buildings

Article

Seismic Damage Index Spectra Considering Site Acceleration Records: The Case Study of a Historical School in Kermanshah

Mahnoosh Biglari [1,*], Marijana Hadzima-Nyarko [2] and Antonio Formisano [3]

[1] Civil Engineering Department, School of Engineering, Razi University, Kermanshah 6718773654, Iran
[2] Faculty of Civil Engineering and Architecture Osijek, The Josip Juraj Strossmayer University of Osijek, 31000 Osijek, Croatia
[3] Department of Structures for Engineering and Architecture, School of Polytechnic and Basic Sciences, University of Naples Federico II, 80131 Naples, Italy
* Correspondence: m.biglari@razi.ac.ir or mahnooshbiglari@yahoo.com

Abstract: The frequency content and time duration of earthquakes are as effective as the peak ground acceleration on structural damage. Therefore, using rapid seismic vulnerability assessment methods that consider the earthquake acceleration time history is noticeable. Kermanshah is a historical city that is generally affected by far-field earthquakes. Therefore, it is necessary to consider the effect of the low-frequency shocks in evaluating the vulnerability of buildings in this city. Herein, a historic school in Kermanshah is assumed as a case study and two well-known damage index formulas are used for determining the damage index spectra of this structure, considered as a single degree of freedom system. Then, the effective parameters of the damage index, including ductility, relative degradation of stiffness, and dissipated energy are determined from a nonlinear analysis of the structure under the effect of the most probable earthquake acceleration records. Finally, the damage index spectra can be used for rapid seismic vulnerability assessment of masonry buildings on similar sites with various fundamental periods for large-scale assessments. The result shows that the building tends to collapse at a peak ground acceleration of 0.15 g. Furthermore, results confirm the seismic resistance reduction effect of flexible floors.

Keywords: seismic vulnerability; damage index spectra; historical masonry building; nonlinear analysis

check for updates

Citation: Biglari, M.; Hadzima-Nyarko, M.; Formisano, A. Seismic Damage Index Spectra Considering Site Acceleration Records: The Case Study of a Historical School in Kermanshah. *Buildings* **2022**, *12*, 1736. https://doi.org/10.3390/buildings12101736

Academic Editors: Rajesh Rupakhety and Dipendra Gautam

Received: 20 September 2022
Accepted: 17 October 2022
Published: 19 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

The first step in reducing the seismic risk in a city is to identify the earthquake hazard and evaluate both the vulnerability of at-risk structures and the consequences of the earthquake. Although the seismic hazard of an earthquake at a site cannot be reduced, it can be determined by studying the seismic sources and determining the set of possible magnitudes of each source with deterministic and probabilistic seismic hazard analysis methods [1]. Realistic knowledge of hazards is helpful in accurately estimating seismic vulnerability and, therefore, seismic risk analysis. Additionally, if there is an accurate assessment of the seismic vulnerability of buildings, it is possible to reduce the seismic risk by retrofitting or renovating vulnerable buildings. Other steps to reduce the seismic risk are providing relief and rescue facilities, and predicting post-earthquake facilities, shelters, and settlement locations [2].

To assess the seismic vulnerability of structures, several rapid and qualitative methods, and different quantitative methods based on the structural condition and modeling of their seismic behavior are available. In the case of historical buildings, destructive identification methods and renovation are usually not available options. Therefore, in historical structures, qualitative and nondestructive identification methods are recommended to evaluate the structural seismic vulnerability. These buildings often have complex geometry and heavy mass, and are not provided with a seismic resistance system, so as a result, they show damage induced by past destructive earthquakes. Choosing the most appropriate vulnerability assessment method depends on the number of assets under investigation, the importance and nature of the structures, the level of access to information, and the available budget. Quantitative assessment methods, based on structural modeling, are time-consuming and expensive and are not recommended in the first evaluation phase. Contrarily, rapid evaluations given by qualitative methods are used in the initial phase of assessment and prioritizing rehabilitation planning. These indirect methods are based on the observation of structural elements and building configurations. An example of an indirect method that uses indicators is the vulnerability index method, introduced by [3] and then developed by other research [4] for masonry buildings. This method uses standard forms to evaluate the seismic vulnerability level of structures by considering several in situ parameters. An extension of the screening tool was presented in [5], where a vulnerability assessment form was used to consider the structural interaction among adjacent buildings. This form added to the basic parameters of the original forms [3] by including five parameters that account for interaction effects among aggregate structural units under earthquakes. Another example of a scoring method is one introduced by the Italian Directive [6], indicated as the Level of Evaluation 1, which was delivered to be used for evaluations at a territorial scale. This method requires only in situ visual inspections, providing a seismic performance in terms of acceptable peak ground acceleration depending on a global vulnerability index. Further, damage matrices and fragility curves help to predict the damage of similar structures by the damage surveys collected after destructive earthquakes. The empirical fragility curves were firstly developed after the 1971 San Fernando (Los Angeles, CA, USA) earthquake by [7], and, subsequently, some remarkable examples came from the 2009 L'Aquila, Italy, earthquake, developed by [8], the 1934 to 2015 Nepali earthquakes, introduced by [9], and the 2017 Sarpol-e-zahab, Iran, earthquake, delivered by [10,11]. Alternative methods to develop fragility curves were provided by studying the structural models of buildings through incremental dynamic analyses (e.g., [12,13]). The advantage to the basic simplified methods is their high evaluation speed. Specifically, the indirect method and empirical fragility curves do not require modeling and structural analysis. The disadvantage to these methods is that they use only the intensity or the peak ground acceleration of the earthquake, without considering the effect of other necessary parameters. Another suggestion is to use a hybrid approach, whereby empirical and analytical methods are combined to obtain quantitative and more reliable results for a group of buildings. A similar way was used by [14] to evaluate a masonry building in Osijek, Croatia.

This research presents the seismic damage index spectra for the historic center of Kermanshah city and evaluates the seismic vulnerability of a historic high school. Kermanshah is the ninth most populated city in Iran and the most significant city in the central region of western Iran. The city of Kermanshah, located in the Zagros seismic zone, has been exposed to several destructive earthquakes throughout history, of which the earthquake of 2016 November 21st is the latest example. The city of Kermanshah is one of the historical and cultural cities of Iran. Its origin dates back to the fourth century AD. It was the second capital of the Sassanid Empire until the Arab invasion of Iran. At the end of the 18th century, Kermanshah's commercial and strategic importance increased with the establishment of the customs office. Most of the attractive post-Islamic historical buildings in Kermanshah include the traditional market (Bazaar), mosques, Takaya, schools, caravanserais, and mansions from the Qajar era. Owing to the high seismicity of Kermanshah, these buildings are prone to seismic damage by the occurrence of destructive earthquakes. One of the issues of earthquake engineering is to evaluate the existing seismic resistance and ductility requirements of existing buildings, and/or prepare crisis maps using real seismic scenarios. Therefore, it is desirable to provide a relatively fast but accurate seismic damage assessment, as the method proposed in this paper. Before this study, a series of investigations were conducted on the seismic vulnerability assessment of the historical mosques of Kermanshah city, including rapid seismic assessment [15], identification of material properties [16], macroelement modeling, pushover analysis, and fragility curves [17].

In this research, the seismic vulnerability of the historic Kazazi High School is evaluated based on the most probable earthquakes at its site by using the damage indices as a measure of structural damage. For the investigated structure, first, a set of three pairs of earthquake records was determined; then, using several assumed single degree-of-freedom (SDOF) systems, the spectral functions of the damage index were determined based on the two definitions presented in the literature. Finally, by knowing the proposed parameters of an SDOF system (e.g., the natural period of investigated structure) representing an unreinforced masonry (URM) building, it is possible to determine the structure's response to a given earthquake using the damage index spectra. Since there is no history of using this methodology and presenting this type of spectra in Iran, this analysis approach can be considered a novel type for the historic area of Kermanshah city. In addition, this method accounts for all the necessary parameters of the earthquake, including the amplitude, frequency content, and duration, by considering the time-history record of the acceleration. Furthermore, equating the structure with an SDOF system facilitates nonlinear analysis. Hence, proposing the seismic vulnerability index spectra, which is not a complicated task, can be very effective. By damage index spectra, the vulnerability of buildings with similar seismic behavior, at a similar seismic site, and different fundamental frequencies (different mass, stiffness, and damping ratio), can be quickly evaluated. It is, therefore, possible to add this method to rapid assessment instructions. The rest of the paper is organized as follows: introduction to the history and architectural characteristics of the school building, description of the damage index functions and properties of the applied seismic accelerograms, presentation of the seismic damage index spectra for original records and different scaled records, and, finally, conclusions on the seismic vulnerability assessment.

2. Kazazi High School

Kazazi High School is the oldest high school in Kermanshah and one of the first Iranian modern-style high schools. The construction of this high school started in January 1921, six years before the modern-style school construction in the Pahlavi period started, by the suggestion and efforts of the late Seyyed Hossein Kazazi (1874–1923). The execution works of the structure ended in 1923. Other traditional schools were established before construction of this high school, but this was the first high school with a modern educational syllabus and equipment, such as classrooms, laboratories, libraries, drawing galleries, and a conference hall. In 1998, this school was registered by the Ministry of Cultural Heritage, Tourism, and Handicrafts (MCTH) of Iran as a national heritage construction of Iran. It operates as a museum after retrofitting in 2009.

The architecture of the building is simple, and more than beautification, a rigorous appearance of the building has been preferred (Figure 1a). Only the brickwork of the facade represents an embellishment system of the building.

In 2006, during the renovation, the building plan changed, and some parts of the transverse walls of the classrooms were removed. Currently, the plan of the building is rectangular, 36 m long in the east–west direction and 16 m wide in the north–south direction (Figure 1b). A corridor with a width of 4.65 m and a length of 36 m (the whole building length) is located in the middle of the building. Classrooms are situated on both sides of this corridor. The width of the classrooms is 4 m, and their length varies from 6.15 to 12.9 m. The main entrance of the building is located on the north side, and another door is located on the east side. Figure 1c–g show the north, south, east, and west perspective views, respectively.

There is another floor in the center of the building, where there are the manager's office, the meeting hall, and the documents archive, along with two terraces on the north and south sides. The staircase is in the middle of the terrace on the north side, which, after renovation, has been surrounded by walls. The height of the first and second floors are 4.00 and 3.80 m, respectively. The wall materials are brick and lime mortar. The ceiling is made of a wooden beam and a gable roof placed on a wooden truss.

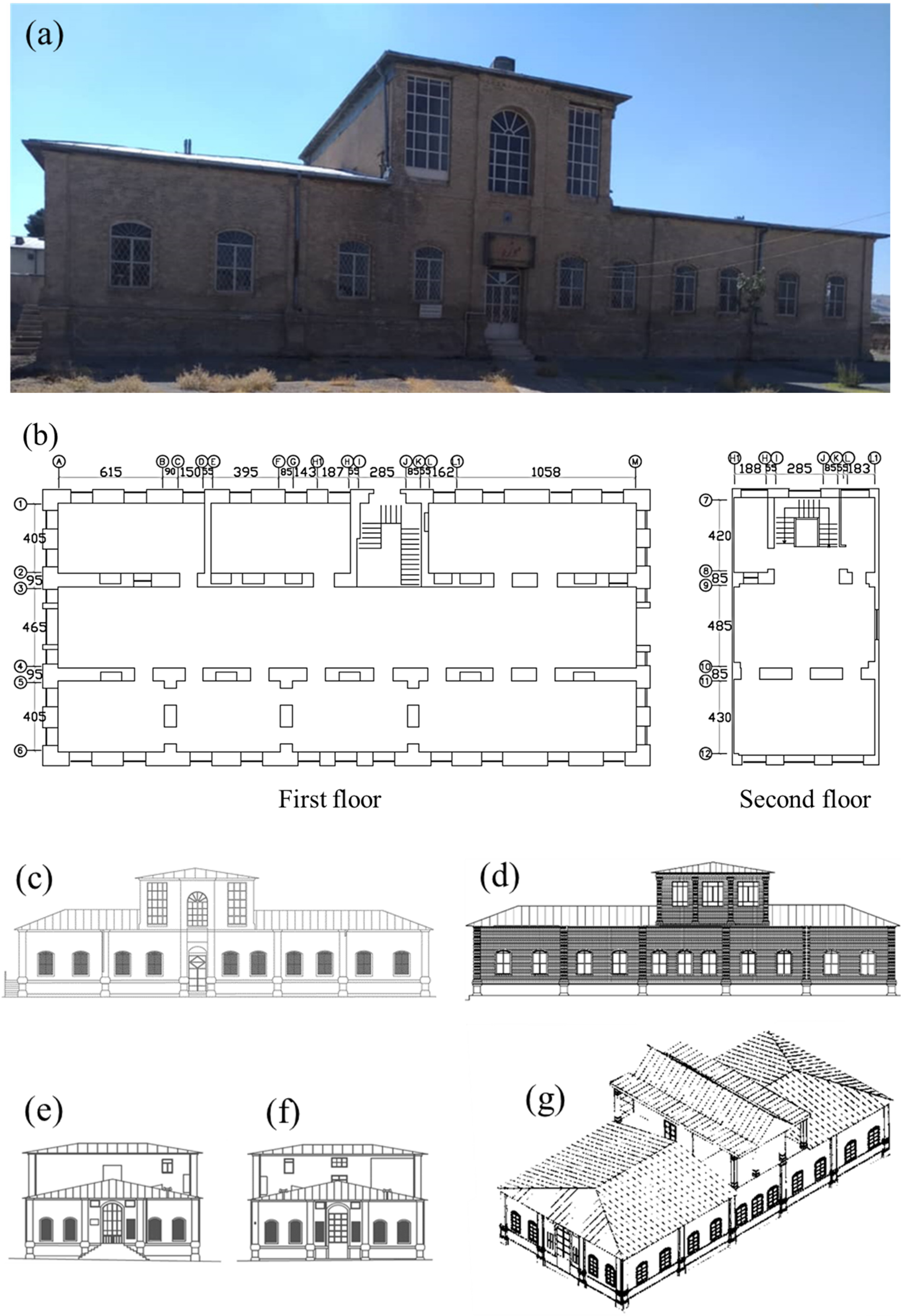

Figure 1. Kazazi High School: (**a**) north-view photo, (**b**) first-floor and second-floor plan (dimensions in centimeter), (**c**) north-view, (**d**) south-view, (**e**) east-view, (**f**) west-view, and (**g**) building perspective.

In addition to the main classroom building, the high school has two additional separate buildings that are not discussed here. These two buildings are (1) the northern building and the main entrance built in 1926 and (2) the meeting hall and theatre built in 1935.

3. Methodologies, Descriptions, and Seismic Records

To perform a seismic vulnerability assessment, the method used in this paper requires the use of appropriate damage index (DI) spectral functions. Particularly, two of these functions are herein considered. One is the function introduced by Park and Ang [18], and the other is the function introduced by Moric et al. [19]. Seismic vulnerability assessments by these methods, in addition to the high speed of the evaluation and the ability to use it for a large number of building stocks on an urban scale, are based on more than just the geometry of the structure, the quality of the materials, and the single parameter of the peak ground acceleration. In these two methods, other than considering the maximum amplitude of the accelerograms, the amplitude in all other cycles, frequency content, and time duration of the record, the force–displacement behavior, and the fundamental frequency of the structure, are also considered. The only simplification made is generalizing the structure with an SDOF system, which is not unrealistic for short buildings. As mentioned, the method of Moric et al. [19] has already been used by [14] to evaluate a historical masonry building in Osijek, named "II Gymnasium Osijek". Further, the well-known function of Park and Ang [18] has not been used to extract the damage index spectrum and is adapted in this research for proposing the damage index spectrum.

The investigated building is modeled by an SDOF system, determined by weight, elastic stiffness, post-elastic stiffness, damping ratio, and strength limit of elasticity. The nonlinear dynamic analyses are performed using the NONLIN code [20] that implements iterative time-history numerical integration. The NONLIN code [20] is a Microsoft Windows-based application for the dynamic analysis of SDOF structural systems. The structure may be modeled as elastic, elastic–plastic, or a yielding system with an arbitrary level of secondary stiffness. The secondary stiffness may be positive, to represent a strain hardening system, or negative, to model P–Delta effects. The dynamic loading may be assigned as an earthquake accelerogram acting at the building's base or as a linear combination of sine, square, or triangular waves applied at the building's roof. The program uses a step-by-step method to solve the incrementally nonlinear equations of motion based on Clough and Penzien's [21] theoretical description. The code needs elastic and post-elastic behavior, damping, and strength limit of elasticity. Then, the code provides dissipated energy, cycle numbers of yielding achieved during the earthquake, force–displacements hysteresis response, and time history of top displacements. These outputs represent inputs for the DI formulas reported in this section.

During dynamic analysis, the input seismic load is represented by a site match acceleration time-history record. DI function calculations are repeated for several SDOF systems with a wide range of fundamental periods from 0.05 to 4.5 s (i.e., T = 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.5, 2.0, 2.5, 3.5, and 4.5 s) by nonlinear analyses. Each spectrum is determined by applying a set of original earthquake acceleration records or the scaled acceleration records to fixed values ranging from 0.075 to 0.75 g (i.e., PGA = 0.075, 0.15, 0.20, 0.30, 0.45, 0.60, and 0.75 g).

For the historical center of Kermanshah city, three pairs of records (i.e., six horizontal records) of real accelerograms recorded in the KRM1 station of ISMN [22] are selected. For any kind of dynamic analysis, the Seismic Code of Iran IRSt2800 [23] suggests applying three pairs of records (i.e., six horizontal records) or seven nonpair records compatible with the site. The KRM1 is the most seismically compatible with the historical center of Kermanshah city. The KRM1 station and the investigated structure are located in the same seismotectonic plateau in Zagros. They are located close to each other and at a similar distance from the active faults of the region. Regarding the geological conditions, both sites are located on type II soil category based on the Seismic Code of Iran IRSt2800 [23] from the average shear wave velocity of the upper 30 m of the soil, as provided by [24].

On the other hand, the Kazazi High School building is located in the vicinity of the Jame Mosque, whose ground seismic properties have been studied and reported by [16] as type II. In addition, the investigated building has experienced the KRM1 recorded events. This provides a benchmark for verification of the vulnerability assessment result with factual events. The records used in this research are presented in Table 1.

Table 1. Accelerograms used in the analysis.

Record Number	Date d/m/y	Time h:min:s	PGA (cm/s^2)	Latitude	Longitude	Epicentral Distance (km)	Focal Depth (km)	Magnitude (Mw)	Reference
2730	24/04/2002	19:48:07	12	34.65	47.47	53	14	5.3	ISMN *
7292	12/11/2017	18:18:16	55	34.81	45.91	120	18	7.3	ISMN
8250	25/11/2018	16:37:31	12	34.31	45.69	128	16	6.3	ISMN

* [22].

The damage index, which can be used for damage estimation, is defined as a mathematical function, where 0 means the undamaged state of the structure and 1 indicates failure.

Equation (1) introduces the DI function developed by Park and Ang [18], which is composed of two terms controlling the seismic behavior of a masonry structure: the first term depends on the ductility and the second term depends on the dissipated energy. This function is expressed through the following relationship:

$$DI = \frac{u_{max}}{u_{ult}} + 0.15\frac{E_H}{F_{cr}u_{ult}} \tag{1}$$

where u_{max} is the maximum displacement reached, u_{ult} is the ultimate displacement, E_H is the energy amount dissipated by hysteresis, and Fcr is the force at the cracking limit, which is considered equal to the strength limit of elasticity fy.

Moric et al. [19] proposed Equation (2) as a DI function. This function has three terms: the first term depends on the ductility, the second term depends on the relative degradation of stiffness at the end of the earthquake, and the third term depends on energy dissipation during loading and unloading cycles. It is expressed through the following relationship:

$$DI = \frac{1}{30}\left[\mu + \Delta k + \sqrt[3]{\frac{N_\gamma E_H}{W}}\right] \tag{2}$$

where μ is the required ductility displacement equal to u_{max}/u_y; $\Delta k = k_{el}/k_R$ is the relative degradation of stiffness at the end of the earthquake, $k_{el} = f_y/u_y$ the initial stiffness and $k_R = f_{max}/u_{max}$ the residual secant stiffness at the end of the earthquake; N_γ is the cycle number of yielding achieved during the earthquake; E_H is dissipated energy during the earthquake; and W is structure weight.

Moric [25] presented a modification to the DI function for unconfined masonry buildings with flexible floor structures (DI_{flex}) by using a correction coefficient, which is a function of the floor type, the masonry tensile strength (f_t), and the ratio between the wall length perpendicular to the direction of the earthquake (l) and the story height (h). For timber-floor-type ceilings and f_t < 0.15 MPa for Kazazi High School, DI/DI_{flex} changes according to the data shown in Table 2. Hence, depending on the maximum l/h ratio, the DI values should be modified to find the maximum DI_{flex} that corresponds to the most damaged state of the investigated structure.

Table 2. DI/DI_{flex} to l/h for URM buildings up to three stories, timber floor, and f_t < 0.15 MPa (after Moric [25]).

l/h	2	3	4	5	6
DI/DI_{flex}	0.70	0.30	0.18	0.12	0.10

The investigated building is modeled as an SDOF system with a constant weight W = 1000 kN or through the lumped weight of the structure, equal to the roof weight plus the half weight of the walls. Since the DI is expressed in terms of the fundamental period of the building (T), the combinations of mass ($m = W/g$), elastic stiffness (k_{el}), and damping ratio (ξ) are necessary. Therefore, any assumption for weight could be considered. Thus, the desired fundamental period of the SDOF system could be obtained by considering the elastic stiffness, mass, and damping ratio. A damping ratio of 5% has been considered for the investigated building.

Furthermore, since masonry structures do not have post-elastic stiffness, the elastic–perfectly plastic behavior is considered for a post-elastic branch (i.e., $k_1 = k_{el}$, and $k_2 = 0k_{el}$). Additionally, the strength limit of elasticity (f_y) is considered equal to 10% of the total weight of the structure (i.e., $f_y = 0.1\ W = 0.1$ mg), since it represents the structure with low elastic earthquake resistance.

Finally, the DI of the investigated building is read from the DI spectra versus the fundamental period of the building. For predicting the fundamental period of the building, this study uses the last version of the Iranian seismic code IRSt2800 [23], which suggests the following empirical Equation (3) for masonry structures:

$$T = 0.05H^{0.75} \tag{3}$$

where T is the fundamental period and H is the total structure height.

To classify structural damage, Table 3 presents damage descriptions related to DI values for both DI functions.

Table 3. DI values and damage description.

DI Function	Damage Index Value (DI)	Damage Description	Damage State
Park and Ang [22]	1.0 < DI	Total collapse	Complete
	0.77 < DI ≤ 1.0	The structure is near to collapse	Extensive
	0.40 < DI ≤ 0.77	The structure has undergone severe and nonreversible damages	Moderate
	DI ≤ 0.40	The structure has limited damage	Slight
Modified Moric et al. [23]	1.0 < DI	Extremely high level or collapse	Collapse
	0.8 < DI ≤ 1.0	Heavy	Extensive
	0.5 < DI ≤ 0.8	Severe	Moderate
	0.3 < DI ≤ 0.5	Moderate	Light
	DI ≤ 0.3	Insignificant	Slight

The DI classification is based on four categories from the Park and Ang [18] DI formula, while the classification of Moric et al. [19] is based on five-category criteria, the same as EMS 98 [26].

Figure 2 shows the methodology flowchart for DI spectra and the seismic vulnerability assessment procedure.

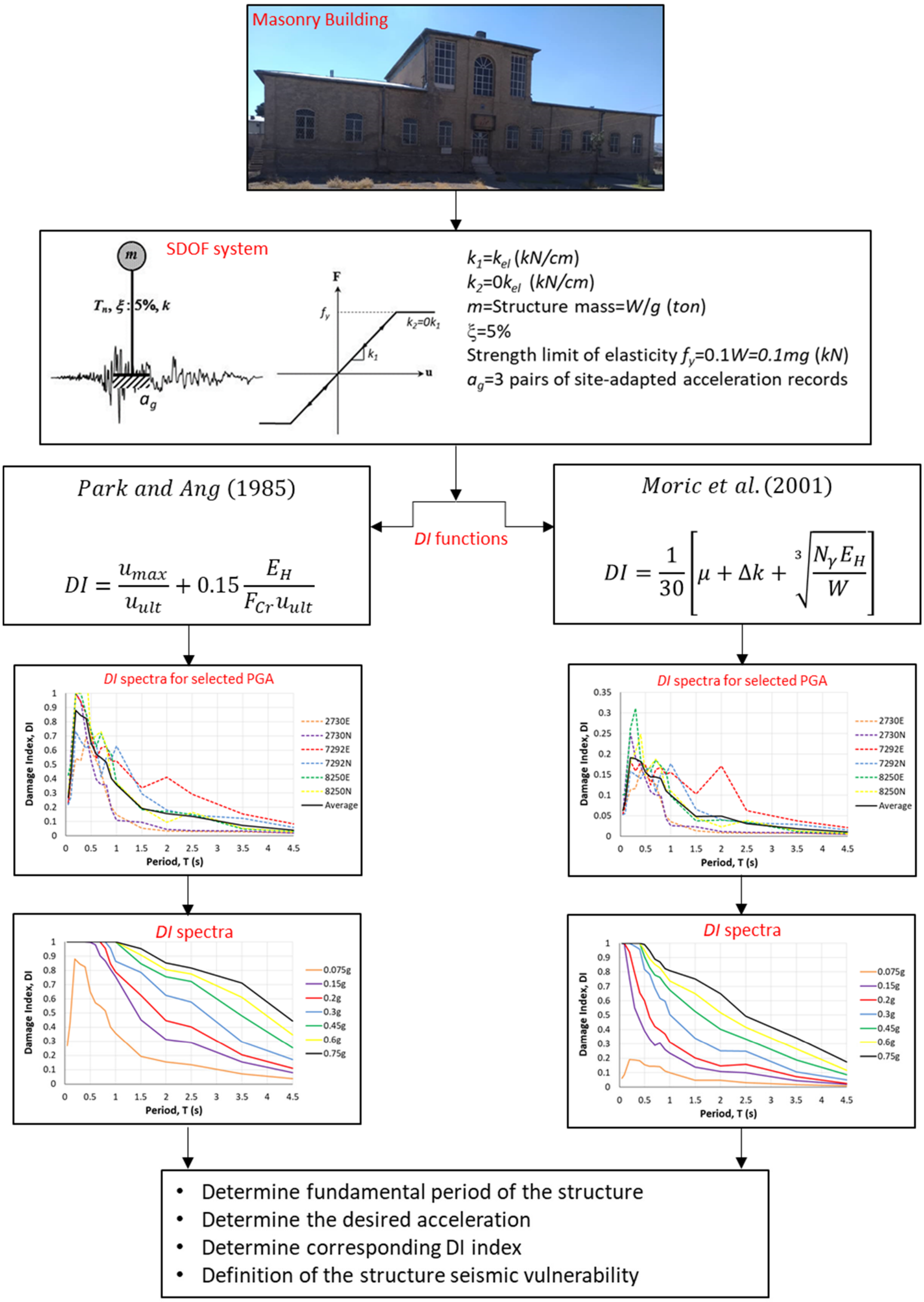

Figure 2. Methodology flowchart for DI spectra and seismic vulnerability assessment procedure [18,19].

4. Seismic Damage Index Spectra

Figures 3 and 4 present spectral functions from Park and Ang [18] and Moric et al. [19] DI functions, respectively, considering the fundamental period (T) (on the x-axis) versus the obtained DI values (on the y-axis) plots for each original earthquake and scaled records to PGAs from 0.075 to 0.75 g. Dashed lines show the period-dependent damage indices from analyzing the natural and scaled earthquake records at the KRM1 station, while the black line is the average curve from all other six spectra. For original earthquakes which the Kazazi High School experienced recently, from 2002 to 2017, Park and Ang [18] and Moric et al. [19] provided limited and insignificant damage states (Figures 3a and 4a). It is confirmed by the evidence of the health state of the building after the occurrence of these earthquakes, so to show that the criteria used, despite being qualitative, are accurate in defining the seismic damage of structures.

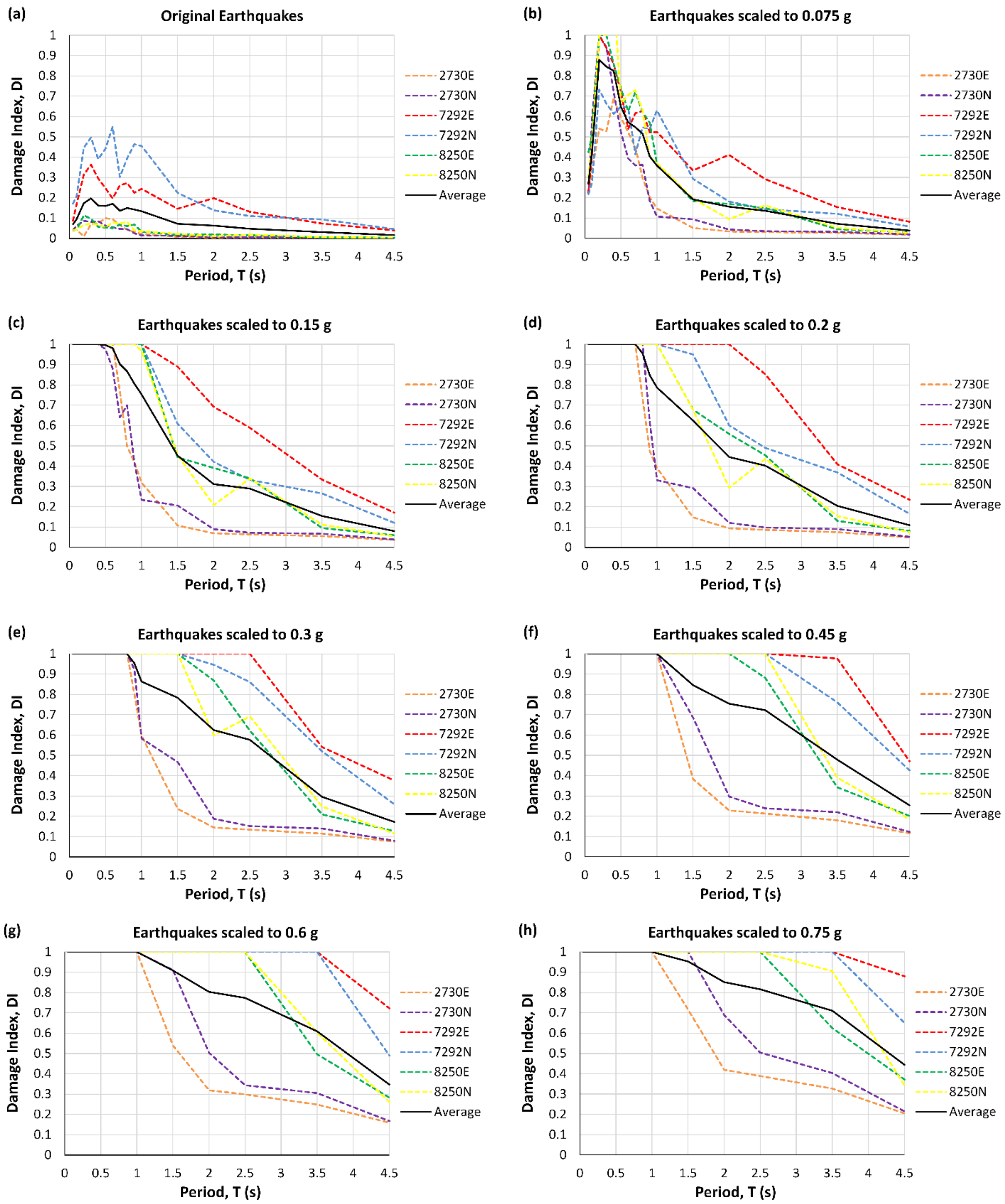

Figure 3. Park and Ang [18] DI spectral functions for seismic records: (**a**) original, (**b**) scaled to 0.075 g, (**c**) scaled to 0.15 g, (**d**) scaled to 0.2 g, (**e**) scaled to 0.3 g, (**f**) scaled to 0.45 g, (**g**) scaled to 0.6 g, and (**h**) scaled to 0.75 g.

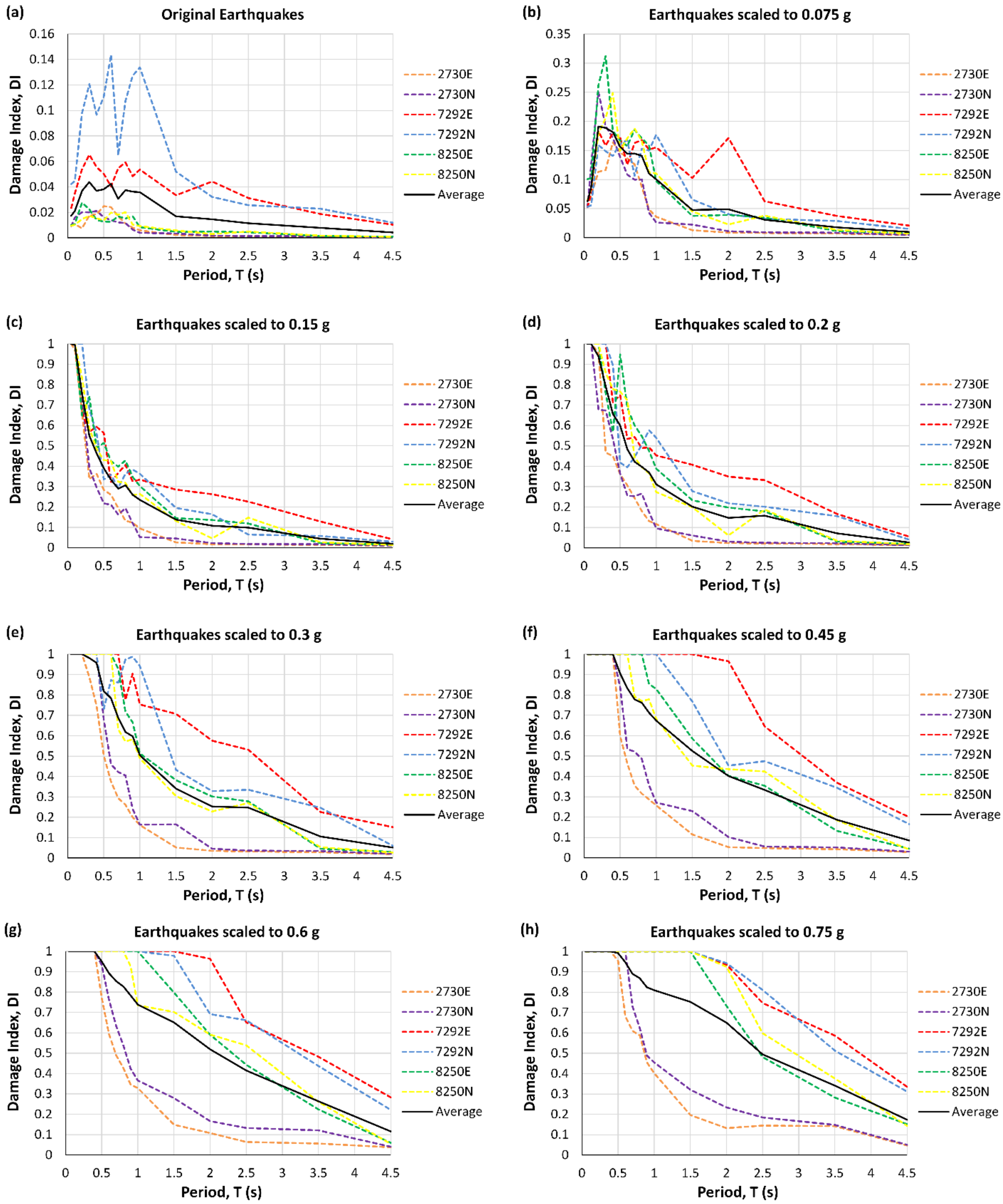

Figure 4. Moric et al. [19] DI spectral functions for seismic records: (**a**) original, (**b**) scaled to 0.075 g, (**c**) scaled to 0.15 g, (**d**) scaled to 0.2 g, (**e**) scaled to 0.3 g, (**f**) scaled to 0.45 g, (**g**) scaled to 0.6 g, and (**h**) scaled to 0.75 g.

At low values of PGA, the DI initially grows by increasing the period up to 0.2 s and then decreases (Figures 3b and 4b). For larger PGAs, the high damage index decreases from about 0.5 to 1 s (Figures 3 and 4c–h). In addition, as expected, the graphs show DI increases with the increase in PGA.

Figure 5 presents the sets of average damage spectra in other PGAs by the methods provided by Park and Ang [18] and Moric et al. [19]. These spectra were used for the rapid assessment of the investigated structure, which is discussed in the next section, and are also helpful for large-scale damage assessment of buildings located on similar ground categories in this area. The PGA considered for this area can be identified from seismic hazard analysis, or the most probable earthquake of the Iranian seismic code (IRSt2800, [23]) is considered as PGA. Alternatively, PGA can be found in the microzonation study of Kermanshah city [27].

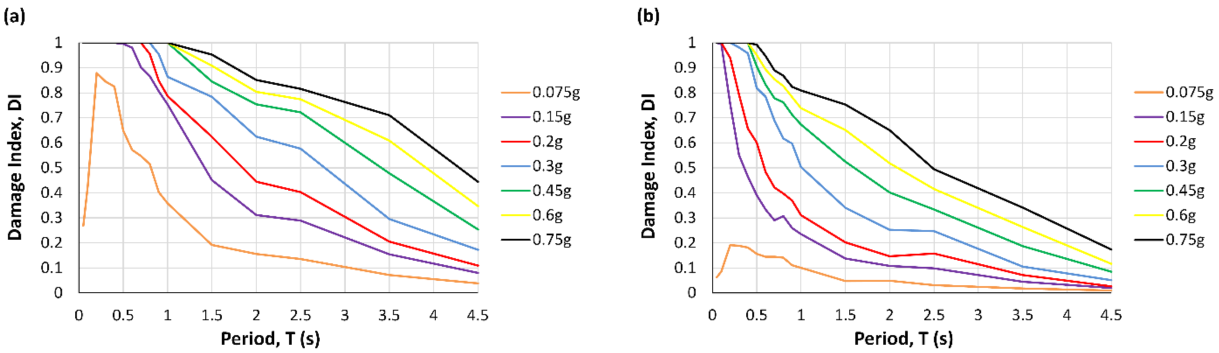

Figure 5. DI spectra for various PGA range by (**a**) Park and Ang [18] DI spectral functions and (**b**) Moric et al. [19] DI spectral functions.

5. Seismic Vulnerability Assessment

This section presents the application of DI spectra on vulnerability assessment of Kazazi High School as an unreinforced masonry historical building with flexible timber floors.

The steps of using DI spectra to assess the seismic vulnerability follow:

1. Determine the fundamental period (T) of the investigated building from empirical equations (e.g., Equation (3)).
2. Define the PGA (e.g., from the zoning or microzoning seismic map).
3. Read the value of DI from the DI spectra, which is determined according to the characteristics of the investigated building, considering site-adapted accelerograms (e.g., Figure 5).
4. Determine the ratio (l/h) and define the proposed DI_{flex} from DI/DI_{flex} (from Table 2).
5. Provide inference of possible vulnerability based on the modified DIflex (Table 3).

The accurate fundamental period of Kazazi High School can be determined by measuring the fundamental periods on the structure. For the building that has not yet been measured, it is specified from empirical Equation (3). The analyzed building has a rectangular plan with a relatively high length-to-width ratio, which leads to different fundamental periods in both directions, while this empirical equation can only provide the first natural period.

Therefore, the foundation period is calculated using Equation 3. Hence, for H = 8.8 m, T = 0.25 s. Depending on the building parameters, DI values for PGAs from 0.075 to 0.6 g are read using the generated DI spectra (Figure 4). The maximum distance of transverse walls is l = 12.9 m and the floor height is h = 4 m; hence, the maximum ratio l/h is 12.9/4 = 3.2, and from Table 2 the correction coefficient for the calculated l/h ratio is DI/DI_{flex} = 0.28. The results of acceleration-dependent DI for T = 0.25 are presented in Table 4.

The results presented in Table 4 show that, under the influence of an earthquake with a PGA of 0.075 g, the building will suffer moderate to extensive damage, which can be displayed as severe damage. According to the formula by Moric et al. [19], the influence of rigid floors on the behavior of the URM building can be seen. For buildings with flexible floors, and depending on the l/h ratio, DI is greater, since it is divided by the coefficient of 0.28 (Table 2). Failure of the building is expected already at an acceleration of 0.15 g. If the building has rigid floors (Table 4), DI is not divided by the coefficient, and the building does not collapse up to 0.2 g, but of course, it would suffer extensive damage.

Table 4. DI values versus different PGAs at $T = 0.25$ s.

DI Function	***PGAs***			
	0.075 g	**0.15 g**	**0.2 g**	**≥0.3 g**
Park and Ang [18]	0.86	1	1	1
	Extensive	Collapse	Collapse	Collapse
Modified Moric et al. [19]	0.19/0.28 = 0.68	0.65/0.28 considered 1	0.87/0.28 considered 1	1
	Moderate	Collapse	Collapse	Collapse

The most probable earthquake expected in Kermanshah from Iranian seismic code IRSt2800 [23] should be the one with $PGA = 0.3$ g. To perform a seismic vulnerability assessment, the method used in this paper requires the use of appropriate damage index (DI) spectral functions. Two damage index spectral functions are used in this research. One is the function introduced by Park and Ang [18], and the other is the function introduced by Moric et al. [19].

Hence, structural collapse is expected for this building. This is mainly due to the long distance of transverse walls, which will cause the out-of-plane collapse of longitudinal walls. The vulnerability would be lower if this distance is decreased.

The recent changes in the transverse walls (removing a part of the walls and opening between the transverse walls to create a connection between the spaces for the new use of the building as a museum) have made the condition even more dangerous. However, according to the results obtained from both methods, modeling of the building and its quantitative investigation are recommended to accurately identify the weak points of the structure and plan effective intervention strategies for its requalification.

6. Conclusions

This research presents the seismic vulnerability assessment of the historic Kazazi High School in Kermanshah. The damage index spectra corresponding to the school building site were determined. Then, the building damage index was evaluated according to its fundamental period. Two formulas developed and reported in the literature by Park and Ang and by Moric et al. were used to determine the damage indices in each period. The damage index parameters were determined from numerous nonlinear analyses of the single degree of freedom system under three pairs of accelerograms. Because there are no suitable natural high acceleration records, the accelerograms were scaled to various ranges of peak ground accelerations. It is worth noting that the second damage formulation considers the effect of the flexibility of the ceiling on reducing the seismic resistance of the building. The results showed that:

- Without considering the ceiling flexibility, the first damage formulation (Park and Ang) provided a higher damage index. Contrarily, the second damage formulation (Moric et al.), which considered the influence of flexible ceilings, significantly reduced the building's resistance to earthquakes.
- Although this school has not been seriously damaged in the past due to the low acceleration of the previous seismic events, in the case of an earthquake with a peak ground acceleration of 0.15 g, collapse can be expected.
- The recent structural intervention, increasing the openings in the load-bearing walls during conversion of the school building to a museum, has increased the seismic vulnerability of the building. This issue shows the prioritization for in situ study and numerical modeling of the building to find weak points in the structure and to plan appropriate retrofit interventions.

In general terms, the most important advantage of the proposed method is that it does not consider only one parameter of the peak ground acceleration/velocity for its application. The DI is obtained from the nonlinear dynamic analysis of the acceleration time history.

Hence, it can take account of the constitutive curve of the structure in a rapid assessment method, other than considering all the necessary parameters of the accelerograms, such as amplitude, frequency content, and duration.

In contrast, the generalization of the structure with an SDOF system, especially for the high-raised buildings, is a disadvantage of this method. For high-raised buildings or systems with multiple degrees of freedom (MDOF), this problem can be solved by MDOF. The problem is the inability to consider architectural diversity in structures with irregular and complex plans. This effect may be reduced by measuring the fundamental period of the building and applying it to the DI selection from the DI spectrum.

When applied to a large urban area or compartment scale, it is possible to select a suitable set of records for each region according to the seismic microzonation and propose DI spectra for each typology of buildings. The use of these spectra is fast and solely needs the fundamental period of each building. These spectra can be recommended in rapid seismic vulnerability assessment guidelines for large-scale urbanized areas.

Author Contributions: Conceptualization, M.B., M.H.-N. and A.F.; methodology, M.B. and M.H.-N.; software, M.B. and M.H.-N.; validation, M.B., M.H.-N. and A.F.; formal analysis, M.B.; investigation, M.B.; resources, M.B.; writing—original draft preparation, M.B.; writing—review and editing, M.B., M.H.-N. and A.F.; visualization, M.B. and M.H.-N.; supervision, M.B., M.H.-N. and A.F.; project administration, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The Authors sincerely wish to thank the Education Department of Kermanshah and the Ministry of Cultural Heritage, Tourism, and Handicrafts of Iran (MCTH) for providing the required permissions and plans, and thank the Office for International Affairs of Razi Univ., Iran, and the Dept. of Structures for Engineering and Architecture of the University of Naples Federico II, Italy, for facilitating the joint research collaboration. The authors also thank Dragan Moric for his input and advice during the writing of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Green, R.A.; Hall, W.J. *An Overview of Selected Seismic Hazard Analysis Methodologies*; University of Illinois at Urbana-Champaign: Urbana, IL, USA, 1994.
2. Coburn, A.W.; Spence, R.J.S. *Earthquake Protection*; Wiley: New York, NU, USA, 2002; 424p, ISBN 978-0-470-84923-1.
3. Benedetti, D.; Petrini, V. On the seismic vulnerability of masonry buildings: An assessment method. *L'industria Delle Costr.* **1984**, *149*, 66–74. (In Italian)
4. National Group for Earthquakes Defense (GNDT). *First and Second Level form for Exposure, Vulnerability and Damage Survey (Masonry and Reinforced Concrete)*; GNDT: Rome, Italy, 1994. (In Italian)
5. Formisano, A.; Florio, G.; Landolfo, R.; Mazzolani, F.M. Numerical calibration of an easy method for seismic behavior assessment on large scale of masonry building aggregates. *Adv. Eng. Softw.* **2015**, *80*, 116–138. [CrossRef]
6. GU. n. 47 (09/02/2011). In *Directive of the Prime Minister Dated on 09/02/2011, Assessment and Mitigation of Seismic Risk of Cultural Heritage with Reference to the Technical Code for the Design of Construction*; Italian Guideline; National Guidelines System (SNLG): Rome, Italy, 2011. Issued by D.M. 14/01/2008. (In Italian)
7. Whitman, R.V.; Reed, J.W.; Hong, S.T. Earthquake damage probability matrices. In Proceedings of the 5th World Conference on Earthquake Engineering, Rome, Italy, 25–29 June 1973; pp. 2531–2540.
8. Del Gaudio, C.; De Martino, G.; Di Ludovico, M.; Manfredi, G.; Prota, A.; Ricci, P.; Verderame, G. Empirical fragility curves from damage data on RC buildings after the 2009 L'Aquila earthquake. *Bull. Earthq. Eng.* **2017**, *15*, 1425–1450. [CrossRef]
9. Gautam, D.; Fabbrocino, G.; Santucci de Magistris, F. Derive empirical fragility functions for Nepali residential buildings. *Eng. Struct.* **2018**, *171*, 617–628. [CrossRef]
10. Biglari, M.; Formisano, A. Damage probability matrices and empirical fragility curves from damage data on masonry buildings after Sarpol-e-zahab and bam earthquakes of Iran. *Front. Built. Environ.* **2020**, *6*, 2297–3362. [CrossRef]
11. Biglari, M.; Formisano, A.; Hosseini Hashemi, B. Empirical fragility curves of engineered steel and RC residential buildings after Mw 7.3 2017 Sarpol-e-zahab earthquake. *Bull. Earthq. Eng.* **2021**, *19*, 2671–2689. [CrossRef]
12. Kappos, A.J.; Panagopoulos, G.; Penelis, G.G. Development of a seismic damage and loss scenario for contemporary and historical buildings in Thessaloniki, Greece. *Soil Dynam. Earthq. Eng.* **2008**, *28*, 836–850. [CrossRef]
13. D'Ayala, D.; Ansal, A. Non linear push over assessment of heritage buildings in Istanbul to define seismic risk. *Bull. Earthq. Eng.* **2011**, *10*, 285–306. [CrossRef]

14. Hadzima-Nyarko, M.; Mišetić, V.; Morić, D. Seismic vulnerability assessment of an old historical masonry building in Osijek, Croatia, using Damage Index. *J. Cult. Heri.* **2017**, *28*, 140–150. [CrossRef]
15. Biglari, M.; D'Amato, M.; Formisano, A. Rapid seismic vulnerability and risk assessment of Kermanshah historic mosques. *Open Civ. Eng. J.* **2021**, *15*, 135–148. [CrossRef]
16. Ashayeri, I.; Biglari, M.; Formisano, A.; D'Amato, M. Ambient vibration testing and empirical relation for natural period of historical mosques; case study of eight mosques in Kermanshah, Iran. *Construct. Build. Mater.* **2021**, *289*, 123191. [CrossRef]
17. Biglari, M.; Formisano, A.; Davino, A. Seismic vulnerability assessment and fragility analysis of Iranian historical mosques in Kermanshah city. *J. Buil. Eng.* **2022**, *45*, 103673. [CrossRef]
18. Park, Y.J.; Ang, A.H. Mechanistic seismic damage model for reinforced concrete. *J. Struct. Eng.* **1985**, *111*, 722–739. [CrossRef]
19. Moric, D.; Hadzima, M.; Ivanusic, D. Seismic damage model for regular structures. *Int. J. Eng. Model.* **2001**, *14*, 29–44.
20. Charney, F.A.; Barngrover, B. NONLIN: A computer program for earthquake engineering education. In *Proceedings of the EERC-CUREe Symposium in Honor of Vitelmo V. Bertero, Berkeley, CA, USA, 31 January–1 February 1997*; Earthquake Engineering Research Institute, University of California: Berkeley, CA, USA, 1997; pp. 251–254. [CrossRef]
21. Clough, R.W.; Penzien, J. *Dynamics of Structures*; McGraw Hill: New York, NY, USA, 1993; Volume 2, ISBN 978-0070113923.
22. ISMN. Available online: https://ismn.bhrc.ac.ir/ (accessed on 15 February 2021).
23. *IRSt2800*; Iranian Code of Practice for Seismic Resistant Design of Buildings, 4th Revision. Building and Housing Research Center: Tehran, Iran, 2014.
24. Ashayeri, I.; Shahvar, M.P.; Moghofeie, A. Seismic characterization of Iranian strong motion stations in Kermanshah province (Iran) using single-station Rayleigh wave ellipticity inversion of ambient noise measurements. *Bull. Earthq. Eng.* **2022**, *20*, 3739–3773. [CrossRef]
25. Moric, D. Seismic resistance diagrams for buildings belonging to architectural heritage. *Gradjevinar* **2002**, *54*, 206–209.
26. Grünthal, G. (Ed.) European Macroseismic Scale. In *Cahiers du Centre Européen de Géodynamique et de Séismologie*; European Center for Geodynamics and Seismology: Luxembourg, 1998; p. 15.
27. Biglari, M.; Ashayeri, I.; Moftizadeh, R. Urban planning of Kermanshah city based on the seismic geotechnical hazards. *J. Seismol. Earthq. Eng.* **2015**, *17*, 203–211.