



**Seismic vulnerability
assessment of
school buildings**

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Seismic vulnerability assessment of school buildings in Tehran city based on AHP and GIS

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Abstract

The objective of the study was to evaluate the seismic vulnerability of school buildings in Tehran city based on analytical hierarchical process (AHP) and geographical information systems (GIS). Therefore, to this end, the peak ground acceleration, slope and soil liquefaction layers were used for preparation geotechnical map. Also, the construction materials of structures, year of construction, their quality and seismic resonance coefficient layers were defined as major affecting factors in structural vulnerability of schools. Then, the AHP method was applied to assess the priority rank and weight of criteria (layers) and alternatives (classes) of each criterion through pair wise comparison in all levels. Finally, geotechnical and structural spatial layers were overlaid to prepare the seismic vulnerability map of school buildings in Tehran city. The results indicated that only in 72 schools (about 3%) out of 2125 schools in the study area, the destruction rate is very high and therefore their reconstruction should be considered.

1 Introduction

The Iranian plateau is located between the continental convergence of the Arabian and the Eurasian plates in the central part of the Alpine-Himalayan seismic belt. Thus, seismicity of this area is high and frequency occurrence of moderate to large earthquakes such as Buin Zahra (1962), Tabas (1978), Manjil-Rudbar (1990), Bam (2003), Avaj (2002), Zarand (2005), and Varzaghan (2012) cause heavy casualties and considerable financial losses.

Tehran, the capital of Iran, with about 12 million inhabitants is one of the dense populated metropolises of the world. This megalopolis is located in a very high seismic zone at the foothills of the southern Alborz Mountains and surrounded by several active faults such as Mosha, North Tehran and North and South Rey faults that movement of each of them could lead to noticeable losses of life and substantial financial damages.

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Therefore, according to abovementioned reasons, producing a seismic vulnerability map for the city is very critical and worthwhile.

Nowadays, vulnerability assessment and modelling buildings behaviour against earthquake have become an essential concept in hazards researches (e.g., Rashed and Weeks, 2003; Maithani and Sokhi, 2004; Servi, 2004; Gulati, 2006; Thapaliya, 2006; Cole et al., 2008; Nath and Thingbaijam, 2009). Thus, many Iranian researchers such as Zahraie and Ershad (2005), Aghataher et al. (2008), Amini Hosseini et al. (2009), Hataminejad et al. (2009) and Hashemi and Alesheikh (2012) determined effective factors in earthquake hazard assessment and applied various methods in preparing seismic hazard map. But among these studies, determination and reducing the seismic vulnerability of school buildings against the earthquake is very important because according to the Standard 2800 (BHRC, 2005) school buildings are among vital structures, which their upgrading against earthquake is highly important in noticeable reduction of both financial and life losses. Based on these reasons, in this research after determining main factors in seismic vulnerability of school buildings in Tehran, structural information and geological and geotechnical data have been collected. Then, based on analytic hierarchy process (AHP) the weights are assigned to the criteria (layers) and alternatives (classes) of each criterion and the geotechnical and structural vulnerability map has been prepared through geographical information systems (GIS). Finally by overlaying of these two maps, seismic status of school buildings in the time of earthquakes occurrence has been analysed.

2 Study area

The rapid growth of urbanity in seismic regions like Tehran has increased the likelihood of vulnerability of these cities in destructive earthquakes due to construction of the buildings without considering engineering principles and disregarding geological and geotechnical characteristics of the region. Tehran with an area of about 615 km², including 22 regional municipality is located between latitudes 51° 15' and 51° 35' E and

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longitudes $35^{\circ} 33'$ and $35^{\circ} 50'$ N and limited to Alborz Mountains from the north and to Bibi Shahrbanoo and Sepayeh heights from the east. Up to now, the city has been confronted strong earthquakes greater than $M_s = 6.5$ (Ashtari Jafari, 2010), which most of them occurred as the result of the movement on the North Tehran, Mosha, North and

5 South Rey, Garmsar and Eshtehard faults (Fig. 1).

The South and North Rey faults lengthen about 20 km with WNW–ESE strikes and reverse mechanism are distributed throughout both sides of the Rey depression in southern part of Tehran plain (Berberian et al., 1985). The distance between these two faults is from 3 to 5 km, and it seems that they are branches of one original fault, which

10 have similar origin. As it is revealed through available information, there is not any record of the activity of these faults over recent 1000 yr, and the newest earthquake, has been occurred due to these faults, backs to 855 AC with magnitude of $M_w = 7$ (JICA and CEST, 2000). Therefore, South and North Rey faults are the most prominent faults in the southern part of Tehran, which can cause strong earthquakes in the future.

In addition, based on the statistics developed by Education and Culturing Ministry of Iran, there are 2125 schools with totally 1 291 628 students and teachers in Tehran. Thus, heavy populated schools and their distribution in a big city such as Tehran with high seismic activity and vulnerability of its structures against earthquake necessitate the vulnerability assessment of the structures and seismic retrofitting of school build-

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20 ings.

3 Methodology

Usually to make a decision the decision makers should consider some criteria. If these criteria are quantitative, there are slightly different mathematical methods for solving them, but since in many decisions, the respective criteria are both quantitative and qual-

25 itative, which sometimes are in conflict with each other, so solving them needs some specific methods such as multi-criteria decision making (MCDM) techniques. MCDM includes a series of techniques (such as sum of weights or correlation analysis) that

allows the experts and respective groups to assess, score and rank a range of criteria, related to a particular issue (Malczewski, 2004; Dodgson et al., 2009). So, by combination of MCDM and methods based on GIS, which have unique ability in management and analysis of spatial data, wide range of spatial decision can be obtained.

AHP is one of the most common and applied techniques of MCDM, which was presented by Saaty (1980). The method is based on three principles of decomposition, comparative judgment and synthesizing of priorities. In decomposition stage, we need to disintegrate the decision making problems into various elements in hierarchy form. In this regard, the first stage is to create a tree structure for criteria and sub-criteria. Principle of comparative judgment involves a pair wise comparison of available alternatives in a hierarchical level in such a way that elements of levels would be compared with elements of the same level and their relative importance would be calculated as is shown in Table 1.

These weights can be calculated individually or by a group of experts. So verification of pair wise comparisons for assessing the accuracy of comparisons between two options is necessary through verifying the consistency of comparisons. For this purpose, consistency index (CI) is used as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1}. \quad (1)$$

where, CI is the consistency index; λ_{\max} is the largest or principal eigenvalue of the pair wise comparison matrix, and n is the order of the matrix. When the matrix has a complete compatibility, CI = 0. The bigger CI, the worse consistency has the matrix. Then, the consistency ratio (CR) was calculated as:

$$CR = \frac{CI}{RI}. \quad (2)$$

where, RI is the average of the resulting consistency index depending on the order of the matrix (Saaty, 1977). When CR was less than 0.10, the matrix had a reasonable

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consistency. Otherwise the matrix should be changed and the original values in the pair wise comparison matrix must be revised by the decision maker. The calculated results of weight would be accepted when the consistency ratio was satisfactory.

In this research, analytic hierarchy process has been used to combine and analyse spatial information to produce a seismic vulnerability map for school buildings in Tehran city. In this regard, the steps taken throughout the study are described as follows and the flowchart for the preparation of the seismic vulnerability map of the study area based on AHP and GIS is shown in Fig. 2.

The major steps are summarized as follows:

1. Definition of the objective (seismic vulnerability assessment of school buildings);
2. Determining main factors and influencing indicators in preparation seismic vulnerability map;
3. Collecting, preparing and transferring of data to GIS environment and classification and ranking them;
4. Applying of analytic hierarchy process and assigning the weights to the factors and indicators via calculation of the pair wise comparison matrix;
5. Calculating CR and repeating weighing of factors if CR is greater than 0.1 and estimating of overall weights and assigning them to each layer.
6. Preparing the geotechnical and structural vulnerability map separately by overlaying the weighted raster layers. The formula proposed by Malczewski (1999) for obtaining the total scores was applied in this study. Accordingly, the weight of each pixel of the output in vulnerability maps (W_i) was calculated by using the following summation:

$$W_i = \sum_j x_{ij} w_j. \quad (3)$$

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where, x_{ij} is rank value of the i -th class with respect to the j -th layer and w_j is normalized weight of the j -th layer. Then final weight can be obtained through multiplying the normalized weight value of each layer in standardized rank value given to the classes of that layer and sum of them.

- 5 7. Finally, since in determining vulnerability of school buildings against earthquake all geotechnical and structural factors should be considered simultaneously, so by overlaying two obtained maps, seismic vulnerability of school buildings in Tehran municipality would be calculated.

4 Data preparation and analysis

10 4.1 Seismic vulnerability indices

In seismic areas, the assessment of geotechnical seismic vulnerability is essential for urban expansion and development and neglecting this issue and no identifying areas with high potential of earthquake occurrences increase likelihood of seismic vulnerability and damages. Generally, seismic hazards can be estimated by analysing past earthquakes activity in the region, evidence of stress-bearing of structures within faults area and how seismic waves travel through the crust and overlying soils beneath the sites. Worthy to be noted that at the time of an earthquake in addition to peak ground acceleration (PGA), the incidence of landslide and soil liquefaction is secondary phenomena which can cause increasing of seismic vulnerability and damages and should be considered to the overall estimating seismic vulnerability.

4.1.1 Peak ground acceleration

Main characteristics of strong ground motion such as duration, amplitude and frequency content have significant effects on distribution of damages and deformations occurred in the surface of the earth during strong earthquakes. Generally, PGA which

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correlated with the amount of the activity of nearby faults in the regions is the most important issue in the context of seismic vulnerability. In this study, according to map of PGA that presented by JICA and CEST (2000) for Rey fault scenario, the PGA is about 200 Gal in the north and more than 400 Gal in the southern parts of the Tehran in case of the activity of Rey fault. Thus, the more PGA is, the seismic vulnerability of an area would be expanded (Fig. 3a).

4.1.2 Slope

Mountainous topography of Iran in most areas, highly tectonic and seismic activity and various geological and climatic conditions of the country provides a wide range of natural conditions for the occurrence of landslide. Foothills of Tehran due to vicinity with active fault systems and relatively high slope provide appropriate conditions for landslide incidence. But in recent decades, population growth and the rise of construction in foothills and mountainside regions of northern and eastern parts of Tehran have led to significant increasing of the risks and losses due to occurrence of landslides in these areas (Safari and Moghimi, 2010). So for the said reasons, identifying vulnerable areas and the regions with high potential for landslides is so important and crucial (Fig. 3b).

4.1.3 Soil liquefaction

Soil liquefaction phenomenon in the sandy soil below structures is one of the most important causes of collapses in the occurrence of earthquakes. Since most soils of Tehran, especially in the south eastern part is alluvial and sandy, and due to water-saturated and loose state of soil in these regions which is the result of the lack of drainage channels and high level of underground water (Askari and Kasaie, 2003), it form a pulp during earthquake. So even buildings which is not damaged by horizontal earthquake force, tilted or completely inverted due to liquefaction, that amount of failure depends on PGA, shaking duration, soil porosity and amplitude of the applied shear stress on the soil mass during an earthquake (Seed and Idriss, 1971). Therefore,

an earthquake with magnitude greater than 6 (Mahdizadeh, 2011) and vulnerability of masonry, concrete and steel buildings decrease respectively (Tavakoli and Tavakoli, 1993; JICA and CEST, 2000; Ghayamghamian and Khanzade, 2008; Ghayamghamian et al., 2012) (Fig. 4a).

5 4.2.2 Year of construction

Optimal lifetime of structures in Iran is usually 30 yr. The more building' lifetime is, the greater would be the amount of its vulnerability. Furthermore, according to Standard 2800 (BHRC, 2005) in an earthquake the amount of structural damage shows a step-linear function because the quality and the type of construction materials would change at each period during various edition of regulation (BHRC, 1988, 1999, 2005). Thus the structures would be divided into four groups according to the amount of their vulnerability as older than 45 yr, between 45–20, 20–7 and younger than 7 yr (JICA and CEST, 2000) (Fig. 4b). However, older buildings do not enjoy adequate safety and are likely to be vulnerable to severe damage or total collapse under strong seismic excitations.

15 4.2.3 Structures quality

Building a structure involves the interaction of different groups that each of them has the responsibility for different parts of that building. So the quality of a structure depends on various factors such as level of the employer education and income, standards of structural design, quality of materials used in the manufacture and insurance status of the structure (Sharifzadegan and Fathi, 2008; Hataminejad et al., 2009). Considering all of the above-mentioned parameters the Iranian experts of Schools Renovation and Mobilization Organization after studying the structure's identity and sometimes doing necessary tests have divided school buildings from the quality of construction point of view into three classes as good, average and bad structures (Fig. 4c).

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the vulnerability of the structures of these areas. But new constructed buildings, observance of construction principles as well as municipal governance over building construction in districts 21 and 22 have led to safety buildings in these areas.

The final map obtained from the processing of the geotechnical vulnerability of schools in Tehran are divided into four categories of high, medium, low and no vulnerability that is shown in Figs. 7 and 8. The respective results showed that 15% of Tehran's areas have high, 25% medium and 29% low vulnerability and 31% of the city is safe areas (Fig. 7). In terms of geographical location, the central regions of the city toward north including districts 6, 7, 8, 21, 22, 1, 2, 3, 4 and 5 despite the high slopes in the northern parts, are considered the regions with low or no vulnerability, due to the low amplitude of peak ground acceleration and low probability of liquefaction occurrence. But the central toward south regions, especially southeast areas namely the districts of 11, 12, 15, 16, 17, 18 and 20 are considered as high vulnerable areas because of the high peak ground acceleration and liquefaction occurrence (Figs. 7 and 8).

Since the main objective of this paper is to determine the seismic vulnerability of the school buildings in Tehran city, the final geotechnical and structural maps have been overlaid which has been shown in Fig. 9. The results showed that most schools located in districts 12, 15, 11 and 16 as well as some schools in districts 17, 18 and 19 have high seismic vulnerability. But, many schools located in districts 4, 5, 1, 2, 3 and 22 and a few schools in districts 6 and 8 would be considered as the safest groups of schools in Tehran city.

6 Discussion

In this study, the vulnerability of Tehran school buildings has been investigated according to geotechnical and structural criteria and sub-criteria by using a combination of GIS and AHP method. Since all geotechnical and structural criteria, despite having effective role in vulnerability of schools, do not have the same importance and value;

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vulnerability of buildings cannot be reviewed only by individually inspection of each elements. Therefore, to achieve the correct results, all elements have to be considered simultaneously. Then, geotechnical and structural maps have been overlaid for determining the seismic vulnerability of school buildings (Figs. 9 and 10). The results of which indicates 16 situations. Meanwhile, to have a better understanding of the issue, just four main situations have been explained as follows:

1. Schools with high geotechnical and structural vulnerability includes 3% of schools, which are the most vulnerable structures, located in regions of 12, 15, 11, 16 and 17, and should be demolished and reconstructed again.
2. Schools have high geotechnical and low structural vulnerability that includes 4% of schools in Tehran city. These schools mostly are located in districts 15, 16, 17, 11 and 18 and their seismic vulnerability can be decreased by their retrofitting.
3. Schools that have low geotechnical and high structural vulnerability that includes 7% of the schools in Tehran city. Most of them located in districts 1, 4, 3, 5 and a few in 21, 22 and 6 regions. Retrofitting or sometimes demolishing and renovation of these schools are the ways for reducing their vulnerability according to the age of construction.
4. Schools which are safe from both geotechnical and structural point of view that includes 9% of the schools. These schools are located in districts 4, 5, 1, 2, 3 and a few in 22, 21 and 6 regions and they are one of the safest groups of schools in Tehran city.

7 Conclusions

Surveys show that collapsing the buildings and structures during an earthquake can cause huge social, economic and human disasters. Therefore, construction of earthquake resistant buildings which can be used as a temporary shelter immediately after

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the earthquake have significant role in saving the life of people who reside in these structures. In this regard, determining vulnerable areas by overlaying geotechnical and structural vulnerability maps is the main step. So, the purpose of the present study is to represent a model for determining the amount of vulnerability of school buildings in Tehran city on the basis of spatial analysis and through a combination of AHP and GIS. The important advantages of using these techniques can be summarized as having relatively incorporation any geotechnical and structural knowledge to create a seismic vulnerability map. The results showed that in case of Rey fault movement, 597 schools out of 2125 schools of Tehran city may experience high destruction because of the oldness of their construction and in some cases their reconstruction is impossible because of their cultural history. Geotechnical vulnerability map also showed that 317 schools can be considered as high geotechnical vulnerable structures in respect to occurrence high peak ground acceleration and soil liquefaction during earthquakes. Finally, regarding geotechnical and structural factors in seismic vulnerability of school buildings, it can be concluded that only 72 schools in Tehran need to be demolished and reconstructed again.

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Table 1. Fundamental scale for pair wise comparisons (Saaty, 2004).

Weight/Rank	Intensities
1	Equal
3	Moderately dominant
5	Strongly dominant
7	Very strongly dominant
9	Extremely dominant
2, 4, 6, 8	Intermediate values
Reciprocals	For inverse judgments

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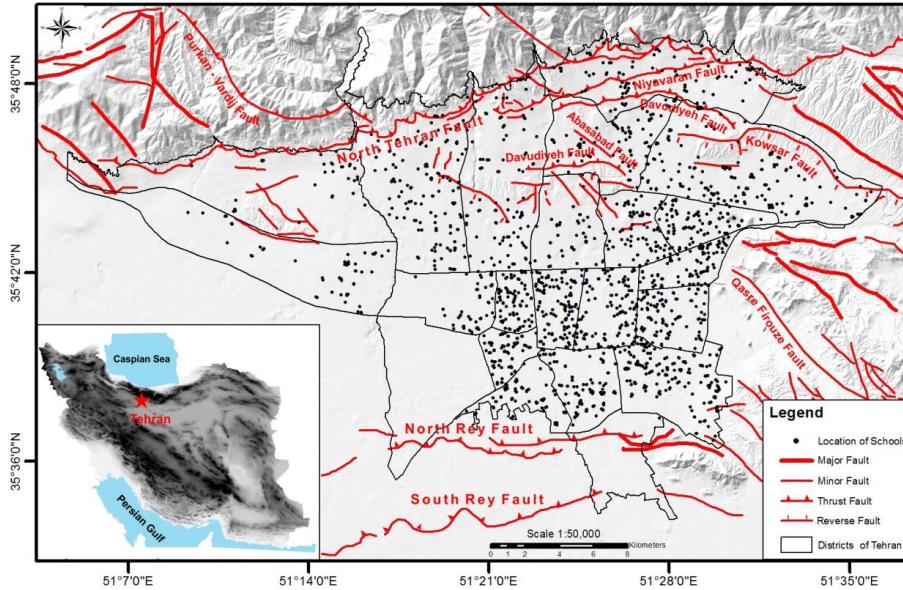


Fig. 1. Study area and the location of Tehran school buildings.

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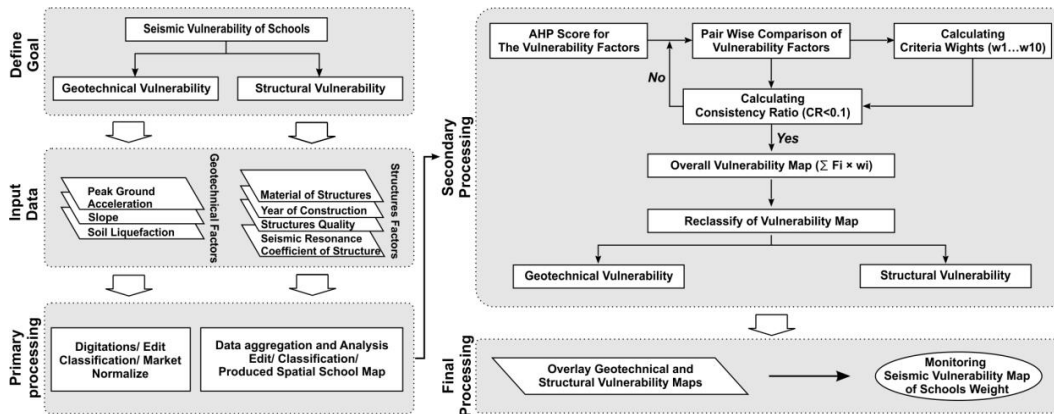


Fig. 2. A flowchart illustrating the methodology used in various stages of the research for the preparation the seismic vulnerability map of the study area.

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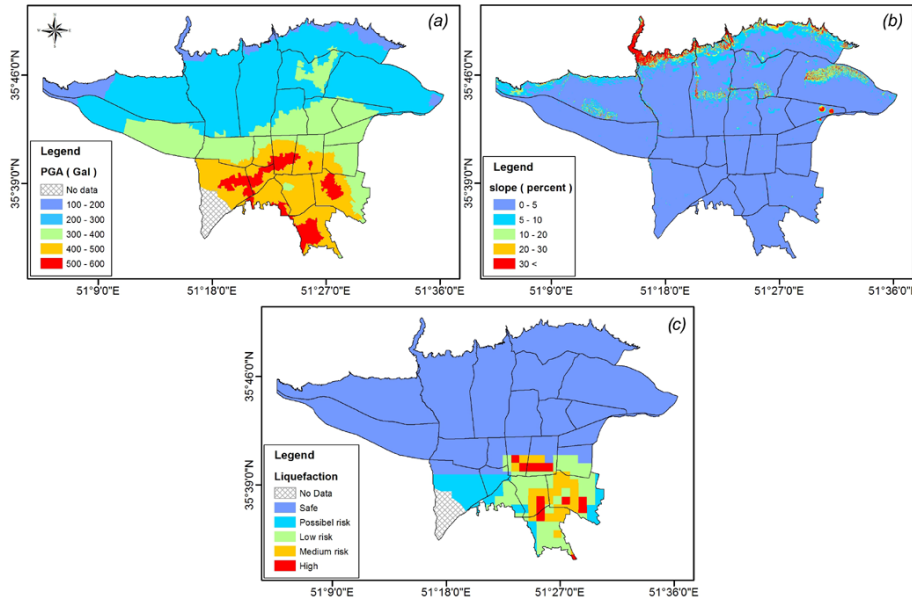


Fig. 3. (a) Distribution of PGA for Rey fault scenario, (b) slope, (c) soil liquefaction in Tehran metropolis.

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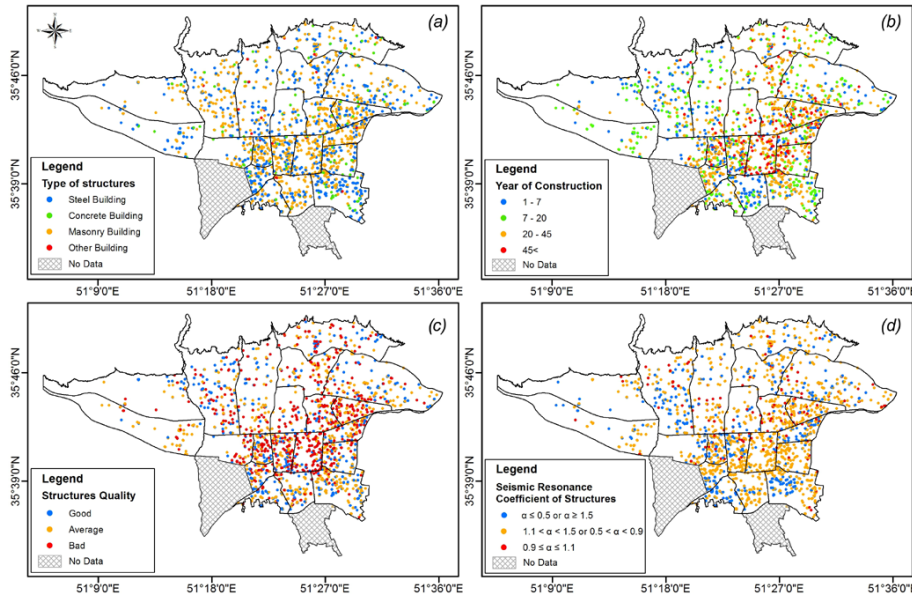


Fig. 4. Schools distribution by **(a)** construction materials of structures, **(b)** year of construction, **(c)** structures quality, **(d)** seismic resonance coefficient of school buildings in Tehran metropolis.

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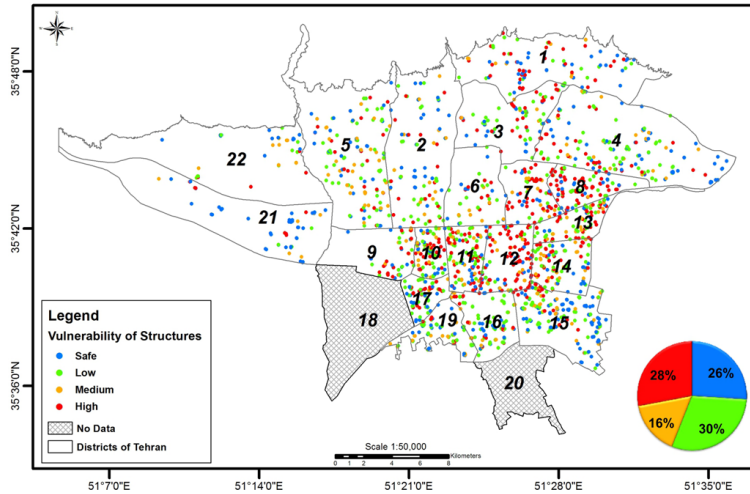


Fig. 5. School distribution based on structural vulnerability in Tehran municipality.

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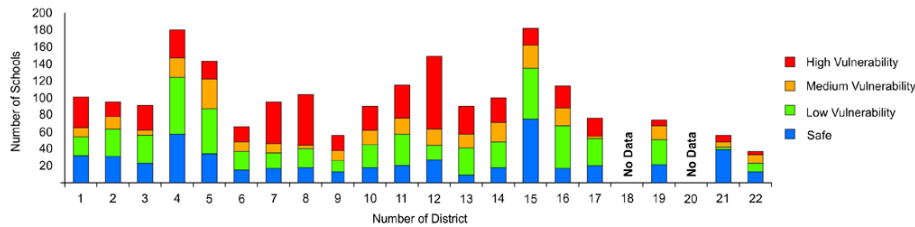


Fig. 6. Number of schools in each district based on structural vulnerability in Tehran municipality.

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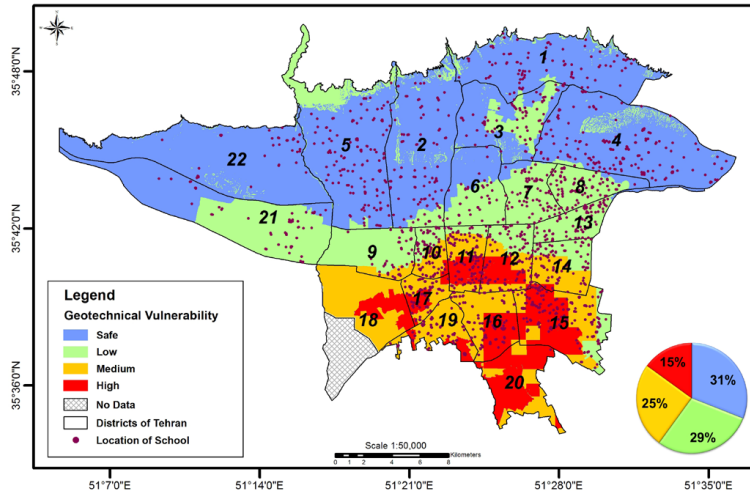


Fig. 7. School distribution based on geotechnical vulnerability in Tehran city.

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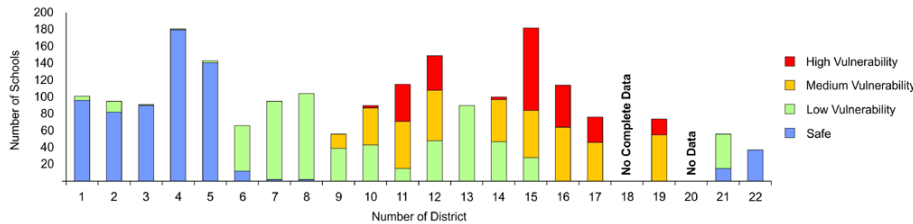


Fig. 8. Number of schools in each district based on geotechnical vulnerability in Tehran city.

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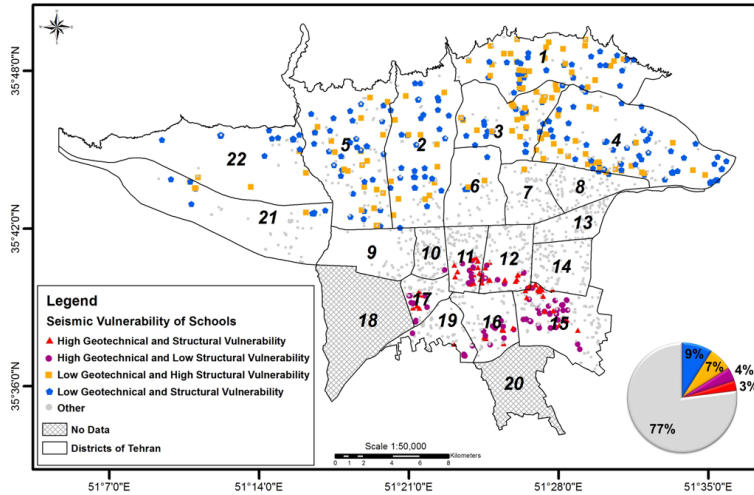


Fig. 9. School distribution based on both geotechnical and structural vulnerability in Tehran city.

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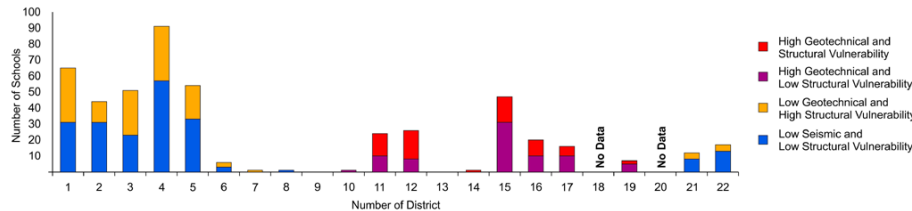


Fig. 10. Number of schools in each district based on both geotechnical and structural vulnerability in Tehran city.

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