Case Studies in Construction Materials 19 (2023) e02534

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Pre-earthquake fuzzy logic-based rapid hazard assessment of reinforced concrete buildings

Atakan Mangir, Vefa Okumus [*]

Istanbul Medipol University, School of Engineering and Natural Sciences, Department of Civil Engineering, 34810 Istanbul, Turkiye

ARTICLE INFO

Keywords:
Fuzzy logic
Hazard
Model
Damage assessment
Rule base

ABSTRACT

The main purpose of this paper is to present a rapid building assessment fuzzy logic (FL) modelling for risk assessment based on expert construction engineering verbal informatics. Before an earthquake, a set of input expert assessment variables are transformed into five types of hazard categorization as "no damage", "slight damage", "moderate damage", "severe damage", and "collapse". Main variables are reported by expert engineers based on visual inspection of structural components in addition to the building location's peak ground velocity (PGV) micro zonation numerical value, soil type and building's material information. Each input variable and output hazard class is fuzzified. A valid set of fuzzy rule base components is written based on input variables, each of which has an appropriate output hazard class. The fuzzy hazard assessment model has input and output variables in terms of fuzzy sets. Thus, the overall model output is in the form of a fuzzy set and then defuzzified to find the percentage of each hazard class for a single building. The application of this fuzzy logic model is presented for twenty existing reinforced concrete buildings, and the final hazard categories of these buildings are presented with interpretations and recommendations.

1. Introduction

Among the natural hazards, earthquakes are the most destructive events that cause property loss and human deaths. Earthquakes are repeatedly active in many parts of the world [1] and in Türkiye. Especially in countries with frequent earthquake potential local and central administrative authorities should collectively update their seismic design codes with successive improvements according to the new information collection to minimize damage-full consequences. Unfortunately, many buildings were built with outdated codes and regulations, thus increasing their vulnerability to earthquakes. The basic elements of reinforced concrete buildings, earthquake-resistant components such as columns, beams and shear walls, should be checked verbally and numerically with the opinion of an objective technical expert considering the physical condition of structural members, micro zonation ground velocity values, floor numbers and other related elements. Rather than the post-earthquake state, pre-earthquake assessments are critical for property and life safety. After the pre-earthquake building assessments, the buildings with "severe damage" or "collapse" results should not be allowed to enter, even for property collection.

In recent years, seismic hazard assessment scale identification modelling studies of buildings have gained extensive importance as a preliminary for future planning by local and central administrative authorities' concern. These models can be adopted to assess cost-benefit analysis for appropriate retrofitting programs [2]. In building hazard assessment studies, it is recommended that there are

---

[*] Corresponding author.
E-mail address: vefa.okumus@medipol.edu.tr (V. Okumus).

https://doi.org/10.1016/j.cscm.2023.e02534
Received 28 July 2023; Received in revised form 8 September 2023; Accepted 2 October 2023

seismic heterogeneities affecting the stability of building engineering structures [3].

In general, earthquake hazard damage assessment tasks have structural and non-structural variables. The former group includes important earthquake-resistant components, while the latter concerns variables such as ground velocity, soil mechanic properties, liquefaction effects, pounding effect and like. Of course, from the mechanical strength point of view, the structural components are the most important as they provide resistance to vertical and horizontal shake loads, which are the main effects of the buildings' safety and stability properties. Any lack of one of these properties increases the buildings' hazard potential.

On the other hand, non-structural components are also very important, as any miscalculation of their effects may cause a severe hazard to the building's seismic capacity design. It is stated by various authors that these components provide building useability, cost and worth [4–6].

Earthquake hazard assessment of existing buildings is of vital importance, especially in pre-earthquake warning, preparedness, vulnerability, and mitigation studies. It is necessary to classify the existing building stoke into different categories according to rapid, simple, reliable, logical, and expert view-based models and software [7].

Recent earthquake hazards in central Türkiye brought into view how important systematic earthquake hazard mitigation programs are for pre-earthquake building assessment. Especially in Istanbul City, seismic code miss-design buildings should be identified rapidly before the upcoming earthquake event. Although the Earthquake Master Plan for Istanbul [8] is prepared in full detail, it should be updated with new additional gained information. This plan suggests three successive building assessments as rapid visual, numerical and detailed assessments for skyscrapers. The first proposal of this paper is implemented with an updated fuzzy logic modelling approach that requires verbal data. Aynur and Atalay [9] aimed to compare various rapid assessment methods such as Principles of the Determination of Risky Structures-2019, Column and Wall Index Method, P25 Scoring Method, and Improved Discriminant Analysis Method in a region prone to frequently occurring destructive earthquakes like in Türkiye, where assessing the seismic safety of reinforced concrete (RC) buildings is a critical concern before and after the currently available seismic building codes. Moreover, for existing RC buildings in Istanbul, Türkiye, Doğan et al. [10] examined and compared various rapid seismic safety assessment methods, including visual screening-based (VSB) methods like FEMA 154, RVS, and RBTE, as well as capacity-based methods such as P25, Yakut, AURAP, and DURTES.

The fundamentals of fuzzy inference system (FIS) model applications are presented in certain previous studies that cover the principles of fuzzy logic (FL) and demonstrate how FISs can handle verbal uncertainties, complexities, complications, and vagueness [11–16]. Furthermore, Ross [17] and Şen [18] comprehensively outlined these principles and frameworks.

The main aim of this paper is to present an FL model rapid assessment procedure for the evaluation and classification of buildings according to hazard categories of "no damage", "slight damage", "moderate damage", "severe damage", and "collapse". Especially buildings that are hazard-labelled as "severe damage" and "collapse" must be demolished immediately. Buildings in other categories must be repaired or retrofitted. A similar methodology was applied to hundreds of buildings in the Zeytinburnu town of Istanbul City, and it was found that many buildings are sensitive and hazardous to subsequent earthquakes [19]. Demartinos and Dritsos [20] presented a fuzzy logic-based rapid visual screening procedure that categorizes buildings into five damage types concerning potential seismic events. Their procedure enhances precision using adaptive neural networks trained with data from 102 buildings affected by the 1999 Athens earthquake. They proposed a more efficient alternative to probabilistic approaches, although the method's prospects depend on the size of the training database, suggesting the potential for improvement with larger datasets. This, in turn, could lead to more reliable pre-earthquake assessment methods.

Bektaş et al. [21] mentioned that over the past three decades, there have been conventionally many rapid visual screening (RVS) methodologies for seismic resistance assessment of existing buildings. Thus, the most susceptible buildings are identifiable to earthquake hazard damages. The RVS methods provide a classification of buildings to their high-risk levels. They proposed a fuzzy logic-based RVS approach to produce an accurate building responsive features' examination for unreinforced masonry (URM) buildings. Bektaş and Kegyes-Brassai [22] also focused on developing a fuzzy logic-based Soft Rapid Visual Screening (S-RVS) method by analysing data from 40 URM buildings that were affected by the 2019 Albania earthquake.

Allali et al. [23] present a fuzzy logic-based methodology for post-earthquake building damage hazard assessment. Their research concentrated on investigating the number and weights of fuzzy rules by considering the relationship between the damage level of each component and the overall damage level by employing a single-antecedent weighted fuzzy rule. De Iuliis et al. [24] presented a fuzzy logic hierarchical method for predicting the downtime of residential buildings after an earthquake. They considered three components, namely, damage, irrational delays, and utility disruption with a focus on building vulnerability and repair time evaluations, which lead ultimately to the estimation of re-occupancy, functional recovery, and full recovery states. Harirchian et al. [25] addressed the global concern of assessing seismic vulnerability in existing RC buildings, particularly those constructed before the availability of advanced seismic codes. They emphasized the need for a practical and efficient method to evaluate seismic vulnerability. Harirchian et al. [26] also explored the use of five Machine Learning (ML) techniques for predicting the seismic vulnerability of older buildings to emphasize the importance of their vulnerability assessments and to determine the need for seismic strengthening measures like retrofitting. Kumari et al. [27] studied the use of Artificial Intelligence (AI) methods, specifically ML algorithms, for RVS to assess the seismic vulnerability of existing RC buildings for the reduction of human intervention, biases, and uncertainties. Their research also introduced a web-based application built on Django for real-time seismic vulnerability investigations, which was validated through two case studies to demonstrate its potential efficiency. Li [28] introduced a novel method for predicting the structural vulnerability of building clusters in seismic-prone areas by using a multivariate fuzzy membership index to account for various influential factors. Li [29] also investigated the damage and vulnerability of various building structures during the Wenchuan and Jiuzhaigou earthquakes in China, focusing on four structural typologies and proposal of a rapid vulnerability prediction method based on multidimensional parameters. On the other hand, Lu et al. [30] proposed a rapid regional post-event seismic damage assessment approach based on the convolutional neural networks (CNN) concept, which combines building inventory, ground motion data, and damage levels into a scenario bank. By generating time-frequency distribution graphs of ground motions and training CNN models, their method can predict damage states with sufficient accuracy in near real-time, addressing the limitations of traditional on-site investigations and other computational alternatives for assessing seismic damages on a regional scale.

Stepinac et al. [31] discussed the impact of a severe earthquake that struck Zagreb on March 22, 2020, during the COVID-19 lockdown, causing significant damage to the city's buildings, especially historic masonry structures in the old town. They provided an overview of the earthquake, building typology, data collection, and proposals on post-earthquake assessment, damage classification, and failure patterns, emphasizing the need to address the vulnerability of Croatia's building stock. Mazumder et al. [32] presented a fuzzy synthetic-based approach for the first-level seismic risk evaluation of old URM buildings in urban areas using 14 risk factors to estimate the overall seismic risk. They focused on an urban settlement in Dhaka city, Bangladesh, and revealed that over 90% of the buildings in the case study area have a high to very high level of seismic risk, thus indicating the potential for severe damage in future large earthquakes. Stojadinović et al. [33] proposed a novel framework for rapid earthquake loss assessment by employing an ML damage classification model and a sampling algorithm. Wang et al. [34] addressed the increasing need for risk-based assessment and management tools in structural and infrastructure systems due to population growth, economic development, and urbanization. They conducted a comprehensive review of ML applications to evaluate progress in risk and resilience assessment in four key areas of structural engineering (buildings, bridges, pipelines, and electric power systems. Their review categorizes literature based on six ML attributes and identifies limitations and challenges, while also highlighting future research needs to further advance ML in structural risk and resilience assessment across different types of interconnected infrastructure.

Pre-earthquake hazard assessment studies provide a fundamental possibility of building early warning systems for local and central administrations as well as building owners [19]. In order to achieve this task, efficient preliminary modelling of building hazard assessment software is necessary for building seismic hazard scale determination with reliable predictions in the study area.

The main purpose of this paper is to develop a new rapid pre-earthquake building assessment program through input fuzzification by fuzzy sets and output defuzzification to know the membership degree (MD) of each building in the hazard categories of "no damage", "slight damage", "moderate damage", "severe damage" and "collapse". The developed model will be used for reinforced concrete buildings. The rule generation procedures are the most essential steps in any FIS modelling. An innovative rule generation process is presented within this study for a robust and reliable FIS model that aims to rapidly predict the pre-earthquake hazard category of RC buildings.

2. Fuzzy logic methodology for hazard categorization

The fuzzy logic technology (FLT) earthquake damage program also includes "building hazard risk score and the score levels in categories close to it" for buildings that fall under the categories of "non-hazardous", "minor/medium damage", and "collapse". Thus, it can help decision-makers to obtain the privileged priority degrees of each building in each category and make the final decisions accordingly. Decisions to be taken can be listed as follows.

- Buildings in the "no damage" category will remain as they are, and no actions will be taken until the next earthquake,
- "Slightly damaged" buildings should be retrofitted and will not be considered in the second phase,
- The demolition of the buildings in the "collapse" category, decided at the end of the first stage, can be started immediately.

Using the visual, verbal or measurement data at hand, all buildings are quickly divided into the following five possible damage categories in the first stage as stated above: "no damage", "slight damage", "moderate damage", "severe damage", and "collapse" categories.

Buildings that fall under the category of "no damage", "slight damage", and "collapse" are excluded from the second stage. With this, upon the request of the person or institution requesting the examination, sometimes due to the importance of the building, some of these may be included in the building group to be subjected to the second stage examination.

In the FLT Stepwise Investigation technique, the expected damage categories of the structures examined under the design earthquake are scored as in the structures assigned a certain "verbal" performance class; they are ranked from worst to best, at the end of the first stage inspection. The structures that ranked in a higher damage category in the first stage inspection can be considered as candidate structures for a second stage inspection or demolition. Those with a lower estimated damage category may be remained as they are or be retrofitted with appropriate strengthening techniques.

According to the results of the first stage examination, the performance classes are evaluated in the following sense:

- Buildings in the "no damage" category provide the "life safety performance" under a design earthquake, their use can be continued without additional construction measures, and the buildings in this category do not require a second-stage inspection.
- Buildings in the "slight damage" category should be strengthened if they are still in use; however, they may not need to be evacuated immediately. Buildings falling into this category do not need to undergo a separate second-stage inspection; however, the owner or decision maker may also request a "Stage Two" review for these buildings or some of them; in this case, the second-stage inspection of these buildings can be made as a "third priority".
- The demolition of buildings that fall under the category of "collapse" can be decided at the end of the first stage and detracted immediately away from people and objects and demolished; however, the owner or decision maker may decide to evacuate these

buildings immediately after the first stage inspection, but may subject some of them to a second stage inspection before demolishing them; in this case, the second stage inspection of these buildings should be done as a "first priority".

- Buildings in the "moderate damage" category should be evacuated and assigned to the second stage inspection class, and this stage inspection should be done as "second priority".
- Buildings that fall under the category of "severe damage" should be evacuated immediately and included in the second stage inspection class, and the second stage inspection should be done "first priority".

The variables that need to be taken into account in the first stage inspection are listed below:

- Peak ground velocity (PGV)
- Average shear wave velocity of soil type above the upper 30 m of depth $(V_S)_{30}$
- Structural system state, including geometric placement of structural members, member dimensions, and design quality of the structural plan
- Concrete class/strength
- Soft story presence
- Floor number and average floor height
- Conditions of rebars, including rebar type (plain/ribbed), corrosion level and stirrup spacing
- Cantilever parts in floor plans and their amount
- Pounding effect (attached buildings)
- The current physical condition of the building, visible cracks and damages on structural elements.

A second stage inspection should be carried out in buildings with "moderate damage" and "severe damage" categories in the first stage inspection. Considering current seismic code provisions, a comprehensive seismic performance assessment may be necessary to decide whether to retrofit or demolish these buildings with an appropriate technique.

2.1. *Hazard parameters (input MFs)*

For the first inspection period, ten input hazard parameters and three membership functions (MFs) for each parameter are defined. The MFs of the input parameters are in trapezoidal and triangular fuzzy set forms with a hazard index varying from 0 to 100, inclusive. The mathematical expression of the inputs in terms of hazard index is done with the normalization procedure of their values. The logical expressions of hazard parameters are explained in detail below.

2.1.1. *Peak ground velocity (PGV)*

Peak ground velocity (PGV) determination at a building's location relies on seismic activity hazard maps. For example, the Disaster and Emergency Management Authority (AFAD) of Türkiye's Earthquake Hazard Map [35] offers PGV values as shown in Fig. 1. Similarly, the United States Geological Survey [36] provides PGV values for various U.S. states through an interactive fault map. These values typically range between 5 and 40 m/s, with higher values that signify elevated hazard risk. The normalization procedure follows direct proportionality principles and PGV is categorized as "Low", "Medium" and "High" within the hazard index.

2.1.2. *Average shear wave velocity of soil type over the upper 30 m of depth* $[(V_S)_{30}]$

The aforementioned PGV values offer a limited perspective on soil behaviour during seismic events. For example, soil type significantly influences hazard risk by potentially amplifying seismic forces at a building's location [37,38]. The average shear wave

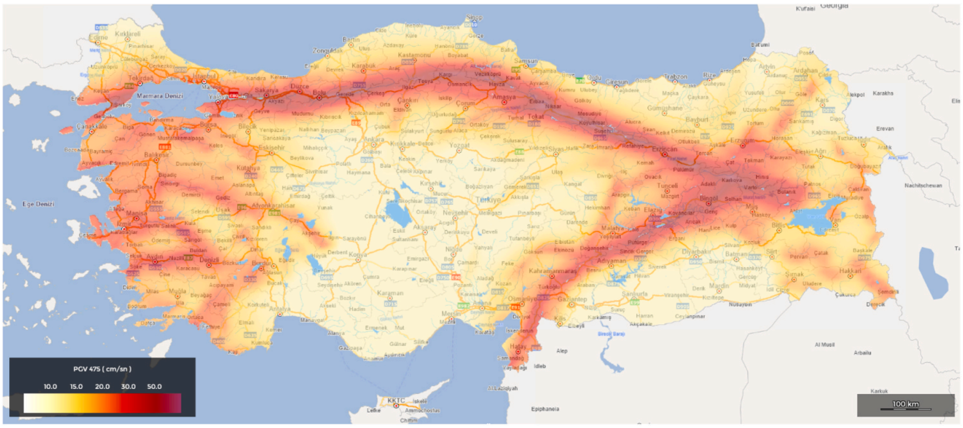

Fig. 1. PGV map of Türkiye [35].

velocity $(V_S)_{30}$ of the upper 30-meter soil layer at the building site is considered to enhance hazard assessment. This parameter is often documented in seismic design codes, like the Türkiye Building Earthquake Code (2018) (Table 1) [39]. Experts can determine $(V_S)_{30}$ values based on prior geotechnical investigations or use micro-zonation maps, such as those from the Istanbul Metropolitan Municipality (Fig. 2) [40]. $(V_S)_{30}$ typically ranges from 150 to 1500 m/s, with higher values indicating lower hazard risk. Normalization follows inverse proportional principles, with 150 m/s corresponding to a hazard index of 100 and 1500 m/s to 0. The hazard index categories of $(V_S)_{30}$ are classified as "Low", "Medium" and "High".

2.1.3. *Structural system state*

This parameter is dependent on the geometric arrangement of structural members, member dimensions, and the design quality of the structural plan. Its scores are assigned by inspection experts within the range of 0–3 with normalization to the hazard index. A score of 0 corresponds to a hazard index of 100, while a score of 3 indicates a hazard index of 0. The hazard index categories are "Weak", "Medium" and "Good".

2.1.4. *Concrete class*

This input parameter assesses the existing concrete strength of the building within the range from 5 to 40 MPa. Higher concrete strength values reduce hazard risk, and normalization is done inversely. The existing concrete strength of the building can be determined by non-destructive Schmidt hammer tests, drilling concrete core sample tests, or a strength value can be obtained directly from the building's structural design project if tests cannot be conducted. The hazard index is divided into "Low", "Medium" and "High" categories.

2.1.5. *Soft story*

Soft story presence in a building is evaluated based on factors like floor height and the absence of required perimeter walls at the first critical storey on the ground level. Scores range from 0 to 2, inversely proportional to the hazard index. A score of 0 indicates the absolute presence of a soft story (100 hazard index), while a score of 2 suggests its absence (0 hazard index). The hazard index categories are considered as "Low", "Average" and "High".

2.1.6. *Floor number*

This parameter considers the total number of stories in a building. A direct proportion is used for normalization within the range of 1–25 floors (3.00 m average floor height). Higher floor numbers increase the hazard risk. The hazard index categories are considered as "Low", "Medium" and "High".

2.1.7. *Conditions of rebars*

Rebar conditions are assessed based on factors such as rebar type, corrosion level, and stirrup spacing. Scores range from 0 to 5, inversely proportional to the hazard index (rebar type range plain/ribbed - 0/2 pts, corrosion level range high/low - 0/1 pts, and stirrup spacing range high/low - 0/2 pts). A score of 0 indicates weak rebar conditions (100 hazard index), while a score of 5 represents good rebar conditions (0 hazard index). These assessments can be conducted through non-destructive means such as X-ray rebar scanning or destructive methods like concrete cover stripping. If on-site methods are not feasible then certain rebar details, aside from corrosion level, may be obtained directly from the building's structural design documentation. For this input variable, the hazard index is divided into "Weak", "Medium" and "Good" categories.

2.1.8. *Cantilever parts in floor plans*

The presence and length of cantilever parts are measured and converted to a hazard index within the range of 0–2 m in direct proportion to the 0–100 hazard index, which is categorised as "Low", "Medium" and "High".

2.1.9. *Pounding effect*

The risk of collision hazards with neighbouring buildings is evaluated, with scores ranging from 0 to 2. This implies an inversely proportional relationship with the hazard index. If there is an adjacent building nearby with misaligned floor levels, it is deemed the worst-case scenario, resulting in a score of zero (100 hazard index) for this input parameter. However, an adjacent building with aligned floor levels receives a score of one point. If there is no neighbouring structure in close proximity to the examined building, it is awarded a score of two points (0 hazard index). The hazard index categories are "Low", "Medium" and "High".

Table 1
Local soil types and corresponding $(V_S)_{30}$ values [39].

Local Soil Class	Local Soil Type	Avg. shear wave velocity of top 30 m soil layer, $(V_S)_{30}$ (m/s)
ZA	Hard rocks	> 1500
ZB	Low-disintegrated, moderately strong rocks	760–1500
ZC	Very dense sand, gravel and hard clay layers or soft rocks having multiple cracks	360 – 760
ZD	Medium dense-dense sand/gravel or multiple clay layers	180 – 360
ZE	Loose sand, gravel or soft clay layers	< 180
ZF	Very soft, risky soils that may also have liquefaction risk.	Site-specific evaluation is necessary

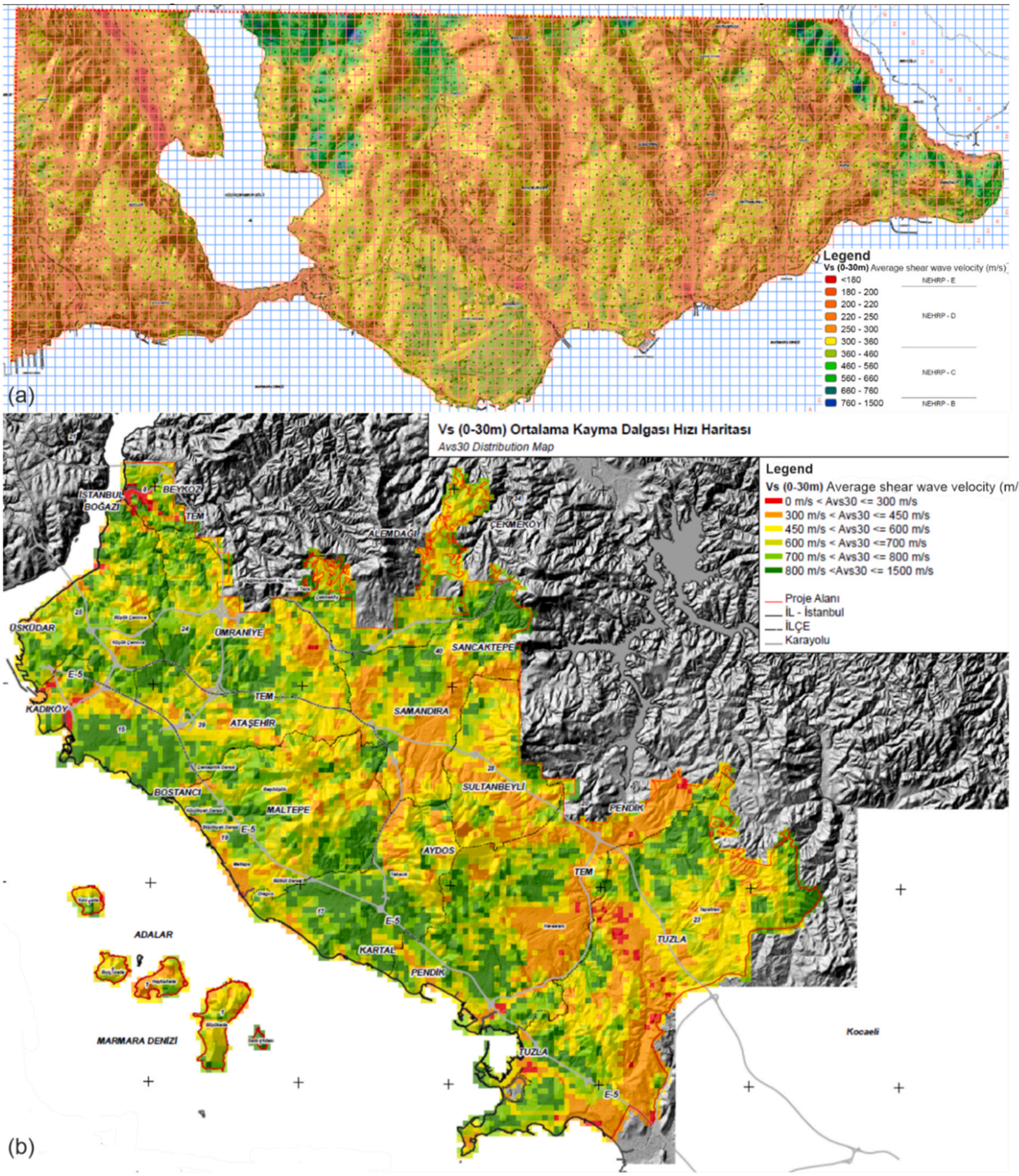

Fig. 2. $(V_S)_{30}$ distribution maps of Istanbul: (a) European (b) Asian Side [40].

2.1.10. Physical condition of the building

This parameter considers the presence of structural damages and cracks in the building. Scores range from 0 to 2 which are inversely proportional to the hazard index. A score of 0 implies severe damage (100 hazard index), while a score of 2 represents no visible cracks or damage (0 hazard index). If some structural members have cracks, the building gets 1 point score. The hazard index categories are considered as "Weak", "Medium" and "Good".

After all that has been explained as for the input parameters, the membership functions (MFs) of all input parameters are given collectively in Fig. 3, where the extremes as “Low”, “Good”, “Weak” and “High” have MFs in trapezoidal forms, while the in-between “Medium” and “Average” categories are in triangular forms.

2.2. Damage function (output MFs)

Expected damages and vulnerability studies are critical for predicting seismic hazard consequences in earthquake-prone regions. The importance of rapid visual scanning of buildings for potential seismic hazards is detailed by FEMA-154 [41]. As a result, the main aim is to determine the vulnerability categories for buildings before a probable seismic event. Hazard levels or seismic vulnerability categories for buildings should be carefully defined as presented in various seismic design codes (TBDY, 2018). This study identifies five different hazard categories for concrete buildings connected with expected structural damage. Brief descriptions of the predicted levels of structural damage for reinforced concrete buildings can be summarized as follows:

- No damage (N): These structures emerge from the earthquake without significant damage.
- Slight damage: (SL): Capillary bending and shear cracks occur in structural elements such as columns, beams and slabs themselves and/or in their joints, and capillary shear cracks in shear walls.
- Moderate damage (M): Local or longitudinal cracks occur in most columns and beams.
- Severe damage (SV): After significant stresses in the columns and beams, most of them reach their yield capacity, wide cracks appear, concrete covers are poured, and in some cases, longitudinal reinforcement bars buckle. Diagonal shear cracks occur in non-ductile frame members and shear walls. "Severely damaged" structures should be included in the demolition scope because it is impossible to strengthen them.
- Collapse (C): Local or total destruction of some building elements. The structure undergoes excessive deformation, and as a result, the structure collapses or becomes very close to collapse.

Fig. 4 presents the output membership functions (MFs) valid for reinforced concrete buildings and descriptions within this section. Trapezoidal MFs are used for the “No Damage (N)” and “Collapse (C)” categories, while triangular MFs are used for those in between.

2.3. Fuzzy inference system (FIS) model and rule base

A FIS model is designed to determine the hazard level by inferencing input parameters with a fuzzy rule base that combines expert views of fuzzy set input variables to generate antecedent logical propositions. Each fuzzy rule proposition links the fuzzy input sets to hazard output for estimation purposes. The Mamdani FIS method is used with the MATLAB fuzzy logic controller tool software for accuracy and practicality [14,15,42]. The proposed model has ten input parameters that are fuzzified for the generation of a rule base in the form of a set of logical propositions. After the generation mechanism of the model, the fuzzy outputs are defuzzified to obtain the hazard level membership degree (MD) value of the building. When the output hazard index is found, the MDs of the intersected damage functions are found, and the building’s hazard state (damage category) is determined. The overall structure of the model is shown in Fig. 5.

Since there are three MFs for each input variable, the fuzzy rule base (FRB) consists of 59,049 fuzzy rules representing the logical input fuzzy sets combination of each variable of ten inputs (Fig. 3). The structure of each rule is in the form of the following fuzzy proposition;.

“**IF** input1 **MF AND** input2 **MF AND**….**AND** input10 **MF THEN** damage function **MF**”

The antecedent part between IF and THEN consists of all input MF combinations connected by the AND logical conjunction. The consequent part after THEN consists of the specified damage function (output) MF for each rule combination. For the completeness of the model, each of the fuzzy rules is combined by the OR logical conjunction. Based on expert opinions, the proposed FIS model FRBs are provided with each rule representing a valid logical relation between the input and output fuzzy MFs. All rules are generated automatically with a code developed by authors considering the logical structure in Fig. 6. The induction of each rule combination is directly related to this logical structure. The combination of 3 MFs for each of the ten input variables leads to a “$3\times3x\ldots x3 \times 3 = 3^{10}$

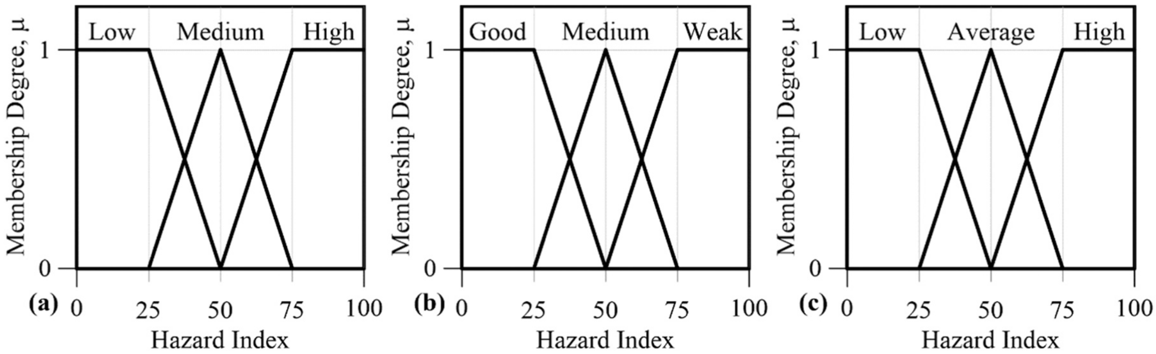

Fig. 3. Input membership functions of; (a) PGV, $(V_S)_{30}$, concrete class, floor number, cantilever parts in floor plans, pounding effect, (b) structural system state, conditions of rebars, physical condition of the building, (c) soft story.

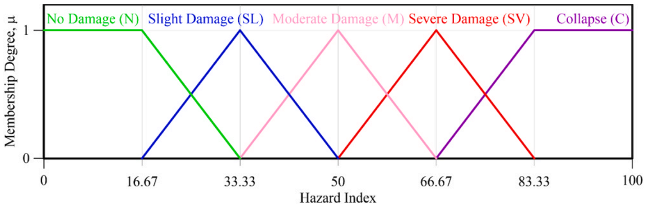

Fig. 4. Output membership functions.

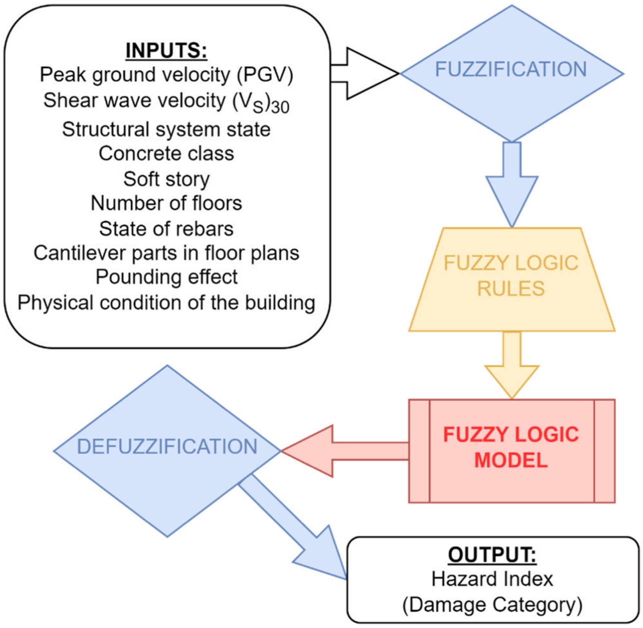

Fig. 5. The overall structure of the FIS model.

= 59,049″ number of rules in the fuzzy rule base (FRB). Specifying the output MF of rule generation starts with a check of a ratio (r) in each rule, which corresponds to the total number of “weak” and “high” inputs divided by the total number of inputs. In the first phase, an appropriate output MF is specified for each rule according to the calculated r value. Then the program checks the designated output MF of each rule by controlling the state of critical inputs. The structural system state, concrete class, conditions of rebars and physical condition of the building inputs are considered "critical inputs" in this logical approach. If at least three or more critical input MFs are Weak/High, then the predesignated output MF of that rule is automatically changed to Collapse (C) MF. Accordingly, the program performs different checks on each rule based on the predesignated output MF as in the logical flow chart in Fig. 6. In cases of necessity, the output MFs are revised which is a sort of model training procedure in this approach.

To obtain the output results, the (MIN) procedure is used in each fuzzy rule proposition minimization because ten input fuzzy sets are connected with each other with the "AND" operator. Similarly, the maximization (MAX) procedure is employed for the combination of each fuzzy rule proposition because they are connected by the "OR" operation. Similarly, the (MIN) operator is used in the implication, and the (MAX) operator in the aggregation procedural inferences during the methodological executions. There is no interconnection among MFs in the consequent part. In light of this fuzzy inference model procedure, the output will also appear in a fuzzy set form. However, in practical application, a single numerical value is required as an output. For this reason, the output fuzzy set is defuzzified. The defuzzification process converts the output into a crisp value. Although there are various defuzzification methods, as explained by Ross (1995), the "CENTROID" method is used in this paper. The obtained output hazard index value is used to find the membership degrees of output categories by designating the intersection points of the damage function.

The outcome of the FIS model manifests as the definitive hazard index in a crisp numerical form after defuzzification. Our computational framework employs this index to navigate through the output MFs chart previously illustrated in Fig. 4. Subsequently, it employs a vertical line to intersect the two relevant output damage category MFs, thereby ascertaining the MD association with the damage categories. The resulting values at the intersection points denote the corresponding MDs, which are subsequently represented as percentages, culminating in the selection of the highest percentage as the ultimate decision. The hazard index evaluation of two example outputs is shown in Fig. 7 for better coherence.

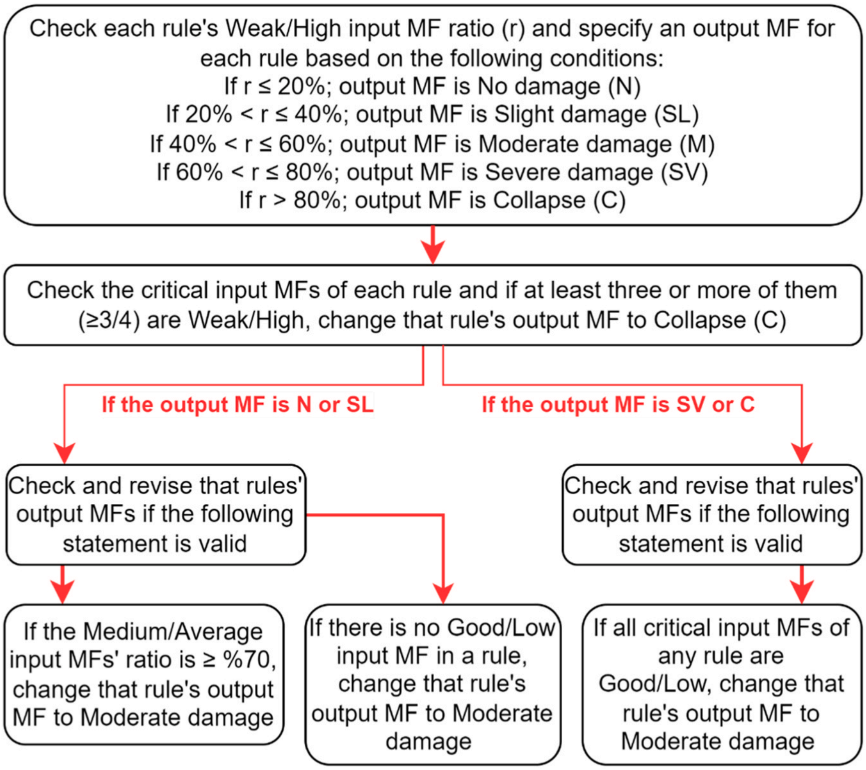

Fig. 6. The logical structure of fuzzy rule base generation.

3. Application

Twenty different case study buildings are examined to apply the proposed FIS methodology. The selected existing buildings are located in various districts of Istanbul City. Each case has different properties and characteristics regarding the input parameters used in this study. Moreover, some of these buildings were previously subjected to a seismic code-based assessment, which means that some of their input data are known. The locations of these buildings on the hazard map of Istanbul with PGV contour are given in Fig. 8 with building identification numbers (IDs). The input data of the buildings are obtained from site observations and expert opinions. The

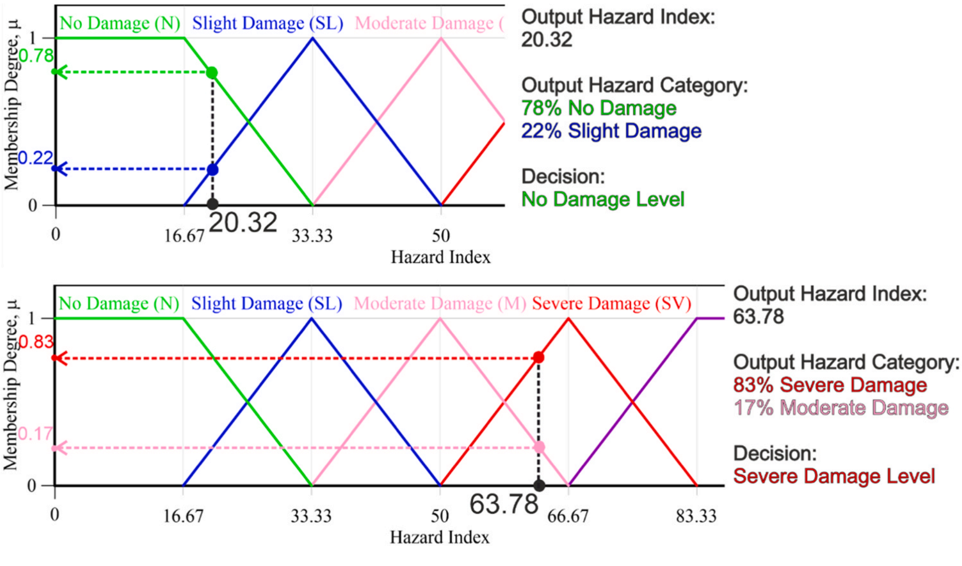

Fig. 7. Output hazard category determination.

input hazard parameters are prepared and normalized as stated in Section 2.1. The list of buildings with input parameters is presented in Tables 2 and 3. Hazard index values of inputs are conditional-formatted in the tables with various colours from highest (red) to lowest (green). After the application of the proposed FL model in this paper, the output hazard index and damage categories of each building are found. The results of these buildings are presented and discussed in detail in the following section.

4. Results and discussion

A detailed presentation of the results for these buildings is given in Table 4. The coloring is the same as explained in the previous section. The final decision on the hazard category is obtained by evaluating the highest MD hazard category of outputs. The comparison of twenty buildings' output hazard categories leads to the conclusion that two buildings are in the "collapse" state, and they must be evacuated and demolished immediately. These buildings have a high seismic hazard risk, and a second-stage inspection is not required. In addition, four buildings are identified under the "severe damage" category, which should be evacuated immediately and included also in the second stage inspection class. The second stage inspection should be done "first priority" on these "severe damage" category buildings in order to assess their structural vulnerability. Two of the buildings appear in the moderate damage category, which should also be evacuated and considered in the stage-two inspection with "second priority".

On the other hand, the hazard category of seven buildings falls within the category of "slight damage". They should not be evacuated but retrofitted to reduce their hazard index to the "no damage" category. Buildings that belong to this category are exempted from a secondary inspection. However, the owner or the responsible person may request a "Stage Two" assessment for some or all of these "slight damage" category buildings. In such a scenario, the secondary inspection of these structures would be given "third priority" and executed as a third option. The two buildings in the "no damage" category will not be affected in case of a seismic event. No preventative measures will be taken before the next earthquake. These structures provide "life safety performance" during a design earthquake, enabling continued use without the need for further construction measures. Moreover, there is no need for a second-stage inspection in buildings falling into this category.

5. Conclusion

In this paper, the details of a new rapid pre-earthquake building evaluation program are developed for reinforced concrete (RC) buildings by fuzzy logic (FL) input fuzzification and fuzzy output defuzzification. The defuzzification operation helps to obtain the membership degree (MD) of each building as a measure of its hazard category as "no damage", "slight damage", "moderate damage", "severe damage", or "collapse". Once the final decision is made on the building damage category in a rapid manner by the proposed model, the authorities may quickly prioritize the necessary precautions for each building for intervention against the next earthquake. The final decision provided by the proposed model is useful under different hazard category scenarios to evacuate people and rebuild or retrofit low-strength structures to ensure life safety before any serious seismic event. The following points are derivable from this study:

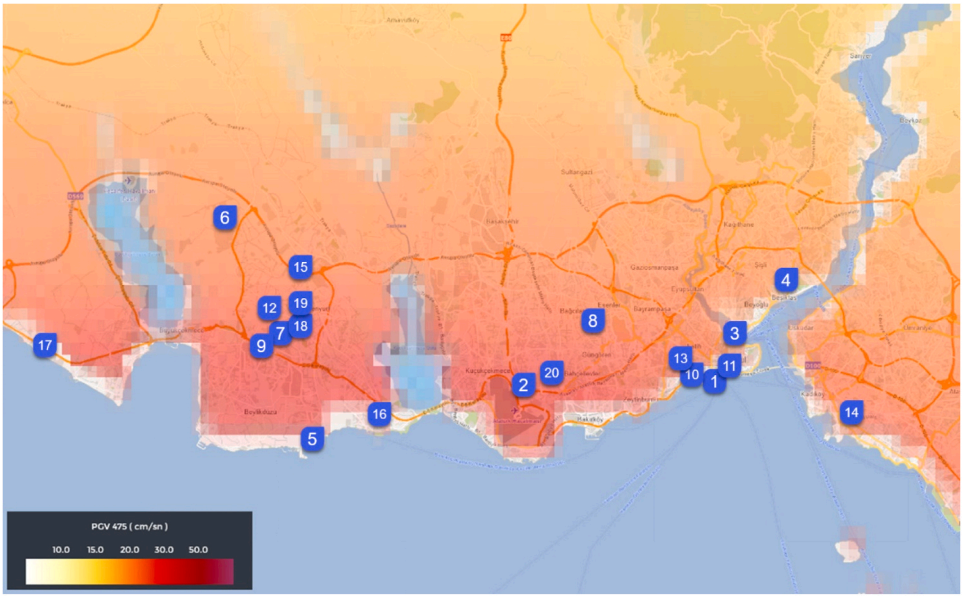

Fig. 8. Locations of the examined buildings with building IDs.

Table 2
Input parameters of the examined buildings (1/2).

Building ID	Peak ground velocity (PGV)		Soil type / Shear wave velocity $(V_S)_{30}$			Structural system state		Concrete class/strength		Soft story presence	
	m/s	H.I.*	Type**	m/s	H.I.*	Score***	H.I.*	MPa	H.I.*	Score***	H.I.*
1	25.04	57.26	ZD	330	86.67	1.0	66.67	13.55	75.57	0.0	100.00
2	26.82	62.34	ZC	455	77.41	2.0	33.33	35.00	14.29	0.0	100.00
3	22.30	49.43	ZE	175	98.15	1.0	66.67	20.73	55.06	1.0	50.00
4	20.80	45.14	ZD	281	90.30	2.0	33.33	35.70	12.29	2.0	0.00
5	34.17	83.34	ZD	230	94.07	1.0	66.67	18.10	62.57	1.0	50.00
6	20.90	45.43	ZD	300	88.89	2.0	33.33	26.98	37.20	2.0	0.00
7	26.50	61.43	ZD	270	91.11	2.0	33.33	25.00	42.86	2.0	0.00
8	23.30	52.29	ZC	560	69.63	3.0	0.00	35.00	14.29	0.0	100.00
9	26.70	62.00	ZC	450	77.78	2.0	33.33	40.00	0.00	1.0	50.00
10	25.40	58.29	ZC	400	81.48	1.0	66.67	13.87	74.66	1.0	50.00
11	24.50	55.71	ZD	230	94.07	1.0	66.67	11.00	82.86	2.0	0.00
12	28.06	65.89	ZD	320	87.41	2.0	33.33	29.00	31.43	2.0	0.00
13	25.08	57.37	ZD	330	86.67	0.0	100.00	23.60	46.86	0.0	100.00
14	24.30	55.14	ZC	400	81.48	2.0	33.33	16.00	68.57	2.0	0.00
15	22.82	50.91	ZC	390	82.22	2.0	33.33	15.60	69.71	2.0	0.00
16	31.40	75.43	ZD	240	93.33	1.0	66.67	13.33	76.20	0.0	100.00
17	24.44	55.54	ZC	390	82.22	3.0	0.00	25.00	42.86	2.0	0.00
18	26.81	62.31	ZB	850	48.15	2.0	33.33	40.00	0.00	1.0	50.00
19	24.57	55.91	ZD	240	93.33	1.0	66.67	25.00	42.86	2.0	0.00
20	26.20	60.57	ZB	910	43.70	1.0	66.67	16.00	68.57	1.0	50.00

*: Hazard index of the input calculated with the descriptions presented in Section 2.1.
**: Designated soil type according to the provisions of TBEC [39]
***: Total score of the input as pts., calculated with the descriptions presented in Section 2.1.

- Model input parameters allow experts to quickly obtain data based on various alternatives such as hazard maps, on-site measurements, visual observations and/or building structural design projects.
- In the proposed model, the fuzzy logic rule base propositions are based on expert civil engineering verbal views and informatics.
- All rules are generated automatically with a code developed by the authors taking into account a logical structure that provides a rapid rule generation alternative for similar fuzzy problems with too many input variables.
- The model also shows the membership degree (MD) of the second most likely damage category so that responsible authorities can consider an alternative course for better decisions. For example, a very close combination of slight/moderate damage category MDs can directly affect the retrofitting priority decision. Additionally, a very close moderate/severe damage category MDs can directly influence the demolition priority decision.
- Design/construction defects and weaknesses in accordance with seismic code regulations are rapidly identified among 20 sample buildings examined in Istanbul City. Demolition and retrofit operations are prioritized according to the final damage category decision of the inspected buildings. Regarding the input values, it is clear that the fuzzy outputs have great consistency with the expected output from the structure, which shows the superiority of this model.

The authors suggest that this model's input range limits can be extended, new inputs can be added, damage function limits and the rules can be adapted for different building types such as steel/timber and masonry structures as future work.

In conclusion, pre-earthquake building fuzzy logic rapid hazard assessment is a promising approach to assess the seismic vulnerability of buildings. This approach provides a more accurate and efficient identification procedure for vulnerable buildings that are critical to ensure the safety of building occupants and minimize the economic and social impacts of earthquakes. Further research is necessary to develop more refined fuzzy logic modelling approaches because whatever the input parameters are, there will always be uncertainties in numerical and especially verbal information forms.

Funding

The APC was funded by Istanbul Medipol University, Türkiye.

Table 3
Input parameters of the examined buildings (2/2).

Building ID	Floor number		Conditions of rebars		Cantilever parts in floor plans		Pounding effect		Physical condition of the building	
	Number	H.I.*	Score**	H.I.*	meter	H.I.*	Score**	H.I.*	Score**	H.I.*
1	9	33.33	0.0	100.00	0.00	0.00	0.0	100.00	0.0	100.00
2	10	37.50	5.0	0.00	0.00	0.00	2.0	0.00	2.0	0.00
3	7	25.00	0.0	100.00	0.00	0.00	0.0	100.00	0.0	100.00
4	5	16.67	5.0	0.00	0.00	0.00	2.0	0.00	1.0	50.00
5	4	12.50	3.0	40.00	2.00	100.00	2.0	0.00	2.0	0.00
6	2	4.17	4.0	20.00	0.00	0.00	2.0	0.00	2.0	0.00
7	5	16.67	5.0	0.00	1.50	75.00	0.0	100.00	2.0	0.00
8	16	62.50	5.0	0.00	0.00	0.00	2.0	0.00	2.0	0.00
9	24	95.83	5.0	0.00	0.00	0.00	2.0	0.00	2.0	0.00
10	5	16.67	0.0	100.00	0.60	30.00	0.0	100.00	0.0	100.00
11	5	16.67	0.0	100.00	0.90	45.00	1.0	50.00	1.0	50.00
12	4	12.50	5.0	0.00	1.00	50.00	0.0	100.00	2.0	0.00
13	5	16.67	0.0	100.00	0.00	0.00	0.0	100.00	1.0	50.00
14	6	20.83	2.0	60.00	1.50	75.00	2.0	0.00	2.0	0.00
15	7	25.00	1.0	80.00	2.00	100.00	1.0	50.00	2.0	0.00
16	5	16.67	5.0	0.00	1.50	75.00	0.0	100.00	1.0	50.00
17	2	4.17	2.0	60.00	1.00	50.00	2.0	0.00	2.0	0.00
18	25	100.00	5.0	0.00	0.00	0.00	2.0	0.00	2.0	0.00
19	5	16.67	5.0	0.00	1.00	50.00	1.0	50.00	2.0	0.00
20	6	20.83	1.0	80.00	1.50	75.00	2.0	0.00	1.0	50.00

*: Hazard index of the input calculated with the descriptions presented in Section 2.1.

**: Total score of the input as pts., calculated with the descriptions presented in Section 2.1.

Table 4
Pre-earthquake building fuzzy logic rapid hazard assessment results of examined buildings.

Building ID	Output Hazard Index	Membership Degrees of Output Hazard Categories	Final Decision on Hazard Category
1	86.18	Collapse – 100.00%	Collapse
2	33.32	Slight Damage – 99.92% No Damage – 0.08%	Slight Damage
3	68.78	Severe Damage – 87.32% Collapse – 12.68%	Severe Damage
4	13.82	No Damage – 100.00%	No Damage
5	41.70	Moderate Damage – 50.20% Slight Damage – 49.80%	Moderate Damage
6	14.39	No Damage – 100.00%	No Damage
7	33.33	Slight Damage – 99.98% No Damage – 0.02%	Slight Damage
8	27.35	Slight Damage – 64.10% No Damage – 35.90%	Slight Damage
9	33.33	Slight Damage – 99.98% No Damage – 0.02%	Slight Damage
10	84.62	Collapse – 100.00%	Collapse
11	68.78	Severe Damage – 87.32% Collapse – 12.68%	Severe Damage
12	33.33	Slight Damage – 99.98% No Damage – 0.02%	Slight Damage
13	50.00	Moderate Damage – 100.00%	Moderate Damage
14	37.92	Slight Damage – 72.48% Moderate Damage – 27.52%	Slight Damage
15	34.32	Slight Damage – 94.08% Moderate Damage – 5.92%	Slight Damage
16	60.60	Severe Damage – 63.60% Moderate Damage – 36.40%	Severe Damage
17	20.81	No Damage – 75.14% Slight Damage – 24.86%	No Damage
18	22.58	No Damage – 64.52% Slight Damage – 35.48%	No Damage
19	25.96	Slight Damage – 55.76% No Damage – 44.24%	Slight Damage
20	67.17	Severe Damage – 96.98% Collapse – 3.02%	Severe Damage

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

1 Guha-Sapir D., Vos F., Below R., Ponserre S. Below R., Ponserre S. Annual disaster statistical review 2011: the numbers and trends. Centre for Research on the Epidemiology of Disasters (CRED) 2012.
2 H. Crowley, J.J. Boomer, R. Pinho, J. Bird, The impact of epistemic uncertainty on an earthquake loss model, Earthq. Eng. Struct. Dyn. 34 (14) (2005) 1653–1685.
3 S.L. Kramer. Geotechnical earthquake engineering, Prentice Hall, New Jersey, 1996.
4 C.A. Kircher, A.A. Nassar, O. Kustu, W.T. Holmes, Development of building damage functions for earthquake loss estimation, Earthq. Spectra 13 (1997) 663–682.
5 Y. Wen, B. Ellingwood, D. Veneziano, J. Bracci, Uncertainty modeling in earthquake engineering. Report No MAE-FD-2, Am. Earthq. Eng. Cent. (2003).
6 R. Villaverde, Seismic analysis and design of non-structural elements, Earthquake engineering: From engineering seismology to performance-based engineering, CRS Press (2004).
7 Z. Şen, Rapid visual earthquake hazard evaluation of existing buildings by fuzzy logic modeling, Expert Syst. Appl. 37 (8) (2010) 5653–5660.
8 EMPI (2003). Earthquake master plan for Istanbul. Istanbul Metropolitan Municipality, 550 pp. (in Turkish).
9 S. Aynur, H.M. Atalay, Comparative analysis of existing reinforced concrete buildings damaged at different levels during past earthquakes using rapid assessment methods, Struct. Eng. Mech. 85 (6) (2023) 793.
10 T.P. Doğan, T. Kızılkula, M. Mohammadi, İ.H. Erkan, H.T. Kabaş, M.H. Arslan, A comparative study on the rapid seismic evaluation methods of reinforced concrete buildings, Int. J. Disaster risk Reduct. 56 (2021), 102143.
11 L.A. Zadeh, Fuzzy sets, Inf. Control 8 (1965) 338–353.
12 L.A. Zadeh, Outline of a new approach to the analysis of complex systems and decision processes, IEEE Trans. Syst. Man Cybern. 3 (1973) 28–44.
13 L.A. Zadeh, The concept of a linguistic variable and its application to approximate reasoning parts I, II, and III, Inf. Sci. 8 (1975) 199–249, 301–357; and 43–80.
14 E.H. Mamdani, Application of fuzzy algorithms for simple dynamic plant, Proc. IEEE 121 (1974) 1585–1588.
15 E.H. Mamdani, S. Assilian, An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller, Int. J. Man-Mach. Stud. 7 (1) (1975) 1–13.
16 Sugeno, Michio, ed. Industrial Applications of Fuzzy Control. Amsterdam; New York: New York, N.Y., U.S.A: North-Holland; Sole distributors for the U.S.A. and Canada, Elsevier Science Pub. Co, 1985.
17 T.J. Ross. Fuzzy logic with engineering applications, John Wiley & Sons, 2009.
18 Z. Şen, Fuzzy logic and modeling principles (Bulanık Mantık ve Modelleme Ilkeleri), Bilge Kültür Sanat Yayınevi [in Turkish], Istanbul (2001).
19 Z. Şen, Supervised fuzzy logic modeling for building earthquake hazard assessment, Expert Syst. Appl. 38 (12) (2011) 14564–14573.
20 K. Demartinos, S. Dritsos, First-level pre-earthquake assessment of buildings using fuzzy logic, Earthq. Spectra 22 (4) (2006) 865–885.
21 N. Bektaş, F. Lilik, O. Kegyes-Brassai, Development of a fuzzy inference system based rapid visual screening method for seismic assessment of buildings presented on a case study of URM buildings, Sustainability 14 (2022) 16318, https://doi.org/10.3390/su142316318.
22 N. Bektaş, O. Kegyes-Brassai, Development in fuzzy logic-based rapid visual screening method for seismic vulnerability assessment of buildings, Geosciences 13 (1) (2022) 6.
23 S.A. Allali, M. Abed, A. Mebarki, Post-earthquake assessment of buildings damage using fuzzy logic, Eng. Struct. 166 (2018) 117–127.
24 M. De Iuliis, O. Kammouh, G.P. Cimellaro, S. Tesfamariam, Downtime estimation of building structures using fuzzy logic, Int. J. Disaster risk Reduct. 34 (2019) 196–208.
25 E. Harirchian, S.E.A. Hosseini, K. Jadhav, V. Kumari, S. Rasulzade, E. Işık, T. Lahmer, A review on application of soft computing techniques for the rapid visual safety evaluation and damage classification of existing buildings, J. Build. Eng. 43 (2021) 102536.
26 E. Harirchian, V. Kumari, K. Jadhav, S. Rasulzade, T. Lahmer, R. Raj Das, A synthesized study based on machine learning approaches for rapid classifying earthquake damage grades to RC buildings, Appl. Sci. 11 (16) (2021) 7540.
27 V. Kumari, E. Harirchian, T. Lahmer, S. Rasulzade, Evaluation of machine learning and web-based process for damage score estimation of existing buildings, Buildings 12 (5) (2022) 578.
28 S.Q. Li, A simplified prediction model of structural seismic vulnerability considering a multivariate fuzzy membership algorithm, J. Earthq. Eng. (2023) 1–24.
29 S.Q. Li, Comparison of empirical structural vulnerability rapid prediction models considering typical earthquakes, in: Structures 49, Elsevier, 2023, pp. 377–401.
30 X. Lu, Y. Xu, Y. Tian, B. Cetiner, E. Taciroglu, A deep learning approach to rapid regional post-event seismic damage assessment using time-frequency distributions of ground motions, Earthq. Eng. Struct. Dyn. 50 (6) (2021) 1612–1627.
31 M. Stepinac, P.B. Lourenço, J. Atalić, T. Kišiček, M. Uroš, M. Baniček, M.Š. Novak, Damage classification of residential buildings in historical downtown after the ML5. 5 earthquake in Zagreb, Croatia in 2020, Int. J. Disaster risk Reduct. 56 (2021), 102140.
32 R.K. Mazumder, S. Rana, A.M. Salman, First level seismic risk assessment of old unreinforced masonry (URM) using fuzzy synthetic evaluation, J. Build. Eng. 44 (2021), 103162.
33 Z. Stojadinović, M. Kovačević, D. Marinković, B. Stojadinović, Rapid earthquake loss assessment based on machine learning and representative sampling, Earthq, Spectra 38 (1) (2022) 152–157.
34 X. Wang, R.K. Mazumder, B. Salarieh, A.M. Salman, A. Shafieezadeh, Y. Li, Machine learning for risk and resilience assessment in structural engineering: progress and future trends, J. Struct. Eng. 148 (8) (2022), 03122003.
35 AFAD (2018). Earthquake Hazard Map. Disaster and Emergency Management Authority (AFAD) of Türkiye. Retrieved from: ⟨https://tdth.afad.gov.tr/⟩.
36 USGS (2022). Interactive Fault Map. United States Geological Survey. Retrieved from: ⟨https://www.usgs.gov/programs/earthquake-hazards/faults⟩.
37 D.J. Wald, V. Quitoriano, T.H. Heaton, H. Kanamori, Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California, Earthq. Spectra 15 (3) (1999) 557–564.
38 Y.M. Wu, N.C. Hsiao, T.L. Teng, Relationships between strong ground motion peak values and seismic loss during the 1999 Chi-Chi, Taiwan earthquake, Nat. Hazards 32 (3) (2004) 357–373.
39 TBEC (2018). Turkey Building Earthquake Code: Rules for design of buildings under earthquake effect, Official Gazette, 18.03.2018, 30364, 2018.
40 IBB (2007). Istanbul Microzonation Studies, Istanbul Metropolitan Municipality Department of Earthquake Risk Management and Urban Improvement (2007), Directorate of Earthquake and Ground. (VS)30 Maps, Retrieved from: ⟨http://www.ibb.gov.tr/trTR/SubSites/DepremSite/PublishingImages/2009.11.11.01.Avs30Map_A3_150000.pdf⟩ and ⟨https://depremzemin.ibb.istanbul/wp-content/uploads/2020/11/C_MIKROBOLGELEME-AVRUPA-RAPOR.pdf⟩.
41 P. FEMA, Rapid visual screening of buildings for potential seismic hazards: a handbook, Fed, Emerg. Manag. Agency Rep., FEMA (2015) 154.
42 MATLAB. version 9.12.0.1884302 (R2022a) 2022 The MathWorks Inc Natick, Massachusetts.