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PGA Estimation for Gulab 2 Water Transfer Tunnel using Probabilistic Seismic Hazard Analysis Method (PSHA)

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ABSTRACT

The Gulab 2 water transmission tunnel in order to supply water to Isfahan city in the length of 17 km from the end of the Gulab tunnel has been done. This tunnel is located in Sanandaj - Sirjan zone and lithostratigraphic the oldest formations of the tunnel site are Paleozoic metamorphic rocks. Based on geological studies, Gulab 2 tunnel in Khamiran shale formation under the alluvial plain has been drilled which mainly is directed in NW-SE. As seismotectonic, the tunnel is located in the northwest of the Zagros zone and witnesses various earthquake events with various magnitudes. Based on seismic calculations, to determine the seismic parameters by probabilistic methods, the tunnel site classification is average risk rating and Gulab 2 tunnel is level 1-important class.

1. Introduction

Earthquakes and seismic forces have always been a damaging factor for geotechnical structures and projects. In this regard, a part of geotechnical science called seismical geotechnics has been developed to investigate the behavior of soil and rock during the application of dynamic load or the role of earthquake on the geotechnical behavior of soil and structure. With the help of this science, it is possible to perform the necessary measures in the dynamic design of structures and estimate the seismic parameters in the design. In general, possible geotechnical risks faced in the construction of the project can be mentioned as earthquakes, intensification of vibrations, liquefaction, etc. These features should be well covered by estimating the optimal reduction relationships and the impact of seismic parameters on the structure (Cambazoğlu et al., 2016). In general, earthquakes indicate the amount of seismic activity in each region, and a careful study of their occurrence process can be a very good solution in estimating the seismicity of the target area in the future (Nikoobakht et al., 2016). Therefore, it is necessary to collect the information of earthquakes in the desired area, to estimate and investigate the seismic characteristics of these events by applying appropriate statistical methods. For this purpose, by creating a database of earthquakes in the desired range, appropriate seismic data are selected, completed and processed (Yazdani and Kowsari, 2013). Seismic data processing is based on the assumption of the Poisson process (Khali and Bahuguna, 2021). With this assumption, the rate of occurrence of earthquakes in the time period is constant and earthquakes will be independent events from each other (that is, the event of one earthquake is not dependent on another). In this case, all foreshocks and aftershocks are removed from the

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region's earthquake data to calculate seismic parameters. It is necessary to say that dynamic analysis should be done in the case of highly important and special structures. In the design of ordinary and low importance structures, it is necessary to use the recommendations and conditions of the code of design of buildings against earthquakes or the 2800 Iran code for seismic design. It is obvious that the amount of vibrations considered and the intensity of the dynamic load used in the dynamic design must be in accordance with the appropriate seismic levels like maximum design level (MDL), maximum selectable level (MCL), design base level (DBL) and in accordance with the seismic conditions of the region, the amount of acceptable risk and longevity (Filippucci et al., 2021).

The relationship between magnitude and frequency of earthquakes is one of the most important and effective approaches proposed in the dynamic design of structures, especially important structures (Taroni et al., 2021). In the meantime, methods such as the Gutenberg-Richter binomial distribution (Kossobokov, 2020), Boore method (Boore and Atkinson, 2008), and Campbell-Bozorgnia method (Campbell and Bozorgnia, 2012) are the leading approaches in parameter evaluation. It is mentioned that seismicity can be expanded using statistical and probabilistic distribution functions. These approaches can be calculated for different levels of design, reduction constants, event frequency, maximum probable magnitude (M_{max}), peak ground acceleration (PGA), return period and probability of earthquake occurrence magnitudes in different time periods, which can be calculated by various deterministic and probabilistic methods (Zaccagnino et al., 2022).

Studying about underground structures due to the high sensitivity of these structures, underground structures due to the inability to control the characteristics of the host mass of the structure, the possibility of slight changes in the materials, the impossibility of accessing all the geological and geotechnical conditions of the mass. The host is considered one of the most difficult and problematic types of evaluations in geotechnical engineering. Therefore, the more studies are done about the various geotechnical aspects of these structures, the more studies and evaluations are needed. One of the main issues in the design and construction of large underground spaces is the prediction of the behavior of the earth including the underground space against dynamic loads such as earthquakes. So that the role of earthquake loading as well as the maximum load on the tunnel along with its return periods is considered a serious issue during its design, construction and operation stages.

In general, tunnels and related structures are considered to be among the special and important structures in terms of risk and the calculation of their resistance against the seismic movements of the earth should be done carefully and based on the established criteria (Perez-Oregon et al., 2018). The impact of seismic loads on the tunnel and its role in the stability of the tunnel is not hidden from anyone. In this regard, in the initial design stages, the seismic characteristics of the region will be investigated and the seismic characteristics of the region (which is based on the tectonic and geological condition of the region) will be estimated.

Gulab 2 water transfer tunnel is one of the biggest water transfer projects in the country. Success in ensuring tunnel stability against earthquakes plays a significant role in the ultimate goal of the tunnel design and the life of the structure. This success will require safe design under seismic parameters under earthquake loading, estimation of M_{max}, PGA, and proper damping of the ground along the tunnel, which is directly dependent on the investigation of seismotectonic condition and estimation of seismic parameters of the tunnel construction. The necessity of such studies is not less than that, if it is not to the extent of designing guarding systems on a permanent basis; because the most powerful guarding structures for static loads will never have optimal performance for earthquake conditions. Therefore, seismic design is considered a serious and necessary priority in stability analyzes and safe design in tunnels. This issue has been considered in this research and an attempt has been made to estimate the seismic parameters for the area of Gulab 2 tunnel.

2. Geological Setting

The investigated area of Isfahan water transfer tunnel is located in Karon plain in Isfahan province (75 km west of Isfahan city). This piece starts in the continuation of Gulab tunnel from the underground Gulab pump house of UTM coordinates, Y=3624178N and X=488630E to +17 km under the Kron Plain, +1.5 km southwest of Verpasht village in coordinates Y=3621469N and X=505516E. In order to supply a part of the drinking water of Isfahan, this tunnel has the task of transferring water from the end of the Gulab 1 tunnel to the Kron plain. The entrance of the Isfahan water supply tunnel (Gulab 2) is opposite to Gulab 1 tunnel. Access to this point is via the Isfahan-Daran road, and after Tiran city, it is possible from Afjan village. This is possible at about 17 km by a local sub-road. The access to the exit of the tunnel is also through the Isfahan-Daran road, 5 km after Tirana, it is possible to access the construction site by the Verpasht village road. The location and access routes to the project are shown in Fig. 1.

As geomorphological point of view, most of the tunnel route is located in the Kron plain and is divided into the plain types. There are elevations in the initial part of the tunnel and around 10.5 to 14 km and also in the end part of the tunnel, and they are divided into mountains and hills in terms of geomorphology. The highest elevations in the region are the western elevations of the region at the entrance of the tunnel, and the highest point is Mount Gadarsorkh (with a height of about 2650 m above the sea water level, SWL), and the lowest point is near the exit of the tunnel and with a height of about 1930 m above SWL.

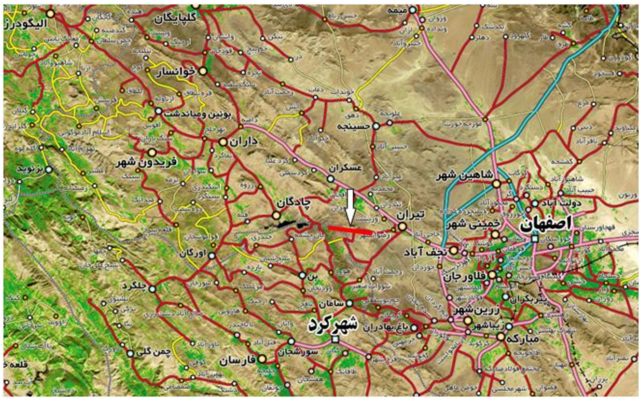

Figure 1. The geographical location of the tunnel in Isfahan

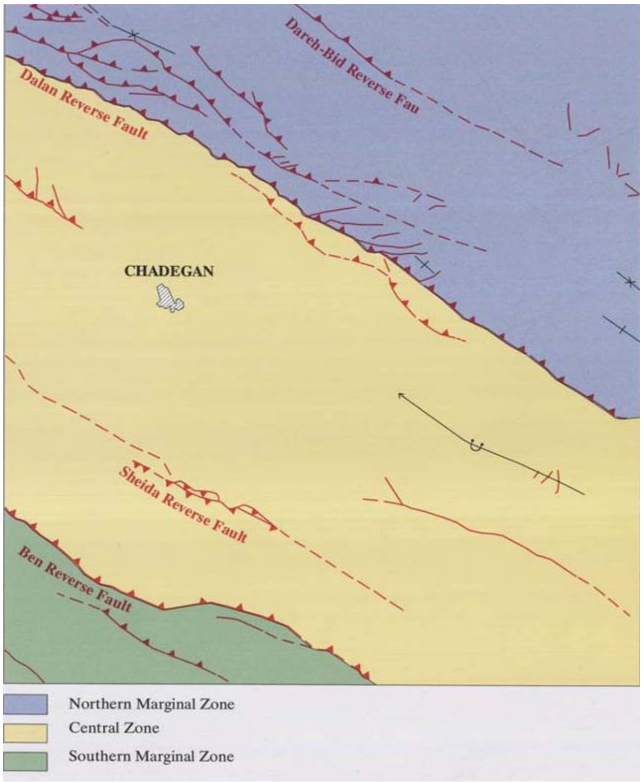

Figure 2. Sanandaj-Sirjan zone techtonical zonations (Zayndab, 2010)

The studied area is located in the Sanandaj-Sirjan structural zone. This zone in the region can be divided into three parts: northern margin, central margin and southern margin (Aghnabati, 2016). Most of the studied area is located in the northern margin of the Sanandaj-Sirjan zone, and part of the tunnel route is located in the central part of the Sanandaj-Sirjan zone. Based on the geological studies carried out in the region by field surveys, sampling, petrological study of thin sections and update of geological maps of Isfahan, Najafabad and Chadegan by using of satellite images, geological maps of the tunnel route have been prepared. The purpose of doing this work is to determine the geological conditions of the tunnel construction. The map of tectonic changes and faults in the region along with the trend of the faults is shown in Fig. 2.

Seismic surveys throughout the surface of the earth show that most of them occur in special areas and mostly along the lines corresponding to mountain belts. One of the active and young belts of the Alpine-Himalayan mountain belt extends from the western shores of the Pacific Ocean to the eastern shores of the Atlantic Ocean with a close east-west direction. Iran is also located in the middle part of this active belt. Active seismicity and the occurrence of destructive and destructive earthquakes in Iran is a proof of this (Berberian, 1995). According to the sedimentary-structural division of Iran by Aghnabati, the area under study is located in the Sanandaj-Sirjan region (Aghnabati, 2016) and is affected by the geo-structural and seismic characteristics of this area. The characteristics of Sanandaj-Sirjan geological unit can be described as follows.

Sanandaj-Sirjan Zone: In some sources, this zone is considered as a long metamorphosed strip along and parallel to the Zagros landslide, from Urmia and Sanandaj in the northwest to Sirjan and Esfandagh in the southeast. In terms of sedimentation and structural features, it is like central Iran, but its general direction and extension follows the general Zagros, the Tarshir volcanoes do not spread much in it. This zone is considered one of the most unstable regions of Iran and has gone through important phases of metamorphism and magmatism until the Cenozoic.

Gulab Tunnel 2 Blocks: The studied area can be divided into two blocks in terms of stratigraphy, and the boundary dividing these two blocks is the Abrizan-Kamason fault. The western parts of this fault have been named as metamorphosed block and the eastern part as Krone block (Zayndab, 2010). The metamorphic block is located in the Sanandaj-Sirjan zone and its oldest metamorphic rocks belong to Paleozoic. The main route of the Gulab 2 tunnel is under the alluvial plain of Kron and in the middle of the bedrock of the plain, which includes the shale units of the Khemiran Formation.

3. Material and Methods

Earthquakes indicate the amount of seismic activity in each region, and a careful study of their occurrences from long ago can be a very good guide in estimating the seismicity of the target area in the future. Therefore, it is necessary to collect the information of earthquakes in the desired area, to estimate and investigate the seismic characteristics of these events by using appropriate statistical methods. For this purpose, by creating a database of earthquakes in the desired range, appropriate seismic data are selected, completed and processed. Seismic data processing is based on the Poisson process assumption (Cornell, 1968). With this assumption, the rate of occurrence of earthquakes in the time period is constant and earthquakes will be independent events from each other. In this case, all foreshocks and aftershocks are removed from the region's earthquake data to calculate seismic parameters. The magnitude-frequency relationship of earthquakes has been estimated by different methods, and the most appropriate form of functions is the Gutenberg-Richter distribution (Gutenberg and Richter, 1956) and the statistical method of maximum likelihood estimation. Gutenberg-Richter relationship constant coefficients including α and β seismic parameters as well as M_{max}, return period and earthquake occurrence probability magnitudes in different time periods are also calculated using different methods.

Main tectonic in-situ stress: According to the active tectonics of the region, the earthquakes (distribution and magnitude), the estimation of the axis direction of the average compressive stress of new construction in this area does not lead to acceptable results. The studies carried out in the area around the Dehdasht region in the southeast location of the tunnel construction indicate an acceptable compatibility of the estimation results of the major stress axis of the new construction with the results of the modeling of the folds axis. In more precise words, from the above study, it is concluded that the temporal changes along the axis of the main stress during the Alpine orogeny in the above range were less than 10 degrees. Assuming that the above conclusion is not general in the Zagros area, by analyzing the axis of the folds in the area under study, the direction of neo-structural stress in this area can be accurately estimated. The mean alignment of the horizontal image of the stress axis, which is equal to calculated.

Earthquake focal mechanism and newly constructed stress field: Fig. 3 shows the model prepared from the mechanisms of the most important earthquakes that occurred in the area under study. The recorded and analyzed earthquakes are concentrated in the area of the tunnel in the fold-erosion-fault belt of Zagros which the earthquakes mechanism occurring in this area mainly have a thrust or a thrust with a right-slip. On the other hand, the dominant trend of these earthquakes, which are all relatively large events in the area, in the northwest-southeast direction and on their center is compatible with the tectonic trend of the Zagros fault or the main faults of central Iran.

Seismic data of the studied area: Earthquakes indicate the amount of seismic activity in each region, and a careful study of the event process can be a suitable approach in estimating seismicity (Azarafza and Mehrnahad, 2011). So, it is necessary to collect the information of earthquakes in the desired area, to estimate and investigate the seismic characteristics of these events by using appropriate probabilistic methods. For this purpose, the earthquake events list in area is collected and after selecting the appropriate information, these data are completed and processed. However, due to its proximity to the Zagros seismic zones and the central Iran zone, the seismic-seismic-structural features of this zone are strongly affected by the tectonic and seismic-seismic features of these two zones.

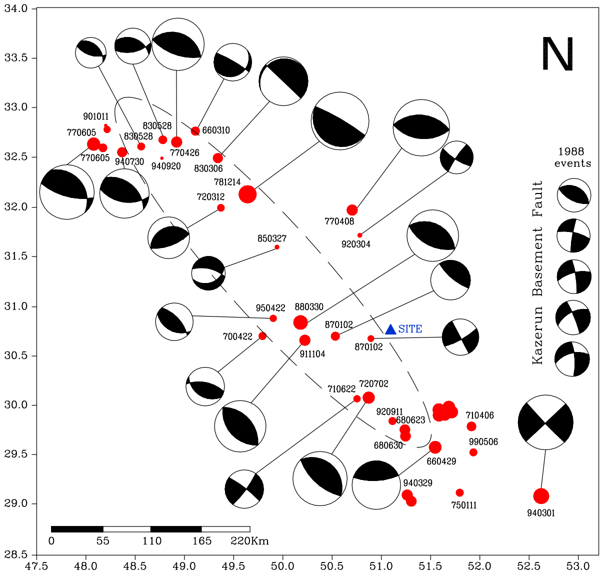

Figure 3. The model of earthquakes mechanism around the tunnel

Despite the history of earthquakes in the Zagros area, the probability of high magnitude earthquakes (Ms>0.7) in this area is low. Unlike Zagros, central Iran has larger earthquakes with longer return period and greater focal depth (Ambraseys and Melville, 1982). The seismic characteristics of the studied area are affected by the two zones of Zagros and Central Iran features in such a way that by advancing towards the northeast and east, the strength and return period of earthquakes increase. But in the west and southwest, earthquakes have less intensity and shorter return period.

Historical seismic data: Having a relatively accurate estimate of the earthquake risk for a specific building requires an accurate study of the occurrence of historical earthquakes in the studied area. Due to the relative shortness of the recorded earthquakes period (about one hundred years) compared to the recurrence period of large earthquakes, it is necessary to use historical earthquakes in these calculations. Also, to clarify some parameters needed in the calculations, such as the depth of earthquakes distributions, the distance to the upper level of the seismic layer, the way of reducing the seismic waves in the crust of the region, etc., a descriptive study of the effects of past earthquakes is necessary (Berberian, 1995). Such tasks are the way to find relatively seismic design parameters for safe design and stability control of tunnels. The main references used in this section include “History of Iran's Earthquakes” (Ambraseys and Melville, 1982) and “The First Catalog of Iran's Earthquakes and Natural Phenomena” (Berberian, 1995).

The 20th century seismic data: With the beginning of the 20th century, systematic earthquakes recording began. After several decades, this led to the creation of seismographic networks and relatively regular reporting of earthquake source parameters (Berberian, 1995). The initial estimation from the center of the earthquakes was associated with a significant error due to various reasons including the small number of devices, inappropriate azimuth coverage and the low accuracy speed models used, which gradually increased the accuracy of the location of the events with the relative reduction of these deficiencies (Aki and Richards, 2009). The amount of the above error reached 15 km in the 1960s and 10 km in the 1970s (Scholz, 2002). In addition to such reports, which were based on the reading of remote seismic maps, case studies of relatively large earthquakes also provided researchers with a valuable set of data. In general, the seismic data of the 20th century refers to the earthquakes that occurred between 1900 and 1963 (Gadallah and Fisher, 2004). Considering this interval apart from the current reading interval is related to the error of primary devices in global seismographic networks. This category in seismic geotechnical studies has its own percentage of error, which is assigned a suitable standard deviation and multiplication values in the statistical equalization of seismic analysis. Anyway, based on the data recorded by seismographic networks around the world such as international seismological centre (ISC), US geological survey (USGS) and international institute of earthquake engineering and seismology (IIEES), the list of earthquakes of the 20th century in the study area of collection and after homogenization is presented in the appendix.

Recent seismic data: The data of the earthquakes that occurred since 1963 are classified in one category due to the implementation of the global coherent network and the improvement of the accuracy of seismograph devices, standardization and recording with high sensitivity all over the world (Gadallah and Fisher, 2004). In the construction area of Gulab 2 tunnel, based on the radial buffering system.

Seismic springs in tunnel site: Seismic sources are used to classify and categorize earthquakes that occur under the influence of faults in the region. Based on this, seismic sources are divided into linear, regional and point sources. According to the definition for linear seismic sources, it can be said that it refers to earthquakes that occur with an almost linear distribution. These sources indicate a main fault causing earthquakes in an almost linear direction. Also, for regional sources, it can be stated that it is characterized by earthquakes that occur with regional distribution. These sources represent the effect of two or more active faults that affect the area. These faults can be activated by themselves or under the action of the main and larger faults of the area. For point sources, as their name indicates. Single earthquakes in areas far from the concentration of earthquakes that occurred under the effect of a sub fault or a hidden or blind fault are referred to. Seismic sources have been identified in the area of Gulab 2 tunnel construction with the help of buffering system of homogeneous seismotectonic zones and the prepared maps are presented below.

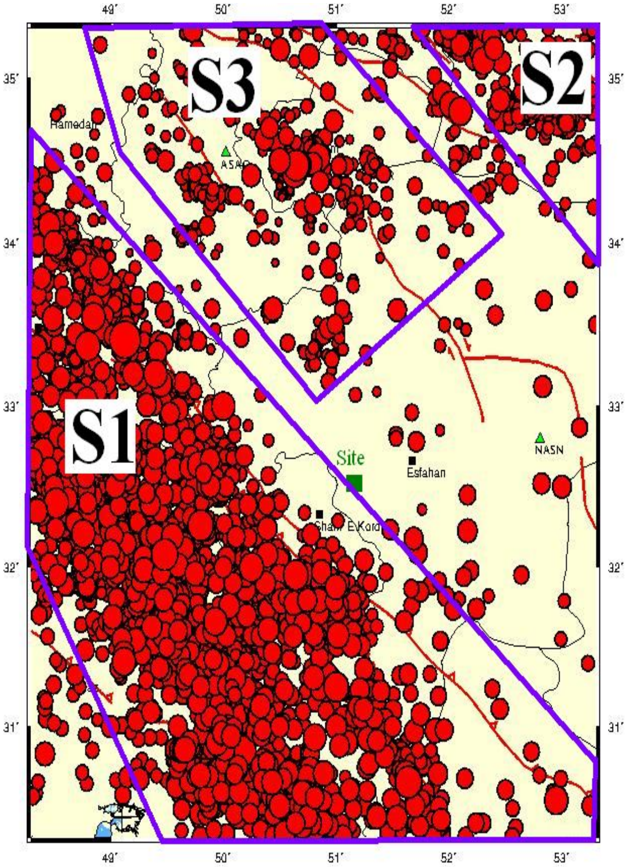

Figure 4. Seismic sources identified in the tunnel area

4. Results and Discussions

The most commonly used parameter is the maximum PGA values which, although it cannot fully answer the dynamic response of the structure, but its increase is always equivalent to a greater seismic risk for the structure (Bozorgnia and Campbell, 2004). At this level of studies, various deterministic and probabilistic methods have been used in order to estimate the M_{max} values of ground motion acceleration at the entrance, center and exit of the tunnel. The most important things that need to be considered in the estimation of this parameter and the analysis of earthquake risk in the mentioned methods are the following parameters (Bozorgnia et al., 2008):

- Selection of appropriate reduction relations.
- Preparation of a model of important seismic springs in relation to the entrance, center and exit of the tunnel.
- Estimating the seismic power of each of the springs.

Estimating the seismic parameters in the tunnel area is compatible with the activity of the identified seismic springs and used in the calculations. In applied methods, the values of the expected parameters of the ground movement caused by the earthquake can be calculated by attenuation relationship models. These relationships show the reduction of seismic waves during their passage from the source of the earthquake to the desired location, and between the parameters of the powerful movement of the earth such as acceleration, speed, displacement, response spectrum, etc. (Campbell, 2003). Attenuation relations are generally obtained in two theoretical ways by using structural earthquake models and experimentally by performing statistical studies on the accelerogram bank resulting from real earthquakes. In the simplest form of these relationships, the parameters of the ground movement, which often follow a logarithmic distribution, are expressed as functions of different scales of magnitude and distance from the seismic source.

In the probabilistic seismic hazard analysis method (PSHA) of earthquake risk, analysis based on all possible situations of the probable earthquake magnitude on the effective seismic springs in the desired area and at all possible distances from the studied building, considering each combination. As a result, by using the probabilistic method, it becomes possible to estimate the potential of the powerful movement of the earth by considering the specific additional probability. In this method, it is possible that the uncertainty of each parameter can be estimated and quantified, and earthquake risk analyzes can be used in order to more realistically estimate the seismic nature of the powerful earth movement (Howell, 1980). In general, the method are contain four steps including the seismic springs identification, return period determination or earthquake event recurrence relations, earthquake event distribution, magnitude and average frequency for each source, selection of attenuation relations, calculation of the earthquake risk.

In this method, the analysis of earthquake risk is based on standard PSHA method introduced by Cornell (1968) and the relations provided by Bender and Perkins (1987), which are presented in the form of the Seisrisk-III program. In this way, the increase probability of the desired parameter of the ground movement (acceleration or response spectrum of acceleration, and speed) is calculated by attenuation relationship selected in the studied location. The most important features of this method can be mentioned as follows (Bender and Perkins, 1987):

- Assign seismic parameters independently, in a group or in a region to seismic springs,
- Modeling and classify sources or seismic zones based on seismic characteristics.
- Calculate the boundary error of springs in seismic regions,
- Entering the maximum magnitude and threshold for the seismic power of each fault,
- Estimation of the maximum values of ground motion parameters based on the return period and the expected increase probability,
- The accurate modeling of springs and seismic zones in terms of geometrical characteristics.

Based on the Campbell and Bozorgnia (2012) attenuation relationship, the M_{max} values of horizontal acceleration in the return period of 500 and 1000 years are considered as DBL and MDL.

At this level of studies, the most important parameter of the powerful earth movement in controlling the design of the structure, in front of the earthquake risk, is the maximum acceleration values for the horizontal and vertical components. In order to estimate the seismic design engineering parameters of Gulab 2 tunnel based on ICOLD recommendations, the results of the probabilistic method to introduce the seismic design levels DBL, MDL and the results of the deterministic method to introduce the seismic design level MCL have been used. The maximum suggested values for different levels of seismic design for the tunnel span in different parts are given below.

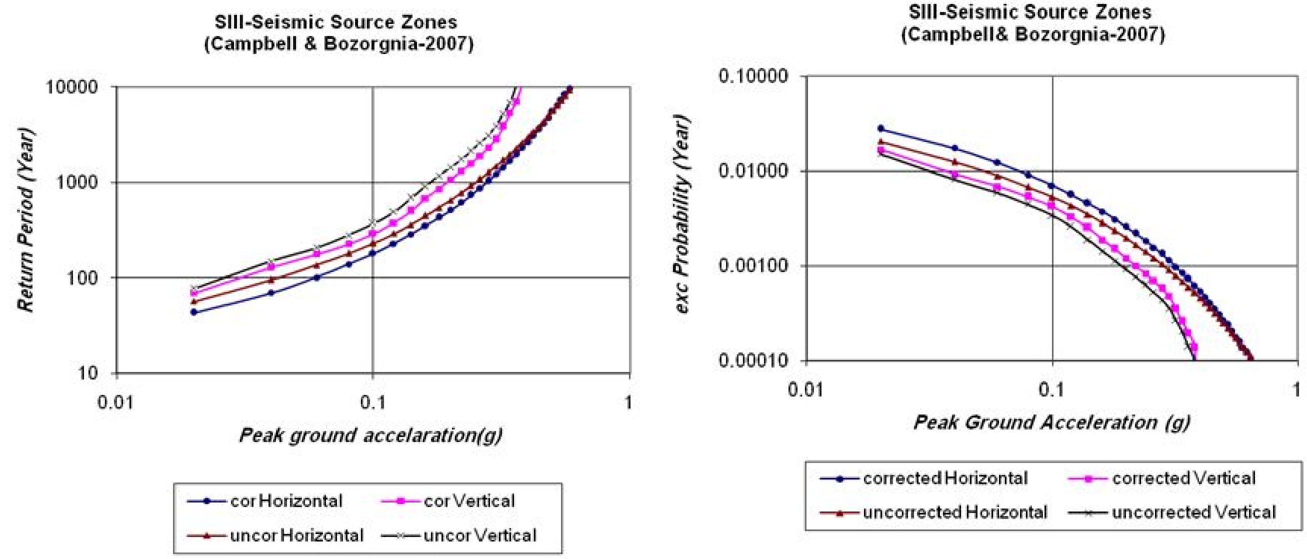

Figure 5. Return period and increase probability of the M_{max} values of horizontal and vertical acceleration in both corrected and uncorrected form at the entrance of the tunnel based on PSHA model

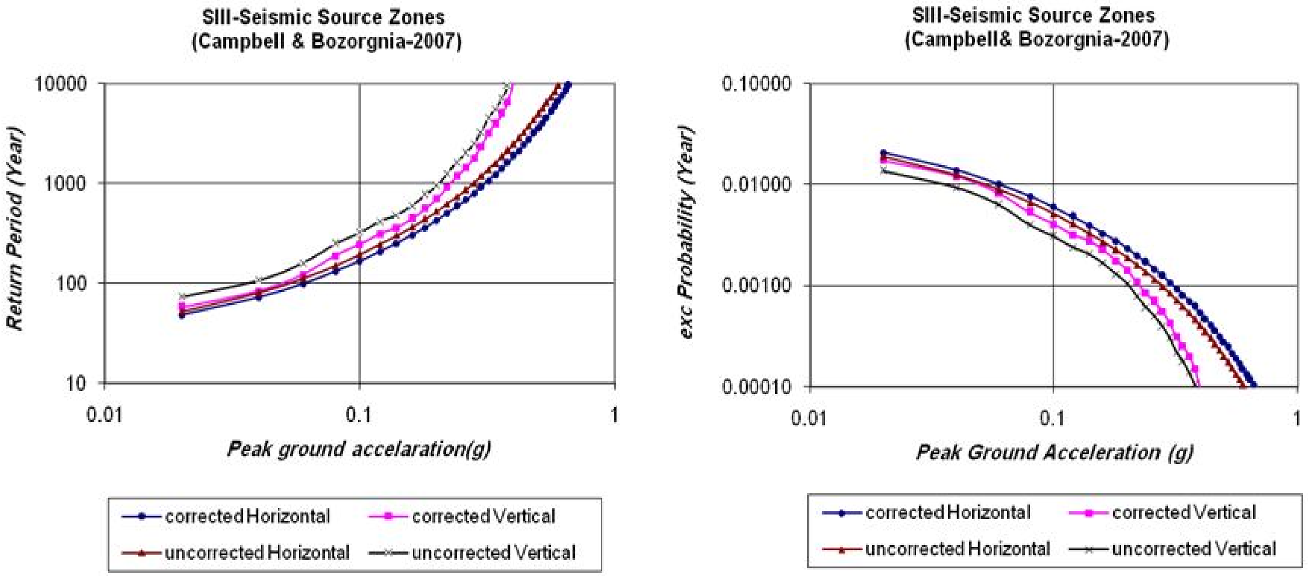

Figure 6. Return period and increase probability of the M_{max} values of horizontal and vertical acceleration in both corrected and uncorrected form at the center of the tunnel based on PSHA model

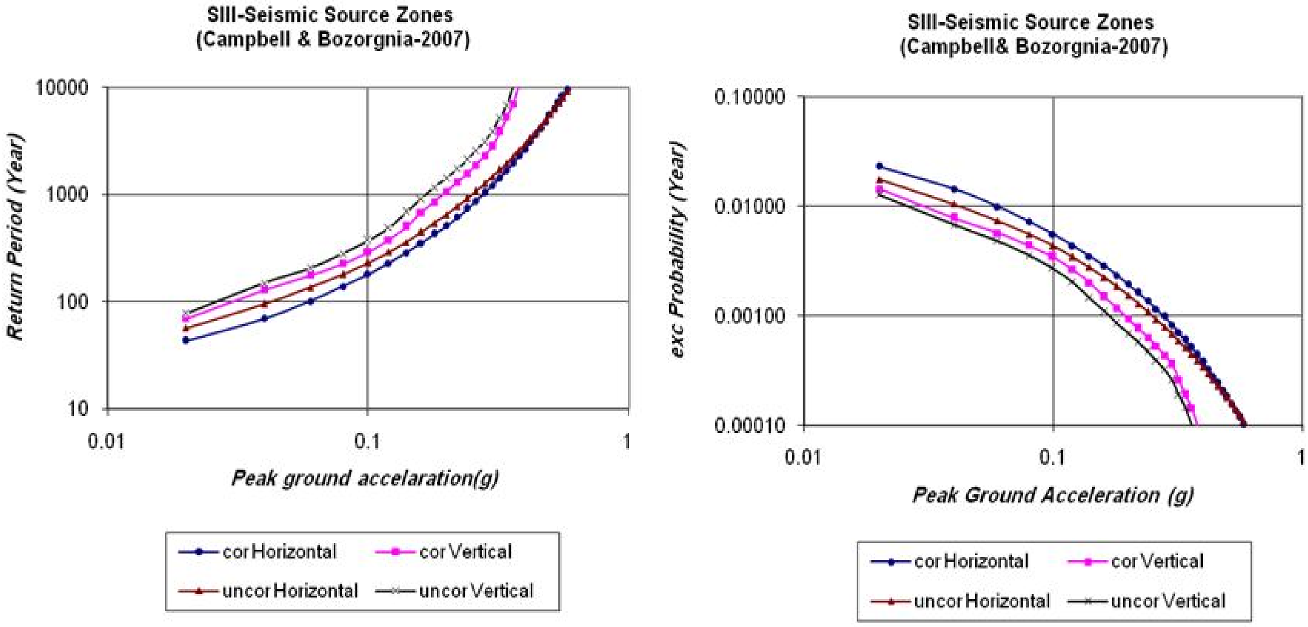

Figure 7. Return period and increase probability of the M_{max} values of horizontal and vertical acceleration in both corrected and uncorrected form at the exit of the tunnel based on PSHA model

Table 1. Maximum acceleration of PGA in 100 years for different levels of seismic design at the entrance of the tunnel

Design levels	PGA (g)			
	Horizontal acceleration		Vertical acceleration	
	corrected	uncorrected	corrected	uncorrected
DBL	0.20	0.33	0.14	0.16
MDL	0.29	0.32	0.19	0.22
MCL	0.38	0.47	0.26	0.31

Table 2. Maximum acceleration of PGA in 100 years for different levels of seismic design at the center of the tunnel

Design levels	PGA (g)			
	Horizontal acceleration		Vertical acceleration	
	corrected	uncorrected	corrected	uncorrected
DBL	0.20	0.22	0.14	0.17
MDL	0.28	0.32	0.21	0.23
MCL	0.34	0.43	0.24	0.28

Table 3. Maximum acceleration of PGA in 100 years for different levels of seismic design at the exit of the tunnel

Design levels	PGA (g)			
	Horizontal acceleration		Vertical acceleration	
	corrected	uncorrected	corrected	uncorrected
DBL	0.17	0.20	0.12	0.14
MDL	0.25	0.28	0.17	0.20
MCL	0.29	0.38	0.20	0.24

5. Conclusion

The results of seismic analysis of Gulab 2, the following can be parametrically expressed:

A) The most important source of earthquakes in relation to the construction of the dam, in terms of creating the M_{max} of the PGA, at a distance of 4 km from the entrance of the tunnel.

B) The main mechanism of earthquakes in the studied area (especially in the Zagros zone) in accordance with the structural trends of the region is of compressional type on the nodal surfaces in the northwest-southeast direction.

C) Based on the PSHA modeling of the axis of the folds in this area, the average alignment of the horizontal image of the main compressive stress axis during the intensity of the folds is estimated to be 224±9°. It seems that the newly constructed stress axis has a similar value within the estimation error.

D) For MCL level, the most important seismic scenario is based on the PSHA method, the maximum horizontal acceleration at the entrance, center, and exit of the tunnel is 0.47 g, 0.43 g, and 0.38 g, respectively.

E) Based on the PSHA method, the model of the seismic springs, DBL level equal to 0.23 g and 0.16 g and for the MDL level equal to 0.32 g and g 0.22 is calculated.

F) For MDL level, the most important seismic scenario is based on the PSHA method, the maximum values of the horizontal and vertical acceleration of PGA in the center of the tunnel is equal to 0.22 g and 0.17 g and for the MDL is equal to 0.28 g and 0.20 g.

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