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Seismic risk analysis of existing building stock in Denizli province using rapid visual screening method

Denizli İl'indeki mevcut bina stokunun hızlı görsel tarama yöntemi ile sismik risk analizi

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Abstract

The Rapid Visual Screening (RVS) methodology was developed to overcome the practical constraints of applying traditional engineering analyses at the urban scale. This methodology was utilized in our study for the comprehensive mapping of earthquake risk in Denizli. A total of 5577 buildings across six neighborhoods were screened to evaluate the seismic performance of the building stock. This research is notable for its scale in Denizli, with reinforced concrete buildings constituting 4967 of the examined structures. For these buildings, a novel scoring methodology was developed based on multi-dimensional matrices. Unlike traditional linear scoring, this approach models the interaction between key parameters such as building age, number of stories, and structural irregularities (soft story, short column, enclosed overhangs). As a result of this assessment, the building stock was classified into low-risk, medium-risk, and high-risk groups. Additionally, risk distributions at the neighborhood level and building clusters requiring priority intervention were identified. This integrated risk approach provides the data infrastructure to support Denizli's disaster preparedness strategies. The resulting risk maps offer a scientific basis for prioritizing urban transformation projects and contribute to decision-making mechanisms for the efficient allocation of resources.

Keywords: Rapid Visual Screening, Seismic Risk Assessment, Building Stock, Urban Disaster Preparedness, Risk Mapping.

Öz

Hızlı Görsel Tarama (RVS) metodolojisi, geleneksel mühendislik analizlerinin kentsel ölçekte uygulanmasındaki pratik kısıtlamaların üstesinden gelmek için geliştirilmiştir. Bu metodoloji, çalışmamızda Denizli'deki deprem riskinin kapsamlı bir şekilde haritalanması için kullanılmıştır. Yapı stokunun sismik performansını değerlendirmek amacıyla altı mahallede toplam 5577 bina taranmıştır. Bu araştırma, Denizli'de gerçekleştirdiği ölçek bakımından dikkate değer olup, incelenen yapıların 4967'sini betonarme binalar oluşturmaktadır. Bu binalar için, çok boyutlu matrislere dayalı özgün bir puanlama metodolojisi geliştirilmiştir. Geleneksel doğrusal puanlamanın aksine bu yaklaşım, bina yaşı, kat sayısı ve yapısal düzensizlikler (yumuşak kat, kısa kolon, kapalı çıkma) gibi temel parametreler arasındaki etkileşimi modellemektedir. Bu değerlendirmenin sonucunda yapı stoku, düşük riskli, orta riskli ve yüksek riskli olarak sınıflandırılmıştır. Ek olarak, mahalle düzeyindeki risk dağılımları ve öncelikli müdahale gerektiren bina kümeleri tespit edilmiştir. Bu bütünleşik risk yaklaşımı, Denizli'nin afete hazırlık stratejilerini destekleyecek veri altyapısını sağlamaktadır. Elde edilen risk haritaları, kentsel dönüşüm projelerinin önceliklendirilmesi için bilimsel bir zemin sunmakta ve kaynakların verimli kullanımı için karar alma mekanizmalarına katkıda bulunmaktadır.

Anahtar kelimeler: Hızlı Görsel Tarama, Deprem Risk Değerlendirmesi, Yapı Stoku, Kentsel Afet Hazırlığı, Risk Haritalama.

1 Introduction

Turkey is located in an earthquake zone with a high concentration of active fault lines. Our country experiences earthquakes of various magnitudes each year. Particularly in rapidly urbanizing regions, a large portion of the existing building stock was constructed before current earthquake regulations were implemented. This situation significantly increases the potential adverse effects of earthquakes. Loss of life and economic damage are the most significant of these effects. Denizli province is also under high seismic hazard due to its geological structure and active fault systems. Therefore, effective earthquake risk management must be implemented in urban areas.

One of the main challenges in urban-scale risk assessment studies is the reliable examination of numerous structures in the field. This challenge is significant in terms of time and cost efficiency. Applying detailed engineering analyses (such as time-dependent nonlinear analyses) to large areas in a short period is practically impossible. To address this need, methods enabling rapid and large-scale screening of buildings have been developed. Examples include FEMA P-154 in the USA, IITK-GSDMA in India, GNDT in Italy, JBDPA in Japan, and NZSEE in New Zealand [1,2]. Rapid Visual Screening (RVS) and similar methods enable the assessment of a maximum number of structures with minimal data. These methods also allow for the creation of urban-scale risk maps [3,4].

Shabani et al. (2021) conducted a study on seismic vulnerability assessment at urban scale. This study emphasized the importance of simplified analytical methods, especially for unreinforced masonry structures. The researchers recommended using collapse mechanism, capacity spectrum, and displacement-based approaches. They also emphasized the need to develop methodologies that are both rapid and computationally efficient [5]. Various rapid assessment methods have also been developed and tested in other studies

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related to masonry structures. Ortega et al. (2019) developed two different index methods called SVIVA and SAVVAS for traditional architecture. These methods were validated using Azores earthquake data. In another study conducted on historical structures within Diyarbakır's city walls, two different methods were compared. These methods were the Risky Building Detection Principles (RBTE, 2013) and the Canadian Seismic Screening method. This study demonstrated the usability of rapid screening methods for masonry structures [6,7].

The main advantage of RVS methods is that structures can be evaluated through observational parameters in the field. With this method, seismic risk levels can be determined in a relatively short time. Thus, numerous buildings with various purposes such as public buildings, schools, hospitals, and historical structures can be evaluated at low cost [8,9]. Domaneschi et al. (2021) conducted a study on the seismic assessment of school buildings. In this study, a finite element model was created using construction drawings and field investigations. The researchers also developed a methodology for real-time monitoring of building performance using a wireless sensor network. This innovative approach has enabled more accurate determination of the seismic behavior of existing buildings [10].

Rapid screening methods are also gaining special importance in the assessment of structures with historical and cultural heritage significance. Castori et al. (2017) conducted a seismic vulnerability assessment of a historical monumental masonry structure. The Civic Museum in Sansepolcro was examined in this study. The assessment was carried out using different approaches such as equivalent frame modeling, rigid macro-block modeling, and finite element modeling. The research results revealed that out-of-plane collapse mechanisms pose significant risks [11]. Such studies make important contributions to developing rapid and effective assessment strategies for the preservation of cultural heritage [12–14].

The RVS method is mostly based on indicator parameters. These parameters include factors such as structure type, construction year, irregularities, number of stories, soil characteristics, and material type. The collected information is converted into risk levels through various scoring, rating, or index systems [15–17]. In recent years, traditional RVS methods have been enhanced with artificial intelligence, machine learning, and multi-criteria decision analyses. Thanks to these developments, the methods have become more robust in terms of both accuracy and scalability [18–20].

The use of fragility curves and related probabilistic tools is an important method in seismic damage assessment, allowing for the estimation of a building's likely damage state under various levels of earthquake intensity. A practical application of this approach is the development of Damage Probability Matrices (DPMs), which convert probabilistic data into a more structured format for risk analysis. For example, Palancı and Şenel (2019) developed and compared DPMs for single-story precast industrial buildings using various analytical methods, highlighting how a logic tree approach can be used to manage uncertainties in damage estimation [21]. These probabilistic methods are also powerful for the comparative risk analysis of different structure types. Yazdanpanah et al. (2021) developed fragility curves for regular and irregular steel frames using wavelet-based features, demonstrating that irregularity increases the probability of damage [22]. Similarly, Magapu and Setia (2023) compared the seismic performance of step-back and step-back setback structures using fragility curves derived from Incremental Dynamic Analysis (IDA), concluding that the latter type exhibits lower damage probability [23].

Studies evaluating the economic dimensions of earthquake risk also hold an important place in the literature. Yamin et al. (2017) proposed a methodology for seismic risk analysis of buildings. This methodology offers a probabilistic assessment in terms of economic losses. The researchers used prototype building models and nonlinear Response History Analyses (RHA). Economic loss probabilities for different structure types were calculated using Monte Carlo simulations [24]. Such approaches provide important data for cost-effectiveness analyses of risk reduction strategies.

Beyond residential and commercial building stocks, rapid screening methods have also been developed for special structures. For instance, Girgin and Krausmann (2013) presented a framework for assessing large-scale "natech" risks in industrial facilities [25]. However, the literature also includes targeted methodologies focusing on more specific structural types, such as single-story precast industrial buildings. In this area, Palancı and Şenel (2013) developed a rapid seismic performance assessment method for these buildings using inventory data and structural capacity curves. In addition to this approach, modern statistical tools are also used to manage uncertainties in the assessment process [26]. For example, Palancı (2019) proposed a fuzzy logic-based risk assessment model (FBRAM) for the same building type, which integrates expert opinion with numerical uncertainties [27]. These studies demonstrate how both structural analysis-based and data-driven intelligent systems can be effectively utilized in the seismic risk assessment of industrial structures.

However, rapid screening methods also have certain limitations. These methods carry a risk of subjectivity in evaluation processes as they are based on observation. Some structural features may not be directly observable. Short columns, soft stories, and weak soil effects are examples of these features. Additionally, it has been emphasized that visual screening results need to be supported, especially in large and complex cities. This support should be provided through digital data and advanced analysis methods [5,19]. Developed hybrid procedures and real-time monitoring systems offer new approaches to enhance the reliability of rapid screening [10].

This study presents a comprehensive seismic risk analysis of the existing building stock in a rapidly developing district of the Denizli province. The analysis is based on a novel Rapid Visual Screening (RVS) methodology developed herein, which overcomes a key limitation of traditional linear scoring systems. Our approach utilizes a multi-dimensional negative score matrix that models the critical interactions between structural parameters, such as building age, number of stories, and seismic vulnerabilities (e.g., soft story, short column). Through an extensive field study covering 5577 structures in six neighborhoods, 4967 reinforced concrete buildings were evaluated against these criteria. Based on the resulting scores, buildings were classified into low, medium, and high-risk categories, providing a quantitative risk distribution. The findings offer local governments crucial data for prioritizing urban transformation and renewal plans. More broadly, this study contributes to the literature by proposing a more nuanced RVS methodology and produces comprehensive, screening-based earthquake risk maps for this specific region of Denizli, supporting proactive disaster management.

2 Methodology

The linear scoring systems used in traditional Rapid Visual Screening (RVS) methods, which treat structural parameters as independent variables, are inadequate for capturing complex interactions. The core innovation of this study is the introduction of a multi-dimensional negative score matrix (Table 2) that fills this gap by modeling the interaction between parameters. For instance, unlike conventional methods that assign a fixed penalty score for a 'soft story' vulnerability, our methodology determines the risk of this defect based on both the number of stories (S1-S3) and the construction period (Y1-Y4) via the NS3 matrix. Although the scores in these matrices were developed specifically for this study, their logic is not arbitrary; the relative weights are based on the destructive impact of brittle failure mechanisms emphasized by authorities such as Sucuoğlu (2007) and Özcebe et al. (2004) [28-33]. Our methodology reflects this engineering principle by assigning high negative scores to critical defects. Consequently, our approach yields a more comprehensive and realistic risk analysis by modeling the cumulative effect of dangerous parameter combinations (e.g., the co-existence of a soft story and a short column in a pre-1975 high-rise building).

2.1 Data Acquisition and Building Inventory

The building inventory data required for the analysis were obtained through a street-level survey based on direct field observations. This process was systematically conducted by a research team, including one of the authors of this paper, through the visual inspection of each building's exterior. The survey captured key structural attributes needed for the parameter-based assessment.

2.2 Identification and classification of risk parameters

Within the scope of the study, the key parameters affecting the seismic performance of structures were determined based on a comprehensive literature review and expert opinions. All parameters and their classifications are shown together in Table 1.

Table 1. Classification of risk parameters.

Parameter	Code	Definition
Year of Construction	*Y1*	Buildings built before 1975
	Y2	Buildings built between 1975 and 1998
	Y3	Buildings built between 1998 and 2007
	Y4	Buildings built after 2007
Number of Stories	*S1*	1-2 story buildings
	S2	3-5 story buildings
	S3	6+ story buildings
Pounding	*P1*	The subject building is located at the edge, with a floor level different from the adjoining building.
	P2	The subject building is located at the edge, with the same floor level as the adjoining building.
	P3	**The subject building is located in the middle, with a floor level different from the adjoining buildings.**
	P4	**The subject building is located in the middle, with the same floor level as the adjoining buildings.**
	P5	**Detached buildings (separately standing buildings)**
Short Column	*SC1*	**Presence of short column effect**
	SC2	**Absence of short column effect**
Enclosed Overhang	*HO1*	**Presence of enclosed overhang**
	HO2	**Absence of enclosed overhang**
Soft Story	*SS1*	**Presence of soft-story irregularity**
	SS2	**Absence of soft-story irregularity**

The construction year classification was established in alignment with the development of Turkish seismic codes. The story number classification was determined to evaluate the impact of building height on seismic behavior. This classification is based on empirical data from past earthquakes. The pounding effect classification was designed to assess the collision risk between adjacent buildings during earthquakes. Structural irregularities (short column, enclosed overhangs, soft story) were considered as present/absent. These irregularities can critically affect seismic performance and create potential damage points. Additionally, the visually assessed construction quality was included in the performance score calculation.

2.3 Parameter-based risk assessment

In the developed methodology, multi-dimensional negative score (NS) matrices have been defined to model the combined effects of structural parameters on seismic risk. This approach evaluates parameters not in isolation, but in interaction with one another. The scoring system employs five different negative score scenarios: NS1 (base case), NS2 (presence of enclosed overhangs), NS3 (presence of a soft story), NS4 (presence of short columns), and NS5 (pounding effect), with their corresponding score matrices presented in Table 2. In cases where a structural defect is absent (e.g., no enclosed overhangs - HO2, no short columns - SC2, or detached building - P5), the score from the corresponding negative score matrix is taken as '0' (zero). When enclosed overhangs (HO1) or soft story irregularities (SS1) are present, the negative scores are determined based on the combined effect of the building's height category (S1, S2, S3) and construction period (Y1-Y4) using the respective NS2 and NS3 matrices. For short columns (SC1) and pounding effects (P1-P4), the scoring is based on construction period and the presence or absence of these conditions. The engineering rationale and scoring logic behind these scenarios are explained in the following subsections. Additionally, the observed physical quality of the structures has been incorporated into the assessment through the AQ parameter.

Table 2. Negativity scores matrix.

	NS1: **Base Negativity Score (No Defects)**			***NS2*: Score if Enclosed Overhang (HO1) is Present**			***NS3*: Score if Soft Story (SS1) is Present**		
	S1	**S2**	***S3***	***S1***	***S2***	***S3***	***S1***	***S2***	***S3***
Y1	-20	-25	-30	-15	-20	-25	-10	-15	-15
Y2	-15	-20	-25	-10	-15	-20	-10	-15	-15
Y3	0	-10	-15	-5	-10	-15	-5	-10	-10
Y4	0	-5	-10	0	-5	-5	-5	-10	-10

	***NS4*: Score for Short Column**		***NS5*: Score for Pounding Effect**				
	SC1	***SC2***	***P1***	***P2***	***P3***	***P4***	***P5***
Y1	-15	0	-15	-15	-15	-10	0
Y2	-10	0	-15	-15	-10	-5	0
Y3	-5	0	-15	-10	-5	0	0
Y4	-5	0	-10	-5	-5	0	0

2.3.1 Effect of number of stories

The combined evaluation of construction year and story number considered both the physical properties of structures and the engineering standards of their respective periods. This approach enabled more accurate risk determination aligned with seismic code development. Earthquake vulnerability increases with higher story numbers. In this study, by considering both parameters together, older high-rise buildings were assigned higher risk scores. For example, as shown in the NS1 (Base Score) matrix in Table 2, pre-1975 buildings with 1-2 stories receive -20 points, while buildings with 6 or more stories receive -30 points.

2.3.2 Effect of enclosed overhang

Enclosed overhangs are architectural elements that affect the stability and rigidity of buildings. They are generally defined as expanded areas projecting outward from the exterior façade on the upper floors. Such overhangs may adversely influence the vibration modes and load distribution of the building. Since enclosed overhangs in older structures were often constructed without proper engineering considerations. Therefore, in the NS2 matrix (Table 2), which represents this scenario, the highest adverse scores (-15 to -25) were assigned to buildings constructed prior to 1975.The risk is more serious in high-rise buildings, and buildings with 6+ stories received higher negative scores in all periods.

2.3.3 Effect of soft story

Soft story refers to floors, typically at ground or first level, that exhibit lower stiffness compared to other floors. This condition represents a critical weakness point for seismic safety. Reflecting this critical weakness, the NS3 matrix assigns the highest negative scores (-15) to pre-1975 and 1975-1998 buildings. Soft story risk increases with the number of stories. In high-rise buildings, force distribution is more complex, and stiffness loss in lower floors seriously affects structural stability.

2.3.4 Effect of short column

A short column is a structural condition where a column's constrained height increases stiffness, leading to a high risk of brittle shear failure during an earthquake. The NS4 matrix (Table 2) models this risk based on a critical evolution in Turkish seismic codes. The 1998 code introduced a mandatory capacity design approach, requiring that short columns be specifically reinforced to resist the maximum possible shear force—a provision absent in earlier regulations. Accordingly, our matrix reflects this codified change in vulnerability by assigning the highest adverse score to pre-1998 buildings and a significantly lower score to post-1998 buildings where this risk is mitigated by design. A zero score is assigned when no short columns are observed (SC2).

2.3.5 Effect of pounding

The pounding effect occurs when adjacent buildings collide during an earthquake, causing structural damage. The positioning of buildings and the gap distance between them are the key factors determining the severity of the pounding effect. Buildings located at edges (P1, P2) are more vulnerable to the pounding effect. This vulnerability is due to their corner columns and beams potentially having lower load-bearing capacities. Detached buildings (P5), however, do not carry any pounding risk.

2.3.6 Effect of apparent building quality

Apparent Quality (AQ) quantifies a building's physical condition and maintenance level based on visual indicators like cracks, spalling, or decay. It is scored on a positive scale from 0 (poor) to 10 (excellent). Unlike vulnerability parameters, AQ acts as a positive modifier; this score is subtracted from the total negative score (NS), thereby rewarding well-maintained buildings and penalizing those with visible signs of degradation.

2.4 Building performance score calculation algorithm

The building performance score (*BPS*) is an assessment criterion developed to quantitatively determine the earthquake risk level of buildings. First, the sum of the building's existing negativity scores is calculated using Equation (1); then, this sum is subtracted from the reference maximum score of 100 to obtain the final building performance score (*BPS*, Equation (2)).

$$\sum NS = NS1 + NS2 + NS3 + NS4 + NS5 - AQ \quad (1)$$

$$BPS = 100 - \sum NS \quad (2)$$

This methodology creates standardized risk scores by evaluating buildings' current conditions using quantitative data. This allows for objective identification of structures requiring priority intervention through comparison of their relative risk levels.

3 Results and discussions

In this study, six neighborhoods of the selected district with high population density and various building typologies were examined in detail. These neighborhoods are among the areas that well represent the district in terms of both physical characteristics and demographic structure. Therefore, they provide an appropriate sample for implementing rapid assessment methods for earthquake preparedness. The general characteristics of the district and the compatibility of the selected neighborhoods with these features guide the evaluation process. The population and surface areas of the neighborhoods included in the rapid assessment are provided in Table 3.

Table 3. Distribution of building types examined on a neighborhood basis.

	Population	Area (km^2)
Neighborhood 1	16637	0.591
Neighborhood 2	3510	0.177
Neighborhood 3	17604	0.476
Neighborhood 4	21411	0.93
Neighborhood 5	8474	0.746
Neighborhood 6	11441	0.513

According to the 2018 population data from the Turkish Statistical Institute (TÜİK), the population of the neighborhoods examined in this study accounts for approximately 27% of the total population of the selected district. This indicates that the assessed neighborhoods are among the areas with the highest population density within the district.

3.1 Classification of building scores

A total of 5,577 buildings in the six selected neighborhoods were examined using the rapid assessment method developed in this study. According to the classification based on structural system types, 89.1% of these buildings are reinforced concrete, 9.0% are masonry, and 1.9% belong to other structural systems (Figure 1). The number of buildings examined per neighborhood is presented in detail in Table 4.

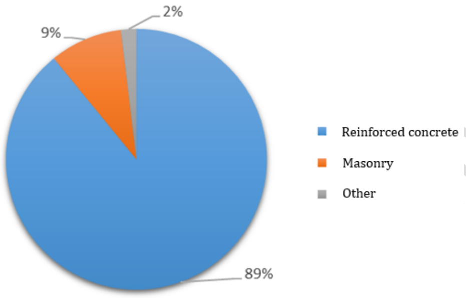

Figure 1. Proportions of building types obtained through street survey.

To ensure the scope of the study and obtain comparable results, the risk assessment analyses were conducted exclusively for reinforced concrete buildings. In determining the seismic performance scores of these buildings, structural parameters such as construction year, number of stories, presence of soft-story irregularity, short-column irregularity, presence of enclosed overhangs, and pounding effect, as well as the apparent building quality, were considered. The weighting of each parameter was carried out based on literature reviews and expert opinions.

The distribution of final performance scores, calculated for each of the 4,967 reinforced concrete buildings, is presented in the histogram in Figure 2. To categorize these buildings into meaningful High, Medium, and Low-Risk groups, a percentile-based classification, which is common in risk assessment literature, was adopted. This method allows for the determination of objective thresholds based on the internal distribution of the dataset itself, rather than relying on arbitrary absolute values. The classification thresholds were defined as follows:

- High Risk: Buildings in the lowest 30% percentile of the score distribution.
- Medium Risk: Buildings in the middle 40% percentile (between the 30th and 70th percentiles).
- Low Risk: Buildings in the highest 30% percentile (above the 70th percentile).

A statistical analysis of the 4,967 building scores revealed that the 30th percentile corresponds to a score of 52.0, and the 70th percentile corresponds to a score of 72.0. Therefore, in Figure 2, the threshold separating high-risk from medium-risk buildings (dashed red line) is set at 52 points, and the threshold separating medium-risk from low-risk buildings (dashed green line) is set at 72 points.

This classification reflects the risk distribution within the building stock in a statistically balanced manner. This approach allows for the identification of buildings that should be prioritized in urban transformation and earthquake preparedness efforts. By directing limited resources to the highest-risk buildings, risk classification contributes to the development of effective response strategies before a potential earthquake and reducing potential loss of life. Because the method is based on the distribution of building performance scores, it is easily adaptable to different urban areas and building stocks.

Table 4. Distribution of building types examined on a neighborhood basis.

	Reinforced Concrete	Masonry	Other
Neighborhood 1	1162	117	34
Neighborhood 2	308	41	6
Neighborhood 3	961	56	3
Neighborhood 4	1466	91	40
Neighborhood 5	243	148	24
Neighborhood 6	827	49	1
Total	4967	502	108

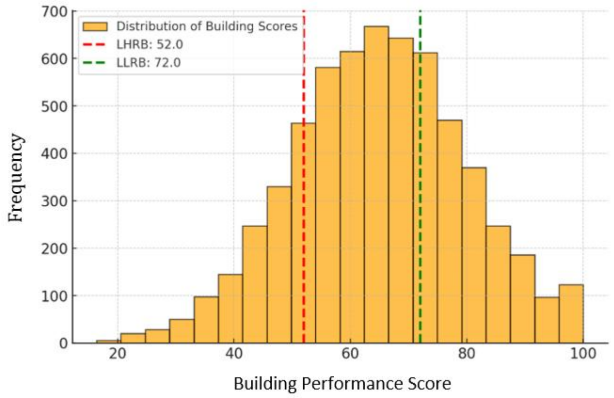

Figure 2. Histogram of the distribution of building scores.

The building score histogram presented in Figure 2 shows a wide range of scores across the analyzed building stock. The distinct thresholds of 52.0 and 72.0 demonstrate the polarization of the risk profiles of buildings in the study area. Once the scoring boundaries were defined, 4967 buildings were evaluated: 1487 were classified as high risk, 1998 as medium risk, and 1482 as low risk. This suggests a heterogeneous urban fabric where buildings constructed in different periods and with varying building quality coexist.

3.2 Evaluation of building scores and risk maps

Building scores obtained using the rapid assessment methodology developed within the scope of the study were analyzed to determine the neighborhood risk profile and visualize the spatial risk distribution. This section evaluates the general characteristics of the building stock, the statistical distribution of building scores, the distribution of buildings by risk class, and the generated risk maps.

3.2.1 General characteristics of the building stock

This section presents the general characteristics of the building stock assessed through Rapid Visual Screening methodology, including distribution by number of stories, construction periods, and associated risk categories.

Figure 3 illustrates the risk distribution by number of stories for the 4967 reinforced concrete buildings scanned in Denizli, revealing that 3-5 story buildings constitute the dominant building type (3235 buildings, 65%). Within this category, medium risk has the highest frequency (1339 buildings). While high risk is almost nonexistent in 1-2 story buildings (4 buildings), this number reaches 695 in 6+ story buildings. This finding demonstrates that the combined effect of structural irregularities and construction period factors significantly increases the risk level in high-rise buildings. Particularly, Denizli's rapid urbanization during the 1975-1998 period and the probability that buildings from this period were designed according to inadequate earthquake regulations explain the observed risk profile.

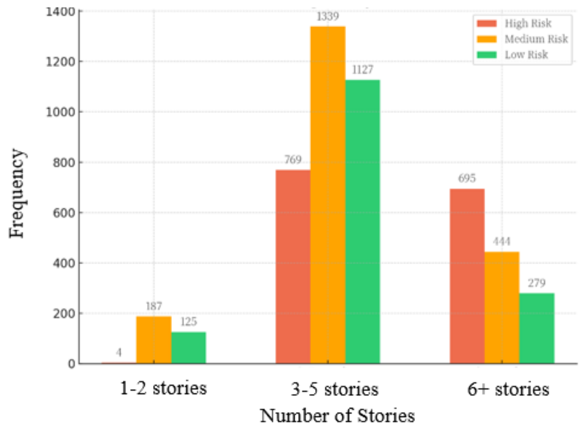

Figure 3. Distribution of data according to the number of stories.

The effect of the construction period on the risk level directly reflects the evolution of Turkey's seismic codes. As shown in Figure 4, the pre-1975 building stock is minimal (80 buildings), which can be explained by both Denizli's limited urbanization during that era and the renewal of old structures over time. The 1975-1998 period has the highest frequency in the high-risk category (1325 buildings, 88%); these years cover a period when the 1975 seismic code was in effect but was accompanied by significant deficiencies in supervision. The impact of the updated seismic codes enacted in 1998 and 2007 is observable; while the medium-risk category is dominant in the 1998-2007 period (380 buildings) and a notable increase in the low-risk category is seen, the low-risk category reaches 1192 buildings in the post-2007 period. This trend points to the positive effect of modern regulations and rising engineering standards on structural safety. However, the presence of 305 buildings in the medium-risk category even in the post-2007 period suggests that the building inspection system and quality control still have potential for improvement.

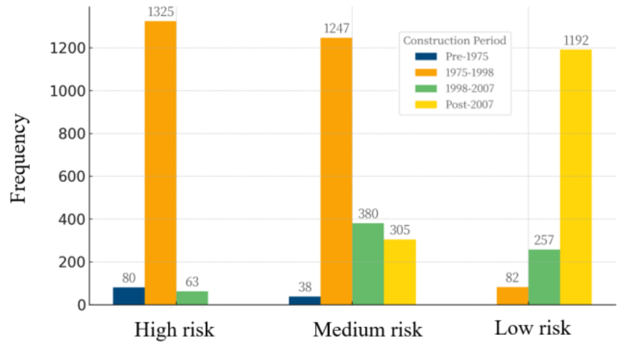

Figure 4. Distribution of buildings by risk category and construction period.

The distribution of structural deficiencies across risk categories is examined in Figure 5. The analysis reveals that the pounding effect is the most dominant vulnerability in both high-risk (1307 buildings) and medium-risk (1515 buildings) structures. This finding indicates that issues arising from adjacent building configurations are the primary threat for the entire building stock, regardless of risk level. Enclosed overhang stands out as another significant deficiency, particularly for high-risk buildings (939 buildings); interestingly, observations suggest that the prevalence of this flaw has increased in newer buildings, likely due to modern architectural trends. In contrast, while well-known engineering flaws like soft story (776 buildings) and short column (730 buildings) still affect a significant portion of high-risk structures, their frequency appears to have decreased over time, reflecting the impact of improved engineering awareness and code enforcement.

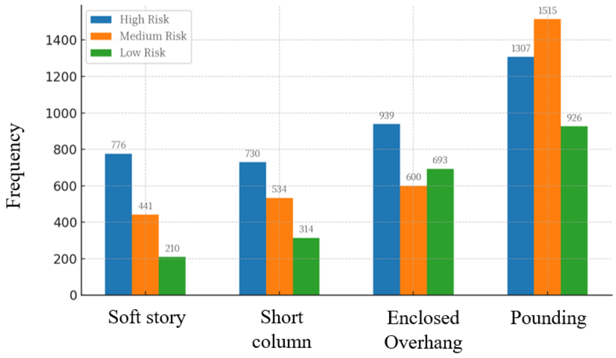

Figure 5. Distribution of structural parameters by risk category.

3.2.2 Neighborhood-based risk maps

Neighborhood-based risk maps clearly reveal the spatial extent of risk distribution. These maps visualize the spatial clustering of high, medium, and low-risk structures and are critical for identifying priority intervention areas for urban transformation strategies.

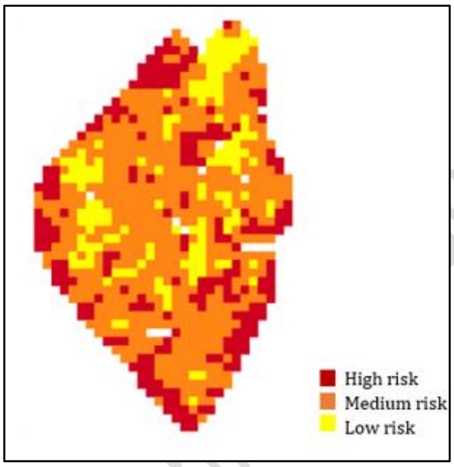

Figure 6. Risk map for Neighborhood 1.

When examining the risk map of Neighborhood 1 in Figure 6, it can be observed that the medium risk level is predominant. However, in this neighborhood containing 1162 reinforced concrete buildings, it has been determined that high-risk buildings are generally concentrated along the border regions of the neighborhood.

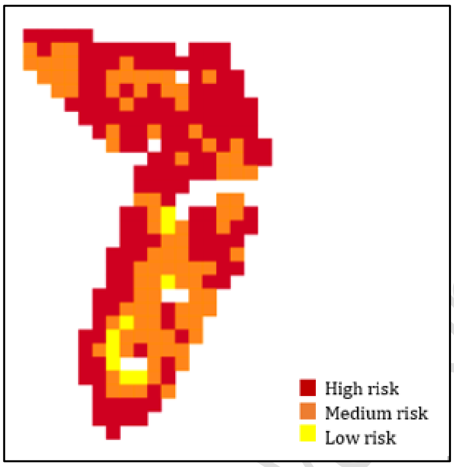

Figure 7. Risk map for Neighborhood 2.

Despite having relatively fewer structures (308 reinforced concrete structures), Neighborhood 2's risk map reveals a high-risk predominance throughout the area. The high-risk structures concentrated in the northern part of the neighborhood create a large risk zone, presenting a critical situation requiring urgent intervention. High- and medium-risk structures are also present in the southern part of the neighborhood, necessitating comprehensive neighborhood-wide risk mitigation strategies (Figure 7).

The risk distribution in Neighborhood 3 exhibits a highly heterogeneous structure. In this neighborhood, home to 961 reinforced concrete structures, it was observed that risk levels do not form a distinct spatial pattern, with high, medium, and low-risk structures interspersed. This may indicate that the neighborhood developed in different periods and with different building quality (Figure 8).

The risk map for Neighborhood 4, home to the largest number of reinforced concrete structures (1466), generally shows that low and medium risk levels predominate. The presence of high-risk structures in isolated clusters indicates that this neighborhood has a relatively newer and more planned urban development (Figure 9).

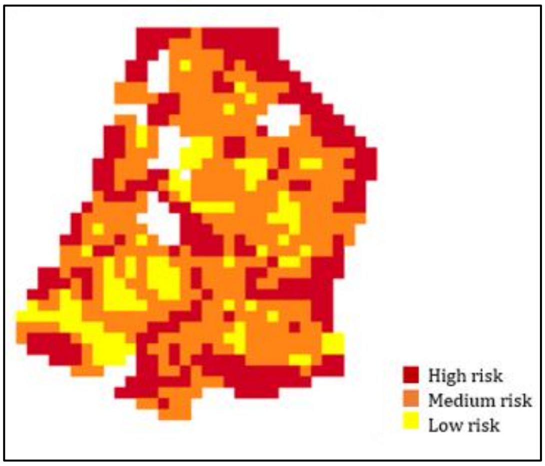

Figure 8. Risk map for Neighborhood 3.

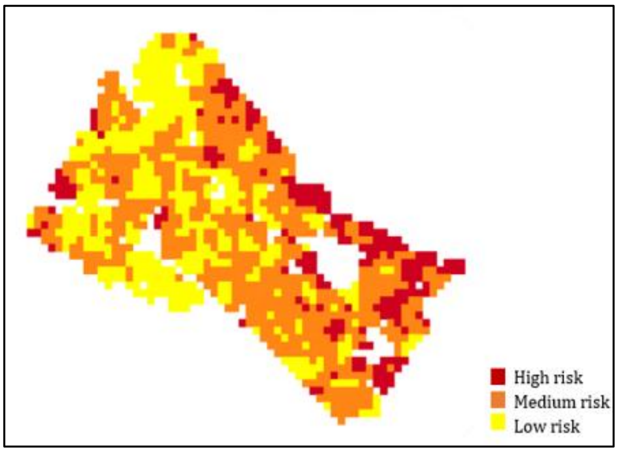

Figure 9. Risk map for Neighborhood 4.

As seen in Figure 10, the risk map for Neighborhood 6 generally shows a distribution dominated by high risk levels. High-risk structures, in particular, form dense clusters in the northern and southeastern parts of the neighborhood.

A risk map could not be created for Neighborhood 5 due to insufficient data.

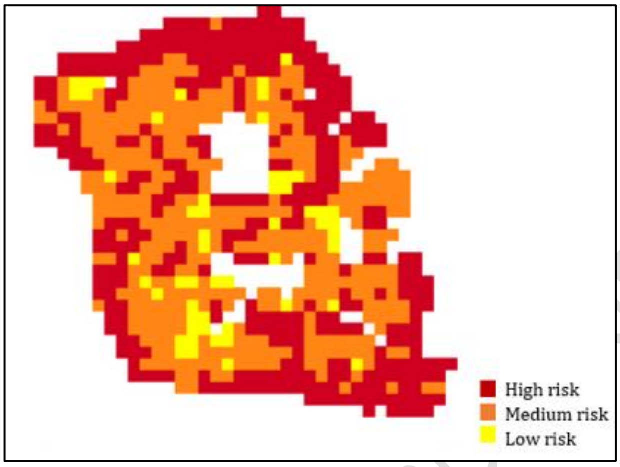

Figure 10. Risk map for Neighborhood 6.

The resulting risk maps clearly reveal that the risk distribution in the study area is not spatially homogeneous. This finding indicates that urban transformation and earthquake risk reduction efforts require specific and targeted strategies for each neighborhood. Areas where high-risk building clusters are concentrated should be considered priority intervention areas. Furthermore, a comparative analysis of the risk maps of five different neighborhoods reveals that high-risk buildings are particularly concentrated at neighborhood boundaries and near major transportation arteries. This demonstrates the need to prioritize high-risk buildings adjacent to major arteries in urban transformation and retrofitting efforts to maintain the continuity of transportation networks after a potential disaster. This will enable both uninterrupted post-disaster response and evacuation processes and neighborhood-wide risk reduction.

Finally, the risk maps also demonstrate how building-based risk assessment can be integrated holistically into risk analysis at the street, neighborhood, and city scales. This integrated perspective will enable more effective and efficient planning and implementation of earthquake risk reduction policies.

4 Conclusions

This study conducted a comprehensive, urban-scale seismic risk assessment in Denizli, Turkey, by analyzing 4967 reinforced concrete structures using an enhanced Rapid Visual Screening (RVS) methodology. By developing a unique, multi-dimensional scoring system and integrating the findings with GIS, this research provides critical insights for urban planning and disaster mitigation. The key conclusions are synthesized as follows:

1. The analysis provides definitive evidence of the positive impact of modern seismic regulations. Buildings constructed post-2007 are predominantly low-risk (1192 buildings), whereas those from the 1975-1998 period, a time of known supervisory deficiencies, constitute the vast majority of the high-risk category (1325 buildings). This clear temporal trend validates the effectiveness of the 1998 and 2007 code updates. However, the study also identifies an alarming trend: "enclosed overhangs" have become more prevalent in newer constructions, likely due to architectural choices, introducing new vulnerabilities even in modern buildings. This highlights that regulatory improvements alone are insufficient without addressing evolving design practices.

2. The analysis reveals that the most common structural risk is not an isolated flaw but a systemic issue of urban planning: the "pounding effect." This deficiency was identified in a staggering 75.5% of all analyzed structures (3748 buildings), making it the single most common threat across all construction periods and risk categories. This finding demonstrates that the widespread practice of adjacent construction in Denizli has created a deeply embedded, city-wide vulnerability. Consequently, mitigating this risk requires not only single-building interventions but also a broader urban strategy that addresses building separation and the dynamics of densely packed city blocks.

3. The GIS-based risk maps reveal that seismic risk is not homogeneously distributed. Instead, it forms distinct spatial clusters, demanding tailored urban transformation strategies rather than a one-size-fits-all approach. Neighborhood 2, with its high concentration of high-risk structures in its northern part, emerges as a top-priority area for urgent intervention. Conversely, Neighborhood 4, characterized by more planned development and isolated risk clusters, represents a model for more resilient urban growth. The analysis also revealed a strategic vulnerability: high-risk buildings are often concentrated along major transportation arteries, necessitating their prioritization in retrofitting efforts to ensure post-disaster accessibility and emergency response.

4. The unique scoring system developed in this study, which accounts for the interaction between multiple structural parameters (e.g., construction year, number of stories, and co-occurring deficiencies), proved essential for a realistic risk assessment. This integrated approach moves beyond simple presence/absence checks of flaws and provides a more detailed understanding of vulnerability, demonstrating that the combined effect of multiple, even minor, deficiencies can significantly elevate a building's risk profile.

In conclusion, this study provides a comprehensive assessment of the existing building stock in Denizli province in terms of earthquake risk. It provides a scientific basis for developing urban transformation, retrofitting, and renovation plans. The application of our proposed methodology to other cities and its integration with GIS technologies will significantly contribute to national earthquake risk reduction strategies. In future studies, further developing the model with AI-supported analysis methods and detailed examination of local soil conditions will increase the precision of seismic risk assessments.

5 Author contribution statements

In the conducted study, both authors contributed to the conceptualization of the study. Author 1 contributed to data collection through street surveys and literature review, while Author 2 contributed to data organization, risk analysis, development of risk maps, and formatting of the manuscript.

6 Statement of ethical committee approval and conflict of interest

There is no need to obtain ethics committee approval for the prepared article.
There is no conflict of interest with any individual/entity in the prepared article.

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