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Earthquake resilience of densely populated settlements: A strategic approach to mitigate Istanbul's earthquake risk

Gülru Koca*

Abstract

One of the most significant challenges confronted by earthquake-prone cities results from the urban planning strategies and interventions preferred during the construction and development efforts. The planning of infrastructure that will serve the increasing population is even more important, especially in cities that have historical importance and have evolved into large metropolises in a short time. Proper planning and renewal efforts that align with earthquake-resistant urban development strategies not only add value for all stakeholders but also help avoid significant material and moral losses caused by poorly planned urban development. Although earthquake-prone settlements have thousands of years of construction traditions, these traditions have often been replaced by modern construction techniques nowadays. In cities where the transformation from traditional to modern construction techniques is rapid and uncontrolled, a severe earthquake is more likely to cause a significant damage. Türkiye has a high earthquake risk due to its geographical location. The Main Marmara Fault is an active fault line that poses a serious threat to Istanbul. The devastating earthquake series along the East Anatolian Fault in February 2023 have once again highlighted the urgency of taking necessary precautions and preparations for the anticipated Marmara earthquake. Istanbul is one of the most historically significant metropolises in the world. Accordingly, the city has expanded by receiving immigration since the last major earthquake. Given its unique place in world history and its centuries-old role as the capital of great civilizations, it is crucial to ensure the seismic resilience in Istanbul to protect both the lives and property of its dense population and to safeguard its cultural heritage sites. The aims of this paper are to evaluate the current characteristics of Istanbul in the event of a possible earthquake, to identify potential challenges of the city and to put forward a strategic approach to improve seismic resistance of the city. The evaluation was carried out by conducting a SWOT analysis based on the physical, environmental, social and economic conditions of the city. For this purpose, firstly the previous and current urban design practices adopted in the city was evaluated. The key features effective in the construction of an earthquake resilient settlement was emphasized and taken into consideration. Besides, the crucial stakeholders and their potential contributions were also evaluated. In this context, the problems that needs to be improved are revealed and a conceptual framework of an urban planning strategy is presented to construct an earthquake resilient city that provides satisfaction to all its stakeholders.

Keywords: densely populated settlements, earthquake prone cities, earthquake resilience, sustainable settlements, strategic urban planning

1. Introduction

The construction of sustainable settlements has become one of the most crucial targets of our time, due to many different reasons. One of the most important reasons for this is the rapid and often uncontrollable population growth in urban areas. Rapid population growth creates an

*(Corresponding author), Assoc. Prof. Dr., Isik University, Türkiye gulru.koca@isikun.edu.tr
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increased demand for housing. However, urban development efforts to meet this demand often brings about a range of challenges in different regions of urban areas. Rapid urbanization frequently leads to construction of high-density, multi-story buildings lacking green areas in regions inhabited by middle and high-income groups. Nevertheless, regions which are inhabited by low-income groups face issues such as unplanned construction and informal settlements.

Uncontrolled population growth and urbanization efforts carried out without following proper planning strategies, has become a significant problem for many major cities today. In addition to these problems, Istanbul also faces the looming threat of high seismic risk. Istanbul is a city that has experienced devastating earthquakes in the past and, a considerable amount of time has passed since its last major seismic event. Although the city has implemented appropriate urban planning strategies after the last major earthquake, the long period of time that has passed since the earthquake has caused these practices to become outdated, forgotten, and disregarded. As the memories of past earthquakes fade, the city continues to grow through migration due to its historical and touristic significance. This situation makes it difficult to implement practices to enhance and maintain earthquake resilience.

There are numerous factors that take active role in the effectiveness of the seismic resilience of crowded cities. The more frequent preference for vertical architectural applications to accommodate the increasing population, the formation of illegal housing, the decrease in green areas as a result of expansion and the existence of densely populated building blocks are important topics that need to be carefully examined in cities with high earthquake risk. The quality of urban transformation efforts, the current seismic resilience of buildings that have been intervened for different purposes over time, and the unknowns regarding the earthquake resistance of buildings with historical and cultural value also gain importance in this context.

This study aims to evaluate the current characteristics of Istanbul in the event of a possible earthquake, to identify potential challenges of the city and to put forward a strategic approach to strengthen the city against potential future seismic events.

2. Key Physical Factors Affecting Urban Vulnerability to Earthquakes

There are many factors that determine the behaviour of cities during earthquakes. These factors create a total effect at the time of the earthquake. The most important of these factors is the city's "physical characteristics", which include its geological features, urbanization-related features, and building-related features. These physical characteristics collectively shape a city's seismic response and different configurations of these factors alter the level of earthquake risk. When viewed from this perspective, it becomes evident that two settlements located within the same seismic zone may face the same earthquake hazard yet experience vastly different levels of earthquake risk due to variations in their physical characteristics. This disparity emphasizes the importance of a detailed understanding of how a city's unique physical attributes interact to influence its seismic resilience (Balyemez & Berköz, 2005).

2.1. Geological Features and Seismic Characteristics of the City

Earthquake damage in urban areas depends on the strength, ductility, and integrity of structures. However, the stiffness of the ground on which the building will be built is another important factor affecting the extent of earthquake damage (Arya et al., 2014).

The above-mentioned characteristics of both the structure and the ground collectively determine the seismic behaviour of cities. The effectiveness of efforts to enhance Istanbul's earthquake resistance is dependent on the city's geological structure, the seismic characteristics and the features of the buildings constructed on this ground.

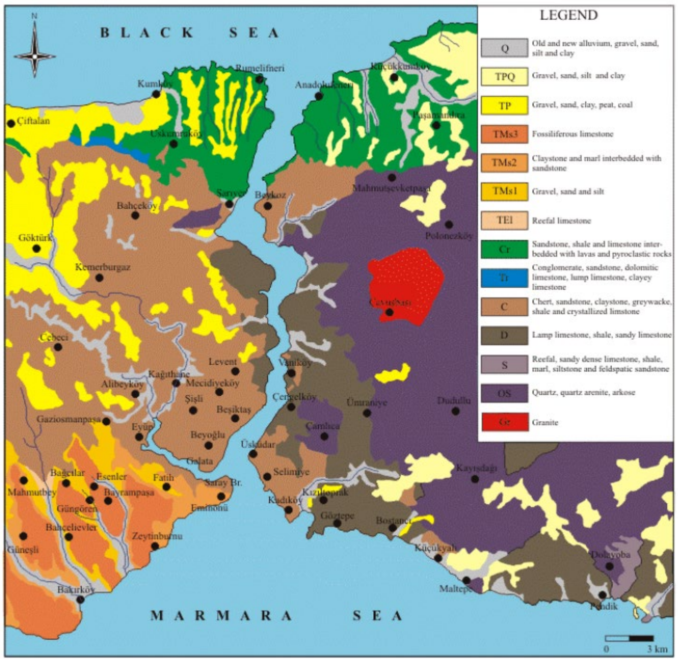

Figure 1 Geological units in Istanbul (Ündül & Tuğrul, 2006)

The geological features of Istanbul can be seen in Figure 1. Chronologically, rock formations belonging to the Palaeozoic, Mesozoic, and Cenozoic periods are observed in the city. The oldest among these, the Palaeozoic rocks, are predominantly clastic and carbonate in nature. A significant part of Istanbul is composed of these Palaeozoic rocks (Ündül & Tuğrul, 2006).

The Palaeozoic rocks are covered by unconformable Mesozoic units. These rocks cover large areas in the northern parts of both the Anatolian and European sides of Istanbul. Mesozoic rock formations are represented by conglomerates, sandstones, dolomites, and limestones (Ündül & Tuğrul, 2006).

The Mesozoic rock formations are covered by Tertiary units from the early part of the Cenozoic era. These units generally consist of organic limestones, clayey limestones, marls, loose sands, silt, and clays (Ündül & Tuğrul, 2006).

The sediments along the Golden Horn and Bosporus coasts include both old and new alluvium and artificial fill cover. The thickness of these layers ranges from 5 to 13 meters at the Marmara Sea coasts. However, the thickness reaches 60 to 70 meters along the Golden Horn coasts. On the European side, old and new alluvium layers are present in the valleys of İstinye, Baltalimanı, and Bebek. They are found in the Kuşdili and Maltepe-Cevizli regions on the Asian side (Ündül & Tuğrul, 2006).

When the geological features of the region are evaluated, it is mentioned that the earthquake risk of Istanbul gradually decreases from south to the north. This variation is attributed to both the characteristics of the rock types of the region and the position and shape of the fault.

When the geological structure of the city is evaluated, it can be mentioned that lithological units can be classified into two as rocks and soil units. Soil units are predominantly observed in the south-eastern parts of the European side of Istanbul. In the remaining areas of the city there are rock units. Generally, the occurrence of weak rock and soil units decreases from south to north in Istanbul (Ündül & Tuğrul, 2006).

Tertiary units, formed at the end of Cenozoic era, cover large areas of Istanbul at shallow depths. These rocks are frequently represented by organic limestone, clayey limestone, uncemented sand, alluvium, or clay. Although tertiary layers do not typically cause bearing capacity problems, they experience some stability problems. This is particularly evident in the south-western parts of the city, in regions such as Avcılar, Küçükçekmece, Büyükçekmece, and Beylikdüzü. The soil structure in these areas can lead to decrease in structural stability and accelerate ground motion after an earthquake (Ündül & Tuğrul, 2006).

The shores of the Golden Horn, the Marmara Sea and the Bosporus consists old and new alluvial layers and artificial infills. The bearing capacity of alluvium, which is frequently encountered on the city's old and current water beds, is very low. Additionally, the artificial fills have negligible bearing capacity. The structures in regions, which consist this type of soil, may face instability and settlement problems (Ündül & Tuğrul, 2006).

Factors related to seismic characteristics of the city such as the proximity to faults, earthquake history and accompanying natural events during an earthquake are also very important factors in determining the effects of seismic activity.

Istanbul is located on the western part of the North Anatolian Fault Line and has experienced numerous earthquakes since the beginning of urban settlement. The North Anatolian Shear Zone, including its most prominent part, the North Anatolian Fault, was initiated 11 million years ago. It is an active, rapidly moving strike-slip fault stretching from Bingöl to the Sea of Marmara. The westward migrating fault has had a remarkable seismic activity between 1939 and 1999 and has generated surface ruptures amounting to about two-thirds of its 1600 km length. The only unbroken segment today is the Marmara Segment (Ambraseys & Finkel, 1991; Şengör & Zabcı, 2019).

As the North Anatolian Fault approaches its western end, it bifurcates into northern and southern branches probably resulting from structures formed during the extension of the Aegean. The northern branch is known as the "Main Marmara Fault" (Ambraseys & Finkel, 1991; Şengör & Kındap, 2019; Şengör & Zabcı, 2019).

The Main Marmara Fault traverses the Sea of Marmara from Gulf of İzmit to Tekirdağ. The fault curves northwards in the west of the Gulf of İzmit and approaches the coast of Istanbul. Although the distance between the fault and various districts in the south of Istanbul changes, there are regions where it comes very close to the shore, particularly along the European side. This distance is mentioned to be 10–15 km between Bakırköy and Avcılar. The southern branch of the fault traverses developed settlements in the Marmara Region, including Bursa, Balıkesir, Çanakkale, and Edremit (Ambraseys & Finkel, 1991; Şengör & Kındap, 2019; Şengör & Zabcı, 2019).

Given its location, Istanbul is considered doubly unfortunate in various seismic scenarios. While a rupture oriented "west-south-west" heavily impacts the "east side of the Bosporus", a "west-north-west" oriented rupture causes more damage to the "west side of the Bosporus". Occasionally, as seen in the 1509 earthquake, the Main Marmara Fault experiences an entire rupture, resulting in widespread destruction from Adapazarı to Thessaloniki (Şengör & Kındap, 2019).

When the return periods of Istanbul earthquakes are examined, it is stated that the city experiences a moderate earthquake (epicentral intensity, Io=VII–VIII) approximately every 50 years and a high-intensity earthquake (epicentral intensity, Io=VIII–IX) about every 300 years (Erdik, 2005).

Various sources indicate that throughout history three earthquakes that have occurred in Istanbul was followed by tsunamis. Considering the Sea of Marmara as a basin, there is a possibility that a large fracture at the basin's floor could trigger a tsunami. However, current seismic scenarios suggest that it is unlikely for a tsunami to accompany a destructive earthquake in the city (Angell, 2015).

Historical sources suggest that even during the most severe earthquakes, the areas which are close to the Black Sea coast and the deepest regions of the Bosporus did not suffer substantial damage. This is likely due to the shape and slip direction of the fault (Şengör & Kındap, 2019).

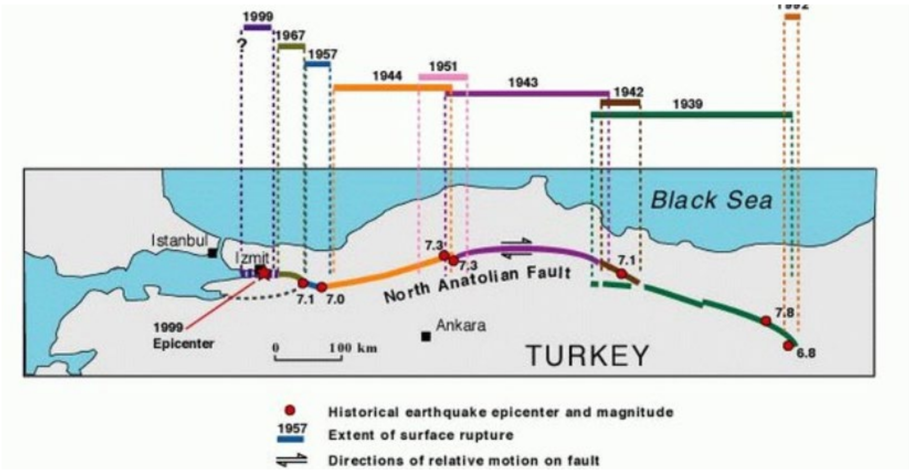

Figure 2 Severe earthquakes occurred on the North Anatolian Fault Line (Sarıbıyık et al., 2003)

The North Anatolian Fault Line has generated numerous earthquakes some of which exceeding a magnitude of 7.0 on the Richter scale over the past 2000 years. Each rupture of the fault transfers stress westward. Consequently, the risk increases at the western end of the fault following each earthquake. The Erzincan earthquake that occurred in the first half of the 20th century and the 1999 Gölcük earthquake strengthen the possibility that the next major earthquake will occur at the western end of the fault, close to Istanbul. Figure 2 shows the significant earthquakes that occurred on the North Anatolian Fault Line.

2.2. Urbanization-Related Features

Urbanization, which started with the Industrial Revolution, remains one of the most important reasons contributing to the challenges of living in many cities today. Urban planning practices that do not keep pace with population growth in densely populated cities give rise to different problems. These problems sometimes manifest themselves as unplanned and illegal construction practices, and sometimes as vertical architectural solutions to accommodate more population. Besides, during the expansion efforts green spaces are often damaged as well. As a city with significant migration, Istanbul faces all these urbanization-related challenges.

Istanbul, which acts as a bridge between Europe and Asia, has served as the capital of the Roman, Byzantine, and Ottoman Empires from past to present due to its location, climatic characteristics and topography. In addition to its strategic location and favourable climatic characteristics, Istanbul is distinguished by its topographical features and is often referred to as "the city built on seven hills".

Due to economic, social, and environmental reasons, Istanbul has been Türkiye's most populous city for many years. TÜİK data for 2023 states that the city's population is 15,655,924 people. Istanbul, with a larger population than many European countries, hosts approximately one-eighth of the country's population and according to economic data accounts for over 50% of the country's exports. In this context, Istanbul causes an imbalance in Türkiye's population density and economy (Erdik & Durukal, 2008; TÜİK, 2024).

Covering a total area of 5461 km², with parts in both Asia and Europe, Istanbul's urban area spans approximately 2577 km². According to these data, the population density of the city is calculated as 2867 people/km² when calculated according to entire surface area. Nevertheless, it is 6075 people/km²when calculated according to its urban area borders (Türkiye İmar Kadastro, 2014).

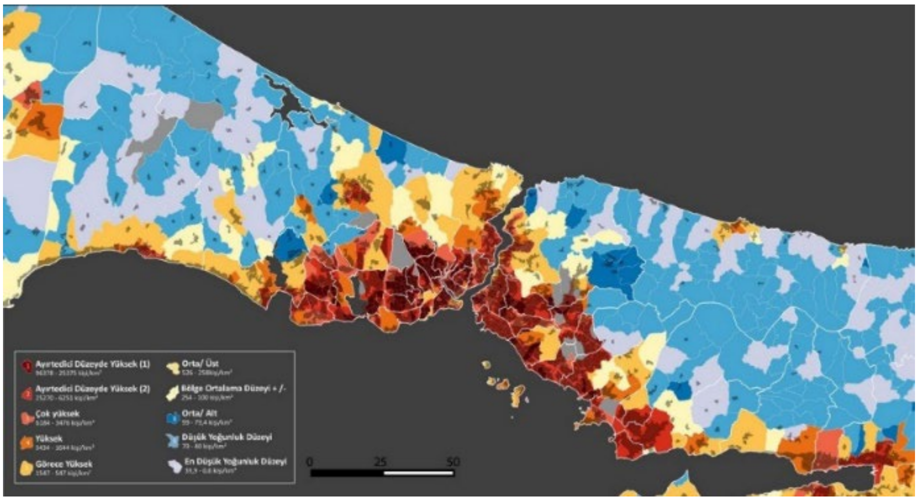

Figure 3 Population density map of Istanbul and its surroundings (Kadıköy Akademi, 2020)

When the population distribution maps of Istanbul and its surroundings are examined, it is observed that the surrounding areas of Istanbul exhibit relatively low density (Figure 3). In contrast, the population density is very high within the city centre. Besides, in certain areas it reaches to distinctly noticeable levels (Figure 4).

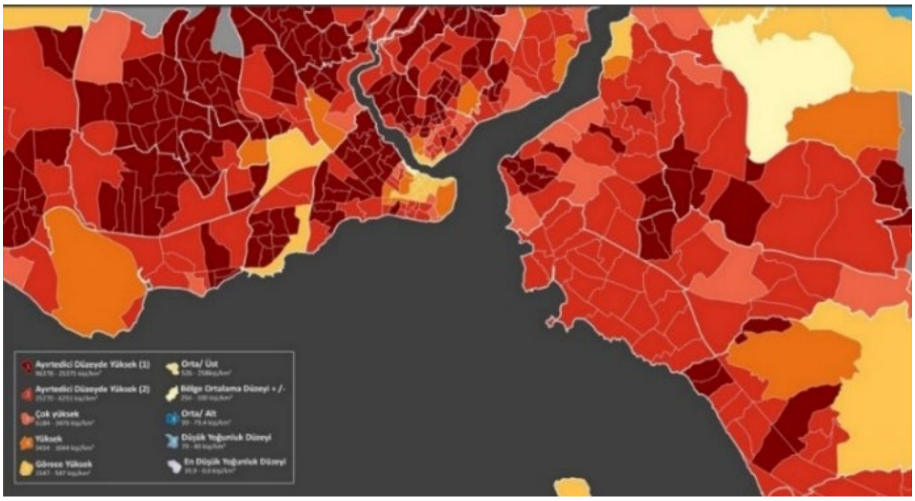

Figure 4 Partial population density map of Istanbul (Kadıköy Akademi, 2020)

Extensive construction activities are carried out to accommodate the growing population in densely populated regions of Istanbul. This situation adversely affects both the life quality of the local residents and the resilience of the region against various risks.

2.3. Building-Related Features

Although nowadays mostly reinforced concrete structures are being built in Istanbul, different traditional building practices have been developed in the city from past to present. The most distinctive characteristic of traditional building practices is that they produce solutions that resist the region's specific problems. Accordingly, the primary purpose of traditional buildings constructed in earthquake-prone regions is to increase the earthquake resistance of the building. As Istanbul has always been a city with a high earthquake risk, traditional construction techniques which have been developed in Istanbul aimed to improve the earthquake resilience.

Figure 5 Traditional Turkish House (Gayatri, 2023)

The wooden framed buildings of Istanbul, which are also known as the "Turkish House" or "Ottoman House" in world architecture, is characterized by distinctive features such as its unique room layout, plan scheme, roof type, and construction type (either infill or wattle-and-daub walls). The Turkish House is constructed with *hımış* technique. Although it is possible to determine three more local techniques in Anatolia, *hımış* is the most common technique within the Ottoman territory, particularly within Constantinople (Güçhan, 2018).

The Turkish House, whose typological development began in Anatolia in the 16th century, was constructed with a hybrid technique. While the foundations and ground-floor walls are constructed with stone, the upper floors are typically constructed with timber and adobe infill (Figure 5). The wooden frame, which was completed with adobe infill in the early periods, later completed with region-specific local materials. The wooden roof is covered with tiles (Günay, 2017; Kuban, 2017).

The traditional Turkish House has been designed with practices aimed at increasing earthquake resistance. Using wooden bond beams, constructing the ground floor with masonry stone walls to move the centre of gravity of the structure closer to the ground, using wood to enlighten the building and using nails to increase flexibility are some key practices which are used in similar systems in many parts of the world to enhance earthquake resilience (Correia et al., 2014; Güçhan, 2007; Langenbach, 2010).

Due to wood's fire sensitivity and the Westernization ideas that began in the 19th century, although they are very beneficial in case of an earthquake, traditional wooden-framed structures were gradually replaced by masonry, and later by reinforced concrete buildings leading to the abandonment of the Turkish House tradition.

It is stated that there are approximately 1,200,000 buildings in Istanbul as of the beginning of 2023. The building density is notably high in the city's coastal areas, in the easy-to-access areas close to commercial centres, and in the historical settlement areas (Figure 6).

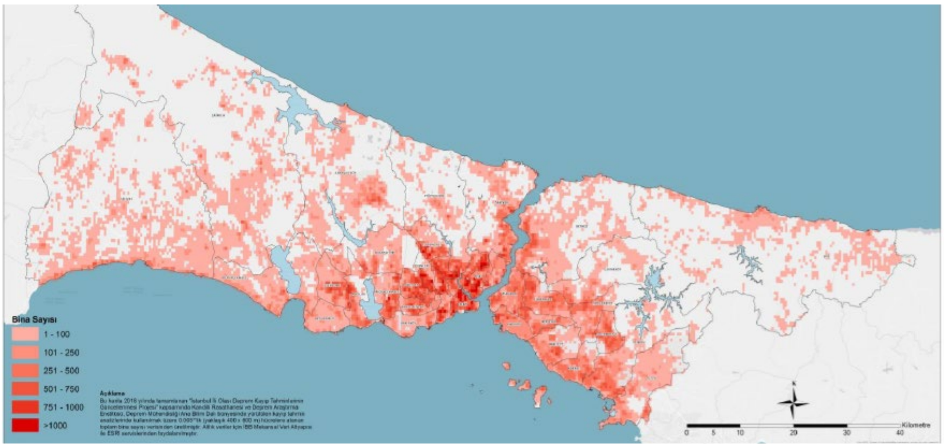

Figure 6 Building density in Istanbul (Kandilli Observatory, 2021)

According to the "Istanbul Earthquake Rapid Response and Early Warning System Report" prepared by Istanbul Metropolitan Municipality (IBB) in collaboration with Boğaziçi University and the Kandilli Observatory, 84% of the building stock is constructed with reinforced concrete systems, 15% with masonry systems, and the remaining 1% with wood, steel, and prefabricated systems (Figure 7). It is noted that 32% of the buildings were constructed after 2000, 46% were built between 1980 – 2000, and 22% were built before 1980. While 2% of the building stock consists of high-rise buildings, 32% consists of mid-rise buildings, and 66% low-rise buildings (Kandilli Observatory, 2021).

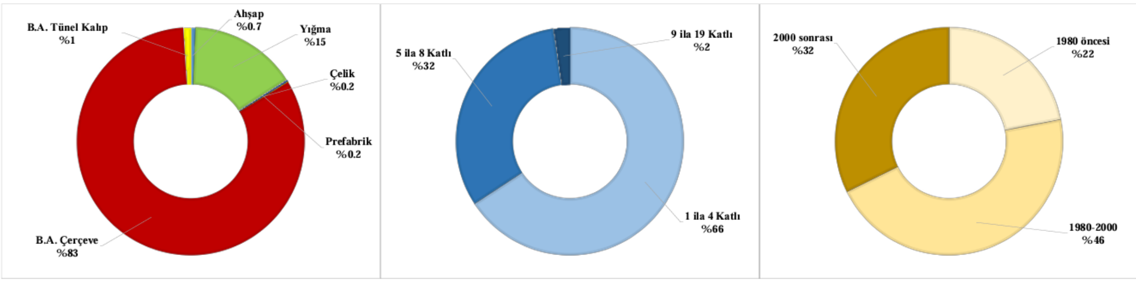

Figure 7 The structural system, number of floors and construction year of the buildings in the Istanbul building inventory (Kandilli Observatory, 2021)

Although the current building stock in Istanbul predominantly consists of reinforced concrete structures, wooden and masonry structures remain prevalent in the city's historic neighbourhoods and tourist areas with buildings of historical significance.

Wooden-framed structures offer high earthquake resistance. However, they also present risks such as fire and biological deterioration. Masonry buildings, on the other hand, may have varying degrees of seismic risk due to structural and architectural interventions encountered over their lifespan. The presence of these traditional buildings alongside reinforced concrete buildings within the city and that the reinforced concrete structures built in these regions are often of low quality, poses a significant threat to all structures in regions with high seismic risk.

The earthquake resistance of monumental buildings is typically higher due to their construction methods and material properties. Nonetheless, the behaviour of these monumental structures during a potential earthquake is not entirely predictable. This uncertainty arises because these buildings have been subjected to environmental factors and previous earthquakes over their lifespan, which may have introduced some weaknesses (Ambraseys & Finkel, 1991; Ferah, 2009).

3. Earthquake Loss and Damage Prediction for Istanbul

The significant amount of time that has passed since Istanbul's last earthquake suggests that a future seismic event may not be too far. Earthquakes primarily lead to loss of life due to the destruction of buildings. Additionally, they cause damage to industrial areas, educational facilities, transportation networks, and historical monuments, impacting cities socially, culturally, and economically. In cities like Istanbul, which serves as a key economic engine for the country, a major earthquake has the potential to affect the entire nation economically and socially, and to erase a significant portion of the collective memory.

"Updating the Earthquake Loss Estimation for Istanbul Report" published in 2019, includes projections for expected building, population, and infrastructure damage and losses in Istanbul. Three recurrence periods were used in the estimation of seismic risk and the scenario was designed with a magnitude of Mw = 7.5 earthquake. These components were integrated using various sources and calculation methods to create 15 earthquake simulations. The project covers the municipal borders of Istanbul. The provided estimations are based on empirical models developed using analytical studies and experiences in the earthquake engineering literature (KOERI, 2019).

The report analyses a total of 1,166,130 buildings in Istanbul and estimates that 57% of these buildings will not be damaged, 26% will be slightly, 13% will be moderately, 3% will be severely, and

1% will be very severely damaged. Severe and very severely damaged buildings will need to be demolished and rebuilt. It is also suggested that it would be more appropriate to demolish and rebuild moderately damaged buildings. Accordingly, approximately 17% of all buildings (around 194,000 structures) will need to be rebuilt. The financial losses due to structural damage are anticipated to be around 12 billion USD (KOERI, 2019).

In separate scenarios created for both day and night, the estimated number of casualties is approximately 14,150 for night and 12,400 for day. It is estimated that approximately 8,100 people will be seriously injured in the night earthquake, and 7,450 people will be seriously injured in the day earthquake (KOERI, 2019).

Determining the urgent shelter needs that arise due to the loss of habitable buildings is crucial for densely populated cities like Istanbul. After an earthquake, residents often prefer not to enter buildings even if they are not damaged, which can exacerbate the consequences of the disaster. The scenario estimates that a significant amount of emergency shelter will be needed in order to host nearly 640,000 households (KOERI, 2019).

The report also states that since monumental structures and historical artifacts are important in terms of earthquakes, the evaluation, analysis and improvement studies of these structures should be carried out more carefully (KOERI, 2019).

The above-mentioned predictions are done by using modern technology and by taking into consideration the magnitude and intensity of previous earthquakes, seismic characteristics of the region, fault location and fault's frequency of generating earthquakes.

3.1. History and Earthquake History of the City

Istanbul has hosted many important civilizations during its long history. Research had shown that settlement in Istanbul dates back to the Neolithic Period (7000-1700 BCE) and the city was controlled by different civilizations including Roman and Ottoman Empires from that period (Barnes, 1981; Ferah, 2009; History.com, 2017).

During its nearly a 1,000-year role as the Byzantine capital, the city was known as Constantinople and was enriched with numerous significant architectural works (Ferah, 2009; Kaçar, 2003; Labatt, 2004).

After the conquer of the city by the Ottoman Empire in 1453, the city remained the capital for nearly 500 years and was extensively rebuilt during this period, with the construction of numerous palaces, religious structures, and educational institutions (Ferah, 2009).

Following the collapse of the Ottoman Empire and with the proclamation of the Republic of Türkiye, Istanbul maintained its economic and social prominence. Accordingly, the population increased and urbanization-related challenges emerged. While some of the city's historical buildings continued to be utilized, some were demolished and new structures were erected in their place with the goal of constructing a modern city. According to 2023 TÜİK data, Istanbul's population is 15,655,924 people. This figure is more than the population of 131 countries in the world (TÜİK, 2024).

The city suffered destruction for various reasons, has been rebuilt, expanded and adopted different types of construction techniques. All of these historical processes have had a lasting impact on the seismic resilience and earthquake risk of Istanbul.

However, one of the most important considerations when assessing a city's earthquake behaviour is the historical record of past earthquakes. Information about the location, intensity, and associated events of previous earthquakes provides valuable data for predicting future seismic events.

According to historical sources, Istanbul was affected by 24 earthquakes during the Byzantine period, between 121 and 1453 AD. The earthquakes that occurred in 447, 478, 557, 989 and 1354 were quite severe and caused great damage. Different sources mention that the dome of Hagia Sophia, which was damaged in the 557 earthquake, collapsed in 558, and it is added that tsunamis occurred after the earthquakes in 557 and 989 (Angell, 2015; Ürekli, 2010).

During the Ottoman period, from 1453 to 1923, 24 earthquakes were recorded in Istanbul and its vicinity. Of these earthquakes, those that occurred in 1509, 1712, 1719, 1754, 1766, 1894 and 1912 were quite severe. The 1509 earthquake, referred to as the *"Kıyamet-i Suğra (Small Apocalypse)"*, reportedly resulted in the deaths of 4,000 to 5,000 people. The earthquake that occurred in 1766 and caused the loss of approximately 5,000 people has been compared to the 1755 Lisbon earthquake. It is stated that after this earthquake, building construction techniques were revised to reduce the risk of fire, and masonry structures began to be preferred instead of hybrid structures such as half-timbered and lath-and-plaster. The earthquake that occurred in 1894 affected a very wide area and caused great destruction. Following this event, Sultan Abdulhamid II initiated seismic research efforts. The 1912 Hendek earthquake, with a magnitude of 7.3, did not cause significant damage to the city as it did not occur close to Istanbul (Angell, 2015; Ürekli, 2010).

In the Republican era, although there were four of the five recorded severe earthquakes, they did not cause significant damage to Istanbul as they were not close to the centre. However, the 1999 Gölcük earthquake, which had a magnitude of 7.4, caused extensive destruction, especially in İzmit and its surroundings, and also caused damage and casualties in western Istanbul (Angell, 2015).

When the earthquakes that occurred in Istanbul and its vicinity are examined chronologically, it is seen that the region has similarities in terms of seismic activity and many earthquakes occurred between the 3rd-6th and 14th-17th centuries. Between the 7th and 13th centuries, the city's seismic activity was weak, especially in terms of severe earthquakes. From the 17th century until the end of the 20th century, the city's seismic behaviour was unusually weak. The 1999 Gölcük earthquake at the end of the 20th century caused great destruction in Kocaeli and its surroundings. In this earthquake, Istanbul was also severely shaken, and destruction occurred in its western parts. Figure 8 illustrates the extent of damage from the August 17, 1999 earthquake (Ambraseys & Finkel, 1991).

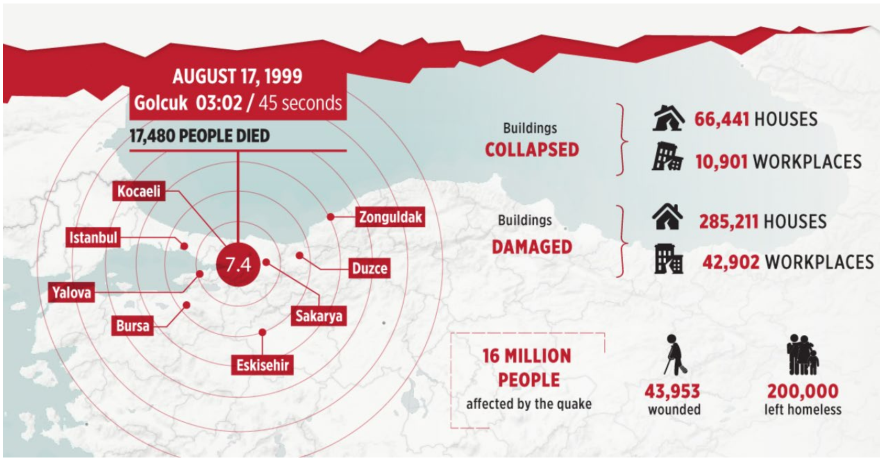

Figure 8 The destruction on August 17, 1999 earthquake in numbers (Anadolu Ajansı, 2018)

Following the 1999 earthquake, a new Earthquake Regulation was issued, and all structures constructed since that day have been subject to this regulation. Additionally, urban transformation projects have been developed in certain regions of the city, leading to the renovation of old buildings in these regions. Despite these efforts, historic areas of the city still have a high density of old buildings. Furthermore, the buildings which were constructed before the earthquake regulations have low construction quality. The current seismic resistance of these structures remains uncertain.

3.2. Evaluating the Earthquake Resilience of Istanbul in Case of a Potential Earthquake

Vulnerability is a widely used concept in evaluating the risk of urban spaces and developing risk mitigation strategies at different scales. Although evaluating vulnerability is crucial, it is also difficult as vulnerability related issues are usually human induced. Particularly, the earthquake vulnerability of urban spaces is not easy to evaluate as it is mostly affected by human behaviour. The most important factors that affect the earthquake vulnerability are urbanization, population growth, and uncontrolled settlements. Construction and social related features are also important as they affect the quality of disaster management strategies. In short, the earthquake vulnerability is affected by the physical, environmental, social and economic conditions of the city (Alizadeh et al., 2021).

As the city is a living organism which responds as a whole during a disaster, the earthquake vulnerability of Istanbul is evaluated by considering the above-mentioned features. These features affect the urban design strategies and construction practices of Istanbul which collectively shape the city's seismic response. Nevertheless, different configurations of these features alter the level of earthquake risk.

These topics have also been stated and discussed in the recent studies about Istanbul. Firstly, according to the results of two comprehensive surveys which were conducted in 2008 and 2013 there is a rising earthquake awareness in all segments of the community which may support the improvement strategies (Kundak, 2017). However, some of these studies emphasize that, the intensive work carried out on neighbourhood regeneration and the dense construction that occurred as a result of this, increased the city's building and population density and therefore also increased its earthquake vulnerability (Arslan & Kayaalp, 2018; Güney, 2024; Kayaalp, 2024).

Another research highlights urban transformation areas where previously middle-income and low-income groups live become unaffordable for these income groups. This results with a tendency towards illegal housing (Gibson & Gökşin, 2016).

3.3. Research Method

This study aims to identify the potential challenges of the city and to put forward a serviceable strategic approach which takes into consideration all participants of the city in order to improve the seismic resilience. Within this scope, a SWOT analysis is conducted to delineate Istanbul's current characteristics in the context of a potential earthquake. SWOT analysis is a useful approach in the evaluation of internal and external environment of a certain problem to develop an appropriate action in strategic decisions. In an earthquake prone region, it may help local administrators to prioritize interventions or establish future urban planning strategies.

The evaluation criteria which were chosen for SWOT based on the physical, environmental, social and economic conditions of the city. Accordingly; urban planning, economic conditions, social conditions, tourism and technological developments are determined as the evaluation criteria. *Urban planning* is selected as the intersection point of physical and environmental conditions of Istanbul. *Economic and social conditions* of Istanbul are the other two important features affective on earthquake resilience. *Tourism* is also taken as another important feature that affect the city in case of an earthquake as it creates a significant pressure on population. Finally, as *technological developments* help to improve the vulnerability of urban settlements it was also taken as a feature in SWOT analysis.

3.4. Findings and Discussion

The strengths and weaknesses of the city and the threats and opportunities affecting it are revealed. In strategic planning efforts, strengths and weaknesses are controllable internal factors that assist in goal setting, while threats and opportunities are factors that cannot be directly controlled. Recognizing the threats and opportunities that impact the city and taking them into consideration in planning efforts can help to mitigate negative outcomes. Integrating the strengths with opportunities will help to strengthen the earthquake resilience of the settlement. Based on this evaluation methodology the current characteristics of Istanbul can be summarized as follows:

Table 1 Energy Performance Table for Case Building Across Locations and Different Climate Scenarios

Feature	Strengths	Weaknesses	Opportunities	Threats
Urban planning	**S1** Implementation of earthquake regulations **S2** Supports on urban transformation projects **S3** Urban transformation efforts **S4** Infrastructure strengthening efforts **S5** Evaluation and retrofitting of the earthquake resistance in public buildings, hospitals and schools	**W1** Buildings and infrastructure components built before the earthquake regulations **W2** High population density **W3** High construction density **W4** High-rise buildings **W5** Illegal construction **W6** Excessive interventions on existing buildings **W7** Narrow streets **W8** Lack of assembly areas **W9** Construction over or near known active fault lines **W10** Low structural and detail quality **W11** Traffic generated in the city centre **W12** Frequent preference of reinforced concrete in construction	**O1** Growth and development efforts in the housing industry to meet increasing demand **02** Expansion of active transportation network	**T1** Upper scale plans which include high rise buildings
Social structure	**S6** Collective memory	**W13** Low earthquake awareness of residents	**O3** Growing trends in the world towards sustainable living and disaster protection	**T2** Decline risk in earthquake awareness due to demographic change in some parts of the city
Economy	**S7** The value of historical cultural assets in the city	**W14** The possibility of low income groups to tend to old buildings or illegal housing	**O4** Incentives given to private companies, especially in housing investments	**T3** Risk of economic crisis, inflation and financial irregularities slowing down urban transformation works **T4** Risk of increasing material costs affecting construction quality
Tourism	**S8** Prioritization of the seismic retrofitting efforts on historic structures due to their heritage value	**W15** A significant number of historical artifacts and heritage buildings are located in areas with soft soil	**O5** Opportunity to benefit from a sustainable tourism approach	**T5** Excessive burden of mass tourism in the city (Overtourism)
Technology	**S9** Increased inventory studies on earthquake preparedness **S10** Increased scientific studies on earthquakes **S11** Earthquake early warning system **S12** Tsunami early warning system		**O6** Technological developments for earthquake resistant building production **O7** Increasing research and development studies to reduce the effects of disasters	

In the construction of an earthquake resilient settlement, the main aim is to improve the life quality of all its users, ensuring a healthy and safe environment. It is also important to preserve the collective memory of the community and maintain a sustainable urban framework.

While planning the efforts to increase the city's earthquake resilience, various improvement proposals should be put forward within the scope of the previously mentioned topics. These proposals should be evaluated together and integrated into comprehensive plans. Accordingly, the strategies planned for development can be formulated with the goals outlined in Table 2.

Table 2 Strategic Goals for Increasing the Earthquake Resistance of the City

Feature	***Strategy***
Urban planning	- To prevent construction near fault lines and on soft soils - To develop urban transformation projects for regions which consist illegal housing and unplanned urbanization - To use alternative construction systems such as steel for high-rise buildings and wooden frame for low-rise residential buildings (taking inspiration from traditional construction techniques of Istanbul) - To retrofit existing reinforced concrete buildings by using external or internal trusses, earthquake bolts, etc. - To increase the amount of green space in densely constructed regions by implementing new urban plans which include transformation by demolishing the old building stock - To take measures to reduce population in densely populated regions. A new urban planning policy that divides the city into several centres could be adopted for this purpose. - To inspect the earthquake resistance of excessively intervened existing buildings. If necessary to oblige retrofit applications, to control and to support them. - To encourage construction firms serving different income groups to develop earthquake-resistant projects, to provide incentives to enable these groups to purchase housing. - To elevate the construction inspection standards and to ensure earthquake resistance in all buildings - To construct multi-functional buildings in order to enhance pedestrian use.
Social structure	- To evaluate the earthquake awareness in regions with high immigration rates and to conduct information and education programmes in regions with low earthquake awareness - To conduct training programmes to increase earthquake awareness among different professional groups involved in the construction industry - To ensure that all income groups benefit equally from earthquake-resistant housing investments
Economy	- To support the local community of low-income group economically in urban transformation projects - To develop projects to find international funds for various artefacts, monuments and structures with historical and touristic value.
Tourism	- To promote sustainable tourism practices in order to mitigate the impact of mass tourism on population density and traffic
Technology	- To design alternative modern technology projects for new development areas that focus on sustainable living and disaster protection

According to above-mentioned strategic goals, it can be stated that the most important priority of Istanbul is to develop projects that are suitable for the economic conditions of different income groups by improving the social structure of the city and utilizing technological opportunities. However, the most important problem of the city in recent years is the increase in the prices of all old and new housing and the problems that arise from this. While this situation makes earthquake resistance of some regions uncertain, it also leads to the deterioration of the social structure and decrease the security. Different strategies are being developed to eliminate this problem experienced in many important cities of the world. The methods frequently used for this purpose can be mentioned as follows;

- Providing land tenure security in low-income areas, expanding microloan opportunities, supporting low-cost earthquake-resistant housing initiatives
- Increasing governments' economic commitments to develop earthquake resistant housing investments with reasonable payment terms
- Developing infrastructure and reducing building density in several pilot areas that are at the highest risk
- Developing renovation projects undertaken by local governments together with private companies, especially for low-income groups

- Municipalities creating more accessible micro-credit opportunities for low-income groups
- Municipalities purchasing old buildings and renovating them to build earthquake-resistant structures in high-risk areas, selling and renting them to low-income families at affordable prices
- Establishing public, private and public organizations to produce solutions for earthquake-resistant affordable housing
- Developing more efficient methods to construct earthquake resistant buildings with innovative methods, materials and technologies
- Developing earthquake-resistant mass housing projects on public transportation lines to reduce traffic pressure in the city and produce affordable housing
- Evaluating public lands through joint ventures instead of offering them to the market

Following the development of strategic goals for the city, urban planning proposals compatible with these goals need to be developed and implemented. Determining the priorities among the targeted strategies and establishing a timeline for the process are crucial steps in planning a city with high earthquake resilience. When determining priorities, the interests of the local community should be kept at the forefront, and the planning should be both sustainable and achievable.

After identifying the priorities and establishing the timeline, stakeholders who will play role within the scope of different targets should be identified. It is not possible for central and local governments to carry out all the implementations in the process of planning a city with high earthquake resistance. Therefore, external stakeholders will also be necessary for various issues. Key stakeholders include universities, private sector organizations, foundations, social organizations, NGOs, professionals, and local community. In the next part of the process, the strategic objectives should be monitored and evaluated.

4. Conclusion

Istanbul is Turkey's most populous city and the locomotive of the Turkish economy. The city has a high tourist intensity due to its historical importance and the immigration rates of the city is also high for economic and social reasons. Some of the most important problems of Istanbul can be mentioned as; uncontrolled population growth, development activities carried out to accommodate the high population, and the problems arising from dense population and intense construction activities.

In addition to all these important features, Istanbul also has a high earthquake risk. The Main Marmara Fault is an active fault line that poses a serious threat to Istanbul. The devastating earthquake series along the East Anatolian Fault in February 2023 have once again highlighted the urgency of taking necessary precautions and preparations for the anticipated Marmara earthquake. Therefore, planning, renewal and construction activities carried out in Istanbul must be compatible with earthquake-resistant urban development strategies.

Following the 1999 Kocaeli/Gölcük earthquake, central and local governments began carrying out various initiatives at Istanbul to increase the city's earthquake resilience. Urban transformation and infrastructure reinforcement efforts supported by the government, along with improvements in the seismic resistance of public buildings likely to be used post-earthquake, are highly valuable in this context. However, as the faulty urban planning practices that have been carried out in Istanbul since the past weaken the city today and as there is a large number of residential buildings constructed before the earthquake regulation, there is a massive urban transformation in many parts of the city.

The urban transformation interventions which continue in different parts of Istanbul, are carried out without considering the economic conditions of the income groups living in the region. These applications often create conditions that the residents of the region will not be happy with or cause the original owners to relocate as they cannot afford the costs. In order to eliminate such problems and create a more equitable environment for all parties, a strategic plan should be put forward in which all stakeholders have a say and take an active role in the decisions to be taken for the development of the city.

The first step in constructing an earthquake-resilient city is to determine the current situation of the city. While doing that, the most important goal should be increasing the life quality of all users. There are many stakeholders in crowded cities like Istanbul. Therefore, in urban design studies that focus to improve earthquake resistance the needs of all stakeholders should be taken into consideration.

This study aims to identify the potential challenges of the city and to put forward a serviceable strategic approach that takes into consideration all participants to improve the seismic resilience. A SWOT analysis is conducted within this scope by focusing on the current physical, environmental, social and economic conditions of the city. Tourism and technological developments were also taken into consideration due to their importance in today's world and hence for the city.

After the determination of the obstacles that affect the city's earthquake resilience, prior goals of an earthquake resilient urban planning strategy are put forward. According to this evaluation; using alternative construction systems, retrofitting reinforced concrete buildings, increasing the percentage of green spaces, developing urban transformation projects for underdeveloped regions, ensuring all income groups benefit equally from earthquake-resistant housing investments can be stated as the most important goals.

The potential long-term effects that improve the urban environment and residents' life quality, by using these strategic applications, can be summarized as follows:

- Ensuring the perception of the city's unique topography by constructing high-rise buildings in certain regions
- Increasing the involvement of public authorities in order to protect the local community while constructing earthquake resistant buildings
- Developing a transport-oriented urban planning in order to connect homes, offices and districts efficiently
- Establishing more economical solutions for low-income groups
- Increasing earthquake awareness of the public
- Reducing public anxiety about earthquakes with information and education programmes
- Reducing building construction practices that compete with or supress natural environment
- Reducing irregularly urbanized regions with the spread of projects that target different income groups
- Reducing problems stemming from economic inequality with projects targeting different income groups

These suggestions can be considered as the first stage of a strategic plan that needs to be carried out in order for different stakeholders to have a say in improving the earthquake resistance of the city. In this context, developing new suggestions by focusing on light, flexible, recyclable and affordable construction systems.

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Resume

Assoc. Prof. Gülru Koca received her BSc in Architecture from ITU in 2000, MSc and PhD from the same institution in 2004 and 2010. She is currently working at Işık University, Department of Interior Architecture and Environmental Design. Her main research interests are evaluation of building materials, timber building materials, traditional building techniques, non-destructive testing, and sustainability in materials.