CITY-SCALE EARTHQUAKE VULNERABILITY ASSESSMENT INCLUDING NONLINEAR SOIL-STRUCTURE INTERACTION

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Abstract

To date, significant research aims towards a resilient, low-risk built environment, leading to an increasing number of seismic fragility and vulnerability assessment studies. However, in most cases, the influence of the underlying soil conditions remains vague. Our purpose is to evaluate the effects of fully nonlinear soil-structure interaction on urban-scale earthquake vulnerability of reinforced concrete buildings, i.e. accounting for the nonlinear behavior of the foundation-soil and the structure, as well as soil-structure interaction. In particular, the soil-structure system is modeled using three different approaches to foundation a) with its base fixed, neglecting soil-related effects (i.e., the superstructure is rigidly linked to the ground which in turn is considered practically rigid) b) with its base fixed, including site amplification effects and (c) with Beam-on-Nonlinear-Winkler-Foundation spring elements that take into account the phenomenon of soil-foundation-structure interaction, as well as the influence of nonlinear soil behavior. Eleven real seismic recordings are used to describe bedrock movement. Incremental Dynamic Analysis is used to determine the interstory drifts for each building model under consideration. We adopt four damage states, namely Slight Damage, Moderate Damage, Extensive Damage and Complete Damage. In this paper we focus on the large-scale risk assessment of a building city block, containing different structural typologies exposed to seismic hazard. This building block consists of ten buildings with a Moment Resisting Frame system and eight with a Dual system. We estimate the vulnerability of a dense city block of Thessaloniki, Greece, and we include detailed soil properties extracted from microzonation studies in the area, as well as information about the buildings' foundation system. We then calculate the seismic vulnerability of the city block neglecting the soil and its interaction with the structure, and we compare to highlight the influence of the foundation-soil to the risk assessment. Pre-processing, post-processing and the numerical analyses are performed using open source tools, namely OpenSees and Python programing language scientific tools.

Keywords: risk assessment, nonlinear soil, SSI, building blocks, moment resisting frames, dual systems

1. Introduction

Seismic risk evaluation has grown into an essential tool for engineers, insurance firms, administration, and civil protection groups regarding disaster risk reduction (DRR), ranging from building-specific to global-level maps [1]. Occasional earthquake events of large magnitude stress the absence of data about earthquake losses and damage, particularly when it comes to specific structural typologies, subsoil conditions and additional particularities that further refine the available information. On the other hand, numerical models represent a nearly-always practical method to assess seismic risk. In specific, numerous fragility and vulnerability functions have already been developed [2], satisfying a broad variety of structural typologies faced worldwide. Nevertheless, subsoil-specific studies of this extent are not available and soil-structure interaction (SSI) effects are infrequently incorporated [3, 4, 5, 6]. As a result, generic fragility functions are usually used, only parameterized in terms of the building typologies and neglecting nonlinear SSI. Recently Petridis and Pitilakis [7] proposed fragility modification factors to include, in an efficient and accurate manner, the nonlinear soil response and the SSI into the calculation of fragility curves for buildings.

The purpose of this study is to extend the assessment of the seismic vulnerability of a single building, including nonlinear foundation soil response and SSI, to a building block in a densely populated city center. The center of Thessaloniki in Greece is used as a case study, and the selected building block consists of eighteen reinforced concrete (RC) buildings. In particular, the soil-structure system is modeled using three different modeling approaches of the foundation: a) as fixed-base, neglecting soil-related effects (i.e., the superstructure is firmly fixed to the ground which in turn is considered practically rigid), b) as fixed-base, but including site amplification effects and (c) with Beam-on-Nonlinear-Winkler-Foundation (BNFW) spring elements that take into account the phenomenon of soil-foundation-structure interaction, as well as the influence of nonlinear soil behavior (site amplification). Eleven real seismic recordings are used to describe bedrock movement. Incremental Dynamic Analysis (IDA) is used to determine the interstory drifts for each building model under consideration.

2. Methodology

2.1 Building models

The numerical models for the buildings are developed using OpenSees [8]. Specifically, the uniaxial “Concrete01” and “ReinforcingSteel” materials are used to create the fiber elements of the buildings. “Concrete01” material object implements the modified Kent and Park concrete model [9] proposed by Scott et al. [10] with degraded linear unloading/reloading stiffness based on the work of Karsan and Jirsa [11]; “ReinforcingSteel” implements the reinforcing steel material model, based on the backbone curve described by Chang and Mander [12]. In this manner, we adopt a distributed plasticity approach which captures material nonlinearities along the length of the elements developed and overcomes the necessity for moment-curvature calculations and plastic hinge length definitions.

2.2 Soil model

The corresponding numerical model of the soil under the buildings is developed in OpenSees as a pseudo-1D equivalent of the physical free field, using “Quad” elements. Soil nonlinearities are inherently taken into consideration via the use of the “PressureIndependMultiYield” soil material. A single “zeroLength” element is used to define the Lysmer and Kuhlemeyer [13] dashpot, hence, compliant with the dashpot configuration, the input motion at the base of the soil model is defined in terms of velocity. The resulting input force series is obtained by multiplying the given velocity time-series by a constant factor equal to the product of the area of the soil column base with the mass density and the shear wave velocity of the underlying bedrock. The mesh size is determined by the scheme of resolving the propagation of the shear waves at/below a specified frequency, ensuring that an adequate number of elements fit within a wavelength of the shear wave considered (typically 8 to 10). The response of each pseudo-1D analysis is calculated in terms of acceleration at the surface of the soil column and is thereafter used as the foundation input motion for the dynamic analyses of the foundation-building models.

2.3 Soil-structure interaction

Inertial SSI effects are implemented adopting the Beam-on-Nonlinear-Winkler-Foundation (BNWF) spring-type elements [14]. We also developed the fixed-base structural models which act as a benchmark for the assessment performed, deliberately free of SSI effects.

The BNWF model is achieved using the "ShallowFoundationGen" command. The footing model consists of a system of closely spaced independent nonlinear springs, coupled with a dashpot and gap elements, with backbone curves of the nonlinear springs. Vertical springs distributed along the base of the footing aim to capture rocking, uplift and settlement, whereas horizontal springs attached to the sides of the footing are used to capture the resistance against sliding and passive pressure. The BNWF model parameters have been calibrated against centrifuge experiments [15].

2.4 Dynamic analyses

Incremental Dynamic Analysis (IDA) is performed to derive a cloud of intensity measure (IM) against engineering demand parameter (EDP) pairs [16, 17]. We select PGA referring to the underlying bedrock as the IM and maximum interstory drift (maxISD) as the EDP. Qualifying PGA on rock conditions as IM facilitates highlighting the differences introduced by soil nonlinearities; the use of maxISD as the EDP provides an efficient overview of the damage at global level. For the IDA, we selected ground motions recorded at soil type A according to EC8. The recordings represent the ground motion at the underlying bedrock and thus eliminate any site effects and soil uncertainties. We deliberately excluded any duplicate events to derive a set of unbiased independent records. The earthquake recordings that we used are shown in Table 1. For the IDA, the input ground motions are scaled at bedrock level from 0.0 to 1.0g by a constant step of 0.05g. Fig. 1 presents the response spectra of the ground motions used, all of them recorded on sites classified as rock.

Table 1. Earthquake recordings.

No.	Location	Database Code	R_{epi} (km)	M_w	PGA (m/s^2)	Vs,30 (m/s)	Soil type (EC8)
1	Tabas/Iran	ESMD_59	12.00	7.35	3.16	826.00	A
2	Montenegro/Montenegro	ISESD_223	21.00	6.90	1.77	1083.00	A
3	App.Lucano/Italy	ITACA_614	9.80	5.60	1.62	1024.00	A
4	Kobe/Japan	NGA_1108	25.40	6.90	2.85	1043.00	A
5	Sierra Madre/Mexico	NGA_1645	6.46	5.61	2.71	821.69	A
6	Loma Prieta/USA	NGA_3548	20.35	6.93	4.12	1070.34	A
7	Whittier Narrows/USA	NGA_680	13.85	5.99	1.10	969.07	A
8	Northridge/USA	NGA_994	25.42	6.69	2.84	1015.88	A
9	Izmit/Turkey	T-NSMP_1109	3.40	7.60	1.65	826.11	A
10	East Sicily/Italy	ITACA_314	28.30	5.60	0.61	871.00	A
11	Western Tottori/Japan	KIK-Net_3775	31.37	6.60	1.55	967.27	A

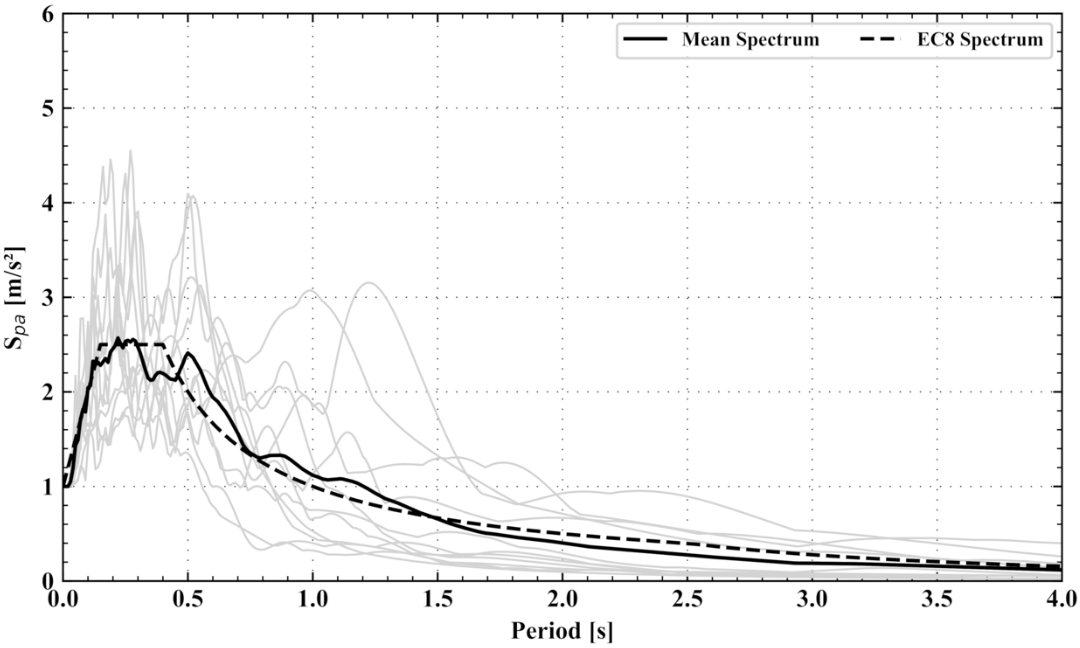

Fig. 1 – Normalized elastic response spectra of the selected ground motions; mean spectrum; EC8 spectrum

2.5 Fragility and vulnerability

Fragility curves represent the probability of exceeding a predefined limit state, as a function of an engineering demand parameter, under a seismic excitation of given intensity. Eq. (1) describes the cumulative conditional probability of exceeding a DS for a given IM.

$$P[DS|IM]=\Phi\left(\frac{\ln(IM)-\ln(\overline{IM})}{\beta}\right) \tag{1}$$

where Φ is the standard normal cumulative distribution function, IM is the intensity measure of the earthquake expressed in terms of PGA, $\overline{\text{IM}}$ is the corresponding median value, β is the log-standard deviation and DS is the damage state. In particular, the log-standard deviation parameter β characterizes the total dispersion related to each fragility curve. There are three primary sources of uncertainty which contribute to the total variability of any given limit state [18]; (i) the variability related to the definition of the limit state value, (ii) the capacity of each structural model and (iii) the seismic demand. The log-standard deviation referring to the definition of the limit states is equal to 0.40 and the corresponding value regarding the capacity is assumed equal to 0.30 for structural systems designed with no/low seismic code [18]. The latter source of uncertainty, associated with the seismic demand, is explicitly evaluated estimating the dispersion for the logarithms of PGA – maxISD pairs, with respect to the selected regression method.

We adopt four damage states, namely Slight Damage (SD), Moderate Damage (MD), Extensive Damage (ED) and Complete Damage (CD) [19]. To further associate nonlinear soil behavior and SSI with damage and expected losses, we derive the vulnerability product of the presented fragility curves. For this purpose, we select the respective Kappos et al. [20] damage indices.

3. The examined city block in Thessaloniki

3.1 Exposure

At the beginning of the interwar era, the use of steel reinforcements in the construction of load-bearing building structures in the urban center of the city began to increase. During the 1930s and 1940s, when construction activity was considerably intense, the use of reinforced concrete was applied to the structural members of high-rise buildings and smaller-sized dwellings, as well as industrial constructions. Until the first Concrete Works Regulation was adopted in 1954, there was no coherent and consistent set of rules for the design and construction of projects, consequently, seismic loads were not taken into account. Buildings before 1959, which make up a fairly significant proportion of city center buildings, become susceptible to seismic excitations, even if they are of medium intensity.

The above also applies to constructions of the period 1959-1985, as the buildings of that period were constructed adopting earlier regulations, with almost no seismic design; even if they somehow include earthquake resistant design compared to the previous ones, they cannot be considered less susceptible to seismic loads. This is due to the under-designed lateral-load system, the lack of quality control during construction, as well as possible arbitrary modifications, damage from past earthquakes and parameters that ultimately lead to deterioration of their bearing capacity. As regards the 1985-1995 structures, which were designed with stricter earthquake regulations (Royal Decree of 1959 with additional provisions of 1984), there are no significant differences observed, compared with previous building projects, in terms of seismic behavior. Finally, the structures that have been constructed since 1995, which constitute the smallest percentage of the building stock in the center of Thessaloniki, were designed and constructed in accordance with the Greek Anti-Seismic Regulation , the Greek Reinforced Concrete Regulation, or recently the Eurocodes. Underlying damage from the past Thessaloniki 1978 earthquake, combined with the lack of mass concern for the repair/retrofit of existing structures and awareness of the residents about potential hazards, a subsequent major an earthquake could have devastating consequences for the historic city center, which demonstrates the need to accurately assess the seismic vulnerability at city level.

Details for the building block studied are derived from the Hellenic Statistical Authority (ELSTAT) database, particularly in the Population and Labor Market Statistics Department and the Census and Status Department, followed by an on-site survey. The census took place in 2011 and includes the building blocks of the Thessaloniki regional unit, which were classified by their respective geographical code and identification number. Classification divides each building block according to the apartments per square meter. Also, classification according to the use of each building is made, either exclusive or mixed use, followed by a more specific characterization about the exact use (e.g. residential, commercial, offices etc.). Finally, the building blocks are classified according to the type of roof of the building and the main roofing material: roofed buildings, roof tiles, roofing sheets or other materials.

For the purposes of the present study, we select an indicative building block, located in the historic center of Thessaloniki. The buildings that compose the block vary in terms of the lateral load resisting system (moment resisting frames or dual systems), their height and are mainly older structures, representative of the city center built environment. According to the above, the block 1858, as reported in ELSTAT database, positioned between Tsimiski, Georgiou Stavrou, Karolou Diehl, and Hagia Sophia streets, is chosen and consists of eighteen buildings. It is essential to note that this building block consists of ten buildings with an moment resisting frame (MRF) system and eight with a frame-shear wall (dual) system.

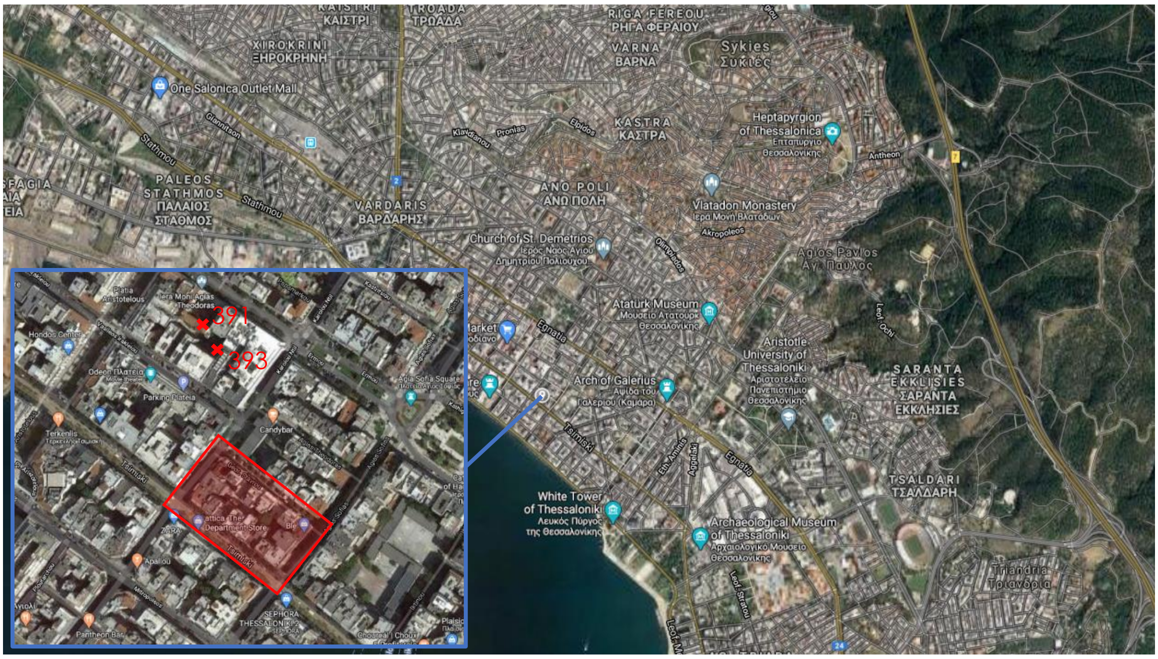

Fig. 2 – Satellite view of Thessaloniki, with the examined building block and borehole locations

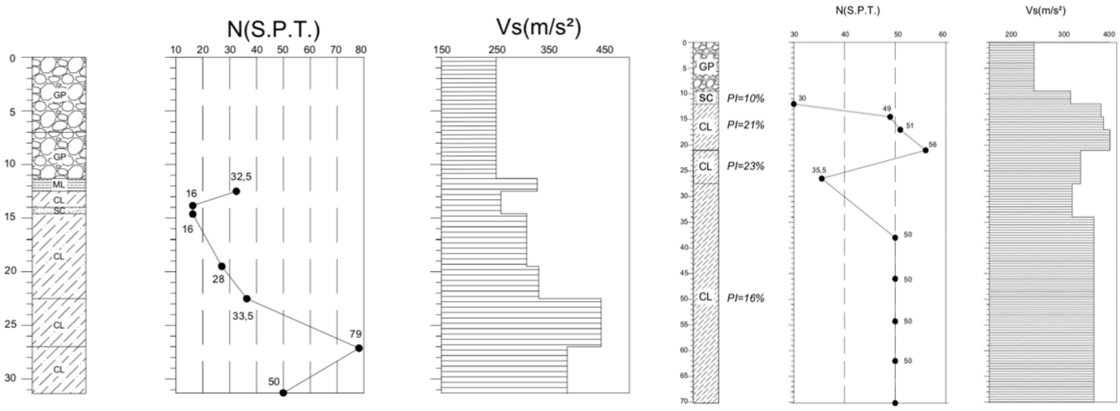

Fig. 3 – Borehole profiles; Left: No.391, Right: No.393

3.2 City microzonation

Thessaloniki is built on top of three major geological formations. These are the metamorphic part, allogeneic deposits and recent holocene deposits. The wider area of the city is characterized by moderate to high seismicity. On the surface layers near the seaside, there are all-terrain formations, consisting of deposits of silty clays, fine sands and loose material. These formations are geotechnically characterized as loose silty to sandy, with varying percentages of clay, low plasticity and varying grading.

The city of Thessaloniki, classified according to EC8, consists of A, B, C and S2 soil types. The basic soil formations of the city are clayey loose formations (Type B soil), located above the rocky substrate. On the surface, soil types A to D are encountered, while the coastal area of the city consists of C-type soils. Their thickness varies from two to ten meters and in some cases from ten to thirty meters, as also happens in the area of the port of Thessaloniki and the western coastal zone towards Kalochori. Subsoil conditions, as shown in Fig. 3, refer to C-type soil according to EC8, while liquefaction effects are practically absent since the block is located at a distance from the coastal front of the city.

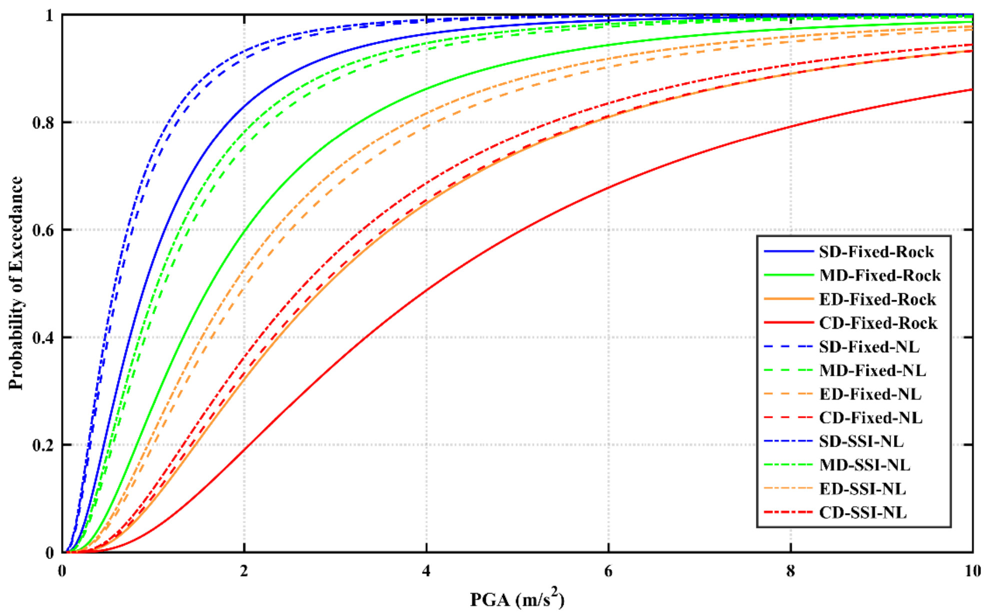

Fig. 4 – Fragility curves for a 9-story MRF building located at the block examined, for the three distinct system configurations (fixed-base on rock, fixed-base on nonlinear soil and flexible-base on nonlinear soil); SD: Slight damage, MD: Moderate damage, ED: Extensive damage, CD: Complete damage

Seismic microzonation studies are essential tools for the organization and planning of urban centers, earthquake preparedness and risk mitigation in areas with high seismicity. Identifying losses for future seismic scenarios is a complex process that requires detail in the modeling of buildings. To include soil-related effects, it is necessary to develop microzonation maps associated with appropriate ground motion parameters according to the selected seismic scenario for the area examined. Hence, the vulnerability of the buildings is assessed on the basis of the calculated ground motion parameters reported in the microzonation study of Thessaloniki [21].

4. Results

This section presents the results of the analyses at single building level and then draws remarks on the total of the building block under consideration. Indicatively, the fragility and vulnerability curves for a 9-story MRF building are presented in Fig. 4 and Fig. 5, respectively. At the macroscopic building block level, we derive the spatial distribution of the damage level and economic remarks on the cost of restoration considering all structures as the worst-case scenario in which the structures contribute with their most damaging seismic response (stress test), i.e. direction. Fig. 6 and Fig. 7 show the results at block level for the seismic scenario where the PGA is equal to 0.16g, i.e. the value corresponding to the seismic zone where Thessaloniki belongs according to the Greek National seismic code.

As already mentioned, fragility curves express the probability that the damage to the structure is equal or greater than a certain level of damage, for a given level of seismic intensity. The earthquake intensity range is here equal to 0-10 m/sec^2 and maximum interstory drift (maxISD) is determined as the EDP at each direction and for each building. The assessment is also made on the basis of vulnerability curves that correlate the probability of damage (e.g. slight, moderate, extensive, complete) and damage index to the level of seismic intensity (PGA). The loss ratio describes the ratio of repair costs to the cost of rebuilding (new). The average loss ratio for a given seismic intensity is calculated based on the probability of occurrence of each damage state and the corresponding loss ratio is determined according to that damage state (for four damage states here). Assuming that the construction cost is 800€/m^2, the economic losses resulting from the impact of the seismic intensity, namely for each seismic scenario, are calculated by multiplying the loss ratio by the total area of the buildings in each category and the abovementioned “per square meter” cost.

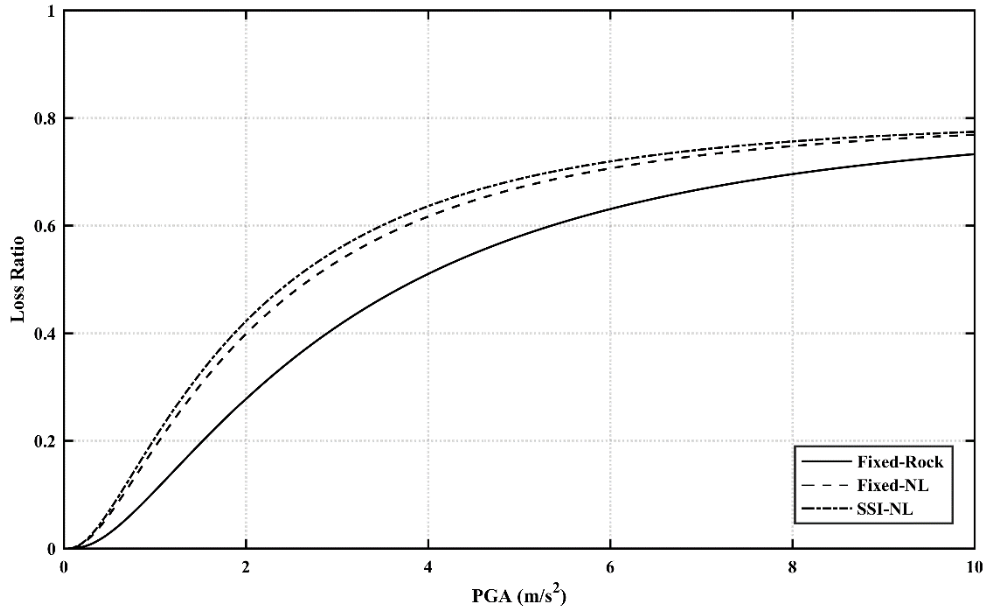

Fig. 5 – Vulnerability curves for a 9-story MRF building located at the block examined, for the three distinct system configurations (fixed-base on rock, fixed-base on nonlinear soil and flexible-base on nonlinear soil)

Fig. 6 – Expected spatial distribution of the losses under the impact of the seismic scenario with PGA=0.16g for the different soil-foundation models; Blue: 0-0.10 level at which construction is moderately damaged; Green: 0.10-0.30 level during which construction sustains major damage; Orange: 0.30-0.60 level at which construction is subject to severe damage; Red: 0.60-1.00, which represents the potential collapse of the structure; Left: Fixed on rock, Middle: Fixed on nonlinear soil, Right: flexible-base nonlinear soil

In the specific case shown in Fig. 4 and Fig. 5, nonlinear soil behavior and SSI effects play a detrimental role in the response of the structure. Mainly, amplification triggered by the soft soil layers above the underlying bedrock and nonlinear soil behavior affect the total vulnerability of the structure. Additionally, SSI influences the assessment results to a lesser -yet substantial- degree.

Fig. 7 – Expected spatial distribution of the repair costs (M €) of the structures under the impact of the seismic scenario with PGA=0.16g for the different soil-foundation models; Left: Fixed on rock, Middle: Fixed on nonlinear soil, Right: flexible-base nonlinear soil

Table 1 – Repair costs (M€) of the structures for the seismic scenario with PGA=0.16g, for the different soil-foundation models

Direction	**Fixed-base on rock**	**Fixed-base on NL soil**	**Flexible-base on NL soil**
X (Tsimiski)	5,0	7,1	7,7
Y (Diehl)	5,1	7,0	7,4
Stress Test	5,5	7,5	8,0

Fig. 6 and Fig. 7 show the spatial distribution of losses and repair cost in the city block for the three different system configurations. It is clear that including actual SSI and nonlinear soil behavior in the vulnerability assessment increases the losses (more severely damaged buildings, Fig. 6) and the total repair cost of the block (Fig. 7). The results are presented in a stress-test form, assuming that each building contributes to the total loss/cost with respect to its unfavorable direction. Table 1 shows the results as total values with respect to each direction examined, as well as with respect to the simplified stress-test attempted. Overall, nonlinear soil behavior is found to be of key importance for the vulnerability assessment results, leading to increased loss/cost due to the motion amplifications caused. Also, SSI appears to have an overall detrimental effect on the vulnerability assessment, again leading to increased loss/cost of repair. However, SSI alone plays a less significant -yet important- role in the assessment, compared to site amplification effects.

5. Conclusions

We have assessed the earthquake vulnerability of a city block at the city of Thessaloniki, Greece. At the building block level, the structural and economic losses of all structures under the impact of seismic excitation with PGA equal to 0.16 g are discussed, which agrees with the corresponding seismic code value for the seismic zone to which the city of Thessaloniki belongs. The conclusions drawn through the procedures outlined above, both at the level of each building individually, and at the level of the city block, are summarized as follows:

- In general, nonlinear soil behavior combined with SSI effects influences vulnerability in a detrimental manner.
- Nonlinear soil behavior seems to have a greater impact on the resulting curves, compared with the influence of SSI. This difference appears to be more pronounced for the PGA values in the range of 2.0-5.0g.
- Soil-related effects influence the resulting fragility curves to a great extent, regarding the less severe damage states, while for extensive and collapse damage levels, nonlinear soil behavior and SSI effects tend to fade.

Also, at the city block level the economic losses resulting from nonlinear soil behavior are again more significant than those arising from soil-structure interaction. It is worth noting that buildings presenting the most economic losses are not necessarily the most vulnerable in terms of their structural response, as the losses occur depending on the built area. Consequently, less structural damage may sometimes lead to greater economic losses for buildings with large built areas.

There is a general belief, which has also been introduced in modern seismic regulations, that the influence of SSI has a favorable effect on the seismic behavior of the structures compared with the rigid base assumption. However, this conclusion is an over-simplification, while the present study indicates the need to consider this effect without pre-judging about the final outcome.

It is demonstrated through analyses that the influence of soil-foundation-structure interaction may be favorable on specific building typologies or cases, but the overall contribution on the seismic response of the building block leads to more damage and economic losses, therefore having an overall detrimental impact. While this conclusion is drawn for older buildings on separate footings, it is generally more accurate to include nonlinear soil behavior and SSI effects in risk assessment procedures, whether it leads to favorable or unfavorable results. This also demonstrates the need for geotechnical surveys prior to the design or assessment of structures so that they can increase structural safety, if the impact of the soil-foundation-structure interaction is adverse to the project's seismic response, or in order to reduce costs in the project, in the case of a favorable effect.

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