Assessment of Physical Resilience and Identification of Vulnerable Neighborhoods Against Earthquake Hazards; Case Study: District 2 of Tehran City*

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ABSTRACT

Studies show that destructive earthquakes along the fault line north of Tehran pose a serious threat to humans and the anthropogenic environment. Urban resilience is a relatively new topic with various aspects, including the ability to predict the occurrence of accidents, limit their effects, and return to the pre-crisis state. The present study was conducted to assess the physical resilience of Tehran Region 2 and identify vulnerable neighborhoods to earthquake hazards. The research method is descriptive-analytical, with a mixed-methods approach, and data were collected through library and document studies. Next, using the Delphi technique and expert opinion, the criteria effective on the level of physical resilience were determined and categorized under the five principles of a physically resilient city (Clark and Nemecek, 2010) against earthquake hazards. Then, using the analytic hierarchy process, the criteria for reducing physical vulnerability were prioritized, and the factors affecting it were identified. Finally, a database was created in ArcGIS, and a comprehensive map of the areas at risk in the mentioned region was generated. Based on the results, it was determined that the neighborhoods of Farahzad, Parvaz, and Faraz were not well located from a physical resilience perspective and would be more vulnerable to earthquakes.

Keywords: Physical resilience, Earthquake hazards, Geographic Information System (GIS), AHP model, District 2 of Tehran City.

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* This article is derived from the master's thesis of the second author entitled "Assessment of the Physical Resilience of District 2 of Tehran City against Earthquake Hazards", which was conducted under the supervision of the first author in 2023.

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1. INTRODUCTION

Tehran City, due to its high population density, strong centralization of administrative, economic, and service centers, and its specific geological setting, is among the areas most exposed to damage. On the other hand, analytical and historical earthquake studies in Iran indicate that devastating earthquakes—particularly along the North Tehran Fault, which is the most significant fault in the city—have, over many years, caused severe damage to man-made structures and, more importantly, extensive human casualties. Annually, approximately 250 earthquakes with magnitudes of 4 to 4.9, 25 earthquakes with magnitudes of 5 to 5.9, two earthquakes with magnitudes of 6 to 6.9, and 0.2 earthquakes with magnitudes of 7 to 7.9 (about two earthquakes every ten years) occur. Even though Iran's population constitutes about one percent of the world's population, earthquake-related casualties account for six percent of global fatalities (Behzadfar 2011). Therefore, the safety of settlements in earthquake-prone areas and the need to evaluate risk-inducing factors have become increasingly important. District 2 of Tehran City, due to its location and proximity to the North Tehran Fault, the presence of worn-out urban fabric in some neighborhoods, as well as its extent, population, and the existence of numerous man-made facilities and buildings, is one of the high-risk areas of Tehran in terms of earthquake hazards. Urban resilience is a relatively new and complex concept encompassing various economic, social, cultural, and physical dimensions. Resilience has three main characteristics: (1) the capacity to withstand the impacts imposed by a hazard in such a way that those hazards do not lead to disaster (reducing the likelihood of failure); (2) the capacity to return to the previous state after a disaster (reducing the impacts of failure); and (3) the ability to transform and adapt after a disaster (Ostovar Izadkhah 2011, 147). Resilience is discussed as a change in relation to social resilience and as the capacity of a community to respond adaptively to transformation; rather than merely returning to a normal pre-disaster condition, it may imply transformation to a new state that is more sustainable in the current environment (Matyas and Pelling 2015, 8). A resilient community has a high threshold and is able to absorb significant pressure before exceeding its threshold (Windle 2011, 54). A resilient community requires less time to return to pre-disaster conditions. In contrast, a community with low resilience takes longer to recover or may not recover at all (Madhuri et al. 2015, 2). Dadashpour and Adeli (2015), in an article entitled "Assessment of Resilience Capacities in the Urban Complex of Qazvin," stated that, among the various dimensions of resilience, the institutional dimension—and, subsequently, the physical dimension—are in a less favorable condition. Kusumastuti et al. (2014), in a study entitled "Developing and Expanding a List of Resilience Indicators against Natural Disasters in Indonesia," propose a framework for assessing the resilience of areas exposed to natural hazards. Cutter et al. (2010), in an article entitled "Disaster Resilience Indicators for Benchmarking Baseline Conditions," present a methodology and a set of indicators for assessing existing conditions and factors influencing disaster resilience. Identifying indicators and factors effective in reducing damage from earthquake hazards can provide a basis for enhancing urban resilience. Accordingly, the present study aims to identify and evaluate the effective criteria in analyzing physical resilience by collecting data obtained from questionnaires completed through the Delphi method by a panel of eight specialists and experts in the fields of urban planning and urban design, and ultimately to prepare comprehensive maps for identifying neighborhoods vulnerable to earthquake hazards in District 2 of Tehran City. Fortunately, in recent years, increasing attention has been paid to the concept of resilience, and studies have been conducted in this field. It should be noted that the innovative aspects and distinctions of the present research compared to previous studies can be summarized as follows:

1. Focusing on the physical dimension of resilience against earthquake hazards;
2. Adopting a neighborhood-based approach and examining each neighborhood of District 2 of Tehran City based on evaluation criteria;
3. Determining the level of hazard exposure of each parcel in District 2 of Tehran City against a potential earthquake;
4. Analyzing the final level of physical resilience of each parcel in the neighborhoods of District 2 of Tehran City;
5. Three-dimensional simulation of District 2 of Tehran City and preparation of a final and comprehensive physical resilience map of District 2 of Tehran City.

Finally, it should be noted that the members of the expert and specialist panel are as follows: (1) Ahmad Nikhah Naeini (Head of the Deputy for Urban Planning and Architecture, Ministry of Roads and Urban Development); (2) Ali-Asghar Kamalizadeh (CEO of the Tehran Urban Renewal Organization); (3) Mohammadreza Ebrahimi (Deputy for Renewal and Development, Tehran Urban Renewal Organization); (4) Nastaran Asgharzadeh (Head of the Department of Inefficient Urban Projects, Tehran Urban Renewal Organization); (5) Alireza Andalib (Lecturer and University Professor); (6) Esmail Shia (Lecturer and University Professor); (7) Ahmad Saeedi Nia (Lecturer and University Professor); (8) Morteza Talachian (Lecturer and University Professor).
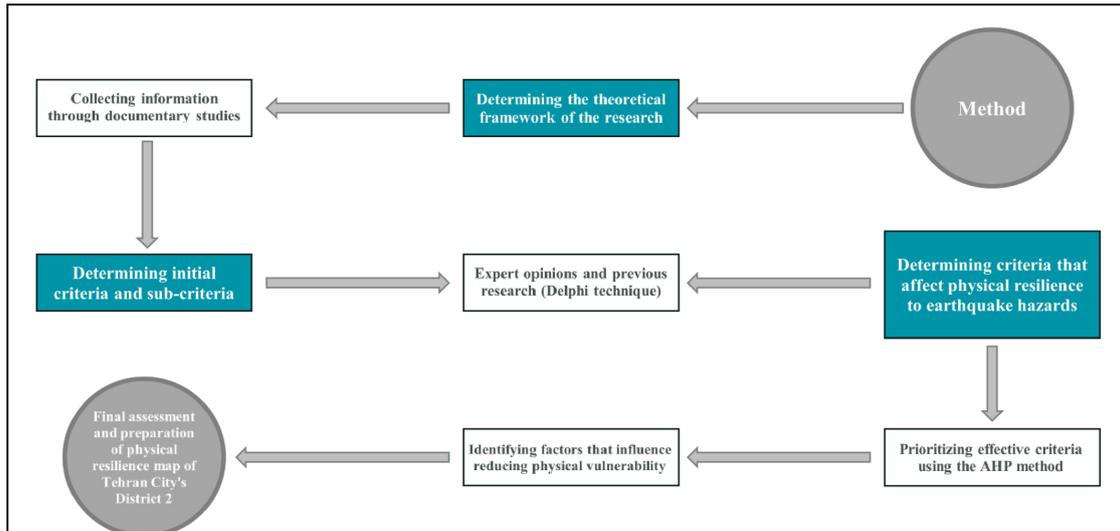
Fig. 1. Stages and Process of Conducting the Research (Methodology)

2. THEORETICAL FOUNDATIONS AND CONCEPTUAL FRAMEWORK OF THE RESEARCH

Timmerman (1981) was the first individual to introduce the concept of resilience in the context of disasters (Mayunga 2007). Today, the large volume of damage and casualties resulting from crises has made the importance of paying attention to resilience more evident than ever (Cangelosi 2015). A resilient city is a robust network of physical systems and human communities. In general, the physical system is analogous to the body of the town. During a disaster, the physical system must remain stable and continue to function even under challenging conditions (Salehi et al. 2010, 101). Decentralization is one of the key characteristics of resilient cities, such that social, economic, and other capacities are distributed across the city (Campanella and Vale 2005, 32).

2.1. Analytic Hierarchy Process (AHP)

The AHP model was first applied by Thomas L. Saaty, an Iraqi-born scholar, in the 1970s. Given that most concepts in urban planning can be analyzed using numerical and descriptive criteria, the simultaneous use of quantitative and qualitative indicators has made this method a powerful approach to urban issues. Flexibility, simplicity of calculations, and the ability to prioritize criteria are among the other advantages of this model. In addition, the possibility of examining consistency in judgments is another of its unique features. This method consists of three main steps: (1) creating a pairwise comparison matrix, (2) calculating the weights of criteria, and (3) examining the consistency of judgments. The scale ranges from 1 to 9, where 1 indicates equal importance of two factors and 9 indicates very high importance of one factor over another (Malczewski 2006, 315).

2.2. Delphi Technique

This is one of the group decision-making methods used to achieve consensus on the issue under consideration from the perspectives of experts. Its main objective is to reach the most reliable consensus of experts through questionnaires accompanied by controlled feedback. The value of this method does not depend on the number of participants in the research, but rather on the scientific credibility of the experts and specialists. The number of participants in this method ranges from 5 to 20 individuals. This method can help achieve expert consensus and develop professional guidelines (Taylor 2020).

2.3. Physical Resilience Criteria and Indicators

One reason for the development of urban planning has been the need to protect settlements from hazards. Predicting the location of land uses and services compatible with hazard-prone areas, paying attention to size, coordination, and flexibility in urban structures, ensuring the appropriateness of form to function, and considering proper accessibility are among the requirements for reducing urban vulnerability in the urban planning process (Roosta 2017). In addition, the undesirable distribution of land uses and physical elements, inefficient transportation networks, dense urban fabrics, compact urban densities, the unfavorable location of urban infrastructures, and the absence or lack of urban green and open spaces play a significant role in increasing vulnerability to earthquakes (Farzad Behtash et al. 2011). Although preventing urban growth is not possible, reducing the damage it causes is feasible. The priority issue is saving human lives. Urban growth and development lead to many facilities; however, crisis-generating factors also increase, and environmental facilities may become disadvantages (Shieh 1999).

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- Internal Building Factors

These include factors whose impacts are related to the building itself and directly affect it.

1. Urban fabric deterioration: The greater the level of deterioration of an urban fabric, the higher the vulnerability to hazards, and consequently, the greater the extent of casualties and damages.

2. Parcel size (gradation): The transportation network is related to the type of urban fabric. Coarse-grained, medium-grained, and fine-grained patterns affect the efficiency of the transportation network. The larger the gradation of the urban fabric, the fewer traffic bottlenecks will exist (Sharifzadegan and Fathi 2008). Moreover, the larger the area of Plates, the less debris resulting from building collapse will damage and affect adjacent buildings.

3. Number of floors: As the number of floors increases, vulnerability also increases, because evacuation and search-and-rescue operations become more difficult. In addition, escape and evacuation from upper floors in high-rise buildings are more challenging, and providing relief to these floors—possibly affected by secondary hazards such as fire—will be more difficult.

4. Height: The greater a structure's height, the lower the likelihood of rapid, easy rescue operations after a disaster, and, as a result, resilience decreases.

- External Building Factors

These include factors in which the impact of an earthquake does not directly relate to the building itself; rather, other elements influence its vulnerability.

1. Width and type of access roads: The transportation network plays a significant role in reducing vulnerability. If the transportation network is not damaged after an earthquake and continues to function efficiently, earthquake casualties will be significantly reduced, as it enables evacuation from hazardous locations, facilitates rescue and relief operations for the injured, and provides access to safe areas.

2. Access to open spaces: One of the most critical issues during and after an earthquake is the distance of settlements from non-built open spaces. These spaces can be used as shelters in the event of an earthquake.

Ample parks and green spaces offer opportunities to establish temporary accommodation and emergency relief bases after an earthquake. Small and medium-sized parks can also be used as evacuation areas and temporary emergency shelters during rescue and relief operations.

3. Urban land use: Some land uses within the city are more important and play a significant role in reducing or increasing vulnerability to earthquakes. These include universities, schools, fuel storage facilities, gas stations, gas facilities, high-voltage power plants, factories, relief centers, medical centers, and similar facilities.

4. Access to medical centers: The shorter the distance between medical centers and residential areas, the faster medical services can be provided. In general, the service radius of hospitals to residential neighborhoods is 1 to 1.5 kilometers (Habibi and Masaeli 1999).

5. Access to emergency service centers: Access to emergency service centers (such as fire stations) is an effective factor in relief operations. Increasing the distance between settlements and emergency centers expands the range of risk.

6. Distance:

a. Distance from high-risk land uses, Such as power plants, fuel storage facilities, and gas stations, which can reduce vulnerability.

b. Distance from faults: The greater the distance from faults, the lower the vulnerability. In this context, the concept of a "fault buffer" is introduced. When faults are well identified, a zone around them—ranging from several tens to several hundreds of meters—can be determined, which is referred to as the "fault buffer" (Mesbahi 2018, 54). Given that construction activities within the buffer zone of the North Tehran Fault are increasing, one of the most important preliminary measures to reduce vulnerability is monitoring the fault buffer. Based on the relationships and studies conducted, as well as the magnitudes obtained from various scenarios, the maximum fault buffer has been calculated as 2.2 kilometers (Mojarab and Zare 2009).

Dominant Approach	An optimistic view in dealing with natural disasters, including earthquakes, attention to natural disasters and the damage caused by them, and failure to provide appropriate solutions in coping with and preventing earthquake damage
Political Economy	Radical perspective, normalizing natural phenomena, confronting the dominant approach, focusing on vulnerability instead of risk.
Structuralism	Attention to social justice, in contrast with the perspective of political economy, attention to social structures
Contingency	Providing a program at a micro level, and in case of emergency, not for prevention
Human Security	Attention to people and emphasis on human security in critical situations, top-down strategy, attention to other sectors, including local groups and NGOs
Sustainable Development	Attention to natural, man-made, and social issues, attention to natural hazards with an economic, social, physical, management, and institution-building approach, attention to participation, education, and institution-building that reduces the effects and damages caused by earthquakes

Fig. 2. Compilation and Comparison of Prevailing Perspectives on Disasters

2.4. Selection of Theory

Based on the evaluation of the characteristics of each perspective, this study attempts to employ the human security and sustainable development perspective. In addition to paying special attention to natural, man-made, and social issues related to natural hazards (specifically earthquakes in this research), this perspective emphasizes a physical approach that reduces earthquake-induced impacts and damage. Moreover, given the central role of resilience, the human security approach is selected as the foundational framework and core theory for the research.

2.5. Selection of Attitude (Approach)

Among the two fundamental approaches to resilience, although distinguishing between the activist and actionable attitudes is not straightforward, in this research—given the objective of assessing physical resilience and ultimately identifying safe and hazard-prone areas in District 2—the passive approach is more applicable. This is because, under the passive approach, society moves toward the future by strengthening and reinforcing existing systems and enhancing their resistance to damage.

2.6. Selection of Doctrine

By studying and analyzing experts' prevailing viewpoints, multiple principles for resilient cities have been proposed. In this research, based on the subject matter and conceptual similarity, it was concluded that the five principles of stability, strength, compatibility, durability, and preparation—introduced by Clark and Nemecek (2010) as the key principles and components of a resilient city from a physical perspective—should be selected as the principles of a resilient city from the physical dimension.

2.7. Selection of Criteria

To select the evaluation criteria, the key principles of a resilient city were first extracted based on the aforementioned theoretical foundations. Then, the evaluation criteria and the indicators related to each criterion were identified. After that, the type of factor (internal or external) was determined, and finally, the indicators and the method of measuring each were specified.

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Principles of a resilient city from a physical perspective	Criteria	Index	Factor type	Scale	Description
Stability	Degree of wear and tear of the structure	Scale and number of worn plates	Internal	Buildings that are dilapidated or in need of renovation	The better the quality of a building's construction, the more stable and resilient it is against earthquake hazards.
	Floors of structures and buildings	Number of floors	Internal	1st floor 2nd floor 3rd floor 4th floor 5th floor 6th floor Above 6th floor	Increasing the number of floors increases structural instability and reduces resilience.
	Height	Height of structures and buildings	Internal	Up to 12 meters 12 to 40 meters 40 to 100 meters Above 100 meters	The higher a structure's height, the lower its stability, the greater the risk of quick and easy relief after an accident, and, as a result, the lower its resilience.
Strength	Type of fault and its degree of danger	Privacy and distance from faults	External	Main fault zone Sub-fault zone Intermediate fault zone	According to studies, the maximum and safest fault zone for the North Tehran Fault (primary and secondary zones) is 2.2 km, with an average of 1 km. As the distance to the fault decreases from this value, the city's resilience and physical strength decrease.
Compatibility	Communication passages	Hierarchy	External	Urban Highway (Highway) First Class Arterial Second Class Major Arterial Local Access	The broader and more arterial the passage, the greater the city's adaptability to a crisis such as an earthquake, and as a result, its resilience increases. To measure resilience from the perspective of passage width, the accessibility of each section to the nearest passage is considered.
	Permeability	Width of roads and network of passages	External	Below 6 meters 6 to 12 meters 12 to 20 meters Above 20 meters	The narrower the roads, the less likely it is that relief will be provided after an earthquake and that the city will adapt to a crisis and its aftermath, and, as a result, the less resilient it is.
	Granulation	Fine-grained or coarse-grained texture	Internal	0-100 meters 100-200 meters 200-300 meters 300 meters and above	The greater the gradation of the pieces, the higher the fabric's permeability, and, as a result, the city's resilience and adaptability in the face of a crisis and its aftermath increase.
Durability	Urban land use	Usage rate per user	External	Residential Administrative and Commercial Military Industrial and Workshop Green Space Military Services (Educational, Medical, etc.) Transportation and Warehousing Other	Medical, residential, and military uses are more frequently used at night and are therefore more vulnerable and less durable during an earthquake.
	High-risk applications	Distance from hazardous uses	External	0-30 meters for petrol and gas pumps 70 meters for the power plant land area	According to the government's resolution on the privacy of overhead power transmission and distribution lines on 19.04.2015, the confidentiality of power lines with a voltage range of 1 to 20 kV is on the ground, which is a maximum of (2.10) meters, and the safe privacy for large power plants is 70 to 100 meters. The privacy for gas stations is 30 meters. The greater the distance from hazardous uses, the greater the resilience and the lower the durability of the structure.
Preparation	Access to medical centers	Distance from hospitals, clinics, etc.	External	0-1500 meters	According to page 31 of Dr. Habibi's book Per Capita Urban Land Uses, the distance between the hospital and the residential areas under coverage is 1 to 1.5 kilometers. The greater the distance between the medical centers and the site of the damage, the less resilient and prepared the city is to face post-earthquake hazards.
	Access to relief centers	Distance from fire stations	External	0-2500 meters	The radius of access to fire stations is 2 to 3 kilometers. The greater the distance between the rescue centers and the site of the damage, the less resilient and prepared the city is to face the hazards after the earthquake.
	Access to open spaces	Existence of green spaces, gardens, and parks	External	0-300 meters	According to page 18 of Dr. Habibi's book Per Capita Urban Land Uses, the proper functional radius and minimum distance from a residential unit for a park at the neighborhood scale is 300 meters. As the distance from open and immaterial spaces increases, the city's Preparation to deal with post-earthquake hazards and, as a result, its resilience decreases.

Fig. 3. Criteria and Indicators for Evaluating Physical Resilience

3. METHOD

The present study is applied in nature, and its method is descriptive–analytical with a mixed-methods approach, incorporating library-based and documentary research methods. Subsequently, using the Delphi technique and expert consultations, the criteria affecting the level of physical resilience against earthquake hazards were identified. Then, using the

Analytic Hierarchy Process (AHP), the requirements were ranked, and their effectiveness in reducing physical vulnerability was assessed. A database was created, tabular data were entered, and the required maps were prepared in Geographic Information System (GIS) software. Finally, analytical statistics and calculations were performed in Excel.
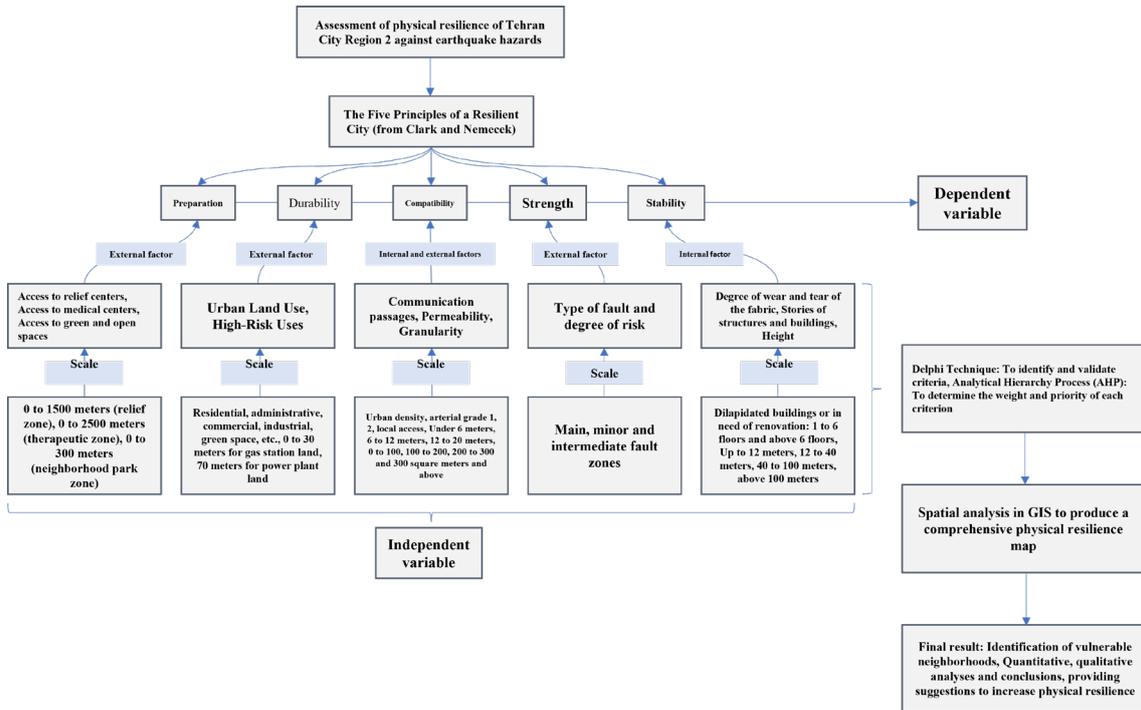
Fig. 4. Conceptual Model of the Research

4. STUDY AREA INTRODUCTION

District 2 is one of the 22 districts of Tehran City. Azadi Street bounds this district to the south, Ashrafi Esfahani and Mohammad Ali Jenah Highways to the west, Chamran Highway to the east, and the Alborz

Mountains to the north. District 2 is subdivided into nine zones and 21 neighborhoods under the city council system. The district covers 47.1 square kilometers and borders Districts 1, 3, 5, 6, 9, and 10 (Fig. 5).
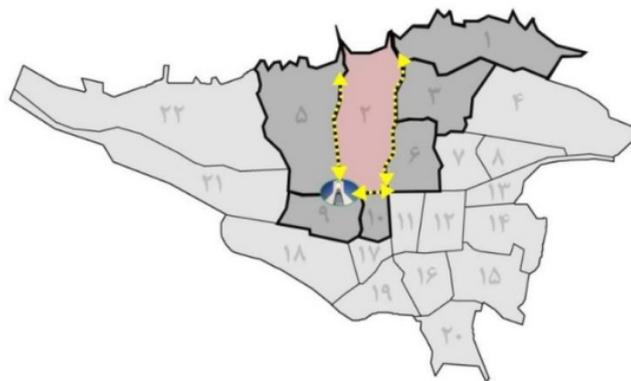
Fig. 5. Location of District 2, Tehran City

The population of this district, according to the latest national census in 2016 (1395 SH), was 701,303 people (239,742 households), including 343,033 men and 358,270 women. The neighborhoods of District 2 are: Poonak, Tehran-Vila, Daryanno, Saadatabad, Shahrara, Shahrak Gharb, Sadeghieh, Tarasht, Farahzad, Nasr Alley, Shahrak-e Azmayesh, Sattarkhan, Marzdaran, Aseman, Behrood, Parvaz, Darya, Sepehr, Eivanak, Sharif, and Towhid.

5. FINDINGS

According to previous studies, research has evaluated the criteria for vulnerability analysis. For example, Ahadnejad and Jalilpour, in a survey conducted in Khoy city, assessed the factors affecting vulnerability and examined indicators such as access to the road network, distance from open spaces, compatibility of uses, and distance from medical centers (Ahadnejad and Jalilpour 2009). In another study conducted in Zanjan city in 2009 by Ahadnejad et al., indicators such as the number of floors, number of neighbors, facade materials, plot location within the block, plot size, and land use were analyzed and evaluated (Faraji and Garakhlo 2010). Also, Faraji, Ahadnejad, and Garakhlo (2010) analyzed and scored other criteria, such as the quality and age of buildings, the location of hazardous uses, the size of the plots, access to utilities, access to open spaces, and materials, in another study in 2010 (Faraji and Garakhlo 2010). Habibi et al. also analyzed and weighted other criteria in a 2008 study, such as the building's skeleton, the ratio of height to width of the adjacent passage, the quality of the building, area, age, number of floors, width of the opposite passage, distance from fire and medical centers, and vacant land (Faraji and Garakhlo 2010).

Based on the theoretical framework of the study and considering the different ways experts scored in previous studies, and in order to standardize the weights assigned to each criterion to provide a better basis for comparison, the numbers of each criterion are normalized by dividing by the total scores in that study (Fig. 6).

Vulnerability Indicators	Ahadnejad and Jalilpour	Ahadnejad and Garakhlo	Habibi et al.	Faraji and Garakhlo
Network	0.443	_	0.06	_
Outdoor Space	0.204	_	_	0.115
Access to the Hospital	0.052	_	_	_
Land Use	_	0.53	_	_
Plot Size	_	0.4	0.12	0.089
Age of Building	_	0.136	0.09	0.051
Building Quality	_	0.99	0.136	0.038
Number of Floors	_	0.75	0.075	_
Fire Department	_	_	0.045	_
Treatment	_	_	_	0.035
Dangerous Use	_	_	_	0.064

Fig. 6. Normalized Weights of Each Criterion in Previous Studies by Various Researchers

By removing criteria with lower weights than other indicators, such as distance from vacant land, amount of barren land, etc., and aligning the ranked criteria provided by experts with the factors effective in evaluating physical resilience—the focus of this study—the table above is obtained. It should be noted that the criteria for building age, quality, and construction materials were removed due to thematic overlap with the criterion for the area of deteriorated urban fabrics in District 2, Tehran.

Additionally, since physical vulnerability to earthquakes was not addressed in previous studies and is of high importance given the aim of this research, the criterion of distance from existing faults was not analyzed or weighted. Therefore, all remaining criteria are evaluated using the AHP method in Expert Choice software.

Figure 8 shows the questionnaire designed to

determine the priority of criteria for evaluating the physical resilience of District 2, Tehran, which was provided to professors and experts in urban planning for weighting purposes.

Score	Definition	Explanation
1	Equal Importance	Two criteria are equally important in achieving the goal.
3	A Little More Important	Experience shows that for achieving the goal, i is slightly more important than j.
5	More Importance	Experience shows that i is more important than j.
7	Much More Important	Experience shows that i is much more important than j.
9	Absolute Importance	The much greater importance of i than j has been conclusively proven.

Fig. 7. Saaty's 1–9 Quantitative Scale for Pairwise Comparison of Criteria

Fig. 8. Questionnaire designed to Determine the Priority of Physical Resilience Assessment Criteria for Region 2

After summarizing the questionnaires and the opinions of the elites and weighing and comparing the criteria in the Expert Choice software, their final prioritization with the AHP method will be as follows. It is necessary to explain that by obtaining several 0.04 (a number less than 0.1 in the software indicates compliance with the consistency in judgment), the consistency in judgments has also been fully observed:
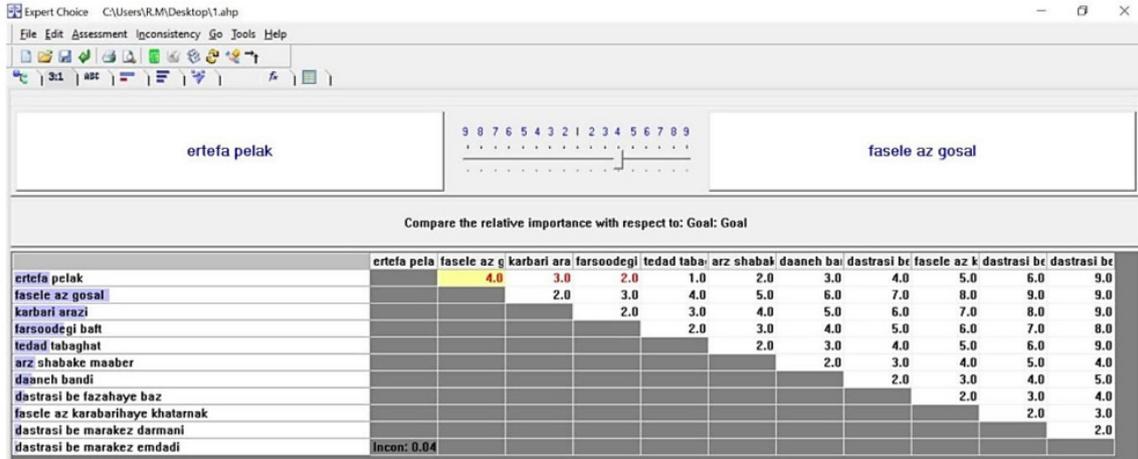
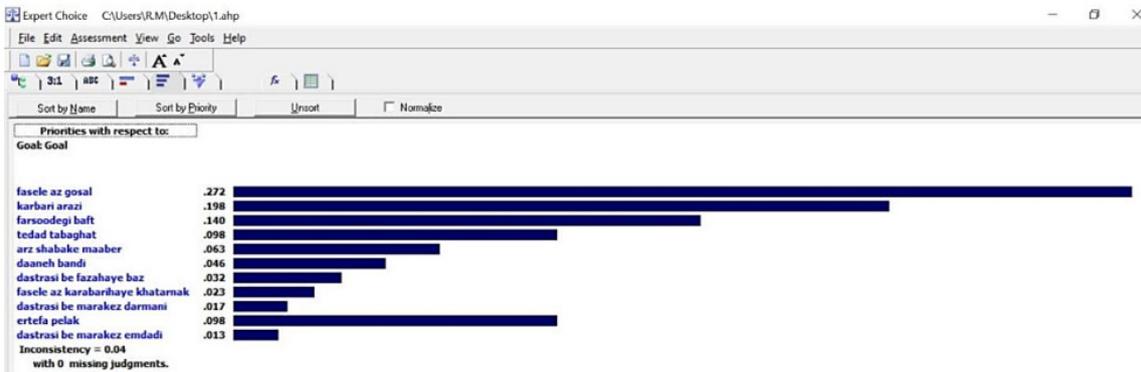**Fig. 9. Final table of Comparison of Criteria in the Expert Choice Software**

Fig. 10. Final Weight of each of the Physical Resilience Assessment Criteria in District 2 of Tehran city

Fig. 11. Final Prioritization of Physical Resilience Assessment Criteria in District 2 of Tehran City

It should be noted that due to the overlap of the criteria "type of passages" and "width of passages", these two criteria were grouped into one criterion and evaluated with other criteria. Also, the criteria "number of floors" and "height" were given the same weight. It is noteworthy that the results obtained from prioritizing the criteria by experts and specialists are very similar to those in previous studies. After normalizing the weights assigned to each criterion by specialists in previous studies, the criteria's priority order will be as shown in Figure 12. Also, the prioritization and final weights of the criteria in this study, using the AHP method and after comparing each criterion in pairs and their final rankings, are shown in Figure 13.

Rank	Criteria
1	Land use
2	Texture deterioration (age and quality of construction)
3	Number of floors
4	Type and width of road network
6	Gradation and size of plots
7	Access to open spaces (parks, gardens, etc.)
8	Distance from hazardous uses
9	Access to medical centers (hospitals, clinics, etc.)
10	Access to emergency centers (fire department)

Fig. 12. Prioritizing Criteria based on Previous Studies

Rank	Criteria	Weight
1	Distance from fault	0.272
2	Land use	0.198
3	Texture deterioration (age and quality of construction)	0.140
4	Number of floors	0.098
4	Height	0.098
6	Type and width of road network	0.063
7	Gradation and size of plots	0.046
8	Access to open spaces (parks, gardens, etc.)	0.032
9	Distance from hazardous uses	0.023
10	Access to medical centers (hospitals, clinics, etc.)	0.017
11	Access to emergency centers (fire department)	0.013

**Fig. 13. Final Prioritization of Research Criteria using the AHP Method after Pairwise Comparison of each
Criterion and Final Weight.**

Based on the final prioritization of criteria according to expert opinions using the AHP method in Expert Choice software, the order of layering the maps was determined to produce the final physical resilience evaluation map of District 2, Tehran (Fig. 35).

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Fig. 14. Existing Faults on the Map

Fig. 15. Plates within the Fault Buffer Zone

Fig. 16. Existing Land Uses

Fig. 17. Hazardous Land Uses

Fig. 18. Neighborhoods with Deteriorated Urban Fabric

Fig. 19. Plates located within the Deteriorated Urban Fabric

Fig. 20. Number of Floors of Parcels

Fig. 21. Existing High-Rise Plates (above 12 Floors)

Fig. 22. Heights of Existing Parcels

Fig. 23. Existing High-Rise Buildings (above 40 meters)

Fig. 24. Existing Roads and Street Network

Fig. 25. Urban Streets with a width of less than 12 meters

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Fig. 26. Gradation of Existing Plates

Fig. 27. Fine-Grained Plots (Under 200 m²) Exist

Fig. 28. Parks (Service Radius) and Existing Green Spaces

Fig. 29. Plates Outside the Boundaries of Urban Green and Open Spaces

Fig. 30. Existing Hospitals
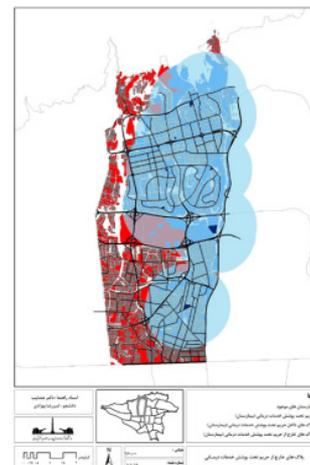
Fig. 31. Plates Outside the Coverage Area of Medical Services

Fig. 32. Existing Fire Stations
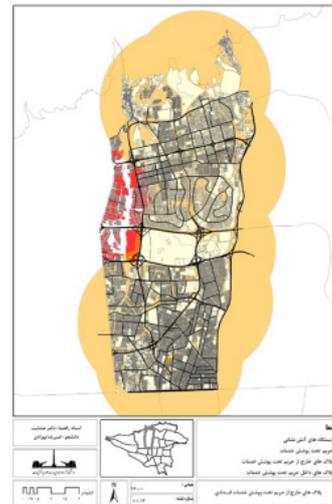
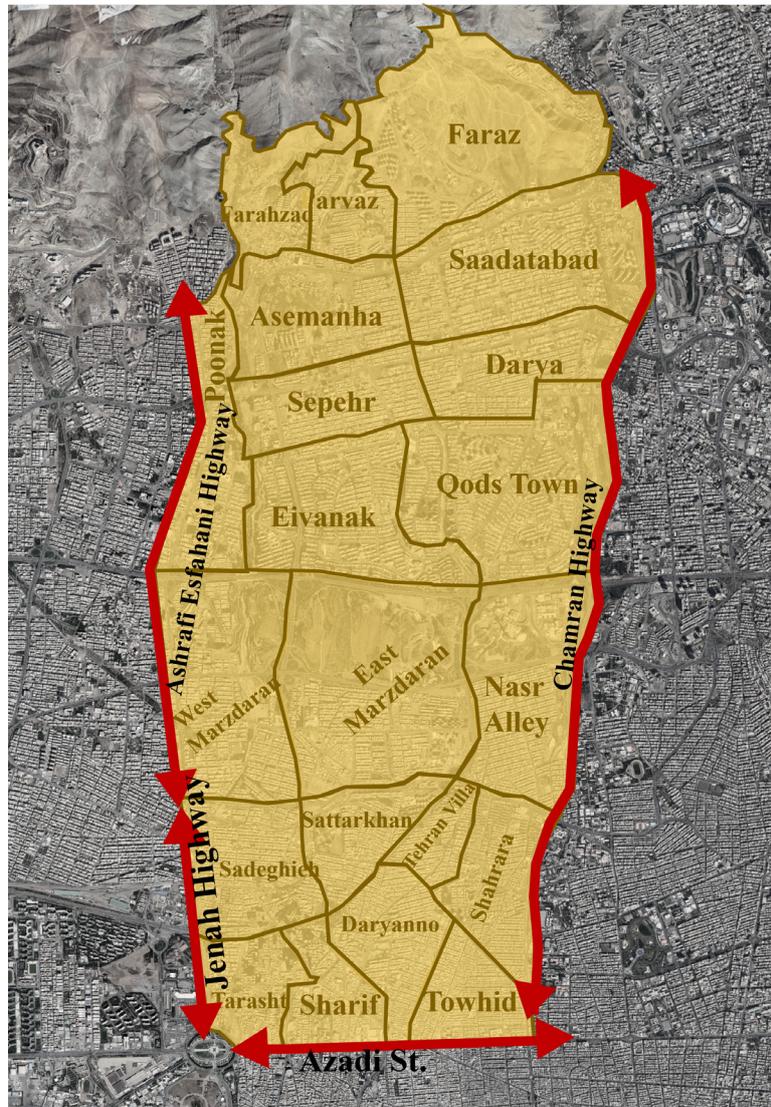
**Fig. 33. Plates Outside the Coverage Area of
Emergency Services**
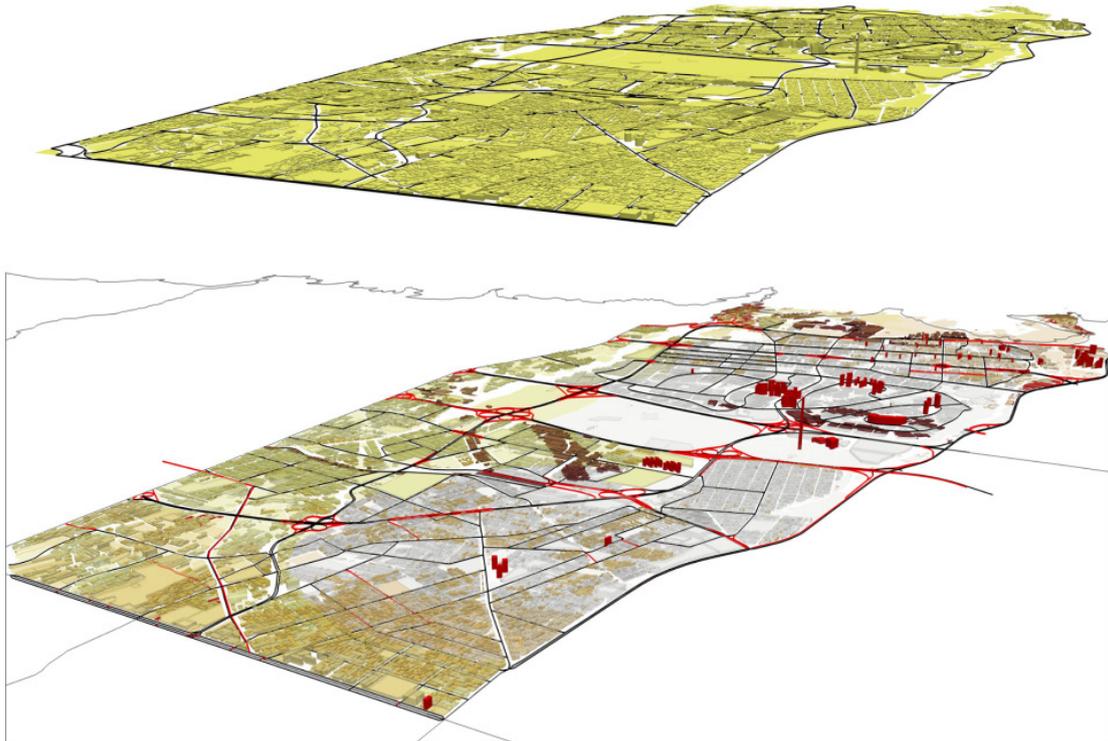

Fig. 34. Location of Neighborhoods in District 2 of Tehran

Fig. 35. Layering Order of Hazard-Prone Maps based on Criteria Prioritization using AHP

Fig. 36. Final Physical Resilience Map of District 2, Tehran

Fig. 37. 3D Map of Physical Resilience in District 2 (Parcel-Based View per Neighborhood – Southeast Perspective)
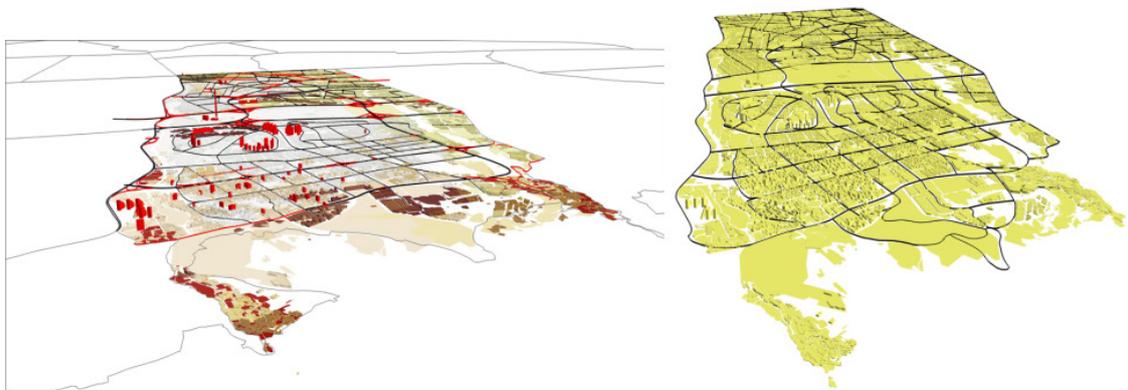

Fig. 38. 3D Map of Physical Resilience in District 2 (Parcel-Based View per Neighborhood – Northeast Perspective)

6. CONCLUSION

By combining the layers, each of which is related to a criterion, and considering their weights and importance, the higher the criterion's weight and importance, the darker the color spectrum; the less important the criterion, the lighter the color spectrum. Therefore, neighborhoods with a brighter color spectrum will be more resilient, while those with a darker color spectrum will be riskier and more unstable.

- Of the total area of Region 2 with 47.1 square kilometers, approximately 13.5%, i.e., an area of over 6.4 square kilometers, is located within the fault zone. The most risky fault in Region 2 is the North Tehran Fault, which passes through the Farahzad and Saadatabad neighborhoods. Another minor fault also passes through the Gisha (Koinsar) neighborhood, and the medium fault of Region 2 passes through the Marzdaran and Poonak neighborhoods. 26% of the area covered by faults is related to the central fault zone, 7% to the minor fault zone, and 67% to the intermediate fault zone.

- Instability and deterioration of the fabric will increase vulnerability. As a result, this issue is

inversely related to resilience. 6% of the region's area (approximately 2.3 square kilometers) with more than 3,200 plates is located in deteriorated fabric, mainly in the neighborhoods of Farahzad, the north of Saadatabad, Evin, and Darakeh, and the southwestern part of the region, including the Sharif and Tarasht neighborhoods.

- In terms of the number of floors of existing plates, most plates have three floors, which have a share of over 26% and include 14,009 plates. Then come two-story plates with 26% and 13,949, and four-story plates with 16% and 8,604. The lowest percentage is for plates above six floors, at 1.3%, and includes approximately 700 plates. - The highest number of plates is for structures up to 12 meters, which constitute 89% of plates and include approximately 48,000 plates. Then come structures between 12 and 40 meters, which constitute 11% of plates and include 6,000 plates. The lowest percentage is for structures above 100 meters, which constitute only 0.03% and include approximately 20 buildings.

- In Region 2, the largest share of arteries is related to passages with a width of over 20 meters, which constitute approximately 40% of the passages, and their length is approximately 138 kilometers. After that, there are passages with a width of 12 to 20 meters, which account for approximately 38% of the total, and their approximate length is 131 kilometers. After that, there are passages with a width of 6 to 12 meters, which constitute approximately 19% of the passages in the region and total approximately 66 kilometers in length. Most passages with a width of less than 6 meters, which constitute only 3% of the passages, are related to metro lines and do not penetrate the fabric and plates. Only 1% of the passages under 6 meters are located within the fabric and are primarily in the northwestern and northeastern regions (Farahzad and Evin).

- The largest share of the area ratio of the existing plates is related to plates above 300 meters, which constitute 79% and have an approximate area of 29 square kilometers and an approximate number of 16,500 plates. After that, there are plates with an area of 200 to 300 square meters, which comprise 13% of the total area and cover about 5 square kilometers, including over 20,000 plates. Plates below 200 square meters have a total of 8% of the area ratio, and their approximate area is 3 square kilometers, which includes a total of 33,500 plates, most of which are located in Farahzad neighborhood in the northwest

of the region and Towhid neighborhood (Azadi and Nosrat streets) in the southeast of Region 2.

- Of the total area of Tehran's District 2, which is 47.1 square kilometers, approximately 6 square kilometers (about 11%) are allocated to green spaces, local parks, and gardens. Considering the minimum functional radius of district parks and the functional radius of urban-scale parks (greater than 200,000 meters), such as Pardisan and Nahjal-Balagheh Forest Parks (with a total area of over 300 hectares), with a functional radius of 6.5 kilometers for forest parks, it is determined that the northern (especially northeastern) and southern (especially southeastern) areas of District 2 are among the neighborhoods with the least amount of green spaces and parks.

- Although most of the private hospitals in Tehran are located in Region 2, considering the 1.5 km radius of each hospital, approximately 36% (an area of over 17 square kilometers) of the neighborhoods in the region, which are mainly located in the western part (Poonak, Marzdaran, Tarasht, and Sadeghieh neighborhoods), are facing a shortage of hospitals. In general, Region 2 has nine general hospitals, and construction of at least two more is underway in the western part of the region.

- In general, the operational radius of fire stations is between 2 and 3 km. In this study, the average operational radius of each fire station was 2.5 km. Region 2 has eight active fire stations that serve their neighboring neighborhoods. However, in the western part of the region (with an area of over 4 square kilometers), there is no fire station to provide rapid services to its neighboring neighborhoods (Poonak neighborhood and part of the western Marzdaran neighborhood) after natural disasters.

According to the final AHP-prioritized research criteria, the most essential criterion for the research topic is distance from the fault. Also, the criteria for access to medical centers and relief centers will have lower importance than other criteria. Being located within the fault zone, which is considered the most critical factor reducing resilience in this research based on the survey, has affected the northern part of the region (Faraz, Parvaz, Farahzad, and Marzdaran neighborhoods). Therefore, these neighborhoods are vulnerable to possible earthquakes. Unlike the aforementioned neighborhoods, Eivanak and Nasr Alley have greater resilience than other neighborhoods in the region and will experience less vulnerability in the event of an earthquake.

Table 1. Recommendations to Enhance the Physical Resilience of District 2, Tehran

Principles of Urban Resilience from a Physical Perspective	Strategy	Executive Policy (Solution)
Stability	Enhancing Safety and Stability	Strengthening buildings through regulations, incentives, and renovation facilities in deteriorated fabrics, especially in Farahzad, Darakeh, Evin, Tarasht, and Sharif neighborhoods.
		Increasing monitoring and enforcing national building codes, particularly for high-rise structures.
Strength	Physical Texture Strength	Evacuating residential units near fault zones, providing loans and financial support for residents to obtain new housing, and creating regulations to prevent construction within fault buffers, particularly in northern neighborhoods such as Faraz, Parvaz, Farahzad, and central areas like East Marzdaran.
Adaptability	Diversity of Access and Permeability of Passages for the Region's Adaptation to a Possible Post-Earthquake Crisis	Defining and strengthening alternative entry and exit routes in the texture
		Improving and expanding neighborhood access
		Reforming the grading system and developing criteria for the consolidation of plots by creating incentive policies in neighborhoods with fine-grained textures, especially in the southeastern communities of Region 2, such as the neighborhoods of Daryanno and Towhid.
Durability	Respecting Neighborhoods in Land Use Planning to Increase the Stability and Durability of the Fabric	Developing rules and regulations for user compatibility
		Removal of hazardous uses from the fabric (gas stations, power plants, etc.)
Preparation	Predictable and Unpredictable Applications are needed in Times of Crisis to Address Potential Terrestrial Consequences.	Scattered and appropriate distribution of treatment centers (especially in the neighborhoods of Farahzad, Poonak, Marzdaran, Sadeghieh, Tarasht, and Sharif) and relief centers (especially in the neighborhoods of Poonak and Marzdaran) in the west of Region 2
		Location and balanced distribution of green and public open spaces, especially in the southern neighborhoods of Region 2, such as Towhid, Sharif, and Tarasht neighborhoods, and the northern neighborhoods of Region 2, such as Faraz neighborhood.

The vulnerability of the neighborhoods in Region 2 varies. For example, the northern neighborhoods of Region 2, such as Farahzad, Faraz Alley, and Parvaz, in addition to being located near the fault in the north of Tehran, have a worn, fine-grained texture; for this reason, these neighborhoods will have the lowest degree of resilience against possible earthquakes. To improve resilience in these neighborhoods, there is a need for long-term planning, the preparation of regulations to prevent construction within the fault zone, and increased construction supervision. Also, considering financial facilities for the renovation of worn-out units, and granting loans and financial assistance to provide housing for owners and to evacuate residential units located within the fault zone, can significantly increase the physical resilience of Region 2. In the short term, creating a green belt can prevent the advance and construction within the fault zone and avoid the intensification of vulnerability.

ACKNOWLEDGMENTS

This article wasn't supported by any financial or spiritual sponsors.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

MORAL APPROVAL

The authors commit to observe all the ethical principles of the publication of the scientific work based on the ethical principles of COPE. In case of any violation of the ethical principles, even after the publication of the article, they give the journal the right to delete the article and follow up on the matter.

PARTICIPATION PERCENTAGE

The authors state that they have directly participated in the stages of conducting research and writing the article.

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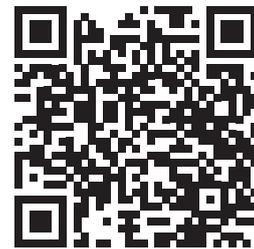
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