıok and Demir 2021). On the other hand, soil domain is considered in the substructure approach, but structure and soil are modeled separately and structure work independently of the soil model (Mylonakis et al. 2006; Wolf 1985; NEHRP 2012; Gazetas 1991). This approach with a flexible support enables the differential soil settlement condition could be applied. Springs are modelled as not to resist tension. In this condition, the settlement is allowed in the structure and damage due to settlement can be achieved (Longo et al. 2021; Brunelli et al. 2021; Anastasios et al. 2020). On the other hand, studies on the detection of damages caused by soil settlements in historical masonry structures using the soil-structure interaction (direct approach) are rare in the literature (Kujawa et al. 2020).

The objective of this study is to assess the modal response and analyze the damage condition of an actual historical masonry building, the deterioration of which can be attributed to underlying soil-related issues. The structure is a historical masonry school building which is constructed in the 1870s in Samsun, Turkey. The numerical evaluation encompasses the creation of a finite element model that takes into account direct soil-structure interaction. This model is then utilized to gauge the impact of soil settlements on dynamic properties, and to scrutinize the state of damage through nonlinear explicit analyses.

2.2 Description of the Historical Building

The subject of inquiry in this study is a historic edifice situated in Samsun, Turkey, which was erected during the 1870s. Originally functioning as both an infirmary and a dormitory, the building underwent a transformation in its history and was repurposed into a school. Notably, the passage of time took its toll on the structure, resulting in substantial damage and the deterioration of key structural components such as doors, windows, floors, and the roof. In the 1970s, a partial fire incident prompted restorative efforts to mend the impaired sections.

Comprising a rectangular layout, the building encompasses three levels: a basement, a ground floor, and a standard floor. Its total vertical extent measures 14.3 m, with the first floor at 2.64 m, the second at 4.26 m, and the third at 4.59 m. The structural support system of the building is characterized by a load-bearing masonry framework, fashioned using brick materials. Within the standard storey, interior walls were introduced as timber frames. Wall thickness is approximately 0.7 m at the basement level, while higher sections exhibit varying thicknesses ranging from 0.45 to 0.60 m. Timber elements were used for the construction of the slabs and roof system. Visual representations and façade depictions of the building can be observed in Fig. 2.1.

2.3 Numerical Model of the Building

The construction of the Finite Element (FE) models for the building was carried out using the Abaqus software (Abaqus 2016). These models took into consideration the soil domain to account for diverse settlements, shifts, and distortions in the foundation arising from alterations in soil properties. Employing the macro modeling technique, the FE models were developed using linear tetrahedral finite elements, specifically the C3D4 element with four nodes, across the entirety of the soil-structure system. The dimensions of the encompassing soil domain were established as 24 by 36 m. To ensure stability, fixed boundary conditions were enforced upon the soil domain. The FE representation of the integrated soil-structure system is illustrated in Fig. 2.2.

Extracting material samples from the walls for material testing to ascertain material properties is not allowed due to regulatory measures protecting historical structures. Consequently, the material characteristics of the brick masonry walls were determined by consulting a specialized guideline titled "Earthquake Risk Management Guide for Historical Buildings" (General Directorate for Foundations 2017), designed for evaluating historical structures. Furthermore, the Concrete Damage

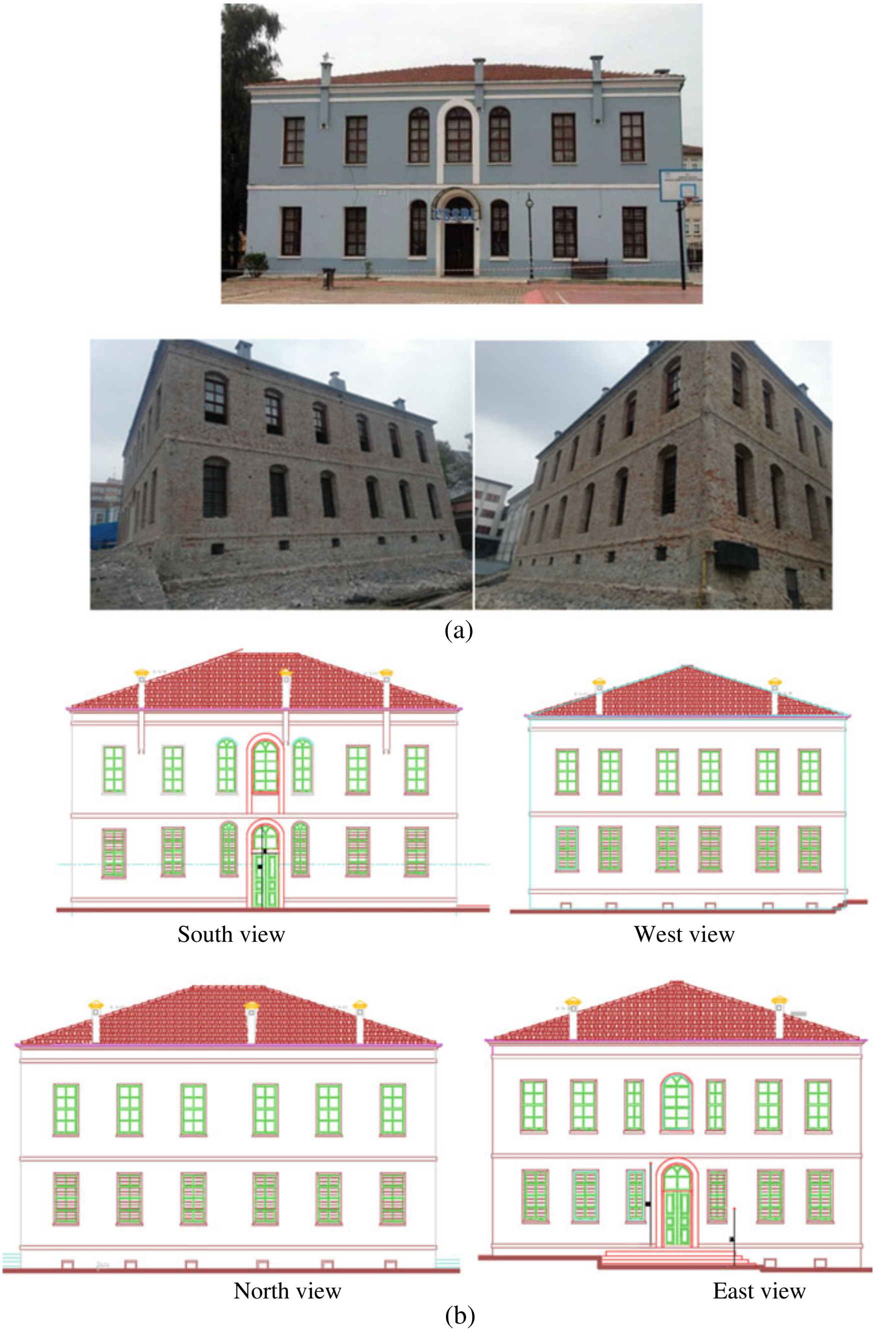


Fig. 2.1 Views of the building

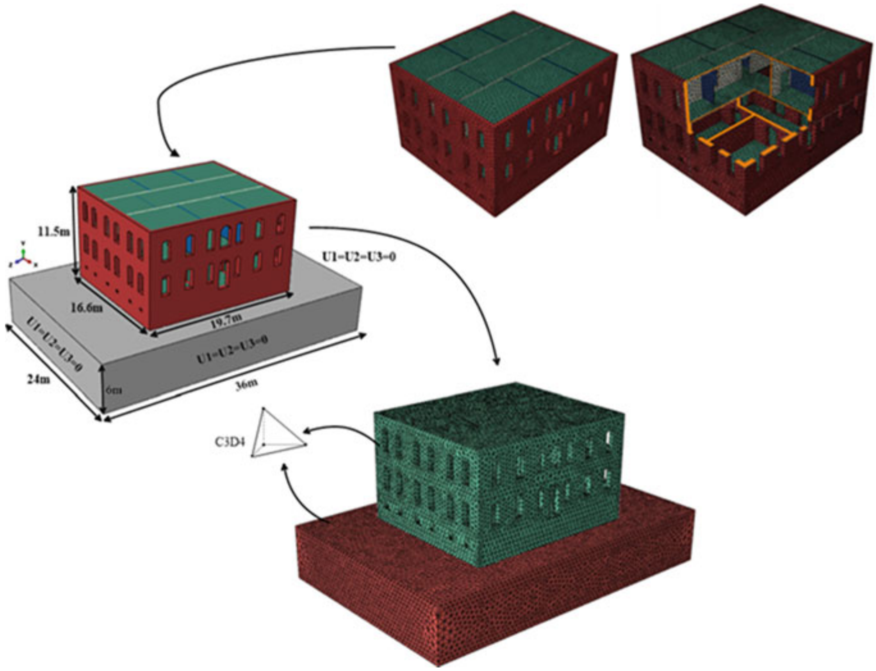


Fig. 2.2 Views of the numerical model with soil-structure system

Plasticity (CDP) model, adept at accommodating masonry structures, was employed to characterize the nonlinear material behavior of the masonry units (Lubliner et al. 1989; Lee and Fenves 1998). The tables containing the chosen linear and nonlinear material properties for the analysis can be found in Tables 2.1, 2.2, and 2.3 (General Directorate for Foundations 2017; Tiberti et al. 2016).

In the literature, soil-structure interaction (direct approach) is rare considered in damage assessment studies caused by soil settlements in historical structures. Generally, substructure approach is preferred over soil-structure interaction (direct approach). In this paper, rare approach in the literature was used to detection of

Table 2.1 The linear elastic parameters used in the numerical model (General Directorate for Foundations 2017)

Elements	Young's modulus (N/m^2)	Poisson ratio (–)	Material density (kg/m^3)
Masonry	1.8E9	0.2	1800

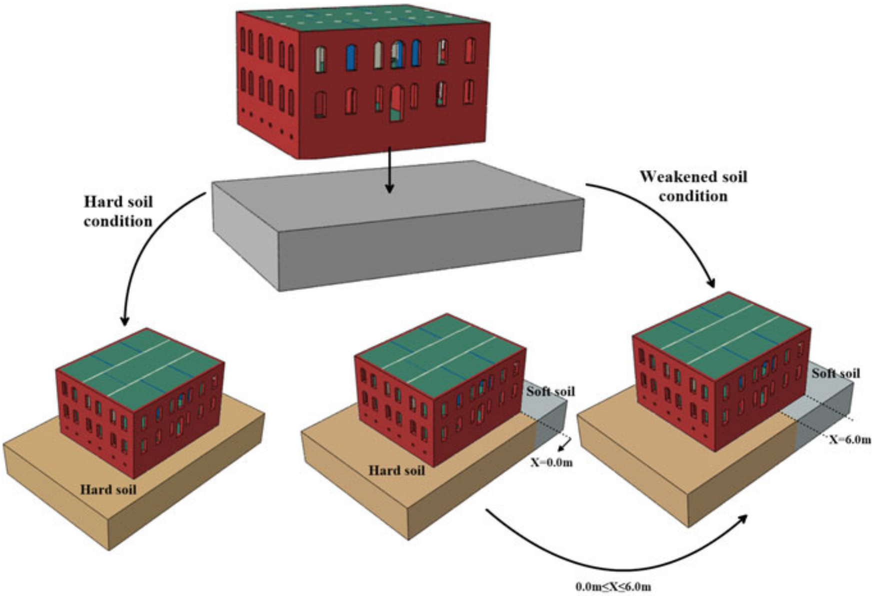
Table 2.2 CDP model parameters (Tiberti et al. 2016)

Material	Dilation angle	Eccentricity	f_{b0}/f_{c0}	K_c	Viscosity parameter
Stone	10	0.1	1.16	0.666	0.002

Table 2.3 Stress–strain values and damage parameters of the masonry (Tiberti et al. 2016)

Compression		Tension		Tensile damage parameters	
σ (MPa)	ε^{pl}	σ (MPa)	ε^{pl}	d_t	ε_t^{pl}
1.22	0	0.04	0	0	0
0.95	0.005	0.0005	0.003	0.95	0.003
0.95	0.001	0.0005	0.1		
0.8	0.1	–	–		

numerical damages of historical masonry school building caused by soil settlement. Therefore, the FE model of the soil domain was considered, and the elasticity module and density of the soil domain were changed to represent the damage to building due to the soil settlement. To achieve this aim, soil domain was tried to represent with a softer soil condition. The soil medium were progressively weakened. The soil domain conditions is shown in Fig. 2.3.



Soil	Modulus of Elasticity (N/m²)	Poisson Ratio (-)	Density (kg/m³)
	5.68E+9	0.30	2064
	3.45E+7	0.40	1667

Fig. 2.3 Views of numerical models for the soil-structure system and soil properties

Table 2.4 Comparison of natural frequencies

		Frequency (Hz)		
		f_1	f_2	f_3
Hard soil condition		7.596	8.528	9.154
SSI system	Z = 0 m	7.579	8.478	9.141
	Diff. (%)	*8.63*	*8.37*	*5.40*
	Z = 2 m	6.925	7.768	8.647
	Diff. (%)	*4.27*	*9.71*	*3.55*
	Z = 4 m	6.629	7.014	8.340
	Diff. (%)	*5.08*	*7.86*	*0.04*
	Z = 6 m	6.292	6.463	8.337

2.4 Numerical Analyses

2.4.1 Modal Response

This section pertains to the vibration response of the building, focusing on scrutinizing the influence of varied settlements, shifts, and deformations at the foundation due to the deterioration of soil properties on both mode shapes and frequencies—integral dynamic attributes of the structure. Through modal analysis, the mode shapes and natural frequencies were extracted. A comparative overview of the natural frequencies is presented in Table 2.4. Furthermore, mode shapes of the building are given in Fig. 2.4. Across all scenarios, the mode shapes were identified as transverse, longitudinal, and torsional modes. Both Table 2.4 and Fig. 2.4 highlight the discernible trend of frequency reduction with increasing distances of soil weakening.

2.4.2 Damage Condition

Geometrically nonlinear analyses were conducted to discern the impact of soil settlement and the resulting structural damage to the building. During the analyses only the self-weight of the building was considered. As a result of the analysis, the displacement values in the Z direction were examined to determine the out-of-plane behavior in the part of the structure where the ground weakening is made. Deformed and undeformed shapes of the building in the Z direction for hard soil and weakened soil conditions are given in Fig. 2.5. Also, the maximum values of these contour diagrams are given in Table 2.5. As seen in Fig. 2.5 and Table 2.5, the higher displacement values obtained in weakened soil condition according to hard soil. In addition, an increase in displacement values was observed as the weakened soil distance increased. From this point of view, it can be concluded that the deformations occurred in the soil and structure will also increase as the distance of the weakened soil increases.

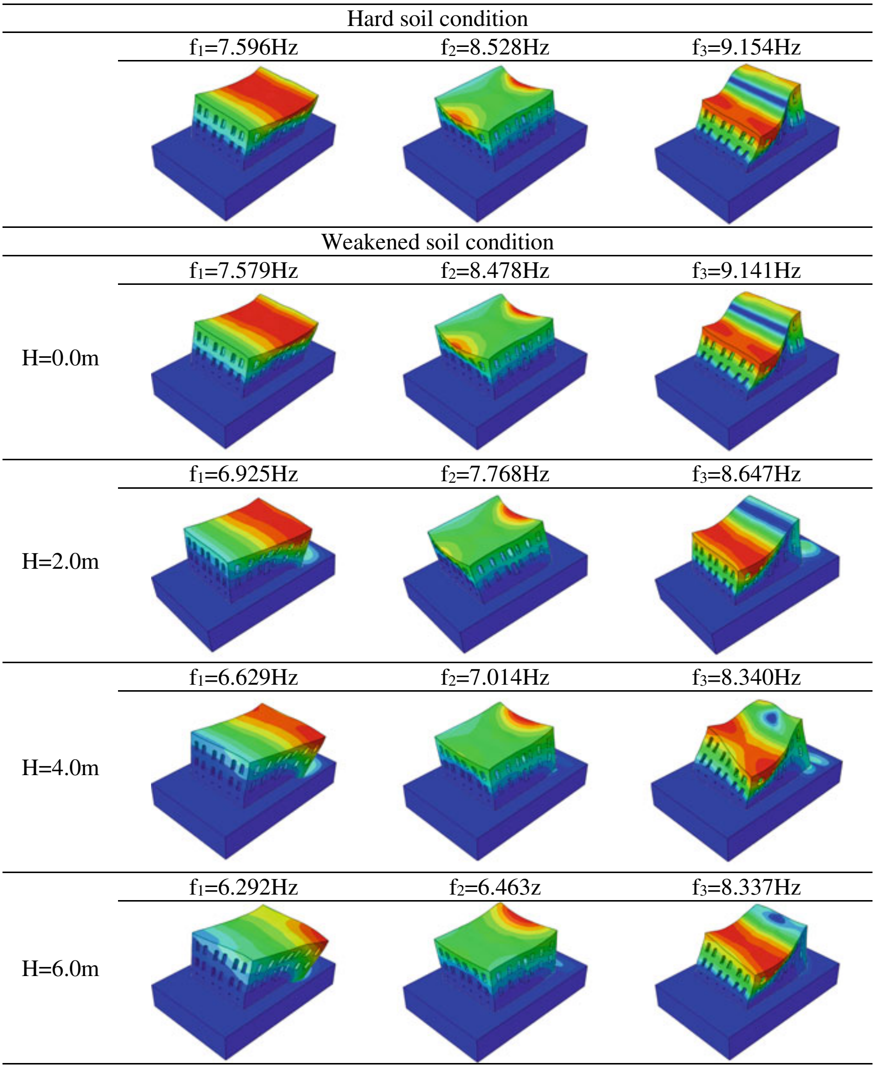


Fig. 2.4 Mode shapes of the building

The damages, which can be occurred based on different settlements, slips and deformations at the foundation due to the weakening of soil properties, were explained with tensile damage. Tension damage results for SSI systems are given in Fig. 2.6. The number of damaged elements obtained numerical analyses are given in Table 2.6. It should be noted from the Table 2.6 and Fig. 2.6 that the building is almost undamaged in hard soil condition and 0 m of weakened soil condition. On the other hand, cracks occurred, and the number of damaged elements increased as

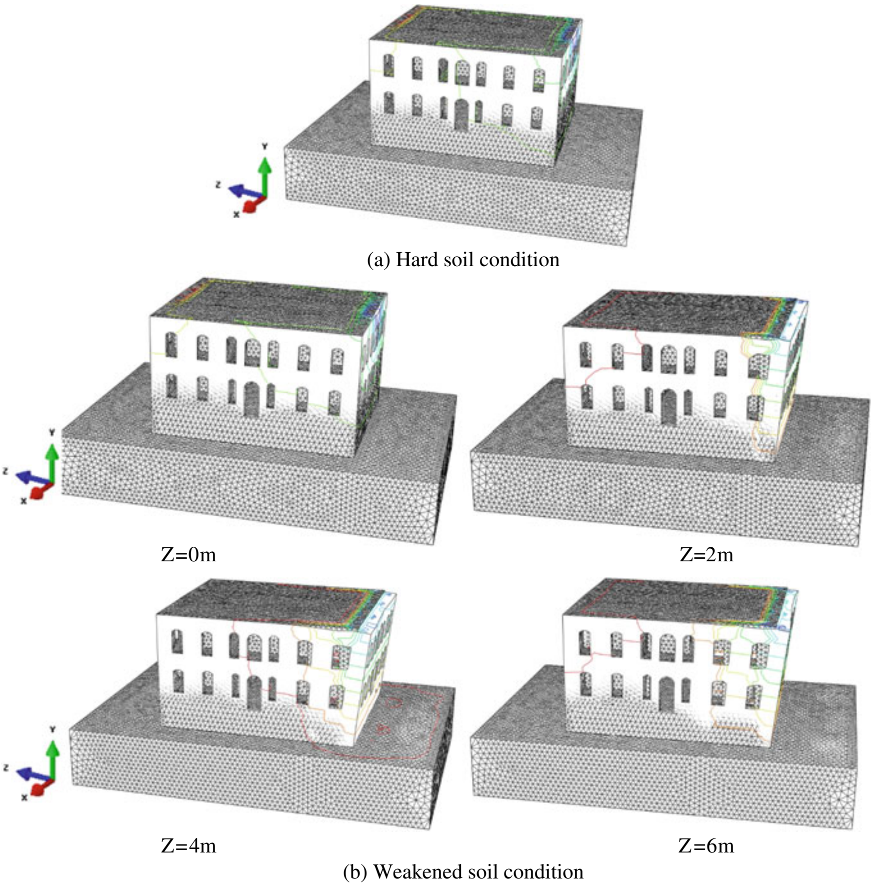
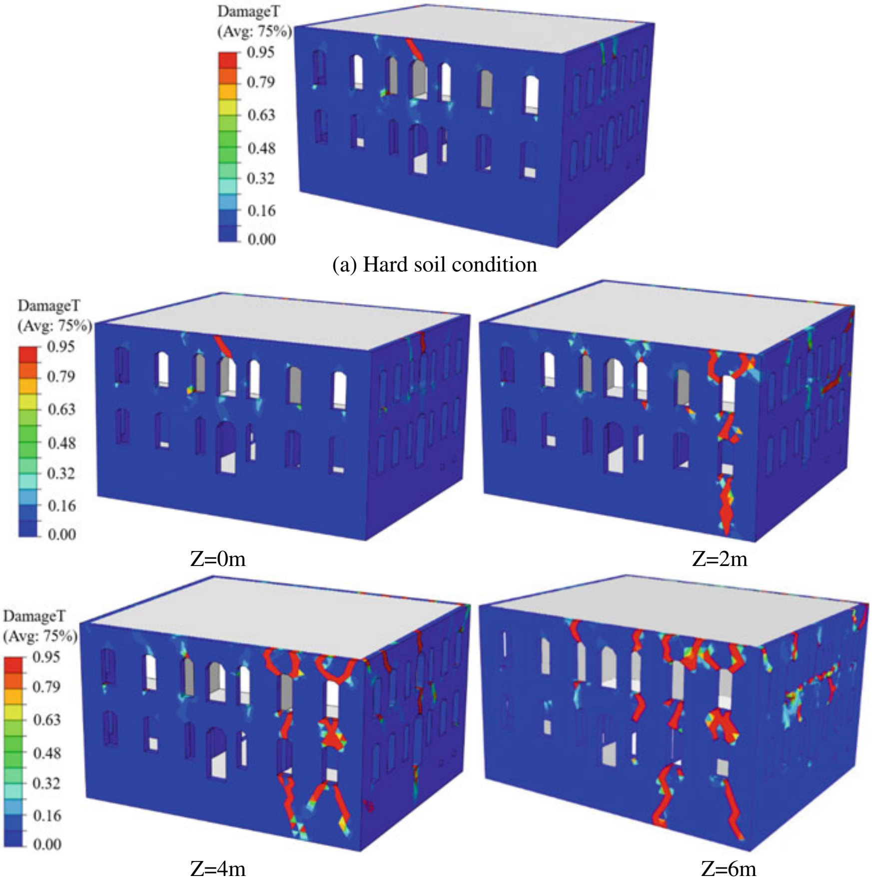


Fig. 2.5 Deformed and undeformed shape of the building in the Z direction for **a** hard soil and **b** weakened soil condition

Table 2.5 The comparison of the maximum displacements

	Max. displacement (m)	
	Z Direction	
Hard soil condition		0.0057
Weakened soil condition	X = 0.0 m	0.0064
	Diff. (%)	*80*
	X = 2.0 m	0.032
	Diff. (%)	*3.03*
	X = 4.0 m	0.033
	Diff. (%)	*5.71*
	X = 6.0 m	0.035

weakened soil distance increased. The structural damages occurred window openings and roof joints. The number of damaged elements constitutes 0.53% of the total number of elements in the hard soil condition. On the other hand, percentage of damaged elements are 0.54%, 1.20%, 1.70% and 2.23% for 0.0 m, 2.0 m, 4.0 m and 6.0 m of weakened soil condition, respectively.



(b) Weakened soil condition

Fig. 2.6 Tension damage level for **a** hard soil and **b** weakened soil condition

Table 2.6 The amount of damaged elements and differences

SSI		Damaged elements	Diff.[a] (%)
Hard soil condition		429	0.53
Weakened soil condition	Z = 0 m	437	0.54
	Z = 2 m	964	1.20
	Z = 4 m	1366	1.70
	Z = 6 m	1788	2.23

[a] Diff. were calculated based on total number of elements (80,338)

2.5 Conclusion

In this paper, modal response and damage condition of a real historical masonry building which was damaged due to soil problems were investigated. The conclusion of this study is given the below;

- The initial three natural frequencies were identified as transverse, longitudinal, and torsional modes across all Soil-Structure Interaction (SSI) configurations. Notably, higher frequency values were recorded in scenarios with robust soil conditions compared to those with compromised soil conditions. Furthermore, it was observed that frequency values exhibited a decrease as the distance of soil weakening expanded.
- The higher displacement values obtained for weakened soil condition according to hard soil in *Z* direction. Also, an increase in displacement values were observed as the weakened soil distance increased. Differences between maximum displacement values changes from 3.03% to 80%
- The building is almost undamaged in hard soil condition and 0 m of weakened soil condition. The number of elements, which reaches damage parameter, 0.53% and 0.54% for these conditions. So, the building can be considered almost undamaged. On the other hand, percentage of damaged elements are 1.20%, 1.70% and 2.23% for 2.0 m, 4.0 m and 6.0 m of weakened soil condition, respectively. It was observed that cracks occurred and the number of damaged elements increased as weakened soil distance increased.
- The main structural damages occurred near the window openings.

In this paper, proposed approach is a rare approach specified in the literature. However, it makes it possible to consider different soil settlements by modeling the soil domain in finite element models. Especially, considering soil settlements is important in the evaluation of the structural behavior of the historical masonry structures. Because, historical masonry structures are very sensitive to the a smallest soil settlement as they exhibit a brittle behavior.

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