

Environmental risk assessment of urban underground public space development in Tehran using EFMEA and TOPSIS techniques

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Original Research

Abstract:

Received:
14 April 2024

Revised:
2 June 2024

Accepted:
3 June 2024

Published online:
25 June 2024

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The purpose of this study was the environmental pollution risk assessment of urban underground public space development in Tehran (Iran). This applied research was conducted by survey and mixed methods in two phases: estimating risk potentials using Environmental Failure Mode and Effect Analysis (EFMEA), and Delphi Technique. The results identified 12 different environmental risks for the underground public space development. Among these, three risks showed high level, including sewage discharge (Risk Priority Number (RPN)=504), inappropriate ventilation (RPN=567) and seismic hazard (RPN=640). Moreover, five cases were classified as medium level risks, including Construction waste accumulation of (RPN = 294), Land subsidence (RPN = 250), Municipal waste accumulation (RPN = 441), Non-renewable energy consumption (RPN = 256) and Thermal pollution (RPN = 210). In addition, three items were among high-level risks, including Sewage discharge (RPN = 504), Inappropriate ventilation (RPN = 567) and Seismic hazard (RPN = 640). The development of urban underground public space in Tehran can be a solution to improve the level of services and urban per capita, which is a great help in the urban management of a metropolis like Tehran. Meanwhile, it is important to pay attention to the environmental, health and safety policies.

Keywords: environmental risk; underground development; public space; EFMEA; Tehran

1. Introduction

Urban areas, as the origin of human civilization, have always been the focus of theorists of various sciences. A city is defined by a higher concentration of individuals, human activities and buildings (Alinia and Khatib, 2021). Urban space accommodates infrastructure facilities and equipment with a variety of uses, including residential, office, and hygiene. In the urban fabrics, public spaces are considered to be the basic priorities for citizens, social relations and mental health of the community. Urban spaces are part of the

open and public spaces of cities that are somehow the nature of collective life, where citizens are present (Deakin, 2013). These spaces are a tool for the communication, a place for the creation of opportunities for direct confrontation of citizens, and a site for the management and coordination of citizens (Ehsani and Bahmanpour, 2018). Such spaces, if properly designed and managed, can play a decisive role in promoting individual well-being and creating positive social values (Lawlor and Nicholls, 2008). According to the United Nations, more than half of the world's population lives in cities (Paul and Sen, 2018). The rise of the urban

population increases the demand for taking advantage of urban opportunities, municipal services and related per capita are among the concerns of municipal managers (Menezes et al., 2019). The complex urban space compels thinking people to create and reform new urban structures to get rid of problems and inadequacies in reaching the sublime limit of life (Broere, 2016). Public spaces are known as one of the important and essential categories in urban design and management, in such a way that the concept of spatial quality is a subset of the category of urban space quality. Nowadays, public spaces are struggling with the challenges of urban life (Mueller et al., 2018). The lack of urban public spaces can be the cause of mental and physical harm and social problems.

One of the new approaches in this field is the use of the spatial dimension (vertical development instead of horizontal development) to provide services per capita in urban areas. This means that vertical development at height or underground is used instead of horizontal development that causes the occupation of land and excessive expansion of cities. Obvious examples are the construction of large complexes and skyscrapers, as well as the development of subway lines. In the meantime, there are many risks and limiting parameters, including natural disasters such as earthquakes, land subsidence, fires and floods, which make it difficult to provide assistance to such uses. Therefore, the spatial distribution of uses is one of the most important functions in order to optimally exploit residential spaces (Asadi et al., 2019). The balance between service providers and service users is one of the important features and elements (Hosseini et al., 2023). Public services should be easily accessible to people regardless of location, limitations and financial resources or people's physical ability (Kaphle, 2006). Accessibility is actually the power of users to have a good access to activities, resources, services and the like (Dixon, 2006).

On this basis and considering that the underground development of public spaces in Tehran (the capital of Iran) has been proposed as a requirement for a long time, this effort was made with the aim of evaluating the environmental pollution risk of urban underground public space development in Tehran. In fact, the main question of the research is that what type and severity of environmental pollution risks caused by the underground development of Tehran should be evaluated and resolved to increase public services per capita. In this research, all aspects of environmental risk have not been investigated and only focused on those related to environmental pollution.

1.1 Theoretical foundations

Public spaces can be defined in different ways. From a social point of view, public space is an atmosphere for creating relationships between people, performing social activities and creating links between different layers of society. From a psychological point of view, public space is an environment for improving the quality of life, which plays an important role in public mental health and social vitality. In architectural concepts, public space is an open and accessible place for all citizens, which is opposite to private space, that is, a place where access is limited and

controlled (Li et al., 2021). In other words, public spaces refer to all parts of natural and man-made environments, where the public has free access to them (Sulis et al., 2018). Francis Tibbalds considers the communication and interaction of people with each other as one of the most vital characteristics of urban public spaces. John Long believes that the way of collective decision-making in a city depends on the public spaces of that city. Nancy Fraser considers public spaces to serve the common good of citizens (Shieh et al., 2020).

Such views remove the use of public spaces from being a place just for fun and spending time and can increase social solidarity and strengthen the integration of society, which in turn helps to create social capital in the society, reduce social pressures and improve the quality of urban life (Dincer et al., 2016). Today, various approaches have been proposed to overcome the problems of urbanization. One of the latest proposals is to use underground development capabilities in cities and especially in megacities (Qihu, 2016). Urban underground spaces are developed with the aim of providing the infrastructure needed in the areas of transportation, facilities and lifeline networks, solving urban problems, creating safe spaces and multipurpose shelters, especially in public places, including the approaches of underground urban development (Gurer et al., 2017). In general, a successful urban underground space must meet the expectations of its users in different dimensions in order to overcome obstacles and shortages. Otherwise, as an abandoned space, it will completely lose its identity over time. These diverse dimensions can be considered in social, psychological, cultural, physical, functional, traffic and access, environmental, technical and executive, economic and legal groups, each of which creates expectations for users (Naser Nasir and Parvaresh, 2021).

The use of underground spaces in most parts of the world has a long history. Many native architects used underground architecture due to climatic conditions and defense of cities and villages and to meet the needs. (Ravanshad et al., 2023). Underground urbanism can play an important role in promoting urban sustainability and resilience. Underground spaces can help create a dense city and prevent excessive urban land use (Chen and Wang, 2015). Underground urbanism has many capabilities in solving urban problems. Solving traffic problems, including vehicular traffic congestion, reducing air and noise pollution, protecting against natural disasters, solving urban space constraints, and protecting cultural and environmental heritage are among the positive capabilities of underground urban development. Underground urbanism is a way of thinking that tries to solve urban issues and problems and create a livable and safe city using underground spaces (Hunt et al., 2016).

It can be said that these spaces, as a major part of the urban spatial structure, play a key role in improving the efficiency of urban land use and reducing traffic congestion in the central areas of the city. The development of these spaces will help to improve the urban environment. Following the acceleration of urbanization, the extent and depth of the use of underground space has reached an unprecedented level, and many problems arise in the underground space

development, including lack of planning, irrational design and indiscriminate use. The urban underground spaces are a valuable non-renewable resource and many of the cavities created in the underground have irreversible consequences (Margherita et al., 2018).

Therefore, the underground space should be developed with careful planning and basic considerations. Ensuring the sustainable exploitation of underground space requires the investigation of factors affecting development potential of underground urban space. Tong (2016) proposed economic growth as the main factor of underground space development. Chen and Wang (2015) confirmed the positive relationship between the use of urban underground space and the annual per capita income of citizens. Wang et al. (2023) reported five key factors affecting the development potential of urban underground space in parts of the city of Nanjing, China, including development benefits of underground space, land price and location condition, compatibility with urban planning, economic development level and geological features. The results showed that the higher the average price of the areas, there was a positive and significant relationship with the development potential of urban underground space.

Therefore, areas with higher land prices and favorable location conditions had priority for development. Bobylev (2016) investigated the infrastructural problems of urban underground space in Moscow.

One of the significant parameters in this field is to pay attention to the environmental aspects. Today, access to and protection of a healthy environment is one of the most important human concerns. Appropriate and effective solutions to preserve the environment, taking into account the limited available resources, have become a big challenge for the international community.

1.2 Study area

In this study, the city of Tehran was selected and investigated as a pilot. Since 1956, this city has experienced an increase in population up to 5 times and an increase in area up to 7.5 times. According to the 2016 census, the popula-

tion of this city was 8,693,706 people and its area was 730 square kilometers. The United Nations declared that Tehran was the 40th most populous city in the world in 2014 and predicted that the population of this city will increase to about 10 million people in 2030 (Darabi et al., 2019).

The significant increase in the population and its imbalance with the city's infrastructure has faced managers and planners with many problems. It is expected that the population of Tehran will continue to grow at the same time as the country's population increases. In this case, the question arises whether planners and managers can devise the necessary infrastructure for a population larger than the current population of Tehran and respond to the needs of this massive population (Bahadori et al., 2022). Figure 1 shows the location of case study and the trend of its spatial changes over time.

As a result of this rapid growth, it can be imagined that the city of Tehran has faced a shortage of urban service spaces and especially public spaces. On the one hand, the occupation of urban land and the construction of residential houses, and on the other hand, the restrictions around the city cause a lack of land that can be converted into public spaces. Therefore, the construction or development of urban public spaces in Tehran is currently accompanied by huge costs (Jalilzadeh et al., 2021).

A look at the ancient history of Tehran shows that this city was originally a village near the city of Ray, which had underground settlements for the people of that region. According to the historians' descriptions of Tehran, the construction of underground settlements is justified for two reasons: the extreme heat of the region in summer and defense against foreign enemies. Underground spaces in old Tehran were mostly used as aqueducts or cisterns, and many of these spaces have been repurposed over time to be reused. One of the limiting factors of underground space development in Tehran is seismic potential. A total of 410 kilometers of seismic faults have been detected inside and outside the boundaries of this city, of which 249 kilometers are inside the boundaries of this city. In total, 80 square kilometers of the seismic faults of Tehran are inside and out-

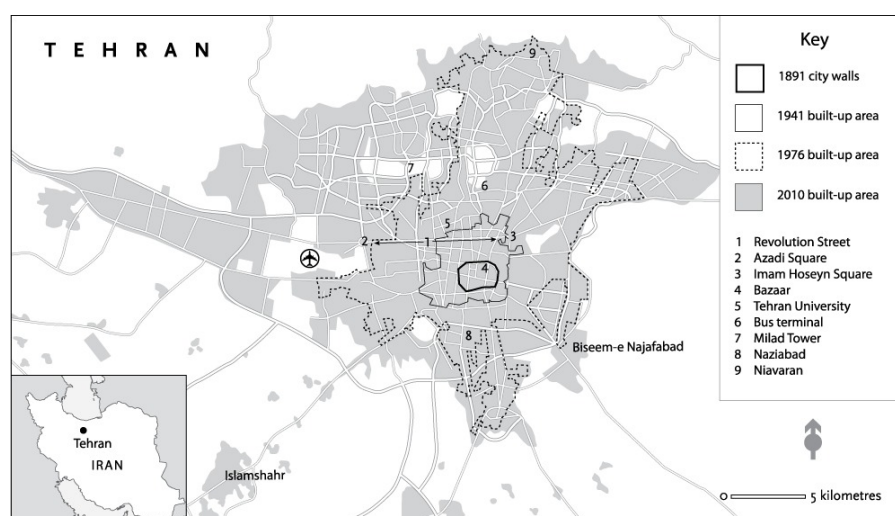


Figure 1. Location of Tehran and tend of its spatial changes in the period from 1891 to 2020.

side the boundaries, of which 47 kilometers are inside the boundaries of this city. In this connection and in line with the implementation of the mentioned method, it should be said that the city of Tehran is located in a very high seismic risk zone, based on the seismic hazard zoning map of the country. According to the studies conducted by Iranian consultants, Japan International Cooperation Agency (JICA) and the Center for earthquake and environmental studies of Tehran (Cest), an earthquake in Tehran can damage about 480,000 buildings and cause direct damage of around 220 billion dollars to the city (Ehsani and Bahmanpour, 2018).

2. Materials and methods

This applied research was conducted by survey and mixed methods in three phases: estimating risk potentials using Environmental Failure Mode and Effect Analysis (EFMEA), analyzing risks and selecting priorities using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and zoning environmental risks at the level of urban areas using geographic information system (GIS). The EFMEA technique is one of the new approaches of risk management and assessment (Allen et al., 2009; Santos et al., 2024). This method estimates the process of analyzing risk potentials and the actualization factor of existing potential risks. The environmental sensitivity and the environmental values of the target area are considered in this method. Therefore, it is one of the appropriate methods for environmental risk assessment (Moulai, 2017). In this technique, first, a list of environmental risks related to the subject in the study area was prepared based on previous studies, theoretical foundations and field observations. Then, a number of experts were requested to participate in the completion of the risk assessment worksheet. For this purpose, 14 experts in the fields of environmental management, architectural engineering, urban planning and crisis management were selected purposefully with the Snowball sampling method.

Thus, the aspects and effects of environmental risks of the underground public space development in Tehran were formulated. In order to score the identified risks and based on field observations, the risk priority number (RPN) was calculated based on experts' ratings and Equation (1).

Risk priority number = Severity of risk effect × Probability of risk occurrence × Pollution rate (1)

Tables 1 to 3 were used to calculate each of these three items mentioned in Equation (1). The more severe the risks to the environment, the more severe the damage to the resources, the higher the score would be (Table 1). Probability of risk occurrence was extracted based on Table 2. The higher the probability of risk occurrence in the environments, the higher the score would be. Finally, the guide listed in Table 3 was used to rank the pollution rate or the recycling rate of environmental aspects. In the next step, the severity of risk effect was calculated in terms of high, medium and low limits (Table 4), as follows:
A) Calculation of the mean RPN
B) Calculation of the standard deviation of RPN
C) Calculation of the risk limit or severity based on the following equations and Table 4:
High risk = Mean + Standard deviation
Low risk = Mean – Standard deviation
Medium risk = Distance between high and low risk

3. Results

According to the findings of previous studies as well as field observations and visits, 12 environmental risks were identified in the city of Tehran in order to develop underground public spaces. Table 5 shows the types of factors and their environmental aspects: Figure 2 shows the comparison of environmental risks. Figure 3 shows the comparison chart of risk levels.

Table 1. Ranking the severity of risk effect based on EFMEA (Ardeshir et al., 2016).

Rank	Severity of risk effect	Description
10	Hazardous without warning	Environmental deterioration is unfortunate, which occurs without warning, and threatens human life and other living organisms. Ecological damage attracts international attention.
9	Hazardous with warning	Environmental degradation is unfortunate, but comes with a warning. Toxic substances are released. Ecological damage happens at the level of the country.
8	Very high	The effect on the environment is very high. Damages occur at the provincial level.
7	High	The effect on the environment is high. There are reportable leaks
6	Medium	The effect on the environment is moderate. Non-toxic substances are released.
5	Low	The effect on the environment is low. There is low leakage of non-toxic substances.
4	Very low	The effect on the environment is very low
3	Minor	There is limited and controlled release.
2	Very minor	Harmful effect on human health or the environment is unlikely.
1	None	No effect

Table 2. Ranking the probability of risk occurrence based on EFMEA (Kamyabi et al., 2014).

Rank	Probability of risk occurrence	Probable rates of risk
10	Ultra high- almost inevitable	several times a day - frequently - constantly - every day
9		Once a week
8	High	Once in two weeks
7	Recurrent risks (most cases are likely to occur)	Monthly
6	Medium	Seasonal
5	Incidental risks	Less than a year - 2 to 3 times a year
4	Relatively low	Once a year
3	Low	In periods of 1 to 5 years
2	Very low: Relatively rare risks (may occur)	In periods of 5 to 15 years
1	Unlikely: unlikely risk	In rare circumstances

Table 3. Ranking the pollution rate or the recycling rate of environmental aspects based on EFMEA (Kamyabi et al., 2014).

Rank	Pollution rate	Probability of recycling or consuming resources
10	at the country level	High waste of resources, and consumption of non-recyclable resources
9		Relatively high waste of resources, or consumption of non-recyclable resources
8	At the regional level	Moderate waste of resources, and consumption of hard-to-recyclable resources
7		Moderate waste of resources, or consumption of hard-to-recyclable resources
6	At the provincial level	Waste of resources, and consumption of hard-to-recyclable resources
5		Waste of resources, or consumption of hard-to-recyclable resources
4	At the county level	Low waste of resources
3		Consumption of recyclable resources
2	At the city level	No waste of resources
1	At the local level	No waste of resources, and easy recycling

Table 4. Degrees of risk for prioritization of risk priority number (RPN) (Dickson et al., 2012).

Degree of risk	RPN range	Status
Low (LR)	0-200	Acceptable risks
Medium (MR)	201-500	Need for long-term corrective action plans
High (HR)	501-750	Need for mid-term corrective action
Very high (VHR)	≥ 751	Need for short-term corrective action

Figure 4 presents the frequency of risks in classes. As shown in the figure above, 4 types of risks were classified at low level (LR), 5 risks at medium level (MR) and 3 risks at high level (HR).

4. Discussion

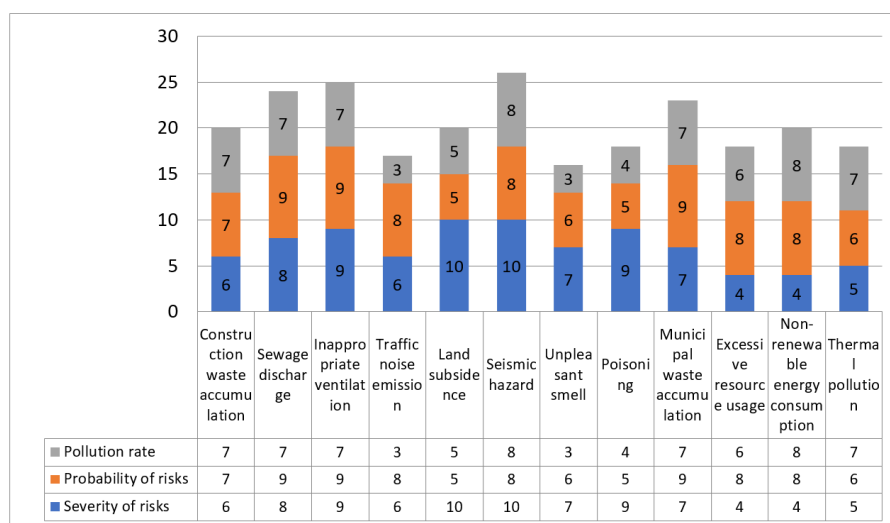
The ever-increasing population growth in spite of the urban land constraints has always been one of the challenges of Tehran. Other problems of this city include high traffic density, bad environmental conditions due to air and noise pollution, insufficient space for work, recreation and entertainment, and bottlenecks in preserving the cultural heritage of the urban environment. The global experience of using underground spaces shows that they have not only responded to urban problems and needs, but also, as the only available solution, helped to improve urban quality and increase citizen satisfaction in many cases. Some of

these cases include adapting to unfavorable climates in extreme cold and heat, developing public transportation in dense and traffic-heavy cities, providing space in areas with land shortages, protecting the environment, increasing urban green space, and building shelters to deal with natural disasters. Therefore, using these models and adapting them to the needs and conditions of each city can always be a suitable solution for many urban problems, especially in the provision of public urban spaces.

Based on previous researches, multiple and diverse applications can be considered for urban underground spaces. For example, according to Li et al. (2021), such spaces can be used as a tool to achieve the goals of passive defense. In addition, this issue is effective to a large extent in solving the traffic problem. Some urban infrastructures and facilities can also be located underground, such as sewers and aqueducts (Sulis et al., 2018). Some types of intended

Table 5. Environmental risks and related aspects.

Environmental risks	Aspects
Solid Waste	• Production and loading of waste
	• Waste release
	• Water pollution
	• Soil pollution
	• Visual pollution
Wastewater	• Odor pollution
	• Transmission of diseases
	• Wastewater production and release
	• Groundwater pollution
	• Soil pollution
Air quality	• Visual pollution
	• Odor pollution
	• Transmission of diseases
Noise	• Production and release of pollutants
	• Damage and diseases
	• Noise pollution
Land subsidence	• Decreasing environmental quality
	• Harm and nuisance
	• Damage to facilities
	• Physical injuries
Seismicity	• Sewage pollution
	• Damage to facilities
	• Physical injuries
	• Sewage pollution
Unpleasant smell	• Air pollution
	• Causing disturbance and inconvenience
	• Reduced concentration
	• Complaint statement
Energy consumption	• Resource consumption
	• Increase in consumption costs
	• Production of air pollution
	• Thermal pollution
	• Thermal pollution
Increase in ambient temperature	• Increasing dissatisfaction
	• Deterioration of environmental quality
	• Waste of capital
Resource consumption	• Increasing consumption demand
	• Production of environmental pollution

**Figure 2.** Comparison of environmental risks.

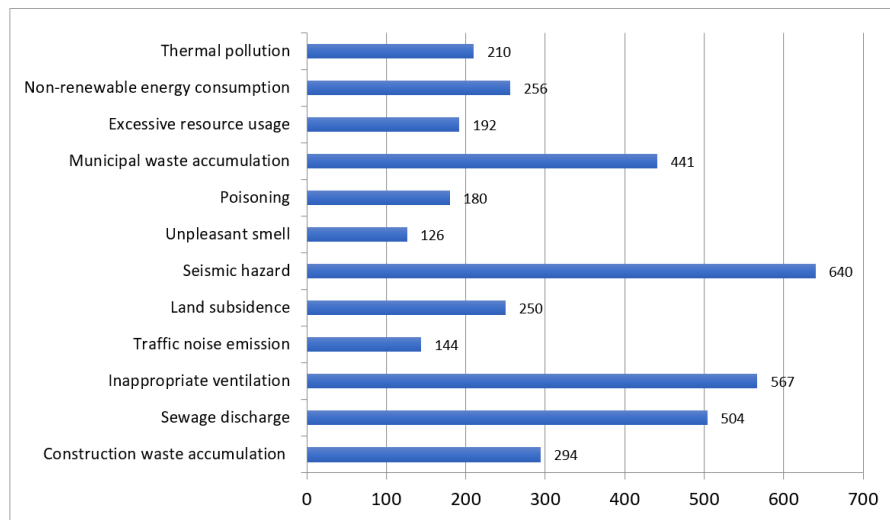


Figure 3. Comparative chart of risk levels.

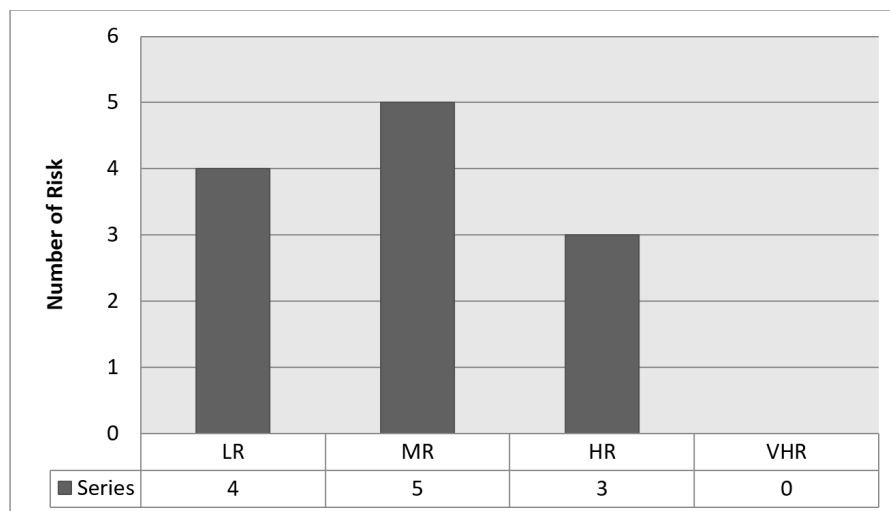


Figure 4. Frequency of environmental pollution risks in classes.

uses can also be developed in underground spaces, such as commercial spaces (Tong, 2016).

In our research, it was found that 12 types of environmental risks can be imagined for the development of underground public spaces in Tehran. Among these, four cases were in the category of low risk levels, including Traffic noise emission (RPN = 144), Unpleasant smell (RPN = 126), poisoning (RPN = 180) and Excessive resource usage (RPN = 192). Moreover, five cases were classified as medium level risks, including Construction waste accumulation of (RPN = 294), Land subsidence (RPN = 250), Municipal waste accumulation (RPN = 441), Non-renewable energy consumption (RPN = 256) and Thermal pollution (RPN = 210). In addition, three items were among high-level risks, including Sewage discharge (RPN = 504), Inappropriate ventilation (RPN = 567) and Seismic hazard (RPN = 640) (Table 6).

This method is also approved by the World Bank (2012); although this combination pattern cannot be called as a method with full confidence. Therefore, it is suggested that other risk assessment techniques or decision-making

models are also examined and adapted.

5. Conclusion

The innovation of this research is the investigation of the aspects and environmental components effective in the use of underground spaces, which was done using the EFMEA technique.

The development of urban underground public space in Tehran can be a solution to improve the level of services and urban per capita, which is a great help in the urban management of a metropolis like Tehran. Meanwhile, it is important to pay attention to the environmental, health and safety policies. If environmental considerations are met and risk levels are reduced, it is possible to develop this type of uses. On the other hand, the priority of underground development programs in this city is in the western and eastern areas, and the southern and northern areas do not have proper points and values.

In total, and based on the research results, the following suggestions are presented:

- In the development of underground spaces, much

Table 6. The identified environmental pollution risks and the degree of risks.

Codes	Environmental risks	Consequences of risks	Severity of risks	Probability of risks	Pollution rate	RPN
R1	Construction waste accumulation	Soil and water pollution	6	7	7	294
R2	Sewage discharge	Soil and water pollution	8	9	7	504
R3	Inappropriate ventilation	Air pollution and health effects	9	9	7	567
R4	Traffic noise emission	Health effects	6	8	3	144
R5	Land subsidence	Human life-economic loss	10	5	5	250
R6	Seismic hazard	Human life-economic losses	10	8	8	640
R7	Unpleasant smell	Psychological and physiological effects	7	6	3	126
R8	Poisoning	Human life losses	9	5	4	180
R9	Municipal waste accumulation	Health effects	7	9	7	441
R10	Excessive resource usage	Waste production	4	8	6	192
R11	Non-renewable energy consumption	Environmental pollution	4	8	8	256
R12	Thermal pollution	Energy consumption and pollution	5	6	7	210

attention should be paid to the parameters of wastewater distribution, ventilation and air purification.

- One of the most important aspects in the development of underground spaces is to adopt strategies to prevent land subsidence.
- Periodic monitoring of environmental aspects should be done.

Funding

No funding was received to assist with conducting this study and the preparation of this manuscript.

Authors Contributions

All authors have contributed equally to prepare the paper.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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