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Araştırma / Research

EARTHQUAKE RISK ANALYSIS AND DAMAGE ASSESSMENT OF DISTRICTS OF ISTANBUL

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ABSTRACT

The main purpose of this study is to obtain the seismo-tectonic characteristics of Istanbul, based on earthquake risk and vulnerabilities of existing structures against a potential earthquake in the region. The hazardous areas of Istanbul with the distribution of structural damage due to different possible earthquake magnitudes with different return periods are determined and hazard maps are produced for the selected 30 districts of Istanbul. By using the Gumbel-Gutenberg-Richter approaches, in order to estimate the maximum magnitude of a possible earthquake to occur in Istanbul within a prescribed period, four different scenario earthquakes are developed according to four different return periods of 25, 50, 75 and 100 years and the earthquake risk for the province of city of Istanbul is obtained. As a result, this study reveals the damage distribution in the selected districts of Istanbul by the help of the estimated possible future earthquakes.

Keywords: Earthquake, hazard map, probabilistic seismic analysis, damage estimation

İSTANBUL İLÇELERİNİN DEPREM RİSK ANALİZİ VE HASAR DEĞERLENDİRMESİ

ÖZ

Bu çalışmanın temel amacı deprem riskine ve mevcut yapıların bölgedeki potansiyel bir depreme karşı zayıflıklarına dayalı olarak İstanbul'un sismo-tektonik özelliklerini elde etmektir. Farklı geri dönüş süreleri ile olası deprem büyüklükleri nedeniyle oluşacak yapısal hasarın dağılımıyla İstanbul'un riskli alanları belirlenmiş ve İstanbul ili için seçilen 30 ilçe için risk haritaları üretilmiştir. Gumbel-Gutenberg-Richter yaklaşımlarını kullanarak, İstanbul'da olası bir depremin öngörülen periyotta maksimum büyüklüğünü tahmin edebilmek için, 25, 50, 75 ve 100 yıllık dört farklı dönüş periyoduna göre dört farklı senaryo deprem geliştirerek, İstanbul için deprem riski elde edilmiştir. Sonuç olarak, bu çalışma tahmin edilen olası depremlerin yardımıyla İstanbul'un seçilmiş ilçelerindeki hasar dağılımını ortaya koymaktadır.

Anahtar Kelimeler: Deprem, risk haritası, olasılıklı sismik analiz, hasar tahmini

1. INTRODUCTION

Earthquakes are one of the most important hazards which affect large areas, cause devastating damages to structures and infrastructures, induce injuries and losses of lives and result in huge socio-economic losses. Earthquakes have low probabilities of occurrence and long return periods such as 30, 50, 70, 200 and 350 years, but because of their serious risk and grave consequences, there is a breadth of research on the occurrence possibilities and estimation of the hazards of future earthquakes. However, the forecast of a specific earthquake at a certain time, space with certain magnitudes is neither easy nor exact. Therefore, several definitions and earthquake prediction methods are developed by many researchers throughout the time.

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Earthquake prediction types can be mainly classified as a deterministic prediction, specific earthquake prediction, specific magnitude prediction, time-dependent seismicity and time-independent seismicity [1]. Among these models, by the specific magnitude prediction, the possible future earthquake magnitudes can be estimated by the relationship between the magnitude and historical earthquake data in any given region by a statistical analysis. Statistical analysis of the earthquake data is one of the approaches assessing the earthquake hazard. There are many quantitative methods used to estimate the seismicity of a region but the most common methods are the Gutenberg-Richter relationship and the Gumbel's probability distributions [2,3].

Besides, for seismic risk analysis, capacity curves and damage probability matrices are the two most common tools used to characterize the relationship between an earthquake intensity and structural damage. In the case of earthquakes, the capacity spectrum method allows characterizing the interaction between the seismic demand and the building [4-6]. Capacity spectrum based methods are also used for assessing the seismic risk of existing buildings [7-10]. In this method, an earthquake is defined by the 5% damped elastic response spectrum and buildings are defined by means of capacity curves obtained by using pushover analysis. When the response of the structure is dominated by the fundamental mode of vibration, the capacity curve can be expressed in the acceleration displacement response spectrum scheme. These spectral values define the so-called capacity spectra and are named as capacity diagrams [11,12].

Turkey is one of the most seismically active countries in the world and Istanbul is the biggest metropolitan city of the country with a significant cultural heritage and a population of over 15 million inhabitants. Istanbul is situated on the North Anatolian Fault and has been affected by earthquakes throughout its history. Since there are serious forecasts of future seismic activities around the city, hazard estimation and risk projection of possible earthquake scenarios in Istanbul have received widespread attention.

Thus, the basic idea underlying this study is to establish a probabilistic evaluation procedure to assess the maximum magnitude of a possible earthquake to occur in Istanbul within a prescribed period by considering the past earthquake magnitudes and to determine the hazardous areas with the distribution of structural damage due to different possible earthquake magnitudes with different return periods. For the reinforced concrete (RC) buildings located in the selected region, the probabilities of slight, moderate, extensive and complete damage are calculated using the appropriate capacity curves for the specific building type. As a result, expected damage assessment for each scenario is exerted from a probabilistic perspective.

2. METHODOLOGY

2.1. Probability Analysis of Earthquake Magnitudes

This study consists of two main parts including probability analysis of earthquake magnitudes and damage estimation, respectively. The region under consideration consists of 30 districts of Istanbul as listed in Table 1.

Table 1. Studied districts of Istanbul

Adalar	Beykoz	Çatalca	Güngören	Küçükçekmece	Şişli
Avcılar	Beyoğlu	Eminönü	Gaziosmanpaşa	Maltepe	Tuzla
Bahçelievler	Beşiktaş	Esenler	Kadıköy	Pendik	Ümraniye
Bakırköy	Büyükçekmece	Eyüp	Kartal	Sarıyer	Üsküdar
Bağcılar	Bayrampaşa	Fatih	Kağıthane	Silivri	Zeytinburnu

For the probabilistic seismic assessment of the selected region, Gumbel-Gutenberg-Richter approaches are used to model extreme earthquakes. Gutenberg and Richter described a methodology for estimating the magnitudes of the future earthquakes by a statistical scheme. The number of annual earthquakes, N, having magnitudes greater than or equal to M, is given by Eq. (1)

$$\log N = a - bM \quad (1)$$

where a and b are the regression coefficients. As it can be seen from Eq. (1), the magnitude of earthquakes in the observation period does not depend on the parameter a. In order to model extreme earthquakes, Gumbel's yearly maxima method is applied. The cumulative distribution function of the occurrence of the magnitude M proposed by Gumbel is presented by Eq. (2)

$$G(M) = e^{-\alpha e^{-\beta M}} \quad (2)$$

where α is the average number of earthquakes per year with magnitudes higher than zero and β is the inverse of the average magnitude of earthquakes in the studied region. According to the Gumbel approach, risk probability, P_r, is expressed by Eq. (3).

$$P_r(M) = 1 - G(M) \tag{3}$$

In order to define the Gumbel parameters α and β, the correlation between Gutenberg-Richter and Gumbel given in Eq. 4 is used.

$$N = -\ln G \tag{4}$$

By using this relation, a and b regression coefficients in the Gutenberg-Richter Method will be applied to the Gumbel Method to obtain α and β. Their expressions are as follows:

$$\alpha = 10^a \tag{5}$$

$$\beta = b/\log e \tag{6}$$

By the help of Gumbel parameters, it is possible to obtain the average return period of an earthquake of magnitude M as given in Eq. (7)

$$T(M) = (\alpha e^{-\beta M})^{-1} \tag{7}$$

In the light of the methodology given above, to begin with, an instrumental earthquake catalog of the selected region covering the time span between 1905 and 2004 is taken from the Boğaziçi University, Kandilli Observatory and Earthquake Research Institute [13]. The location of the epicenter is assumed to be close to Bakırköy in the Marmara region with a location of 40.90 latitudes and 28.70 longitudes. The earthquakes with magnitudes higher than 4 are selected. Extreme magnitudes are estimated and return periods for different magnitudes are calculated along with the exceedance probabilities. The probability of exceedance results is given for the return periods of 25, 50, 75 and 100 years in Figure 1 and they are assumed as the earthquake scenarios for the damage estimation and risk analysis.

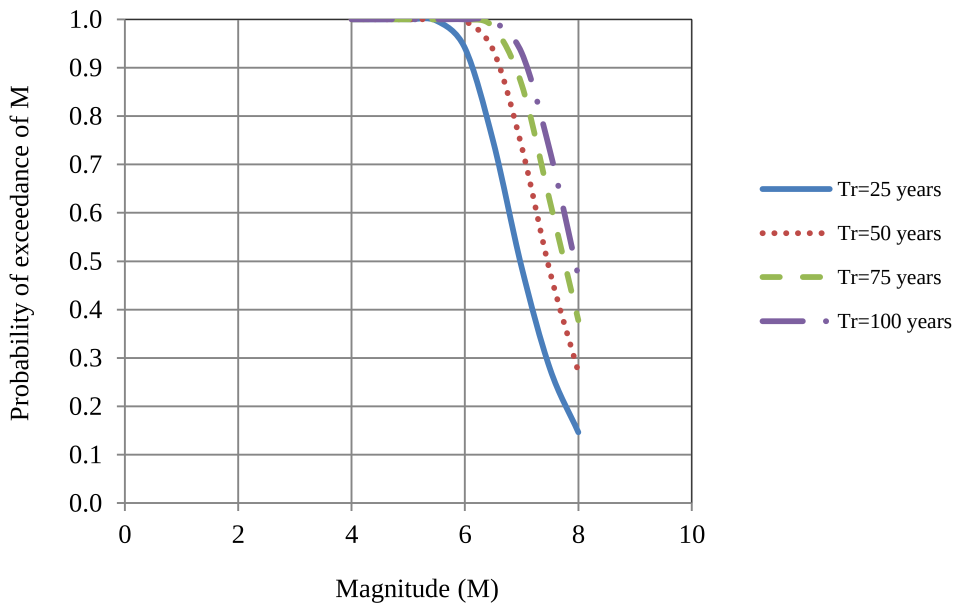

Figure 1. The probability of exceedance of M with respect to return periods

2.2. Damage Estimation and Risk Analysis

This part of the study contains the probabilistic seismic risk assessment of the selected provinces of Istanbul showing the distribution of the probable structural damage states for different earthquake scenarios. The scenario earthquakes are identified according to the magnitudes with different return periods which are designated as 25, 50, 75, and 100 years. These return periods having maximum magnitudes are obtained along with the exceedance probabilities as summarized in Table 2.

Table 2. The scenario earthquakes and the probabilities of exceeding

	T_r (years)	M_{max}	P_r
1. Scenario	25	6.72	0.63
2. Scenario	50	7.2	0.63
3. Scenario	75	7.48	0.63
4. Scenario	100	7.68	0.63

In this study, only RC frame buildings in the region are taken into consideration. Table 3 shows a summary of building classification with respect to the number of stories in the selected districts. For the damage estimation carried out in this study, buildings are classified into three categories depending on their story numbers as low-rise having 1-3 stories (1-3F), mid-rise having 4-7 stories (4-7F) and high-rise having 8-15 stories (8-15F). As it can be noticed from Table 3, total number of surveyed RC buildings is 538977 of which 219903 are low-rise, 299671 are mid-rise and 19403 are high-rise buildings.

Table 3. Total number of RC buildings with respect to the numbers of stories in the surveyed districts

District Name	Total Number of RC Buildings	Number of Buildings with different numbers of stories			District Name	Total Number of RC Buildings	Number of Buildings with different numbers of stories		
		1-3F	4-7F	8-15F			1-3F	4-7F	8-15F
Adalar	2767	1129	1538	100	Kadıköy	30730	12538	17086	1106
Avcılar	13165	5371	7320	474	Kartal	17594	7178	9782	633
Bahçelievler	18957	7734	10540	682	Kağıthane	19187	7828	10668	691
Bakırköy	8851	3611	4921	319	Küçükçekmece	38452	15688	21379	1384
Bağcılar	34116	13919	18968	1228	Maltepe	19708	8041	10958	709
Beykoz	17034	6950	9471	613	Pendik	28027	11435	15583	1009
Beyoğlu	13762	5615	7652	495	Sarıyer	19270	7862	10714	694
Beşiktaş	9985	4074	5552	359	Şişli	16240	6626	9029	585
Büyükçekmece	3127	1276	1739	113	Tuzla	11302	4611	6284	407
Bayrampaşa	15324	6252	8520	552	Ümraniye	32029	13068	17808	1153
Eminönü	7397	3018	4113	266	Üsküdar	33748	13769	18764	1215
Eyüp	15225	6212	8465	548	Zeytinburnu	13736	5604	7637	494
Fatih	19336	7889	10751	696	Esenler	21051	8589	11704	758
Güngören	10058	4104	5592	362	Çatalca	1434	585	797	52
Gaziosmanpaşa	40486	16518	22510	1457	Silivri	6879	2807	3825	248

The soil type for each district is classified according to National Earthquake Hazards Reduction Program (NEHRP) [14]. Table 4 shows the site classification applied in the study. According to these soil types of NEHRP, the ground classification map of Istanbul region is arranged by Japan International Cooperation Agency (JICA) and the analyses are performed by the help of this map [15].

Table 4. Soil classification

Site Class	Average S Wave Velocity Over Upper 30m
A	>1500 m/sec
B	760-1500 m/sec
C	360-760 m/sec
D	180-360 m/sec
E	<180 m/sec

Spectral response shapes can be constructed for any of the soil types given in Table 4 for various levels of shaking. Maximum considered earthquake spectral response accelerations at 5% damping are calculated by Eq. 8 and Eq. 9 for short period motions centered at 0.2 sec, $S_{MS,}$ and for longer period motions centered at 1 sec, S_{M1}, respectively.

$$S_{Ms} = F_a S_s \tag{8}$$

$$S_{M1} = F_a S_1 \tag{9}$$

The 5% damped S_s and S_1 values for the short period of 0.2 sec. and a long period of 1 sec. are calculated in Eq. 10 and Eq. 11, respectively. A quadratic form is used for the attenuation relation where R is the hypocentral distance, M is the local magnitude and Vs is the surface wave velocity [16, 17].

$$\ln Y = 1{,}089 + 0{,}711(M-6) - 0{,}207(M-6)^2 - 0{,}924 \ln R - 0{,}292 \ln(V_s/2118) \tag{10}$$

$$\text{Ln}\, Y = 1{,}08 + 1{,}036(M-6) - 0{,}032(M-6)^2 - 0{,}798 \ln R - 0{,}698 \ln(V_s/1406) \tag{11}$$

F_a is defined as the amplification factor assigned to each site class. The amplification factor of the acceleration response spectrum is defined at 0,2 sec and 1,0 sec. The soil amplification factor of site class B is defined to be 1,0. Figure 2 shows the modified amplification factor of S_s at 0,2 sec whereas Figure 3 shows the modified amplification factor of S_1 at 1.0 sec.

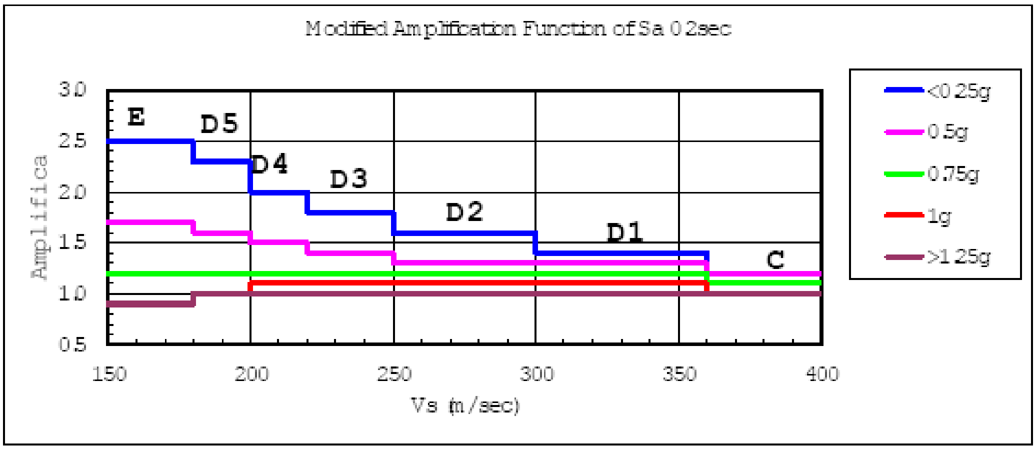

Figure 2. Modified amplification factor at T=0.2sec.

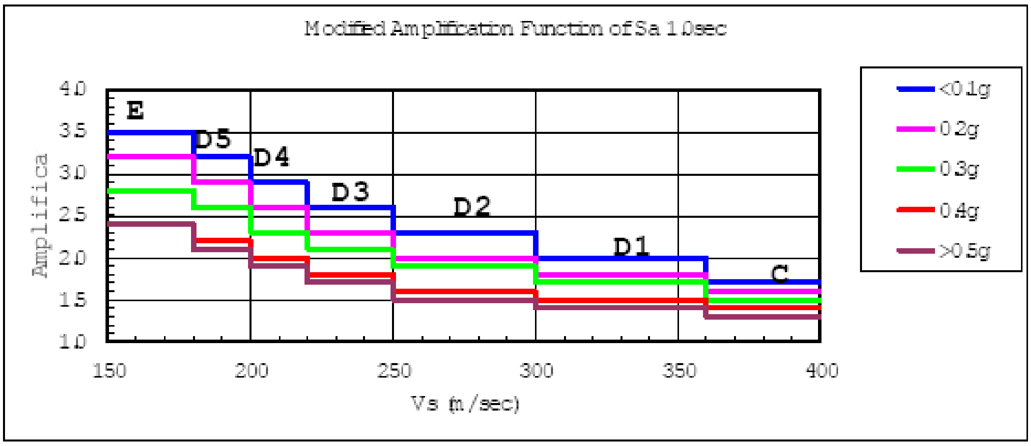

Figure 3. Modified amplification factor at T=1.0sec

The design response spectrum is as indicated in Figure 4.

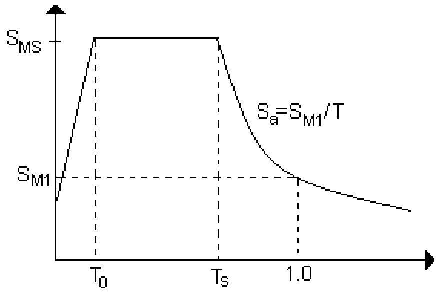

Figure 4. Design Response Spectra

For the design response spectra, T_0 and T_s are expressed as:

$$T_0 = 0{,}2\ \frac{S_{M1}}{S_{Ms}} \tag{12}$$

$$T_s = \frac{S_{M1}}{S_{Ms}} \tag{13}$$

T_s refers to the transition period from the constant acceleration region to the constant velocity region of the code-based elastic acceleration spectrum. For periods less than or equal to T_0, the design spectral acceleration, S_a, is given by Eq. (14);

$$S_a = 0{,}6\ \frac{S_{Ms}}{T_0} T + 0{,}4 S_{Ms} \tag{14}$$

For periods greater than T_s, S_a varies inversely with period as given in Eq. (15).

$$S_a = \frac{S_{M1}}{T} \tag{15}$$

Building capacity curves (push-over curves) are the plot of a building's lateral load resistance as a function of a characteristic lateral displacement. It is derived from a plot of static-equivalent base shear versus building displacement. In order to facilitate direct comparison with earthquake demand, the force (base shear) axis is converted to spectral acceleration and the displacement axis is converted to spectral displacement. Such a plot provides an estimate of the building's true deflection (displacement response) for any given earthquake response spectrum. Thus, building capacity curves, used with capacity spectrum method techniques, provide simple and reasonably accurate means of predicting inelastic building displacement response for damage estimation purposes.

In order to obtain the capacity curve of a structure, push-over analysis should be performed. Since the main aim of this project does not include the dynamic analysis, the results of the push-over analysis are taken from JICA. Figure 5 represents the typical capacity curve of the RC frame structures applied in this study.

In the Capacity Spectrum Method, the spectral displacement demand is obtained through the intersection of the first slope of the capacity spectrum with the so-called "demand spectrum". An alternative approach is developed in connection with the earthquake loss assessment studies carried out for Istanbul [18]. In this approach, the estimation of spectral displacement demand is based on the so-called Displacement Coefficient Method described in FEMA 356 [19]. The inelastic spectral displacement demand, S_{di}, is given as

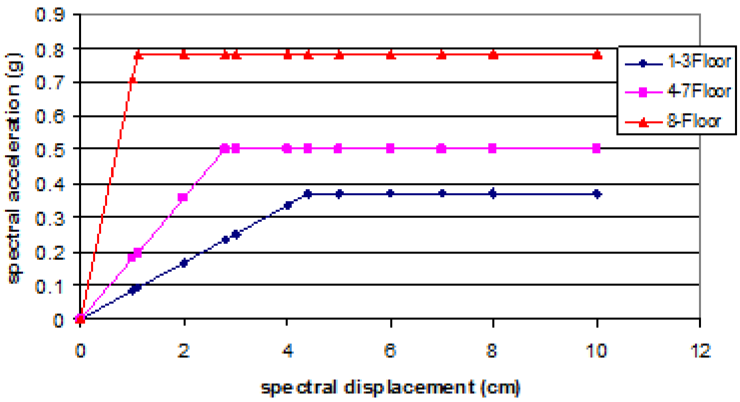

Figure 5. Capacity curve of the RC buildings

$$S_{di} = C_1 C_2 \left(\frac{T}{2\pi}\right)^2 S_{ae}(T) \tag{16}$$

In Eq. 16, C_2 is the spectral displacement modifier and $S_{ae}(T)$ represents the elastic spectral acceleration. S_{di} is obtained by amplifying the elastic spectral displacement by the so-called "spectral displacement amplification factor", which is represented in the referred FEMA documents by the coefficient C_1

$$C_1 = \left[1 + \frac{(R_y - 1)T_s}{T}\right] / R_y \quad (T<T_s) \tag{17}$$

$$C_1 = 1 \quad (T \geq T_s) \tag{18}$$

where R_y represents the strength reduction factor, T is the natural period of the structure. The strength reduction factor R_y is defined as:

$$R_y = \frac{S_{ae}(T)}{S_{ay}} \tag{19}$$

where S_{ay} refers to the yield spectral acceleration defined above. The fragility of structures is defined as the conditional probability of failure at a given value of seismic response parameter which is taken as spectral acceleration here. In the acceleration-displacement demand spectrum, both the structural capacity curve and the demand spectra are plotted in spectral-acceleration versus spectral-displacement coordinates. The procedure compares the capacity of the structure in the form of a pushover curve with the demands on the structure in the form of response spectra. The graphical intersection of the two curves approximates the response of the structure. Hence, Figure 6 and 7 show the results of the capacity spectrum method for the 1st and the 4th scenarios, respectively.

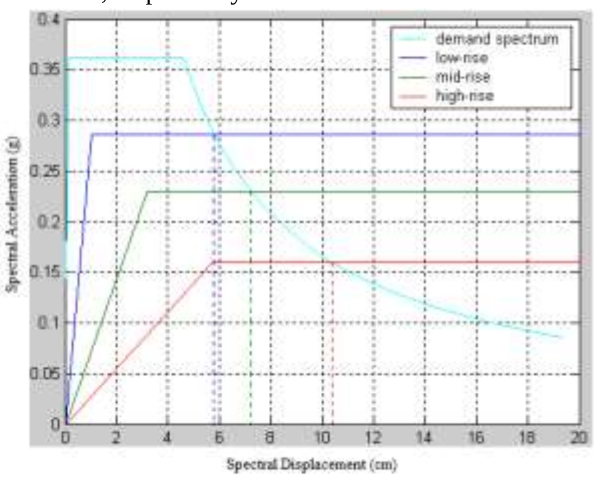

Figure 6. Capacity spectrum for Scenario 1

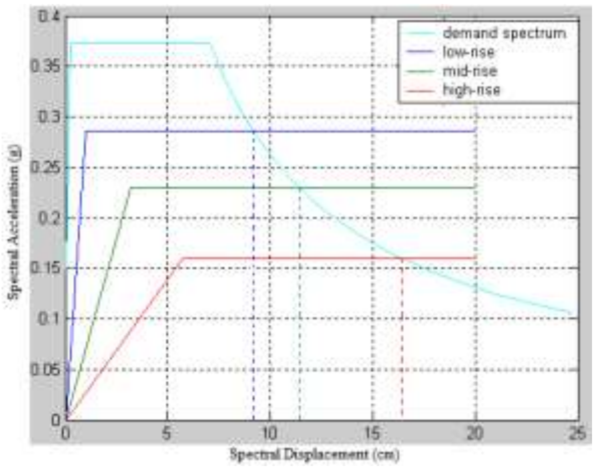

Figure 7. Capacity spectrum for Scenario 4

Building fragility curves are lognormal functions that describe the probability of reaching or exceeding structural damage states, given median estimates of spectral displacement. For any given value of the spectral response, discrete damage state probabilities are calculated as the difference of the cumulative probabilities of reaching or exceeding successive damage states. In this study, damage evaluation is carried out using Fragility Function in which a spectral displacement is applied as a stochastic variable. The seismic fragility is customarily modeled by a lognormal cumulative distribution function as given in Eq. 20

$$P[D \geq d_s S_d] = \Phi[\left(\frac{1}{\beta_{ds}}\right) \ln\left(\frac{S_{di}}{S_{d,ds}}\right)] \tag{20}$$

where D denotes damage, Φ denotes the cumulative standard normal distribution function, β_{ds} denotes the standard deviation of the natural logarithm of the spectral displacement corresponding to the damage state concerned, S_{di} is the inelastic spectral displacement demand and $S_{d,ds}$ is the median value of spectral displacement corresponding to the threshold of the damage state reached. On the basis of the given probability function, 4 fragility curves representing the probable slight, moderate, extensive and complete damage states for low-rise, mid-rise and high-rise RC buildings are generated with respect to the estimated spectral displacements and presented in Figures 8-10.

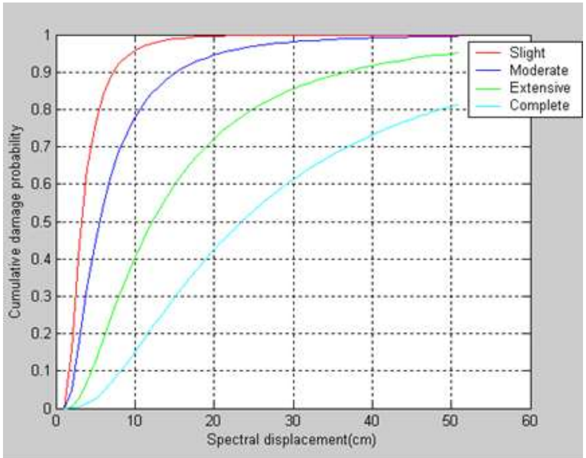

Figure 8. Fragility curves for low-rise RC buildings

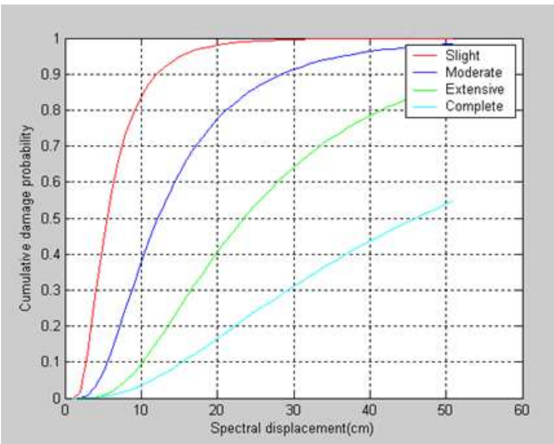

Figure 9. Fragility curves for mid-rise RC buildings

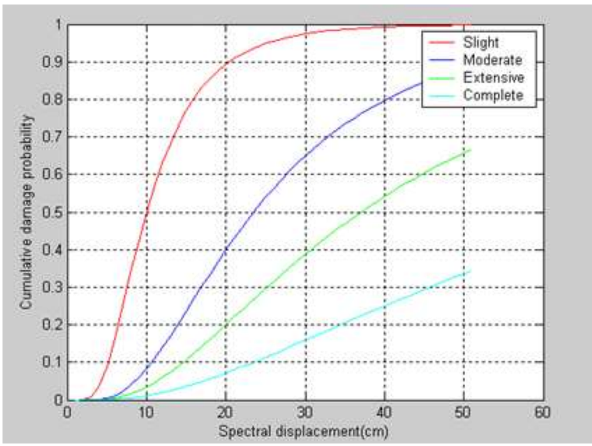

Figure 10. Fragility curves for high-rise RC buildings

3. RESULTS AND DISCUSSIONS

In the present research, by the help of the Gumbel-Gutenberg-Richter approaches, recurrence time period for four scenario earthquakes are obtained by using instrumentally recorded earthquake data. The corresponding scenario earthquake magnitudes are found as 6.72, 7.2, 7.48 and 7.68 for the first, second, third and fourth scenarios, respectively. Building damages in the selected districts are estimated as completely, extensively, moderately and slightly damaged for each of these four earthquake scenarios. According to the first scenario, 2% of the total buildings in the study area are completely and 4% of the total buildings are extensively damaged. In the second scenario, the results show that the damage ratios of completely and extensively damaged buildings are 4% and 8% of the total buildings, respectively. For the third scenario, 6% of the total buildings are completely and 11% of them are extensively damaged. Finally, for the fourth scenario, the ratios for the completely and extensively damaged buildings to the total buildings are estimated as 7% and 12%, respectively. The damage distributions of the damage states are shown in Figure 11.

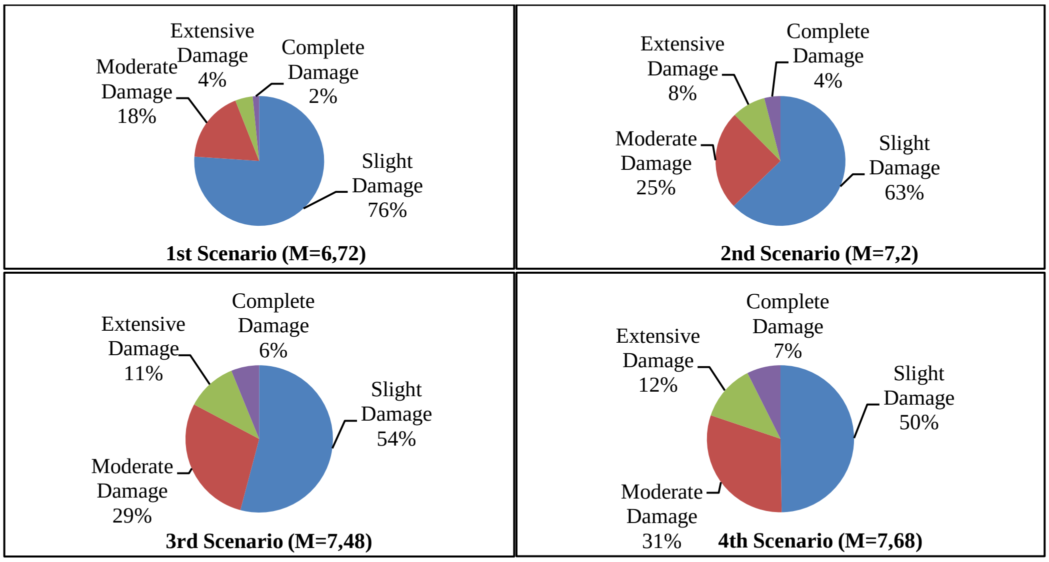

Figure 11. Damage state probabilities for four scenario earthquakes

4. CONCLUSION

Istanbul is a city having a significantly high population. Besides, the city hosts numerous individual buildings and monuments of outstanding importance. As the city is under a risk of a major earthquake in the coming years, it is important to evaluate the statistical probability of the occurrence of a large-magnitude earthquake in Istanbul.

In this study, an application of the probabilistic approach for assessing expected damage and risk under the selected earthquake scenarios is emphasized. In the first part, an instrumental earthquake catalog covering the time span between 1905 and 2004 is used for the calculation of the recurrence time period for a large earthquake. Accordingly, four different earthquake scenarios with different return periods are obtained. Hence, it is seen that the probability of exceedance of any magnitude Mmax within its own return period is always 63%. In the second part, damage state probabilities for each scenario are achieved. It is concluded that the estimated building damages of the 4th scenario which has a magnitude of 7.68 is the worst scenario for Istanbul. Since the estimated magnitude of this scenario is the highest one, the results make sense and are expected. Besides, the results indicate the districts in the southern area of Istanbul are more heavily damaged than the ones in the northern area. Therefore, as a result of this study, it should be noted that the southern coast of the European side is the most severely affected area. Also, it might be preferred to reside in the area which is indicated as hazardous with the assumption of a possible earthquake of 6.72 occurring in 25 years. In addition to this, the difference in damage between one district and another in Istanbul can be attributed to local site amplifications. Therefore, another factor causing the southern part of Istanbul to be more risky than the northern part is the type of the soil.

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