

## Analyzing and investigating the effects of Naqadeh earthquake aftershocks in West Azerbaijan on the results of probabilistic seismic risk estimation using clustering analysis

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**Abstract:** In risk analysis, parameters such as distance, height, attenuation relationships, local soil conditions, etc. are used, and a certain parameter of the ground movement in the desired site is predicted. The effects of future earthquakes cannot be determined exactly, and these effects can only be partially predicted with probabilistic methods. Earthquake (seismic) risk analysis includes research and methods that can be used to estimate the effects of future earthquakes on construction. These effects mainly include ground motion parameters. In the past, the earthquake intensity parameter was used due to the lack of earth movement measurement tools. In this study, a probabilistic seismic hazard analysis was performed considering the effects of the aftershocks of the Naqadeh earthquake (July 18, 2021) and compared with the conventional analysis results. The results of the analysis show the importance of aftershocks in the estimation of seismic risk and the necessity of considering these events as part of the seismic risk of the region.

**Keywords:** Earthquake, West Azerbaijan, Clustering Analysis, Criticism, Seismic Hazard, Aftershock.

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## 1. Introduction

Iran is one of the countries that is highly at risk of earthquakes, so every few years an earthquake causes a lot of damage and loss of life in a part of the country. Therefore, efforts to increase the safety and resilience of society against seismic events are inevitable. Although it is not possible to predict the earthquake and determine the exact location and time of its occurrence in the current range of earthquake engineering findings, studying and predicting seismic hazards is possible and can be done. In seismic hazard analysis, the annual probability of exceeding the specified earthquake intensity (usually the maximum ground acceleration or spectral acceleration of the first mode) for a structural period and damping ratio is determined (Gheitarani et al., 2013).

Earthquake risk analysis is an essential and integral part of the seismic design of structures, earthquake risk analysis, loss and damage estimation, and related insurance calculations. Earthquake hazard analysis is essential for the preparation of seismic maps that provide important information for the design of conventional structures. The design and safety estimation of all kinds of important metal and concrete structures such as dams, nuclear power plants, etc. is dependent on the earthquake risk analysis of their construction. Earthquake risk analysis is a quantitative estimate of the risks of ground shaking in a particular location (Baranov et al., 2022).

The rate of occurrence of main earthquakes, and constant values are assumed, and generally homogeneous Poisson models are used. The formulation of probabilistic seismic risk analysis requires a model of earthquakes that represents the randomness of the distance from the site for each rupture scenario and the possible earthquake distribution for an earthquake with a certain magnitude and distance. Also, the randomness of the time of occurrence and magnitude of earthquakes are considered conventional possibilities in the process of seismic hazard analysis; for this reason, the impact of dependent events is generally not considered in the conventional risk analysis process.

After the occurrence of the main earthquake, the rate of occurrence of aftershocks is not constant in time and immediately after the occurrence of the main earthquake, it has its highest value and decreases with time. In this situation, to assess the confidence after the earthquake to determine the rate of occurrence of aftershocks, seismic hazard analysis of aftershocks is a suitable tool, which is especially useful in the hours and days after the main earthquake to help with restoration efforts and so on (Zakerhaghighi et al., 2015).

However this type of analysis takes place in a relatively short period; while it seems that dependent events are capable of producing damaging earthquakes, the possibilities related to the lifetime of the structure should be considered in the seismic risk analysis. To include dependent events in the probabilistic seismic

hazard analysis, they can be considered together with the main earthquake in such a way that they have the possibility of increasing the magnitude of the specified earthquake at the site.

In other words, each of the clusters, which is a combination of the main earthquake and its aftershocks, may be seen as individual events that occur at the same rate as the main earthquake. To include dependent events in probabilistic seismic risk analysis, they can be considered together with the main earthquake to have the possibility of participating in determining the seismic risk of the site. In other words, each cluster, which is a combination of the main earthquake and its aftershocks, may be seen as individual events that occur at the same rate as the main earthquake.

For this purpose, behavioral patterns of aftershock activity should be studied and appropriate statistical relationships should be used. These relationships are suggested based on the seismic activity patterns reported from past earthquakes and using different statistical tools. One of the most common relationships in predicting the behavior patterns of aftershocks is the model proposed by Rosenberg and Jones.

In this research, using the method proposed by Yaghmai et al., seismic risk analysis is performed by considering the clustered dependent events that lead to more accurate seismic risk predictions.

In this method, the main earthquake and its dependents are considered as a cluster, and each cluster is temporally and spatially independent from the other. Each cluster has the return time of the main earthquake, and thus by considering the earthquakes in the cluster as a set of events, it will be possible to apply the effects of dependent events in the risk analysis.

## 2. Theoretical

**Natural earthquakes.** Tectonic earthquakes will occur anywhere on Earth where enough elastic strain energy is stored to propagate a fracture along a fault plane. At the boundaries of the Earth's crustal plates, which form the largest fault planes on Earth, the plates will move seismically if no irregularities or roughness along their boundaries would increase frictional resistance. Most boundaries have this roughness and this leads to stick-slip behavior (Naghbi Iravani et al., 2024). When the plate boundaries are locked, the continued relative motion between the plates leads to an increase in stress and, as a result, an increase in the accumulated energy in the masses near the fault surface (Farrokhi & Gheitarani, 2024).

This increase continues until the increased stress is high enough to suddenly allow slip from the locked part of the fault by breaking through the asperities, releasing the stored energy. This energy is released in the form of seismic waves and the frictional heat of the fault surface is radiated, and the rock is broken, which causes an earthquake. This gradual process of building stress and strain, which causes sudden failure and earthquake production, is called the elastic rebound theory. It is estimated that only 10% or less of the total energy of an earthquake is released as seismic energy (Toda & Stein, 2022).

Most of the earthquake's energy is spent on breaking rocks or turning into heat produced by friction; therefore, an earthquake reduces the elastic latent strain energy of the earth near the fault and increases its temperature, although these changes are small

compared to the convection currents and the conduction of heat released from deep within the earth. Earthquakes occur due to the sudden breaking of rocks inside the earth (Gheitarany et al., 2013).

**Induced earthquakes.** Although most earthquakes have tectonic and natural origins, a significant number of earthquakes also have non-tectonic origins, which are known as induced earthquakes or earthquakes with artificial factors. In Iran, despite the presence of many oil and gas fields, active mines, large dams, and geothermal resources, the characteristics of induced seismicity in these areas are not yet known correctly. The Zagros mountain range hosts one of the largest hydrocarbon reserves on the planet, and numerous gas and oil fields are operating and being extracted in this region. The existence of a high number of hydrocarbon fields and their extraction, as well as the natural tectonic activity in Zagros, has made this orogeny an unparalleled example on the planet. A study in the Zagros region has shown that although Zagros is classified as an active region from a tectonic point of view, the extraction of hydrocarbon reserves also causes induced earthquakes in this region (Samami et al., 2024).

**Types of earthquake faults.** Three main types of faults may cause earthquakes: normal, reverse (axial), and strike-slip. Normal and reverse faults are examples of dip-slip, where displacement along the fault in the direction of the dip and movement on them includes a vertical component. Normal faulting mainly occurs in areas where the crust is being extended, such as a divergent boundary. Reverse faulting occurs in regions where the crust is shortening, such as a convergent boundary. Strike-slip faults have steep structures where both sides of the fault slide horizontally next to each other; transform boundaries are a special type of strike-slip fault. Many earthquakes are caused by movement on faults that include both dip-slip and strike-slip, this slip is known as oblique.

**Earthquakes away from plate boundaries.** Since plate boundaries occur within the lithosphere of continents, the deformation is spread over an area much larger than the plate boundary. As with the continental transform of the San Andreas Fault, many earthquakes occur far from the plate boundary and have developed variants in a wider region of deformation caused by irregularity associated with the trace fault (e.g. the "Great Bend" zone). The Northridge earthquake was associated with movement in a mountain slide within such a region. Another example is the convergent and strongly tilted plate boundary between the Arabian and Eurasian Plates, which is part of the northwestern Zagros Mountains (Khanian et al., 2019).

Deformation associated with this plate boundary is divided into nearly pure crustal boundary-perpendicular movements over a large area in the southwest and nearly pure strike-slip movements along major faults near the actual plate boundary. This is shown by the focal mechanism of the earthquake. All tectonic plates have an internal stress field resulting from their interactions with adjacent plates and sediment loading or unloading (e.g., deglaciation). These stresses may be sufficient to cause rupture along existing plate faults, triggering interpolate earthquakes (Maleki et al., 2024).

**Shallow focus and deep focus of the earthquake.** Most of the tectonic earthquakes originate in the Ring of Fire at a depth of less than tens of kilometers. Earthquakes at depths less than 70 km are classified as shallow-epicenter earthquakes, while epicenters between 70 and 300 km are usually called 'intermediate-epicenter'

or 'medium-depth earthquakes'. In subduction zones, where older, cooler oceanic crust subducts into another tectonic plate, earthquakes may occur at much greater depths (in the 300-700 km range). These active seismic zones with subduction are known as (Wadati-Benioff) zones. The deep center of earthquakes is at a great depth, in that area, the rock is no longer fragile due to the high temperature and pressure (Zaker Haghighi et al., 2014). A possible mechanism for the deep-focus generation of earthquakes is caused by the first phase transition to a rigid structure (Yang et al., 2022).

**Earthquakes and volcanic activity.** Some earthquakes occur in volcanic regions, they are caused by the movement of magma in volcanoes. Such earthquakes can serve as early warnings of volcanic eruptions, such as those during the 1980 Mount St. Helens eruption. An increase in earthquakes around an active volcano can be a sign of impending volcanic activity. The increase in seismic activity before the eruption of a volcano can be recorded by seismographs and tilt meters (Geobel et al., 2023).

**Aftershocks.** An aftershock is an earthquake that occurs after the main shock. The aftershock is in the same region as the main shock but is always smaller in strength. If the aftershock is larger than the main shock, the aftershock is called the foreshock and the main foreshock is called the aftershock. Aftershocks occur when the crust around the displaced fault plane adjusts to the effects of the main shock (Gheitarani et al., 2020).

**A swarm of earthquakes.** An earthquake swarm is a series of earthquakes that occur in a specific area in a short period. They differ from earthquakes that are followed by a series of aftershocks because none of the individual earthquakes are in the sequence of the mainshock, so none are significantly stronger than the others. An example of an earthquake swarm is the activity of Yellowstone National Park in 2005 (Gheitarani et al., 2024).

**Earthquake storm.** Sometimes a series of earthquakes occurs as an earthquake storm, where an earthquake strikes a multicluster fault, causing shaking or redistribution of the stress transmitted from the previous earthquake. Similar to aftershocks but on fault-adjacent sections, these storms occur over years, with some earthquakes as destructive as the initial earthquakes. Such a pattern was observed in a sequence of earthquakes on the North Anatolian Fault in

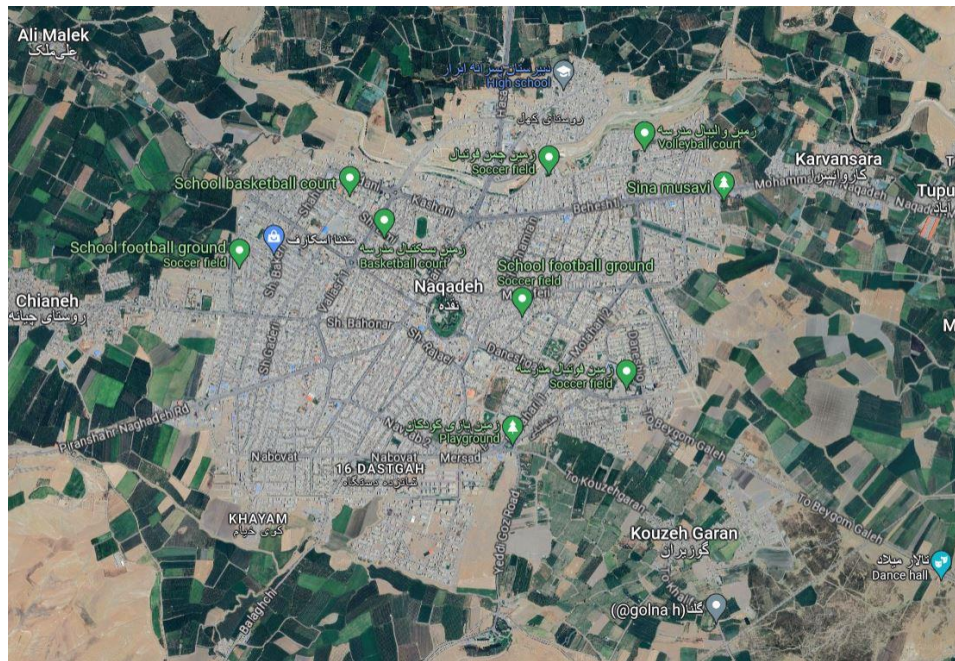
Turkey in the 20th century and inferred for old anomalous clusters from large earthquakes in the Middle East (Wang et al., 2021).

**Measuring the intensity and location of the earthquake.** Earthquakes can be recorded by seismometers up to very large distances because seismic waves even pass through the ground. The absolute magnitude of the earthquake size is conventionally reported by the numbers on the moment magnitude scale (previously on the Richter scale, magnitude 7 caused serious and large damage in most areas), while the sense of magnitude is reported using the Mercalli scale. Each tremor produces different types of seismic waves that travel through the rock at different speeds: longitudinal P waves (shock or compression waves), transverse S waves (both body waves), and various surface waves (Railway waves) (Ghadarjani & Gheitarani, 2013).

The propagation speed of the resulting seismic waves varies from the approximate range of 3 km/s to 13 km/s, depending on the density and tension of the middle value. Inside the Earth, shock or P waves travel much faster than S waves. (Approximately 1.7:1). The difference in the travel time of the waves from the source to the observatory is used to measure the distance and can indicate the source of the earthquake and the structure inside the earth. Also, the depth of the hypocenter can be roughly calculated. General rule: On average, the distance (km) to the earthquake is equal to the time (seconds) between the P and S waves. The slight deviation is due to the inhomogeneity of the subsurface layers of the Earth (Kahvand et al., 2015).

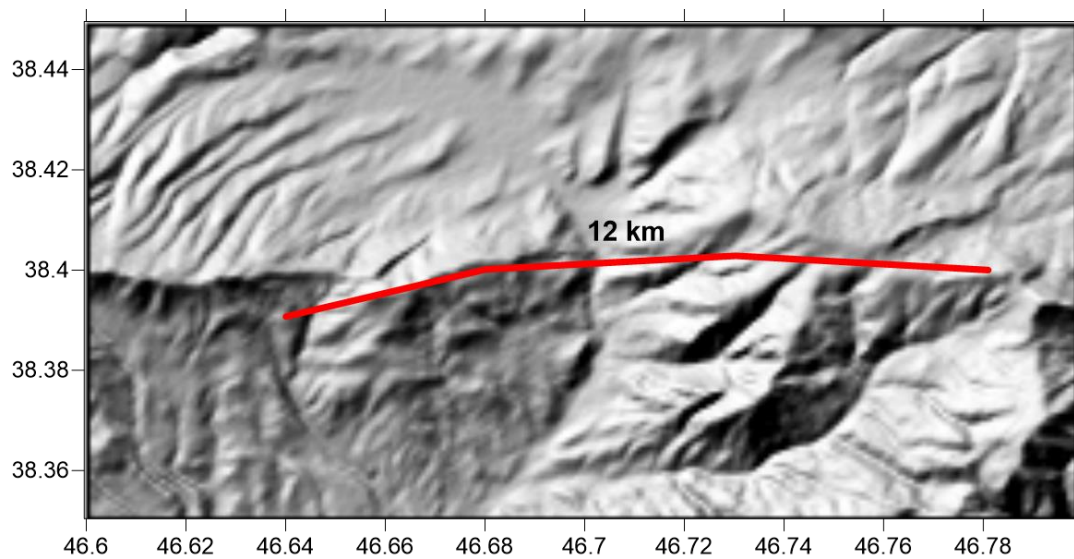
### 3. Methodology

The research method used in this research is the quantitative research method. In this research, the tool for analyzing mathematical equations and through model equations is the Rosenberg and Jones model. The earthquake investigated in this research is the earthquake of Naghde city in West Azerbaijan which happened in 2021. The earthquake of 2021 with a magnitude of 5 on the Richter scale shook West Azerbaijan. This earthquake occurred on Friday, July 18, 2021, at 20:11. This earthquake occurred 4 km from Naqadeh. The longitude of this earthquake was 45.35 and the latitude was 36.98 at a depth of 10 km (Ghadarjani et al., 2013).



**Figure 1: The studied area and the assumed fault for the rupture of the 2021 Naqadeh earthquake**

There were no casualties in this earthquake. Another earthquake with a magnitude of 3.6 on the Richter scale occurred in Naqadeh at 16:15 on the same day.



**Figure 2: The studied area and the assumed fault for the rupture of the 2021 Naqadeh earthquake**

#### 4. Findings and Results

**Riesenberg and Jones model.** According to this model, the rate of occurrence of earthquakes after the main earthquake is a function of time and magnitude, so this rate increases suddenly immediately after the main earthquake and then starts to decrease, and the magnitude of earthquakes also follows an exponential distribution. In this model, a heterogeneous Poisson process is considered for the occurrence time of aftershocks, and the modified Emory law is used to express the occurrence rate of aftershocks concerning time (Kato, 2024).

Amory's law shows the time reduction rate of the occurrence of aftershocks. In this regard, the occurrence rate of aftershocks is approximately proportional to the inverse of the time elapsed since the main earthquake. This law was later modified by Otsu and is known as the modified Amori Law and is according to the following relationship:

$$\lambda \equiv \frac{dN}{dt} = \frac{K}{(c + t)^p} \quad (1)$$

K is the ability to produce aftershocks by the main earthquake with magnitude m, c is the time transition and t is the time elapsed since the main earthquake occurred. The p parameter shows the intensity of the decrease in the rate of occurrence of aftershocks and is determined along with other parameters in this regard by using appropriate statistical tools. In relation 1, the presence of c makes the rate of occurrence of aftershocks not infinite when t tends to zero.

Such behavior at  $t=0$  has been described in such a way that the main earthquake is obtained from the sum of an infinite number of earthquakes that occur in an infinitesimally small time interval. Because of such ambiguities, the parameter  $c$  is usually assumed to be non-zero so that there is no divergence at  $t=0$ , although its presence in this relationship makes the reduction of the aftershock occurrence rate smoother. This softening is mainly in the early times after the occurrence of the main earthquake, especially in the interval  $t < c$ . For the magnitude distribution of aftershocks, Rosenberg and Jones have used the Gutenberg-Richter relationship, which is in the form of relationship 2.

$$\lambda(m) = A10^{-b(m)} \quad (2)$$

$m$  is the aftershock magnitude and  $A$  and  $b$  are constant parameters. They have presented the rate of occurrence of aftershocks caused by an earthquake with a magnitude of  $m_m$  as follows.

$$\lambda(t, m) = 10^{a+b(m_m-m)}(t+c)^{-p} \quad (3)$$

## 5. Discussion

**Application of aftershocks in probabilistic seismic risk analysis.** By using the presented models, it is possible to predict the aftershocks that occur after a destructive earthquake and provide useful information for initial measures after the occurrence of the main earthquakes. Because strong aftershocks can lead to structural weakness and collapse of damaged structures. Aftershocks are often considered for short-term risk management purposes using the method proposed by Yoo called Probabilistic Aftershock Seismic Hazard Analysis (APSHA). As mentioned, PSHA usually refers to a homogeneous Poisson process to describe the occurrence of events, while APSHA models the occurrence of aftershocks along with a conditional inhomogeneous Poisson process.

So the rate of occurrence of each depends on the magnitude of the earthquake that initiates the sequence. To consider dependent events in probabilistic seismic risk analysis, dependent events can be considered together with the main earthquake associated with them as a set, so that this set has the possibility of increasing the amount of the desired earthquake at the site. The concept of clustering in probabilistic seismic hazard analysis was presented by Toro and Silva and further studies were done by Boyd.

In this method, the related events along with the main earthquake associated with them are considered as a set, so that this set has the possibility of exceeding the ground motion parameter in the desired site. In other words, each of the clusters is considered as individual events that occur at the same rate as the main earthquake. For events with long return periods, all earthquakes in the cluster influence the seismic hazard results, while this is not true for shorter return periods.

Therefore, the risk curve resulting from this method will be close to the risk curve of main events in shorter return periods and to the risk curve of independent events in long return periods. Although the foreshocks and aftershocks are temporally and spatially dependent on the main earthquake, in this method, it is assumed that the probability of each event exceeding a specific earthquake is independent of other events in the cluster and the case that the probability of each event is close to one (the state corresponding to events with a short return period), the earthquake with the greatest probability of exceeding the earthquake in question prevails.

As the probability of exceeding each of the events within the cluster decreases (the state corresponding to the long return period), the probability of exceeding a certain earthquake is accumulated and each event independently participates in the seismic hazard. The results of the risk analysis, in which pre-earthquakes, main earthquakes, and aftershocks are considered, are obtained by multiplying the probability values obtained for each cluster by the annual rate of the cluster, which is equal to the annual rate of occurrence of the main earthquake of the cluster, according to the following relationship:

$$\lambda = \sum v_c \cdot p_c \quad (4)$$

$v_c$  is the annual rate of each cluster, which is equal to the annual rate of occurrence of the main earthquake corresponding to that cluster.  $p_c$  is the probability of exceeding the desired earthquake caused by the events in each cluster, which includes main earthquakes and aftershocks. Analysis parameters based on the Rosenberg and Jones model for the sequence of aftershocks are considered using Rezapour's study according to 1 table.

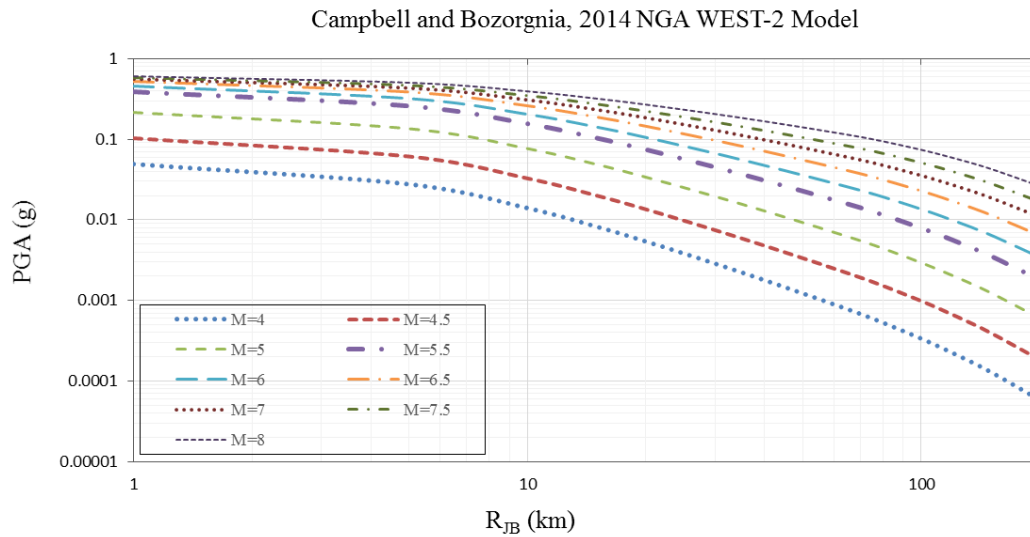
Earthquakes with a magnitude less than 4 have been omitted due to their small effect on the results of the regional seismic risk analysis. The sequence of aftershocks of the Naqadeh earthquake has two phases of activity, the second phase started about three months after the main earthquake. The parameters related to each phase are presented in Table 1.

**Table 1. Analysis parameters based on the Rosenberg and Jones model**

| K1 | K2   | b        | c1       | c2       | p1       | p2       | min | max | mainshock |
|----|------|----------|----------|----------|----------|----------|-----|-----|-----------|
| 10 | 1.02 | 0.287496 | 2.514897 | 1.004859 | 1.000487 | 1.028479 | 2.5 | 5   | 5         |

## 6. Conclusion

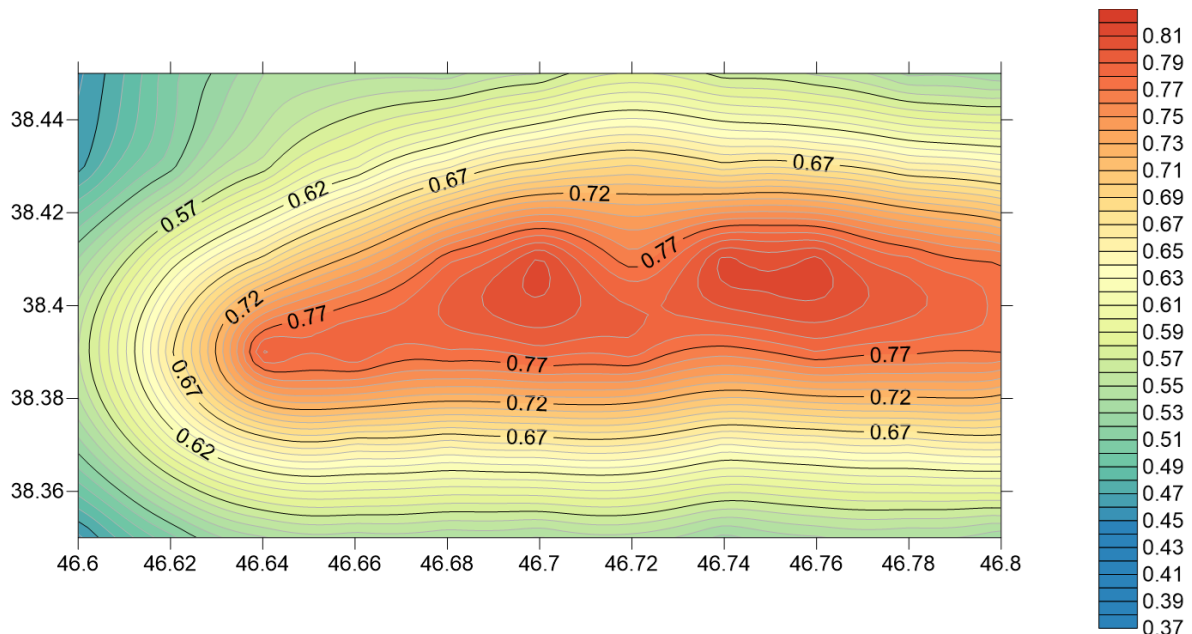
In this study, the reduction relationship provided by Campbell and Bozornia is used, the results of which are shown in Figure 3 for different M and R:



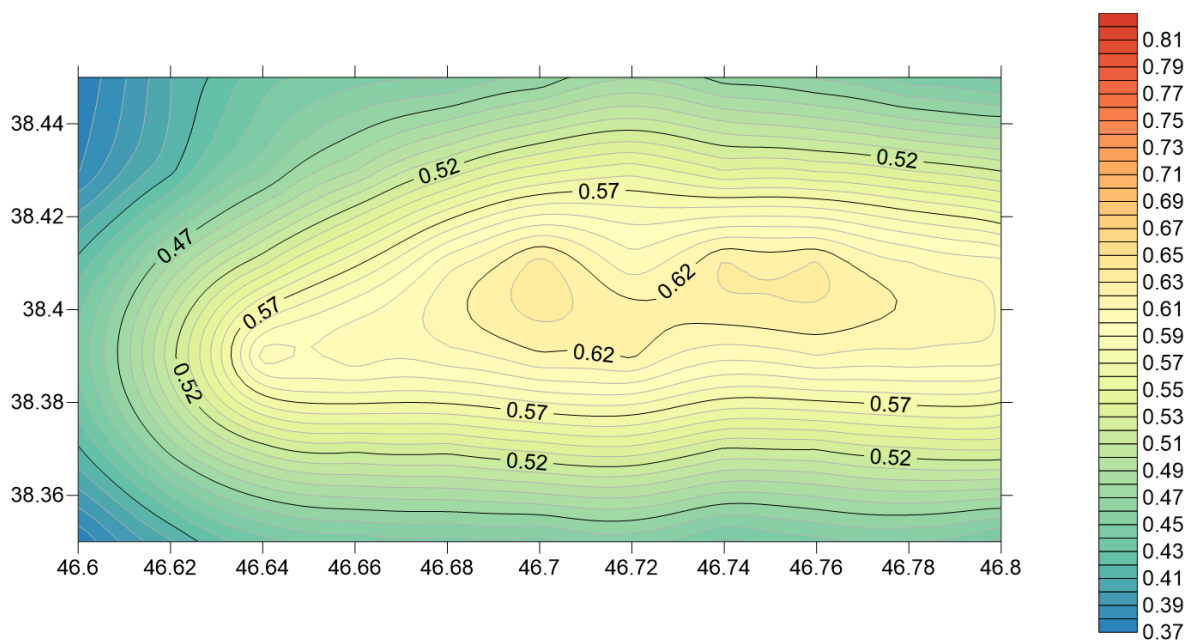
**Figure 3: Campbell's and Bozornia's attenuation relation for different magnitudes and distances**

In Figures 4 and 5, the seismic risk maps of the study area for sites with 0.02-degree latitude and longitude intervals are presented, respectively, for clustering analysis using the Riesenberg and Jones model and conventional risk analysis in terms of g. These maps are presented for a probability balance of 2% in 50 years. According to the figures, it can be seen that the greatest amount of difference in the results is related to the areas close to the fault and this difference decreases with increasing distance from the fault.

Based on the seismic risk maps presented using conventional analysis and clustering and considering that the difference between the results of clustering analysis and conventional analysis decreases as the distance from the fault increases, it can be said that in areas with low seismicity that are relatively far from active faults. The results of the clustering analysis have a smaller difference from the results of the conventional analysis, while this difference increases in areas with high seismicity that are close to active faults.



**Figure 4: Clustering analysis with the assumption of Rosenberg and Jones model for the probability of passing 2% in 50 years**



**Figure 5: The results of the conventional seismic risk analysis for the probability of passing 2% in 50 years**

In this research, the temporal behavior patterns of aftershocks have been considered and according to what is often considered in conventional risk analysis, the spatial distribution of earthquakes has been assumed to be uniform on the desired fault. Further studies are suggested in the field of clustering analysis using temporal and spatial models and ignoring the assumption of uniform distribution of earthquakes on the fault.

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