



Original paper

Analysis of Potential Disruptions from Earthquakes in Istanbul and 3D Model Based Risk Communication

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Abstract Making cities disaster resilient is important as proven by the increased number of city networks such as 100 Resilient Cities. The major difficulty on this trajectory is the interrelated components in urban systems that influence each other and increase uncertainty in risk assessment and management. Therefore, this study analyses the potential road blockages that impact traffic control using a multi-hazard risk assessment for the historical peninsula of Istanbul, Turkey. To support the communication of the causes of such potential disruptions, a 3D city model is created for the visualisation and analysis of the consequences from a disaster. For the socioeconomic, physical and systemic vulnerability and risk assessments, the additive normalization indicator-based approach is used. Besides, to determine the building vulnerability and damage grades, the EMS-98 Macroseismic method is applied. This study found that the socioeconomic vulnerability is high to very high which could contribute to emergent behaviour causing traffic congestions and communication issues. In addition, most buildings have been determined to be ‘very heavily damaged’. Consequently, there is high risk for road blockages in the narrow streets within the case study area, while the roads themselves have low risk to damage. The usage of 3D modelling techniques for visualisation and analysis improves understandability, visual problem identification and support decision making for mitigation strategies in case of road blockages.

Keywords: Earthquake, Vulnerability, Risk, Road blockage, 3D models

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1. INTRODUCTION

The recent earthquake disaster on 6 February in Turkey and Syria showed us the destructive force of disasters and the immediate humanitarian crises. Though the exact number is now known yet, the death toll is expected to surpass 50.000 people. The earthquake and its aftershocks have destroyed buildings, and more than 10 cities in the area are deserted. Such disasters negatively affect the socioeconomic development of cities in the long term. They cause infrastructural damages, injuries, economic loss and loss of human life (Sim *et al.* 2018). The importance of making cities disaster resilient is proven by the increased number of city networks such as 100 Resilient Cities and Global Resilient City Networks. However, cities or so-called urban systems can have many interrelated components such as the economy, organisations, technology, built-up environment and people which affect each other. These interactions increase the complexity of cities, causing uncertainties in the impact of disasters which makes them hard to predict. This is a major difficulty in increasing the disaster resilience of cities (Shimizu and Clark 2015).

One of such complex cities is Istanbul. It is a megacity with an increasing population that is currently over 15 million inhabitants (World Population Review n.d.). The city is located in the western part of Turkey and extended parallel to the North Anatolian Fault (NAF). A worrying phenomenon is the east to west progression of the epicentres of earthquakes along the NAF as illustrated in Figure 1, which causes Istanbul to be at increased risk to major earthquakes (Atun and Menoni 2014). Experts predict that a major earthquake with a magnitude larger than 7 will strike Istanbul within the next 30 years ($62\pm 15\%$ chance) since the 1999 Kocaeli earthquake (Parsons *et al.* 2000).

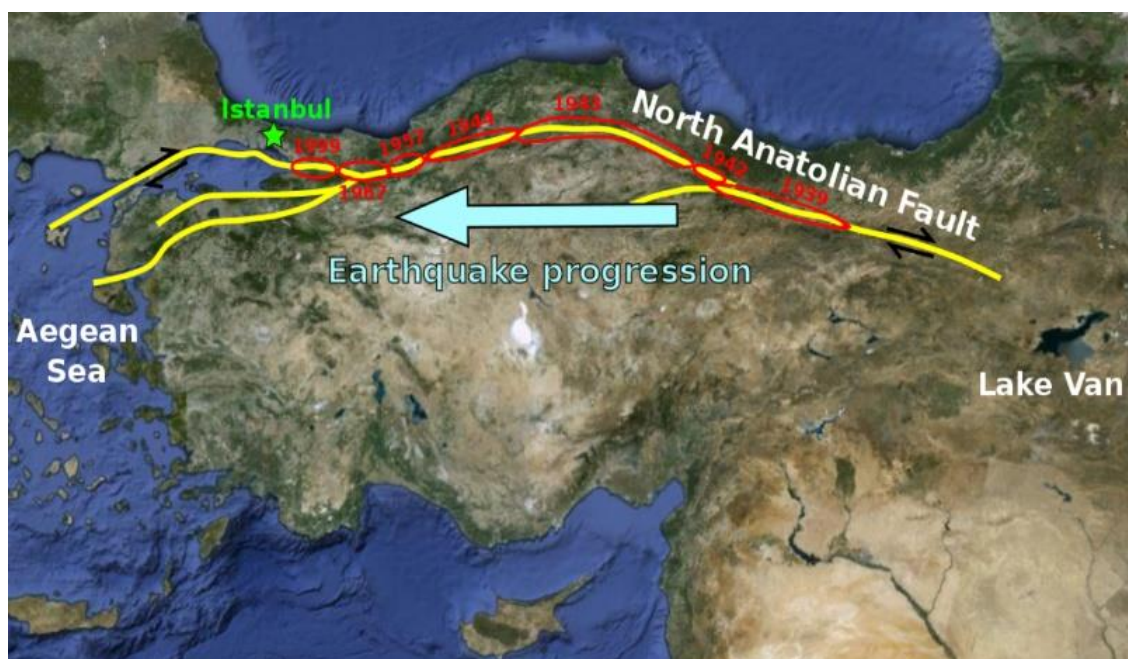


Figure 1. East to West progression of the NAF. Source: CGS Leeds (n.d., n.d.)

Besides this, Istanbul has shown to be at risk to the cascading effects of earthquakes including fires, liquefaction and tsunamis (Alpar et al. 2003; JICA and IMM 2002; Pampanin 2021). Contributing to the risk are the many vulnerable structures that are illegally built but legalised after issuing various amnesty laws, the high urban and population densities, the inadequate infrastructure for the large amount of traffic and the unbalanced socioeconomic society (Atun and Menoni 2014).

So far, two dimensional representations have been used for seismic risk assessment maps and plans. However, based on the research of Hollnagel *et al.* (2006), such plans are not sufficient enough to take into account the dynamics of the constantly changing environment. As a consequence, some potential disruptions caused by disasters can be missed and predictions and mitigation strategies may not be fully applicable. Thus, the challenge is that static solutions are incorporated in a complex and dynamic environment. Blocking of roads by debris from collapsed buildings is an example of a disruption. Therefore, it is important to enhance the visual communication methods of risk.

In this study, the focus is on one hand investigating potential disruptions within traffic control, and on the other hand providing some measures to mitigate the risk. Traffic control covers the operational procedures that depict the movement of vehicles *i.e.* evacuation and access to and from disastrous areas for emergency services. After having an insight on the potential blockage, it is essential to suggest measures that reduce the impact of earthquakes, to keep the roads functional during an earthquake. We started with investigating the causes of potential disruptions which is why they are analysed using a multi-hazard risk assessment. Additionally, the disaster risk is visualised using 3D models. Based on the research of Redweik *et al.* (2017), Duzgun *et al.* (2011) and Kemec *et al.* (2010), analysing a situation requires less cognitive effort when using 3D models due to their multi-dimensionality. Thus, by using them, spatial interactions become easily recognisable. This could support the understanding and communication with experts (*i.e.* disaster coordinating and managing organisations) of the root causes of disruptions which impact traffic control. Based on that, more dynamic solutions can be suggested.

The case study area includes three neighbourhoods: Sehremini, Topkapi and Molla Gürani, which are located within the historical peninsula of Istanbul (the Fatih municipality, see Figure 2, known as the heart of Istanbul's tourism and transportation (Turgut 2008). They surround one of the main hospitals of Istanbul, Çapa, which is of great importance for medical aid after an earthquake event. However, the earthquakes could cause surrounding roads and ports to be lost, impacting the highly required traffic control.

2. IDENTIFYING POTENTIAL DISRUPTIONS

This study analysed three earthquake events that happened around the world and significantly impacted communities to increase the understanding of how different components

within an urban system interact and how these result in disruptions. This is used to identify potential disruptions that could occur in the case study area. The events include the Kobe earthquake that happened in Japan in 1995, the Tohoku earthquake that happened in Japan as well in 2011, and the Christchurch earthquake that happened in New Zealand in 2011. For each of them, the impact of disruptions on the traffic control are highlighted.

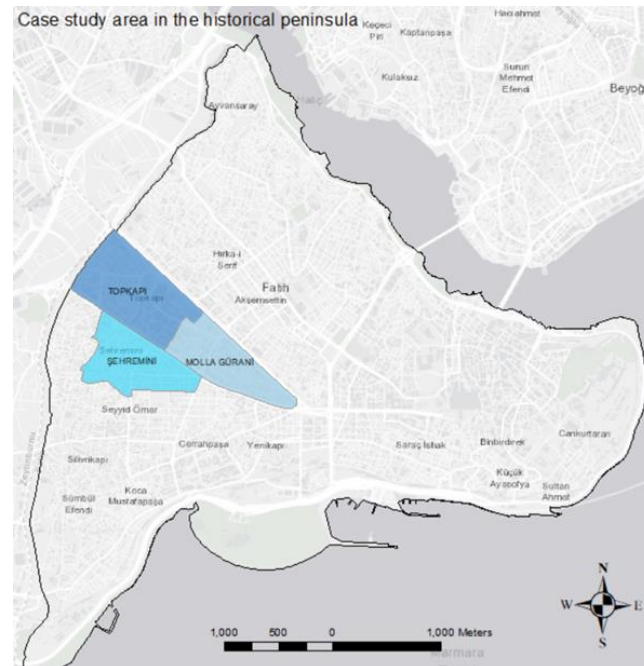


Figure 2. Case study area in Fatih, Istanbul. Source: Author (2022)

The **Kobe earthquake** and resulting fires and liquefaction led to great devastation of buildings, roads, railways, the harbour and people (Esper and Tachibana 1998). The traffic control was impacted by the loss of major expressways that connected Kobe with other parts of the country (Iida *et al.* 2000). Consequently, Kobe's transportation system was at less than 5% of its normal capacity and important access routes for emergency services and transportation of goods to impacted areas were lost. Contributing to this were the blockages on many narrow roads caused by debris and other infrastructural elements (Helbing *et al.* 2006). Besides this, human behaviour contributed to a large number of abandoned cars and people leaving the city, causing traffic congestion that obstructed the emergency services (Iida *et al.* 2000).

The **Tohoku earthquake** and cascading tsunami caused widespread damage to buildings and roads, blocked roads by mud and debris and a nuclear accident at the Fukushima-1 and -2 nuclear power plants which resulted in concerns about radiation. This made several areas inaccessible for emergency services (Khazai *et al.* 2011). Human behaviour caused a surge in the use of the communication network, causing communication issues which led to confusion in critical information distribution, hampering the disaster coordination (Shimizu and Clark

2015). Besides, people used their cars to evacuate which caused one third of them to get stuck in traffic congestions which obstructed the emergency services (Ranghieri and Ishiwatari 2014).

The **Christchurch earthquake** and especially the resulting liquefaction caused extensive damage to the road networks, bridges and tunnels. It led to ground deformations and roads flooded with mud and silt. In combination with road blockages due to rock falls, (important) roads became unusable which greatly obstructed the emergency services and the transportation of goods (Giovinazzi *et al.* 2011; Koorey 2018). Besides this, the evacuation of people from major buildings contributed to the impact on traffic control as it caused traffic congestions throughout the city (Koorey 2018).

Based on these events in combination with the local characteristics of the case study area known from literature, it was identified that it is likely that the (low-quality) buildings and roads in the area could be damaged. Besides this, the resulting building debris is likely to block narrow passageways due to the high urban density. Fatih is also known to have a lot of traffic, low-income newcomers and tourists who are expected to have low risk awareness and preparedness, and many businesses. Thus, unexpected behaviour during an earthquake is likely. This could cause traffic congestions as people will evacuate in a chaotic manner like during the Christchurch earthquake. Contributing, are the major hospitals near the area which will attract many people. Besides this, like happened during the Tohoku earthquake, the use of the communication networks could peak, causing communication issues for the disaster management organisations. The potential for road damage, road blockage, communication issues and traffic congestions are the disruptions which will be the focus in this study.

3. METHODOLOGY

3.1 Proposed Research Design and Input Data

An overview of the applied research design is presented in Figure 3. The input datasets as shown in

Table 1 are pre-processed using GIS methods to represent the vulnerability indicators and hazard models used for the vulnerability and risk assessments of this study. The Istanbul Metropolitan Municipality (IMM) General Directorate of Mapping, the Istanbul Planning Agency (IPA) and the Land Registry and Cadastre of the Republic of Turkey (TKGM) provided data used to describe the vulnerability. Data on the hazards were obtained from the worst-case scenario (Model C) of JICA and IMM (2002). The model assumes a simultaneous break of the entire NAF with a magnitude of 7.7, causing peak ground accelerations of over 400 cm/s².

Ugur *et al.* (2018) determined the social vulnerability in Istanbul. The study considers two aspects of social vulnerability: the capacity to cope with the consequences of a disaster and the characteristics of the person and the society before they encounter the danger. The questions

of the survey were used as indicators about socio-demography, length of stay in Istanbul, socio-economics, health access to services, social solidarity, perception of risk and attitude, and people's values.

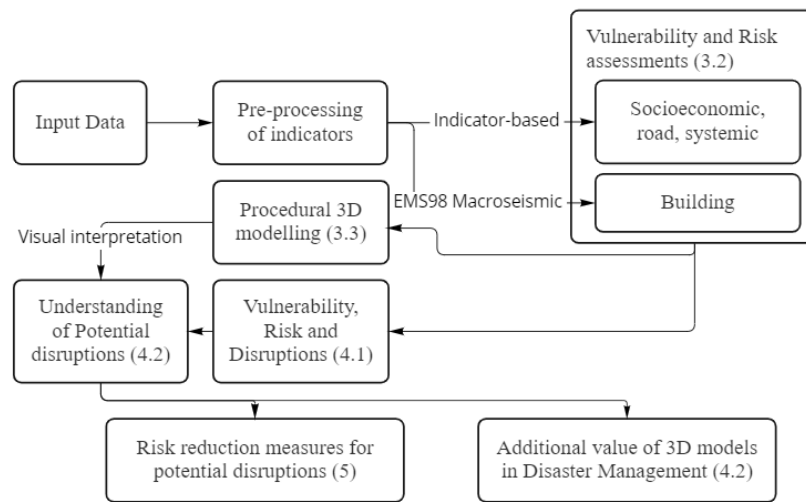


Figure 3. Research design of this study. Source: Author (2022)

Table 1. Overview of the input data. Source: Author (2022)

Data	Type	Date	Source
Building and road footprints with semantic information <i>e.g.</i> building type and road width	.shp	2013	IMM
Administrative boundaries of the case study area and Fatih	.shp	2013	IMM
Gender-based population and education-level per age group	.xlsx	2020	IPA
Average day-time vehicle velocity and traffic intensity	.shp	2021	IMM
Buildings with additional semantic information <i>e.g.</i> construction year and height	.mdb	2018	IPA
Different types of facilities and road network within Faith	.shp	2015	TKGM
Survey data about risk perception and income levels	.xlsx	2018	Ugur <i>et al.</i> (2018)
The peak ground acceleration (cm/s ²), fire distribution and liquefaction potential based on the worst-case scenario	.pdf	2002	(JICA and IMM, 2002)

Based on the results, the most vulnerable and at-risk parts of the case study area are identified. Then, the results based on procedural 3D modelling methods are visualised for further analysis. The different potential disruptions as identified in Section 2 are assessed using the vulnerability, risk and the created 3D models. Lastly, the results are used to suggest measures which reduce the risk for potential disruptions. Throughout the study, information was used that was gathered through interviews with related stakeholders. See Appendix E for an overview of the interviews.

3.2 Vulnerability and risk assessment

The latest definition of disaster risk by the UNISDR's in 2017 is: 'the potential loss of life, injury, destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity' (Schneiderbauer *et al.* 2017, p. 40). As such, according to the Sendai disaster risk definition, risk exists of three components: hazard, vulnerability and exposure. The fourth component, coping capacity, is generally considered to be a part of vulnerability (Schneiderbauer *et al.* 2017). For example, a minor earthquake in a highly populated area has more consequences than a severe earthquake in a less populated area. Consequently, risk can be defined according to Equation 1.

$$Risk = Hazard \times Vulnerability \times Exposure \quad (1)$$

In this study, the multi-hazard risk is determined using the additive normalisation indicator-based approach and the EMS-98 Macroseismic method (LM1) as proposed by the Risk-UE project (Milutinovic and Trendafiloski 2003) and applied by *e.g.* Redweik *et al.* (2017). These approaches represent the vulnerability and hazards of a community or area of interest using indicators. In the case of this study, the types of hazards include: earthquake, liquefaction and fire. The spatially distributed, quantitative values of the different vulnerability and hazard indicators are overlayed and aggregated by addition to get a vulnerability and hazard index. These are multiplied to acquire a risk index.

This study distinguishes between four vulnerability and risk assessments: physical road, physical building, socioeconomic and systemic. These assessments remained separate throughout the study to clearly distinguish between the different types of vulnerability and risk that could cause a certain disruption. The **physical vulnerability** of buildings and roads represents their structural strength (Banica *et al.* 2017). **Socioeconomic vulnerability** represents the ability of people to resist and anticipate the impact of disasters depending on their situation and characteristics (Konukcu *et al.* 2015). This is assumed to represent the behaviour of people. **Systemic vulnerability** represents the accessibility of emergency services to and from the disastrous areas (Banica *et al.* 2017). An overview of the vulnerability indicators that are applied to this case study is presented in Appendix A.

3.2.1 Additive normalisation indicator-based approach

This method is applied to determine the road, socioeconomic and systemic vulnerability and risk. Equation 2 is used to aggregate the indicators and determine the different vulnerability and risk indices.

$$Index = \sum_{i=1}^n w_i I_i \quad (2)$$

Where w_i = weight of the indicator

I_i = value of the indicator

n = the number of indicators

In order to apply Equation 2, the selected indicators are first standardized into a small, specified, unitless range to remove the unit of measurement (Yoon 2012). Appendix B provides an overview on how the indicators are standardized. In this study, each indicator has equal weights, because this is most common according to Yoon (2012). Note that the impact of liquefaction has been included as the ‘proximity to the liquefaction zones’. The liquefaction model of JICA and IMM (2002) shows that only the main roads on the coasts of Fatih are at risk of being affected by liquefaction. This is assumed to cause a change in traffic flow along roads near the liquefaction zones which could impact the accessibility of the case study area.

After aggregation, the vulnerability and hazard indices are multiplied according to Equation 1 to acquire the risk indices. Both the vulnerability and risk values are rescaled using the min-max rescaling technique (Equation 3). After this, the standardized vulnerability and risk indices are categorized according to Table 2.

Table 2. Vulnerability and risk classes.

Source: Author (2022)

Vulnerability and risk indices	Classification
Index ≤ 0.25	Low
Index > 0.25 and Index ≤ 0.5	Medium
Index > 0.5 and Index ≤ 0.75	High
Index > 0.75 and Index ≤ 1	Very high

$$Y_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (3)$$

where Y_i = standardized index

X_i = value of the index

X_{min} = lowest possible index

X_{max} = highest possible index

3.2.2 EMS-98 Macroseismic method

This method defines the building typologies and damage grades with great quality and is therefore used to determine the physical vulnerability and damage of the buildings in the case study area. This method introduces six vulnerability classes (A to F) of decreasing vulnerability (see Appendix C).

The vulnerability classes are initially derived from the different building typologies: masonry, reinforced concrete (RC), wooden and steel. Next to the typology of a building, it is possible that the vulnerability is affected by other structural characteristics which change its

seismic behaviour. Consequently, Equation 4 is applied to determine the overall Vulnerability Index ($\bar{V}_i$) of a building.

$$\bar{V}_i = V_i^* + \Delta V_r + \Delta V_m \quad (4)$$

Where $\bar{V}_i$ = vulnerability index

V_i^* = typology vulnerability index

ΔV_r = regional vulnerability factor

ΔV_m = behaviour modifier factor

Table 3 shows the building typology classification used in this study. Masonry buildings constructed before 1980 are assumed to have wooden slabs, and after 1980 to have RC slabs. Table 4 shows the behaviour modifier factors that were applied considering the available data.

These are summed to acquire the total behaviour modifier factor. According to Gunes (2015), the grouping of buildings with respect to age is generally done by distinguishing between buildings constructed pre-1980, between 1980 and 2000 and post-2000. This is based on the seismic code development throughout the years. Early codes were mostly prescriptive, so seismic codes pre-1980 are considered pre or low code. From 1975 onwards they became more like modern seismic codes, so codes between 1980 and 2000 are moderate codes. In 2001 the Law No 4708 Construction Inspection Law passed which led to better quality control, so codes post-2000 are high code. The regional vulnerability factor, which can be used to alter the vulnerability indices based on expert judgement or historically observed vulnerability, was excluded in this study.

Table 3. Building typology classes.

Source: Author (2022)

Building typology	Designation	V_i^*
Steel	S1	0.363
Reinforced concrete	RC1	0.442
Wood	W	0.447
Masonry with RC slabs	M3.4	0.616
Masonry with wooden slabs	M3.1	0.74

Milutinovic and Trendafiloski (2003) presented Equation 5 as an approach to correlate the calculated vulnerability indices to a damage grade for a certain seismic intensity scenario. The results of this equation are rounded to agree with the Macroseismic damage scale which include five damage grades (see Appendix D). The same approach is used by Redweik *et al.* (2017).

$$\mu_D = 2.5 \left(1 + \tanh \left(\frac{I + 6.25\bar{V}_i - 13.1}{2.3} \right) \right) \quad (5)$$

Where μ_D = damage degree

I = Macroseismic intensity

$\bar{V}_i$ = vulnerability index

Based on their own (local) database from Turkey, Bilal and Askan (2014) presented the following relation (Equation 6) between the Peak Ground Acceleration (PGA) and the EMS-98 intensity scale.

$$I_{EMS-98} = 0.132 + 3.884 \log PGA \quad (6)$$

Where I_{EMS-98} = Macroseismic intensity
PGA = Peak ground acceleration (cm/s²)

Table 4. Behaviour Modifier Factors for RC buildings. Source: Author (2022)

Behaviour Modifier Factor	Option	V _m RC Buildings			V _m Masonry
		Pre or Low code	Moderate code	High code	
Age/code level		+0.16	0	-0.16	
Number of stories	1-2	-0.04	-0.04	-0.04	-0.02
	3-5	0	0	0	+0.02
	>6	+0.08	+0.06	+0.04	+0.06
Vertical Irregularity		+0.04	+0.02	0	+0.02
Aggregate building: position	Detached				0
	Middle				-0.04
	Header				+0.06
Aggregate building: elevation ²	1				-0.04
	2				-0.02
	3				0
	4				+0.02
	5				+0.04

3.2.3 Road Closure Analysis

This study analysed the risk for roads to be blocked by debris from buildings. The same assumptions from the road closure analysis of Cakti *et al.* (2019) is applied to determine this road closure risk: Completely damaged low-rise buildings (1-4 storeys) cause total closure in one-lane roads and partial closure in two-lane roads. Completely damaged mid-rise buildings (5-8 storeys) cause total closure in one- and two-lane roads and partial closure in three-lane roads. Completely damaged high-rise buildings (9-19 storeys) cause total closure in one-, two-

²(1) Adjacent buildings are higher (2) An adjacent buildings is higher and another at the same level (3) Adjacent building have the same level (4) An adjacent buildings is lower and another at the same level or is higher (5) Adjacent buildings are lower (Ademovic *et al.*, 2022; Hadzima-Nyarko *et al.*, 2016).

and three-lane roads and partial closure in four-lane roads. One lane is assumed to be 3m wide. According to Milutinovic and Trendafiloski (2003) buildings with damage grade 4 and 5 are considered completely damaged. In this study, omnidirectional buffers representing the debris are created surrounding the buildings for which the assumption applies. It is possible that adjacent buildings create overlapping debris buffers. When this is the case, an increasing number of overlapping layers is assumed to represent an increasing likelihood that the debris occurs at that location and an increasing amount of the debris making it more time-consuming to remove.

3.3 3D-Model Creation

Procedural 3D modelling method has been selected to be used for this research, because as from literature it has been recommended e.g. Catulo *et al.* (2018) and Redweik *et al.* (2017). According to Ying *et al.* (2020) it has easy modelling operability, can be combined with the commonly available GIS data and potentially generates a clear visual representation of the city and attributes.

Considering the available data, Level of Detail 1 (LoD1) as defined by Kolbe (2009) was used for the 3D models. Consequently, CGA rules are applied to extrude the building footprints based on their height information, to create textured roads, and to apply a green to red colour scheme to both the buildings and the roads representing low to high vulnerability and risk. Colours are considered more appropriate than realism for the visualisation of vulnerability and risk, because the purpose of this study is to show which areas are more at risk and where potential disruptions are more likely to occur. Debris from buildings is visualised in 3D by extruding the debris footprints and applying a white to red colour scheme depending on the number of overlapping footprints, representing the likeliness and size of the debris. Lastly, All of the models are then exported using the CityEngine web scene export function for the purpose of sharing.

4. RESULTS

4.1 Vulnerability, Risk and Disruptions

4.1.1 Socioeconomic Vulnerability and Risk

As determined using the additive normalisation indicator-based approach, the socioeconomic vulnerability is high or very high as presented in Figure 4. As can be seen, the socioeconomic vulnerability is on neighbourhood-scale. Knowing the socio-economic data at this scale is considered sufficient to understand the vulnerability, awareness and reaction of the people. With a very high socioeconomic vulnerability, the neighbourhood Molla Gürani is most

vulnerable of the three neighbourhoods. Its enlarged vulnerability can be attributed to the low risk awareness and risk preparedness in the neighbourhood.

The socioeconomic risk is determined by combining the vulnerability with the hazards in the area *i.e.* the earthquake and cascading fires (see Figure 5). It shows to be medium to high. The combination of a very high socioeconomic vulnerability and a high fire outbreak potential causes a significant area in Molla Gürani to be at high socioeconomic risk. Next to this, the combination of an increased fire outbreak potential and peak ground acceleration (400-500 cm/s^2) causes a significant area in the neighbourhood Topkapi and small parts of the neighbourhood Şehremini to be at high risk as well.

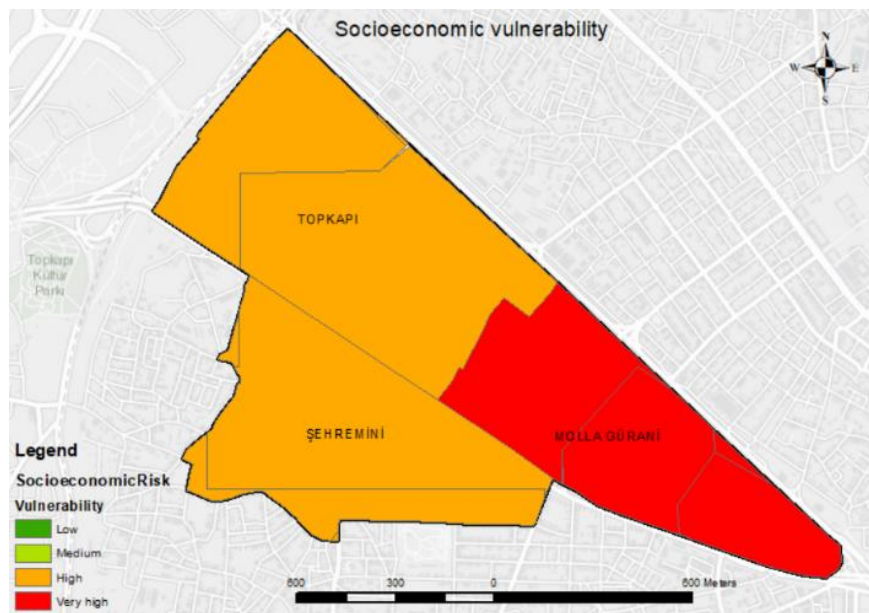


Figure 4. Socioeconomic vulnerability. Source: Author (2022)

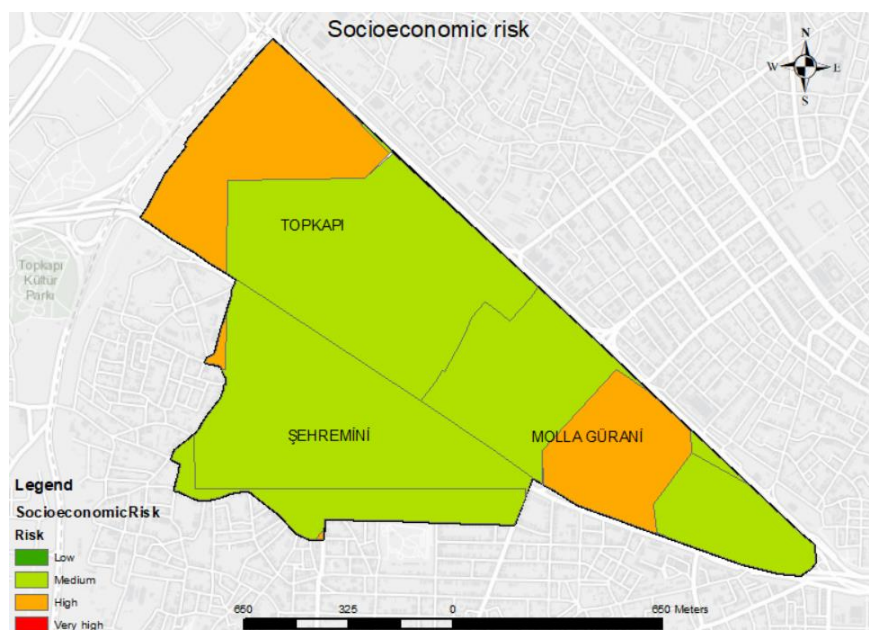


Figure 5. Socioeconomic risk. Source: Author (2022)

As described in Chapter 2, a recurring factor that contributed to the impact of the Tohoku, Kobe and Christchurch earthquakes is the emergent behaviour of people that caused traffic jams and communication issues. It can be said that such unsuitable behaviour during an earthquake event is the result of their socioeconomic vulnerability including their risk awareness, preparedness, education level, *etc.*, because this represents their knowledge on how to act and ability to act properly (*e.g.* elderly can be considered less mobile). Consequently, unfitting behaviour can be expected in the area due to the high socioeconomic vulnerability by such indicators.

According to the IMM, people are likely to move out of the dense area during an earthquake. As stated by to the IPA, they will travel by car and move to the coasts or stay in the neighbourhoods. Consequently, it can be expected that there will be a lot of traffic on the main roads and within the neighbourhoods of the area. Similar to the historical earthquake events of Chapter 2, this is likely to obstruct critical services from reaching the impacted parts of the area. Moreover, as mentioned before the increased socioeconomic vulnerability can be attributed to the low risk awareness and preparedness. These are assumed to be two of the main factors that contribute to unsuitable behaviour of people.

Besides this, it is likely that not only the people who live in the area, but also those in the rest of Istanbul, will use the communication networks to contact for example their families as happened during the historical earthquake events. As a result, it can be expected that the communication services will collapse. This is an issue that is also considered likely by the Disaster and Emergency Management Presidency (AFAD) and Istanbul Technical University (ITU). It will cause difficulties for the emergency services since they will receive less coordination from the disaster related organisations such as the Metropolitan Municipality Disaster Coordination Centre (AKOM), as known from previous disastrous events. This might delay them in or even prevent them from operating properly.

4.1.2 Road Vulnerability and Risk

By applying the additive normalisation indicator-based method to the roads in the case study area, the vulnerability of these physical elements has been determined. Figure 6 presents the road vulnerability. It shows low vulnerability along the main streets of the area (>9m wide). The reason for this is that they are maintained well, paved with asphalt or parquet (which are strong materials), and are significantly wide. The other roads have medium vulnerability. Similar to the main roads, they are made of asphalt or parquet and are maintained well. However, they are more likely to become impassable when they are damaged due to the narrow width of the streets, increasing the vulnerability.

Continuing the indicator-based approach, the road risk was determined (see Figure 7). Most roads shows to have low risk. Roads with a width of less than 4m are and roads with a width of 5 to 12m which are prone to high PGA levels (400-500 cm/s²) are at medium risk. There are

no roads that have (very) high risk to damage meaning that it is unlikely that the roads become impassable due to damage during an earthquake. Therefore, road damage is not expected to disrupt the traffic control. The IPA confirms this, because the infrastructure is considered resilient against earthquakes.

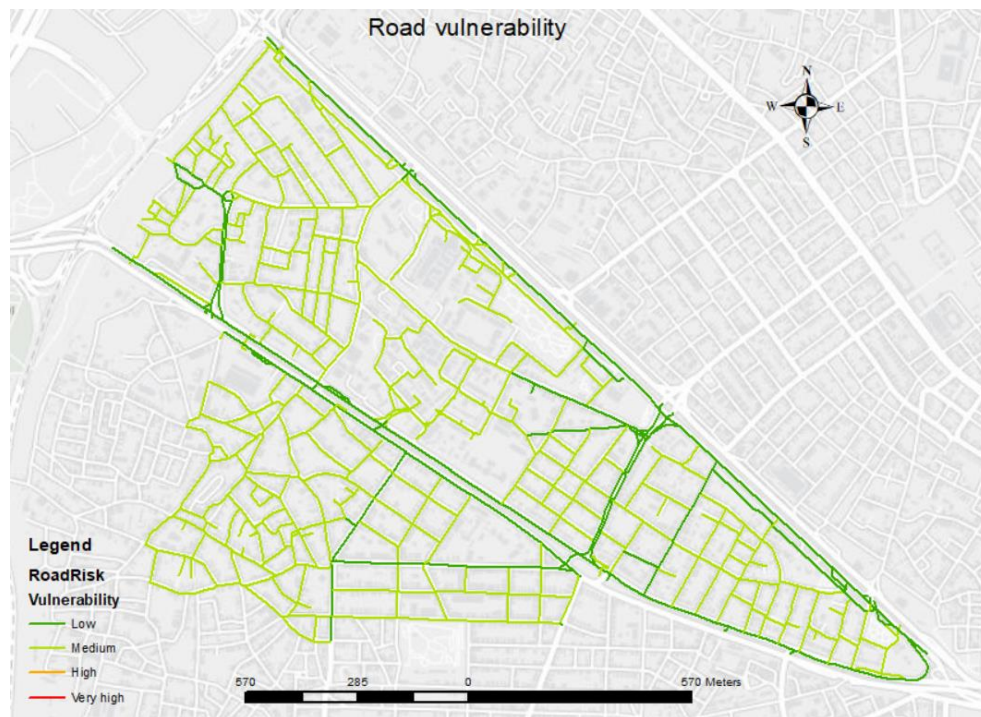


Figure 6. Road vulnerability. Source: Author (2022)

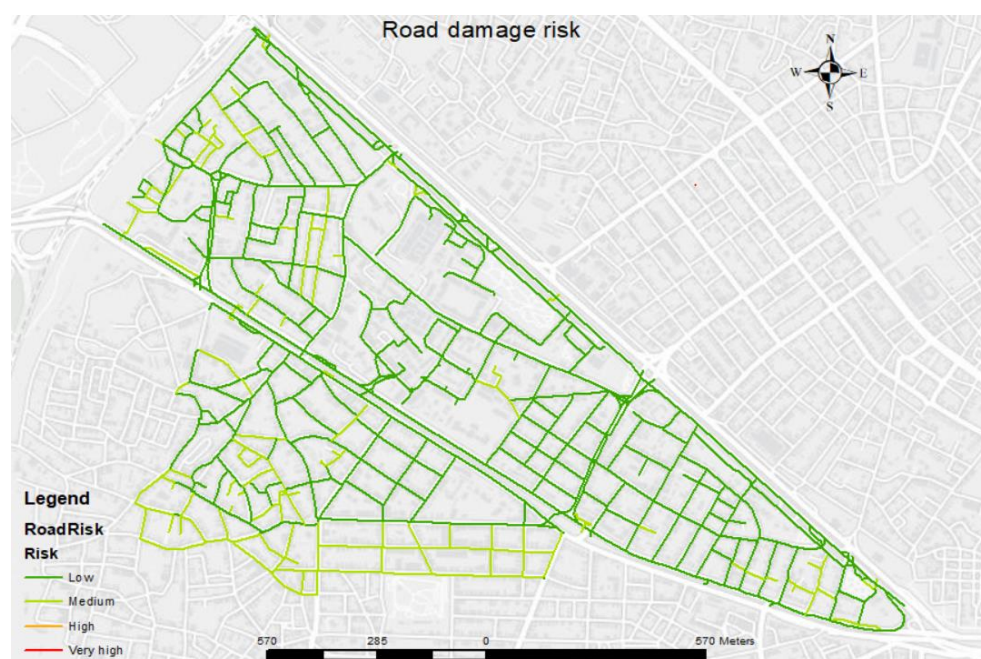


Figure 7. Road risk. Source: Author (2022)

4.1.3 Building Vulnerability and Damage Grades

By applying equation 4 of the EMS-98 Macroseismic method, the building vulnerability is determined (see Figure 8). It shows that 76.5% of the buildings have vulnerability class B or C. This is to be expected considering the fact that the area mostly consists of low-quality dwellings (Atun and Menoni 2014). The largest component of buildings with vulnerability class B are located in Molla Gürani. Most of the buildings with vulnerability class C are located in Topkapi and Sehremini. Buildings that have another vulnerability level are scattered throughout the area. As a result, the buildings in Molla Gürani can be considered most vulnerable.

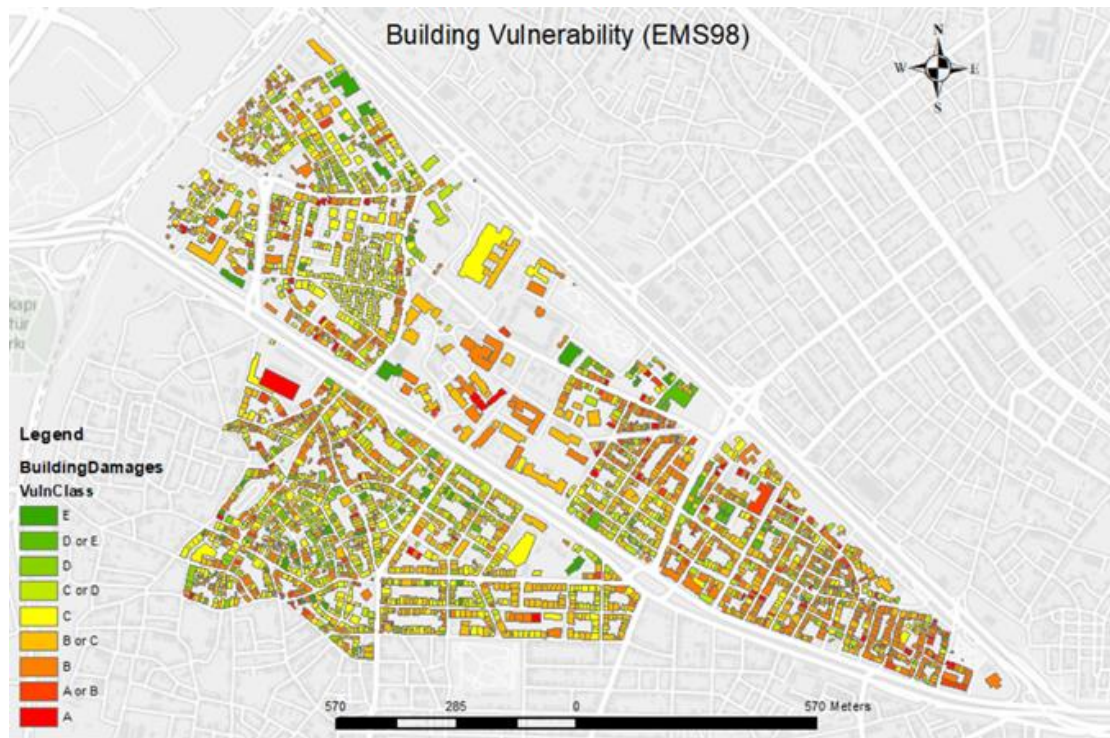


Figure 8. Building vulnerability. Source: Author (2022)

Equation 5 is used to determine the building damage grades based on the building vulnerability. The applied Macroseismic Intensity was X as based on equation 6. As presented in Figure 9 and Table 5 the damage grades show to be 3 (substantial to heavy damage) or 4 (very heavy damage) for 89.2% of the buildings. These are based on an earthquake event of intensity X according to the EMS-98 Macroseismic intensity scale as determined using equation 6. The statistics show that masonry buildings are most prone to receiving damage with 87.1% of them having damage grade 4 and 66% of all buildings with damage grade 4 being masonry. RC buildings mostly receive damage grade 3 (57.3%). The RC buildings that

received damage grade 4 are all buildings constructed before 1980 according to low design standards. Buildings with other typologies received damage grade 2.

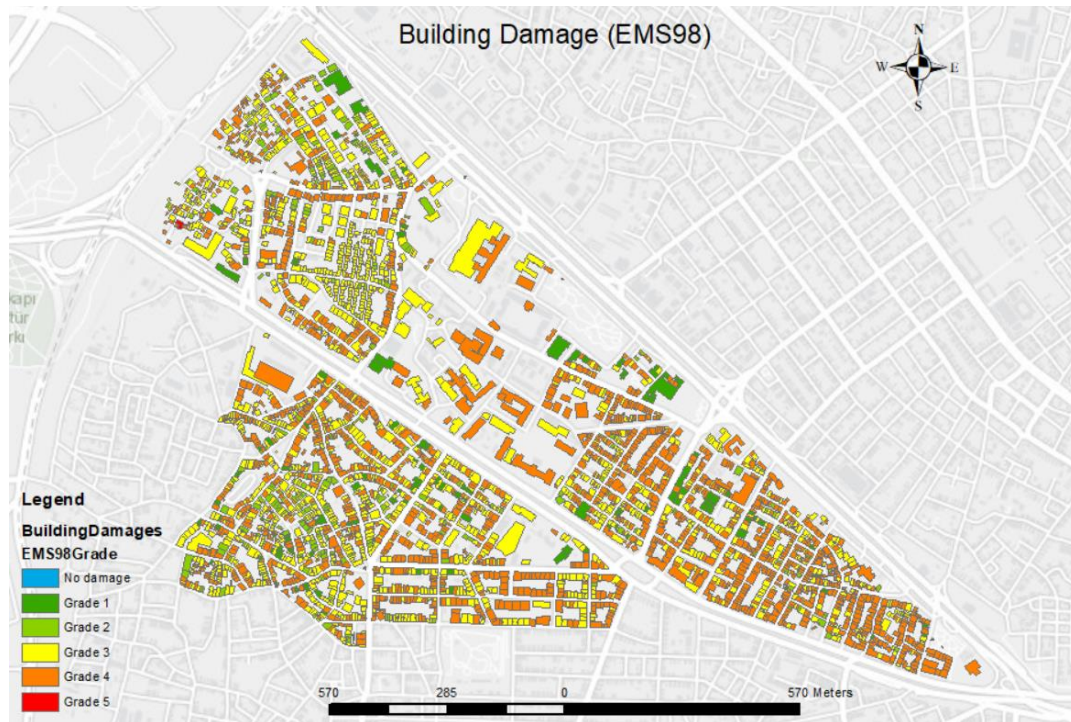


Figure 9. Building damage grades. Source: Author (2022)

Almost half (43.8%) of the buildings with damage grade 4 are located in Molla Gürani, 36.7% is located in Sehremini and only 19.4% in Topkapi. Buildings with damage grade 3 are for 21.8% located in Molla Gürani, for 44.5% in Sehremini and for 33.6% in Topkapi. Within Molla Gürani most buildings receive damage grade 4 (65.4%), in Sehremini damage grade 3 and 4 are almost equally present, and in Topkapi most buildings receive damage grade 3 (52.0%). Based on this, it can be said that the buildings in Molla Gürani are most at risk to receiving building damage.

As mentioned in Section 2, the traffic control during the Tohoku, Kobe and Christchurch earthquakes was greatly disrupted by road blockages caused by debris from buildings. Based on the determined building damages, the road closure analysis of Section 0 was done. The results as presented in

Table 6 show that 43.2% of the roads are at (very) high closure risk. These mainly include relatively narrow roads (<8m wide). The statistics show that the largest component of roads of 0 to 4m wide are at very high risk to being closed. Similarly, the largest component of roads of 5 to 8m wide are at low or very high risk to being closed. Wider roads are increasingly less likely to be blocked, because the largest components of them are at low risk.

Table 5. Building damage statistics. Source: Author (2022)

Damage grade	0	1	2	3	4	5
<i>Number of buildings per Building typology</i>						
Reinforced concrete	0	131	251	1334	613	0
Masonry	0	0	0	176	1192	1
Wood	0	0	12	1	0	0
Steel	0	0	6	0	0	0
All	0	131	269	1511	1805	1
<i>Number of buildings per Neighbourhood</i>						
Sehremeni	0	64	132	673	663	0
Topkapi	0	19	97	508	351	1
Molla Gürani	0	48	40	330	791	0

Table 6. Road closure risk statistics. Source: Author (2022)

Width(m) Risk	0-4	5-8	9-12	13-16	>16	All
Low	26	152	31	30	97	327
Medium	19	47	9	6	3	84
High	21	70	12	2	0	101
Very high	41	150	6	1	0	211

As presented in Figure 10, mainly the narrow roads (<8m wide), especially in Molla Gürani and Sehremeni, are prone to road closure. The wider roads show to remain accessible during the earthquake. As such, areas within the neighbourhoods are prone to isolation which could prevent the emergency services from providing emergency aid. According to the AFAD, ITU and fire brigade this is as expected. They believe that road blockages by debris are very likely, because there are a lot of tall, densely constructed buildings near narrow roads.

4.1.4 Systemic Vulnerability and Risk

The systemic vulnerability was determined by applying the additive normalisation indicator-based approach (see Figure 11). The statistics show a medium systemic vulnerability for approximately half (49.2%) of the roads, while the others have low systemic vulnerability. Medium vulnerability can be found for the inner roads of Molla Gürani and Sehremeni, and for some parts of the main roads. This can be attributed to the combination of a relatively long travel time to the fire brigades, and a high solid to void ratio or traffic intensity. Due to these factors, the accessibility to an area is reduced which could cause the emergency services, especially the fire brigade, to take a relatively longer time to reach the impacted areas. The

large amount of traffic and parked cars in the dense area is a problem which the fire brigade already faces in their daily activities according to their spokesperson.

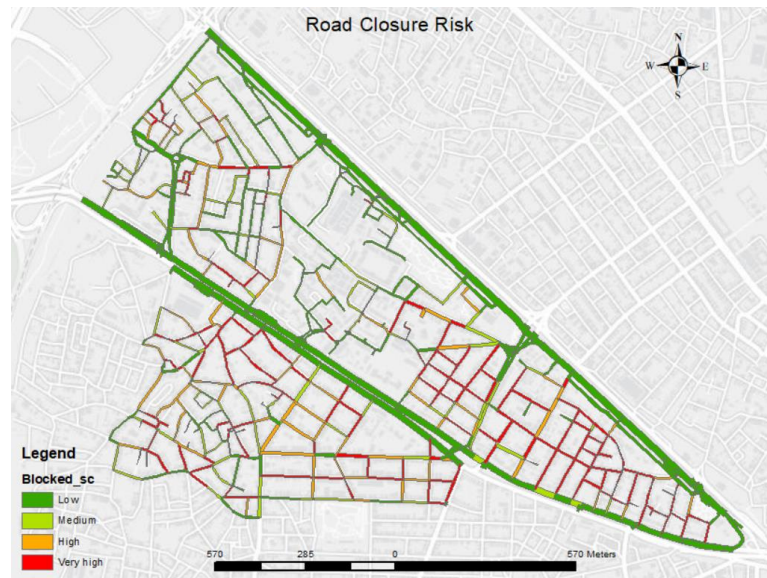


Figure 10. Road closure risk. Source: Author (2022)

Figure 12 presents the systemic risk showing that the roads in the area mainly have low systemic risk with just 13.8% of the roads having medium risk. The enlarged risk can be attributed to a medium systemic vulnerability in combination with an increased distance to the liquefaction zones and road closure risk. Consequently, the systemic risk is highest in the south and southwest of the neighbourhood Sehremeni and around the road that connects the two main roads of the area, located in Molla Gürani. These parts are expected to be more difficult and time-consuming to reach for emergency services after an earthquake due to the potential traffic and road blockages. So, the major roads and adjacent critical facilities (*e.g.* the hospital) will remain functional like normal and will not affect the functioning of the large scale transportation. Only some narrower roads could be more difficult to access. So, the main challenge is accessing the people under debris during the first 48 hours after an earthquake.

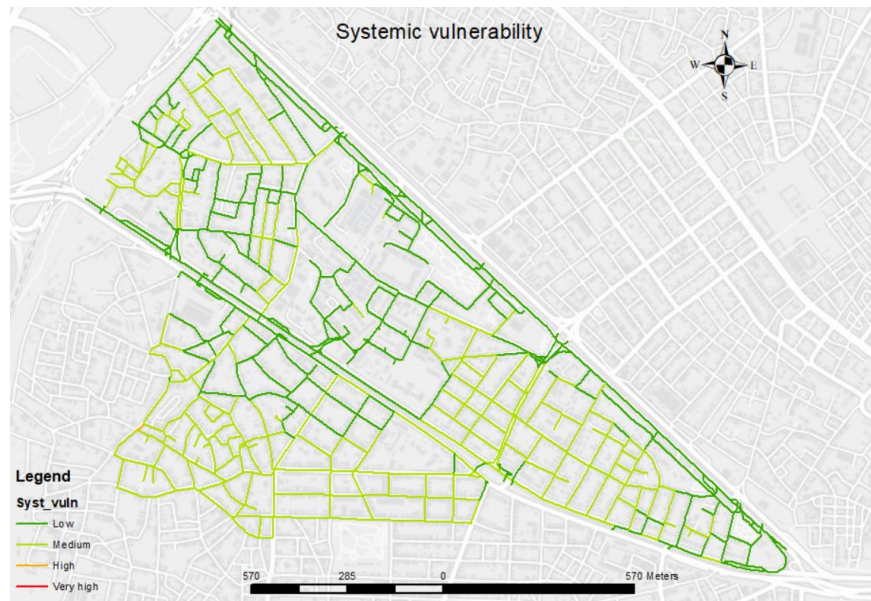


Figure 11. Systemic vulnerability. Source: Author (2022)

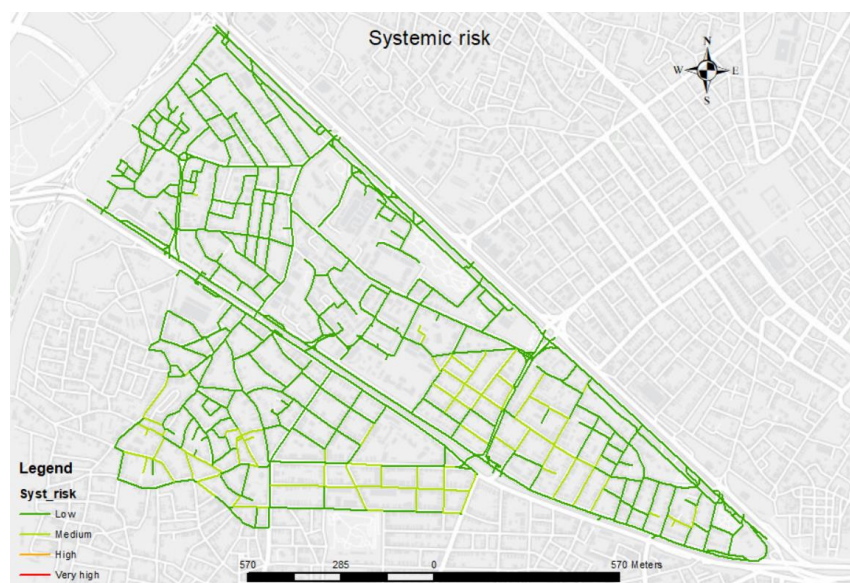


Figure 12. Systemic risk. Source: Author (2022)

4.2 3D-Model Visualisation

By applying the method as described in Section 0, the 3D model is created. Figure 13 visualises the entire case study area in 3D with the building damage and the risk to road damage. By visual interpretation, it becomes apparent that there are narrow roads which are surrounded by relatively high, densely built buildings which are expected to receive damage grade 3 or 4. Besides this, the height information improves the identification of the different buildings, because they are recognized easier in comparison to the 2D map as presented in Figure 9.

Especially when zoomed-in, this becomes apparent. Figure 14 visualises the zoomed-in 3D environment presenting the building damage grades and road closure risk. The focus area is an example clarifying that the narrow roads with (very) high road closure risk are usually surrounded by high buildings with very heavy damage. In contrast, the major road does not have this risk, as it will not be blocked by debris entirely due to its large width. As such, the created 3D model helps in understanding where building height contributes to the occurrence of road closure. Also, it is more convincing for communication with experts, because the potential disruptions, such as traffic jams, become more realistic as the density of the area is more apparent. As discussed with the experts (from AKOM, AFAD, *etc.*) during the fieldwork visit, a clear visualisation, with realistically represented influence of the third dimension contributes to the understanding on where there can be road closure and where urgent support will be needed. Further exploration of the 3D models can be done in the web scene which can be accessed via the link in the caption of the figure.



Figure 13. 3D model of the entire area. Source: Author (2022)

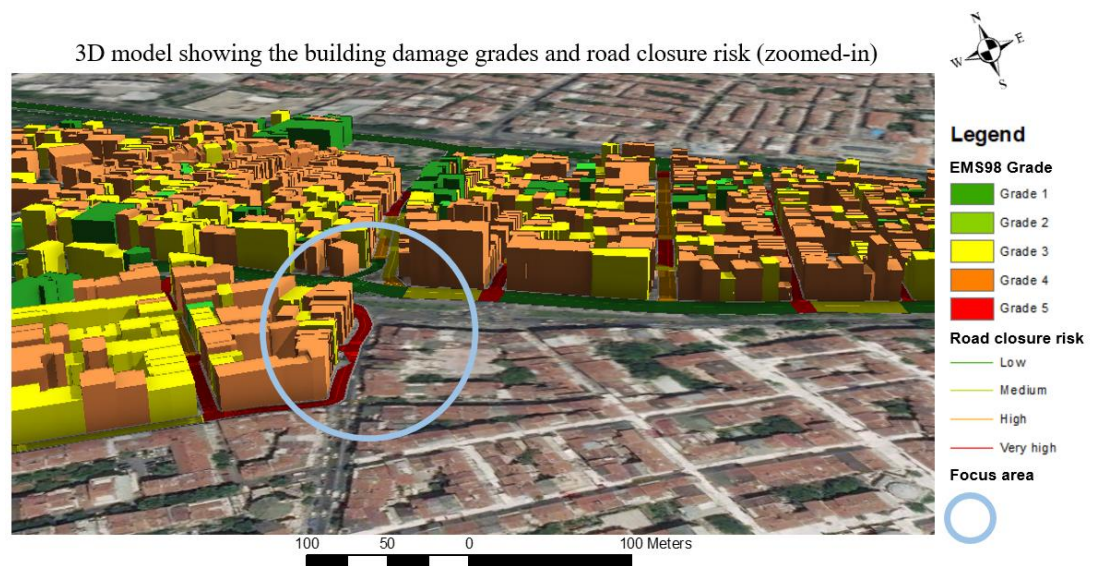


Figure 14. 3D model zoomed-in. Web scene: <https://bit.ly/3KJiv7c> . Source: Author (2022)

5. SUGGESTED INTERVENTIONS

5.1 Structural interventions

First of all, it is suggested to apply seismic retrofitting to structurally weak buildings. This aids in protecting the lives and assets of the building occupants and the continuity of business practices (FEMA 2022). In addition, it decreases the risk of debris from buildings. This reduces the road closure risk causing the case study area to remain more accessible for emergency services.

However, not all weak buildings can be reinforced, because they can be cultural heritage buildings or host low-income newcomers who do not have enough money for the reinforcements as mentioned by the spokespersons of the AFAD, IPA and Fatih municipality. Based on these two reasons, this study suggests to retrofit the limited number of buildings which are located in building blocks without any listed buildings as shown in Figure 15. Their prioritization is based on the location of buildings with damage grade 4, road closure risk and systemic risk.

Secondly, it is suggested to assign locations within the case study area that can host the gathering of volunteers. According to National Research Council (1991), major disasters have shown that spontaneous volunteers are invaluable during the emergency response, because during the first hours after a disaster, they make the majority of the rescues are often active in clean-up activities. However, the availability of essential resources can be an issue. The gathering facilities will make it easier to coordinate rescue and clean-up activities and can store resources that are helpful in for example removing debris from the roads and reaching and aiding the people in need. The suggested locations in Figure 16 will remain accessible and include damage-resistant buildings and open spaces.

Besides this, critical locations for fire hydrants are suggested to aid the fire brigade in fighting the potential fires that might occur. This is considered important, because, according to Section 4.1.3, it is likely that several areas will become difficult to reach. The suggested locations in Figure 16 have shown to become isolated due to road blockages and host a significant number of heavily damaged buildings are located which are assumed to be a source of ignition.

5.2 Non-structural interventions

The first non-structural intervention is to raise awareness and educate the people in the area, especially in Molla Gürani, on the risk that exists for them to earthquakes and on how they can prepare for it. This should reduce the high socioeconomic vulnerability as described in Section 0, mitigating emergent behaviour. Educating people is an important task mentioned by the spokesperson of AFAD.

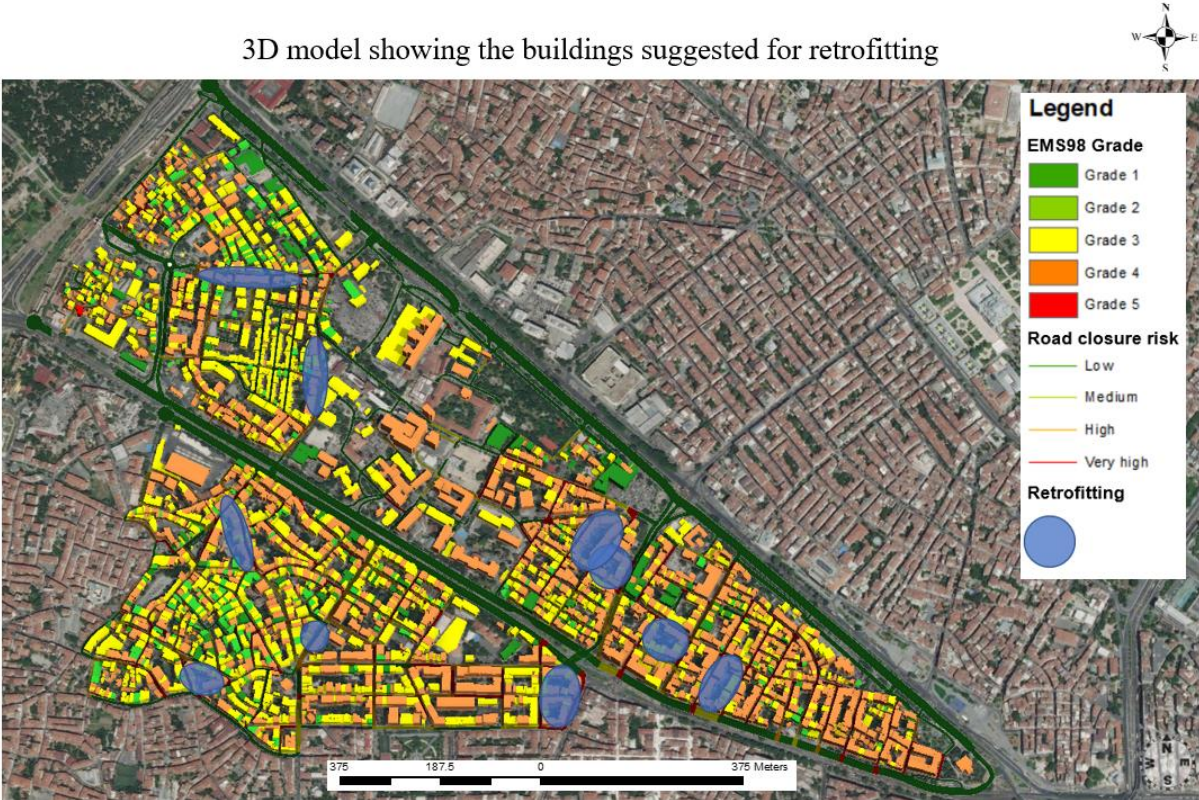


Figure 15. 3D models showing the buildings suggested for retrofitting. Source: Author (2022)

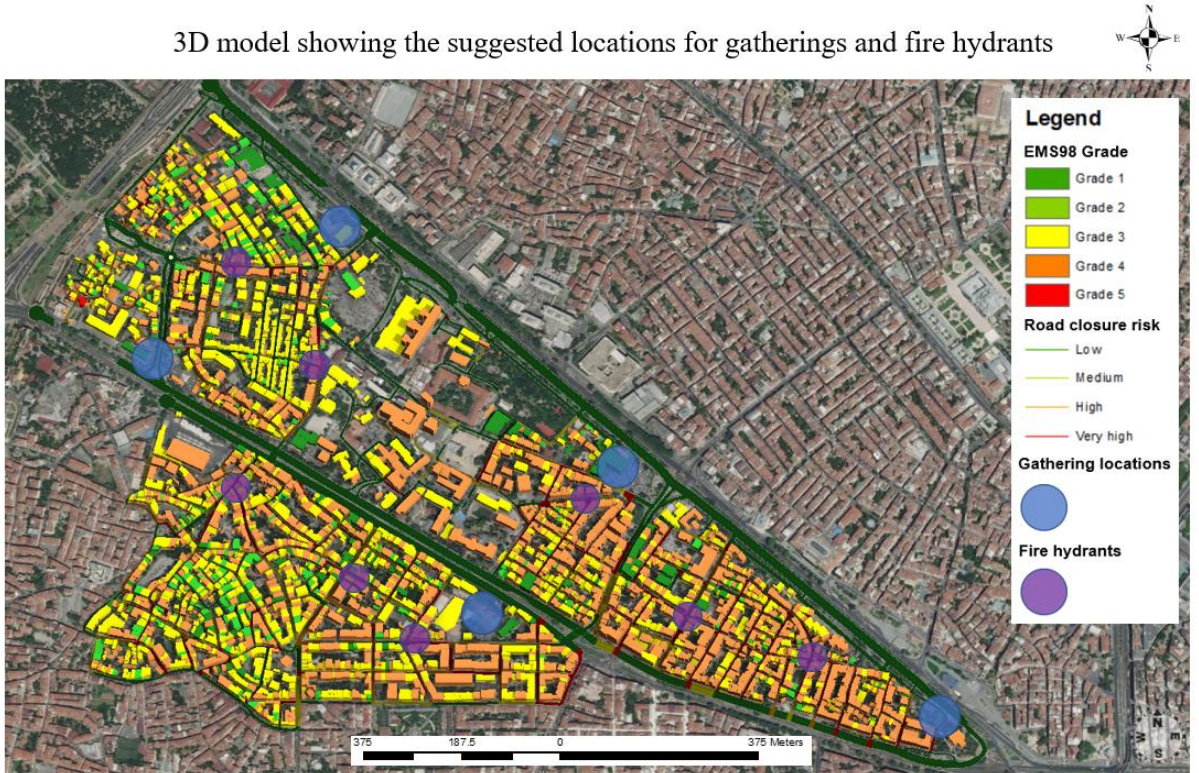


Figure 16. 3D models showing the suggested locations for gathering facilities and fire hydrants. Source: Author (2022)

It can be done through several activities such as through booklets and the media, active involvement with recurring, participatory education sessions, and earthquake safety exhibitions (National Research Council 1991). These education activities should cover topics from the mitigation, preparedness, response and recovery phases of disasters such as disaster legislation, risk preparedness, appropriate behaviour, and essential skills (*e.g.* stabilizing furniture, first aid, search and rescue, healthy living during temporary relocation, *etc.*). These suggestions are based on those suggested by Bogazici University *et al.* (2003) and Jimée *et al.* (2012).

In order to increase the risk preparedness of the community, incentives by for example the government can be implemented which allows people to implement risk reduction measures within their own buildings (*e.g.* emergency resources, stabilizing furniture and structural measures). The focus group for such incentives are people who do not have enough money nor the luxury of spending their money on such measures due to other problems such as illnesses or their economic conditions which they have to prioritize. It is expected that such households are mostly located in Molla Gürani which has the highest socioeconomic vulnerability.

As suggested by the IMM, promoting the use of micro-mobility could be one of the measures that will reduce the traffic intensity within the case study area, which reduces the traffic congestions and increases the accessibility of the area. According to Møller *et al.* (2020), e-scooters improve the access to public transport and reduce taxi and car trips in cities. Surveys done by the micro-mobility organisation Voi show that 63% of their users combine e-scooters with public transport, 12% of the e-scooter trips are replacing cars, taxis and ride hailing services, it is increasingly being used for commuting purposes instead of leisure and the latest innovation, swappable battery scooters, has shown to reduce emissions by 51%. Besides this, they can be used by 8 to 10 people per day and 10 to 15 e-scooters can be placed in one car parking spot, while cars can transport 1.3 people and are parked for 95% of the time. Contributing to this, Incentivized Parking Zones as used by Voi can be implemented which encourage people to park in the designated area with ride discounts. Consequently, this would decrease pollution, noise and congestions, while using the already scarce urban space in the case study area more efficiently. Eventually, introducing micro-mobility helps in cities reaching their climate goals, reclaims space and improves the quality of life. Implementation of e-scooters requires cities and policy makers to invest in effective policies, micro-mobility infrastructure (*i.e.* parking spots and safe infrastructure), innovation and responsible business practices. Policies can include requirements, such as safety, sustainability, operations, data-sharing, national traffic and product requirements, the allocation of parking spaces and limits for the number of micro-mobility service providers.

6. DISCUSSION

To analyse the disruptions of the historical earthquake events and compare them with our results, additional literature review was conducted. We looked at the Izmit earthquake in 1999, which hit an industrial and populated area in Turkey as described by JICA and IMM (2002), and the Haiti earthquake in 2010, which affected the capital Port-au-Prince causing great damage as described by Pallardy (2022). Studies reveal that in complex cities the most common disruptions occur because of the impact of road blockages, traffic congestions and lack of resources on traffic control. However, additional disruptions were identified as well, including failure of telecommunication cables and power systems, untrained personnel and loss of critical facilities such as the hospitals. Having additional insights on disruptions and their corresponding impact on traffic control can provide additional directions for the analysis on potential disruptions in the case study area.

In our study, we applied a limited number of indicators to determine the vulnerability and risk. In literature, a wider variety of indicators can be found for such assessments, *e.g.* the building maintenance and plan irregularity, soil type and road embankments. The use of a limited number of indicators could have affected the results of this study. However, the results on the socioeconomic vulnerability show to be in line with Ugur *et al.* (2018). The study categorizes Faith as a mid-upper vulnerable county and shows that Molla Gürani is most vulnerable of the three considered neighbourhoods. The building damage grades as determined by JICA and IMM (2002) under the same earthquake scenario show to be different from the results as presented in this study. Their number of buildings with damage grade 4 or 5 are significantly lower and Topkapi is shown to be most prone to earthquake damage. This is likely the result of applying different methods to determine the building damage grades. However, according to Milutinovic and Trendafiloski (2003), an earthquake that causes an intensity of X as is the case for this study, should results in many (approximately 15% to 55%) buildings of vulnerability class B to have damage grade 5, many (approximately 15% to 55%) buildings of vulnerability class C to have damage grade 4 and a few (less than approximately 15%) of grade 5. This is similar to what is found in this study, meaning the results are realistic. Lastly, in both JICA and IMM (2002) and Cakti *et al.* (2019), the neighbourhoods Molla Gürani and Sehremini show to be more prone to road closure than Topkapi. JICA and IMM (2002) show very high road closure for narrow roads (0-7m) and a medium to high road closure risk in somewhat wider roads (7-15m). Similarly, Cakti *et al.* (2019) show that roads with one- or two lanes (up to 6m wide) have a large number of points where partial or total road closure is possible. Larger roads (that are over 16m wide) are not a high risk to being blocked. This is in line with the results of this study.

Lastly, Redweik *et al.* (2017) suggests to use LoD2 instead of LoD1 for the 3D models which could for example increase the interpretation of the area. Consequently, the results might become more convincing and useful for the communication of disaster risk. Besides this, Redweik *et al.* (2017) states that colour only indicates the relative severity of the damage, but

does not show what might happen to the buildings. Consequently, by applying a colour scheme for the visualisation of for example the damage grades of the buildings instead of more realistic textures could have reduced the communication of the actual expected damage to buildings. However, since the purpose of this study is to show which areas are more at risk and where potential disruptions are more likely to occur, visualising the vulnerability and risk using colours is considered more appropriate.

7. CONCLUSION

This study analysed the potential disruptions that impact traffic control with the help of multi-hazard risk assessment (*i.e.* earthquakes, fires, and liquefaction). Moreover, it introduces the use of 3D models for the visualisation of disaster risk. The results show that the roads are not prone to damage. In contrast, buildings are prone to damage. Therefore, road blockage shall occur due to vulnerability of buildings but not roads. Almost all buildings (89.2%) were determined to receive substantial to heavy or very heavy damage. Significant building damage is especially expected in Molla Gürani. Such buildings can create debris that will likely cause road damage and blockages. It was determined that 43.2% of the roads are expected to be blocked by debris. These mainly include narrow roads (<8m wide) that are surrounded by a large number of very heavily damaged buildings located in Molla Gürani and Sehremini. The socioeconomic vulnerability is also shown to be high, especially in Molla Gürani. As a consequence, it is expected that in their panic human may start chaotic evacuation and overloading the communication networks will cause traffic congestions. As a result, the communication and adequate reaction of the disaster management services may become problematic. All this contributes to the increased systemic risk in the south and southwest of Sehremini and around the road that connects the two main roads of the area, in Molla Gürani.

By visual interpretation of the created 3D model, this study found that the additional value of including 3D modelling in disaster risk reduction is that it makes it easier to recognize the morphology of an area. Besides this, it supports the understanding and communication of the underlying causes of potential disruptions, road blockages in the case of this study. This could help decision-makers in suggesting more local measures that mitigate the potential for disruptions and help disaster coordinating organisation in preparing more dynamic action plans.

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