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Probabilistic earthquake risk consideration of existing precast industrial buildings through loss curves

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Abstract. In this study, the earthquake risk assessment of single-story RC precast buildings in Turkey was carried out using loss curves. In this regard, Kocaeli, a seismically active city in the Marmara region, and this building class, which is preferred intensively, were considered. Quality and period parameters were defined based on structural and geometric properties. Depending on these parameters, nine main sub-classes were defined to represent the building stock in the region. First, considering the mean fragility curves and four different central damage ratio models, vulnerability curves for each sub-class were computed as a function of spectral acceleration. Then, probabilistic seismic hazard analyses were performed for stiff and soft soil conditions for different earthquake probabilities of exceedance in 50 years. In the last step, 90 loss curves were derived based on vulnerability and hazard results. Within the scope of the study, the comparative parametric evaluations for three different earthquake intensity levels showed that the structural damage ratio values for nine sub-classes changed significantly. In addition, the quality parameter was found to be more effective on a structure's damage state than the period parameter. It is evident that since loss curves allow direct loss ratio calculation for any hazard level without needing seismic hazard and damage analysis, they are considered essential tools in rapid earthquake risk estimation and mitigation initiatives.

Keywords: hazard analysis; loss curves; seismic risk; vulnerability functions

1. Introduction

Seismic risk assessment and loss estimation are important tools for minimizing the damage caused by earthquakes and post-earthquake preparedness. In addition, seismic risk and loss estimation studies enable public education and awareness raising, estimation of workforce needs for disaster management, budget planning, and systematization of retrofitting practices. The UN-IDNDR program, the RADIUS project, is one of the main sources of earthquake risk assessment and mitigation studies on an international scale. In the study, risk assessment results are presented by calculating the probabilities of physical damage, economic and social losses (UNISDR 2009). Earthquake risk outputs also allow estimating the insurance premium of the building stock for a given earthquake hazard level. At this point, it can be said that the popularity of probabilistic financial risk assessment methodologies has been increasing over the last few decades (Melani *et al.* 2016).

Earthquake risk methodology consists of three main components; earthquake hazard, vulnerability, and exposure model. Many researchers have examined the effects of earthquakes in terms of loss of life, business interruption, and economic loss. Among these studies, more practical and simpler application studies have been carried out concerning the performance-based earthquake engineering (PBEE) methodology developed at the Pacific Earthquake Engineering Research center known as PEER-PBEE (Del Vecchio *et al.* 2018, Cremen and Baker 2019, Papadopoulos *et al.* 2019, Xu *et al*. 2019).

The earthquake risk methodology, proposed by Cornell and Krawinkler and later developed as PEER-PBEE by the Pacific Earthquake Engineering Research Center (PEER) in California, allows the estimation of performance-based, direct or indirect losses (Cornell and Krawinkler 2000). This PBEE-PBEE methodology is widely used in earthquake engineering (Carofilis *et al.* 2020). The triple integration equation developed by PEER for probabilistic seismic risk assessment is often used to estimate the probability of exceeding a performance requirement (Solberg *et al.* 2008). The basic steps of this method are hazard analysis, structural analysis, damage analysis, and loss assessment (Günay and Mosalam 2012).

HAZUS (Multi-hazard Loss Estimation Methodology), designed for national application in the USA, is another risk assessment methodology widely used in many countries today (FEMA H.M.M. 2010). It is a comprehensive study presented by the US Federal Emergency Management Agency (FEMA) in the early 1990s to assess social and economic losses caused by seismic impacts on superstructure and infrastructure. The HAZUS method includes loss functions that enable damage assessment and calculation of various losses (direct loss, loss of life, business interruption, etc.). These functions have been

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adopted by many researchers for use in different regions of the world and considered in various earthquake risk assessment studies (Nastev 2014, Fallah-Aliabadi *et al*. 2020, Mangalathu *et al.* 2017).

Another method used in the seismic risk assessment is the Displacement-Based Loss Assessment (DBLA) (Priestley *et al.* 2007). Based on the direct displacement-based design approach, this method considers the lateral displacement value of the building as the main parameter for the seismic evaluation of the structure. This method, which can be used in the design and evaluation of reinforced concrete precast structures, is also taken into account in the earthquake loss assessment of a certain class of structures (Bosio *et al.* 2020, Torquati *et al*. 2018, Belleri 2017). Finally, important studies in probabilistic earthquake risk methodology can be listed as LESSLOSS, RISK-UE, The World Bank's CAPRA, SYNER-G, GEM and NERA (Calvi and Pinho 2004, Spence 2007, Mouroux and Le Brun 2006, Pitilakis *et al.* 2014a, Pitilakis *et al*. 2014b).

Single-story RC precast buildings are widely used in Turkey's organized industrial zones (OIZ). When the studies conducted for such structures in Turkey are examined, there are many vulnerability/fragility assessment studies. Risk outputs (loss curve) are much less compared to these studies (Yesilyurt *et al*. 2023, Eren and Luş 2015, Khanbabazadeh *et al.* 2020). In order to use fragility curves or vulnerability curves in practice, hazard analysis, building capacity, and earthquake demand values should be known. If these curves are evaluated alone, incorrect evaluations can be made. However, this situation is different in loss probability curves. These curves, which give the direct loss ratio for any seismic hazard level, are tools that even non-engineering experts can use practically.

In this study, the location of Kocaeli in the Marmara region, where seismic hazard is high, is considered. Nine sub-classes were assigned to represent most of this building class in Turkey. The vulnerability curves of these buildings were obtained using four different central damage ratios (CDR), also known as consequence models. Afterward, probabilistic seismic hazard analyses (PSHA) were performed for two different site conditions by taking the investigation time of 50 years for the earthquake hazard level with OpenQuake software. In the last step, 90 loss probability curves were calculated depending on the seismic hazard and vulnerability functions. Subsequently, it is seen that CDRs are highly influential on loss assessment. Therefore, for two different soil conditions, the loss ratio and damage state for each sub-class building are comparatively analyzed by considering the average loss curves.

2. Building type and fragility functions

When the industrial zones in Turkey are examined, it is seen that single-story precast reinforced concrete structures are frequently preferred. The main reasons for this are the advantages of the large internal volume it provides in manufacturing and use, the shorter construction time

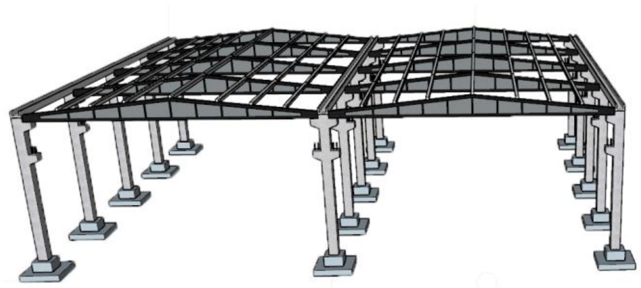


Fig. 1 A general configuration of typical single-story precast RC buildings in Turkey

compared to traditional reinforced concrete structures, and the more economically attractive. Considering the information gathered from the field studies, the general characteristics of existing precast industrial buildings have square cross-section cantilever columns that change from 40 cm to 60 cm tied with precast beams. In general, beam-column connections are pinned by the steel dowels at the top of buildings considered in the study (Yesilyurt *et al.* 2021a). In general, precast RC buildings have symmetrical forms in the plan view, and the height of these buildings varies between 4 and 13 m. The precast roof girder span values of these structures, which have single or multiple spans in the precast roof girder direction, vary in the range of 10-25 m. It has multi-spans in the perpendicular direction of the precast roof girder, and the span dimensions vary between 6 and 10 m (Fig. 1).

Considering the data obtained from the structural projects of the existing buildings, it is determined that hot-rolled ribbed bar S420 steel grade is used for longitudinal and transverse reinforcement in the columns. It is seen that the majority of the concrete class in the columns varies between C30 and C40 concrete class, and the concrete cover is 2.5 cm or 3 cm. It is observed that the stirrup diameter used in the columns was 8 mm, and the stirrup spacing was mostly 10 cm in the seismically active Marmara region. However, in some other regions, for instance, in eastern and south Anatolia regions, it has been observed that in such buildings, the stirrup spacing increases up to 20 cm. In addition, in the site studies conducted after the February 6, 2023, Mw7.8 Pazarcık, Mw7.5 Elbistan earthquakes, it was observed that there were differences between the existing structure and its static project.

Yesilyurt *et al.* (2021b) examined the effect of structural and geometric parameters on fragility curves by considering two different site conditions and 80 widely preferred single-story RC precast industrial building models.

In the current study, nine sub-classes were defined, taking into account these 200 fragility curves. Firstly, probable maximum loss (PML) values were obtained for all buildings by considering the constant earthquake hazard level. Subsequently, the three most effective parameters for structural damage were determined. The first criterion is the confinement condition of the column elements (cross-sectional stirrup configuration), the second criterion is the longitudinal reinforcement ratio, and the last criterion is the

Table 1 Limit values of the criteria considered in the sub-class classification

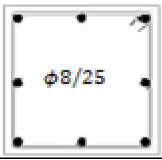
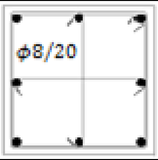
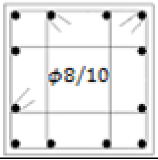
Quality			Period	
Classes	Confinement configuration	Longitudinal reinforcement ratio (ρ_l)	Classes	Period Ranges
Low Quality (LQ)		ρ_l<1.5	Low Period (LP)	$T_{eff} < 1.10s$
Moderate Quality (MQ)		1.5≤ρ_l≤2.5	Moderate Period (MP)	$1.55s \geq T_{eff} \geq 1.10s$
High Quality (HQ)		1.5≤ρ_l≤3.2	High Period (HP)	$T_{eff} > 1.55s$

Table 2 Median (g) and standard deviation values of the log-normal distribution for the subclassification for each damage state

		Slight		Moderate		Extensive		Collapse	
		Median	St.Dev.	Median	St.Dev.	Median	St.Dev.	Median	St.Dev.
HP	Low Quality (LQ)	0.125	0.274	0.218	0.268	0.364	0.263	0.517	0.263
	Moderate Quality (MQ)	0.199	0.260	0.343	0.234	0.571	0.231	0.801	0.227
	High Quality (HQ)	0.277	0.233	0.469	0.232	0.762	0.227	1.074	0.234
MP	Low Quality (LQ)	0.206	0.274	0.368	0.216	0.639	0.203	0.898	0.207
	Moderate Quality (MQ)	0.299	0.254	0.518	0.230	0.872	0.221	1.210	0.206
	High Quality (HQ)	0.386	0.223	0.673	0.200	1.090	0.211	1.479	0.168
LP	Low Quality (LQ)	0.265	0.298	0.473	0.263	0.842	0.252	1.187	0.242
	Moderate Quality (MQ)	0.368	0.287	0.651	0.262	1.105	0.244	1.533	0.228
	High Quality (HQ)	0.539	0.252	0.946	0.255	1.538	0.246	2.145	0.245

effective period of the first mode of the structure to be obtained by considering the cracked section stiffness defined in TBSDC-2018. The confinement condition and longitudinal reinforcement ratio of the structure are associated with quality, while the column dimensions, roof weights, and truss span length are associated with the period parameter and are given in Table 1. The median and standard deviation values of the mean fragility curves of the nine sub-classes are given in Table 2 as a function of spectral acceleration.

3. Seismic risk assessment methodology

Seismic risk estimation studies are critical for rational realization of various activities such as risk mitigation and emergency planning. In the earthquake risk methodologies available in the literature, the seismic risk is computed based on the ground motion intensity value obtained from probabilistic or deterministic seismic hazard analysis. In general, for a given earthquake hazard level "im", the probability of damage "P(D>d)" expresses that the obtained damage value "D" probability of exceeding the predefined damage level "d", Eq. (1).

$$P(D > d) = \int P(D > d|IM) \times d\lambda(IM > im) \quad (1)$$

$P(D > d|IM)$ represents the fragility/vulnerability function of the considered building, while $\lambda(IM > im)$ represents the seismic hazard of site. Based on the three

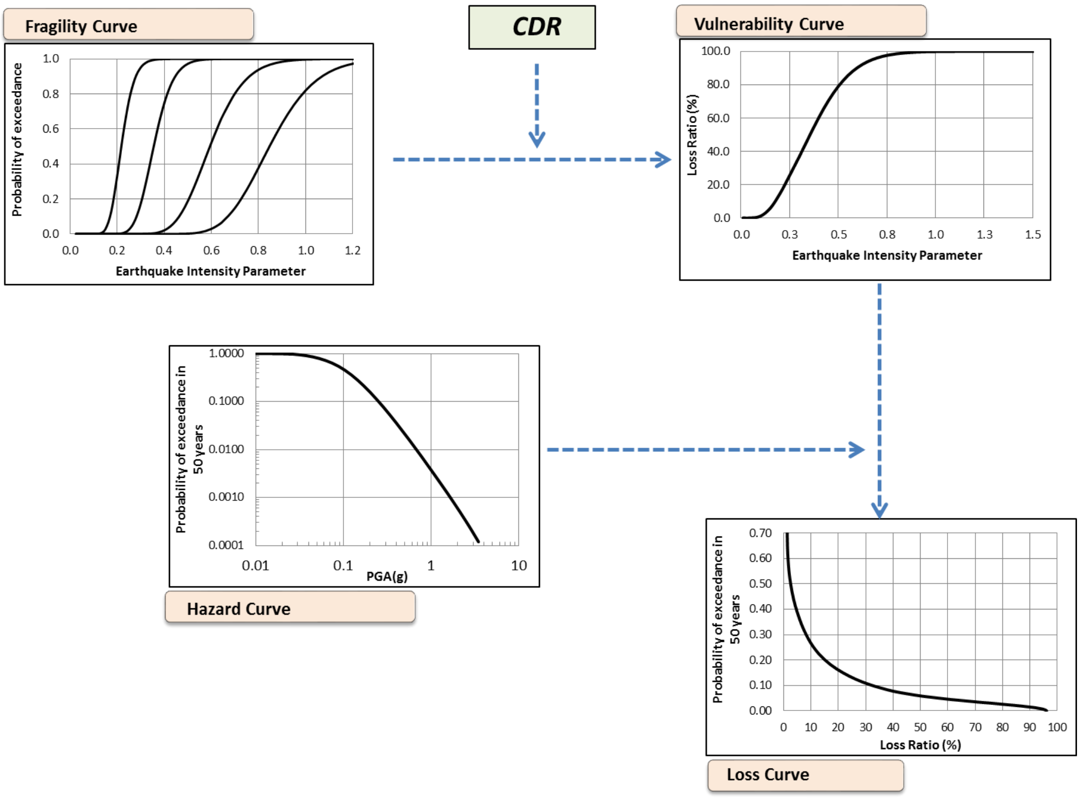


Fig. 2 Steps in the current PSHA-based risk assessment framework

integration methodologies presented by PEER-PBEE, the basic steps of the earthquake risk assessment study for a single-story precast reinforced concrete industrial building are given below. A graphical representation of the methodology is given in Fig. 2.

- Obtaining Damage Probability Matrix (DPM) values for a given ground motion Intensity Measure using mean fragility curves
- Calculation of vulnerability curves for each sub-class via mean fragility curves and different CDR factors,
- Estimation of the rate of exceeding the ground motion intensity measure for different recurrence periods by probabilistic seismic hazard analysis for the considered region,
- Damage Analysis, calculating the PML value for a given Intensity measure (IM) and repeating these calculations for each increment of the IM,
- Finally, by taking the investigation time of 50 years for the earthquake hazard level, for different exceedance probabilities, the relationship between the exceedance probability and the loss ratio value is defined in a discrete form, then the continuous curve is obtained by interpolating these points.

3.1 CDR and vulnerability curves

Seismic vulnerability assessment is calculated separately for each building class, and/or each building class is sub-classified within itself. Moreover, considering the engineering practices, it is known that the same building class varies from region to region. Therefore, the seismic vulnerability assessment by an analytical method is performed separately for different types of structures in each different region.

The fragility curves express the probabilities of exceeding the different damage states considered for a given intensity level. In other words, these curves represent the damage probability distributions of the structure. The vulnerability functions for a given structure are obtained using the fragility curves and CDR. A curve expresses these functions with damage ratio (DR) on the vertical and earthquake intensity parameters on the horizontal axis. As a result, the probabilistic representation of damage is expressed by a single curve.

In a seismic risk assessment, damage ratio (DR) has been defined to find the financial equivalent of possible damage. DR is the ratio of the cost to repair structural damage to the cost to rebuild the structure. Lower and upper limit values of DR are defined for different possible damage

Table 3 CDR factors considered in the study

Intact	Central Damage Ratio (%)			
Damage States	DEE-KOERI (2003)	Askan and Yucemen (2010)	Bal *et al.* (2008)	Gurpinar *et al.* (1978)
NONE	5	0	0	0
Slight	20	5	16	5
Moderate	50	30	33	30
Extensive	80	85	100	70
Collapse	100	85	100	100

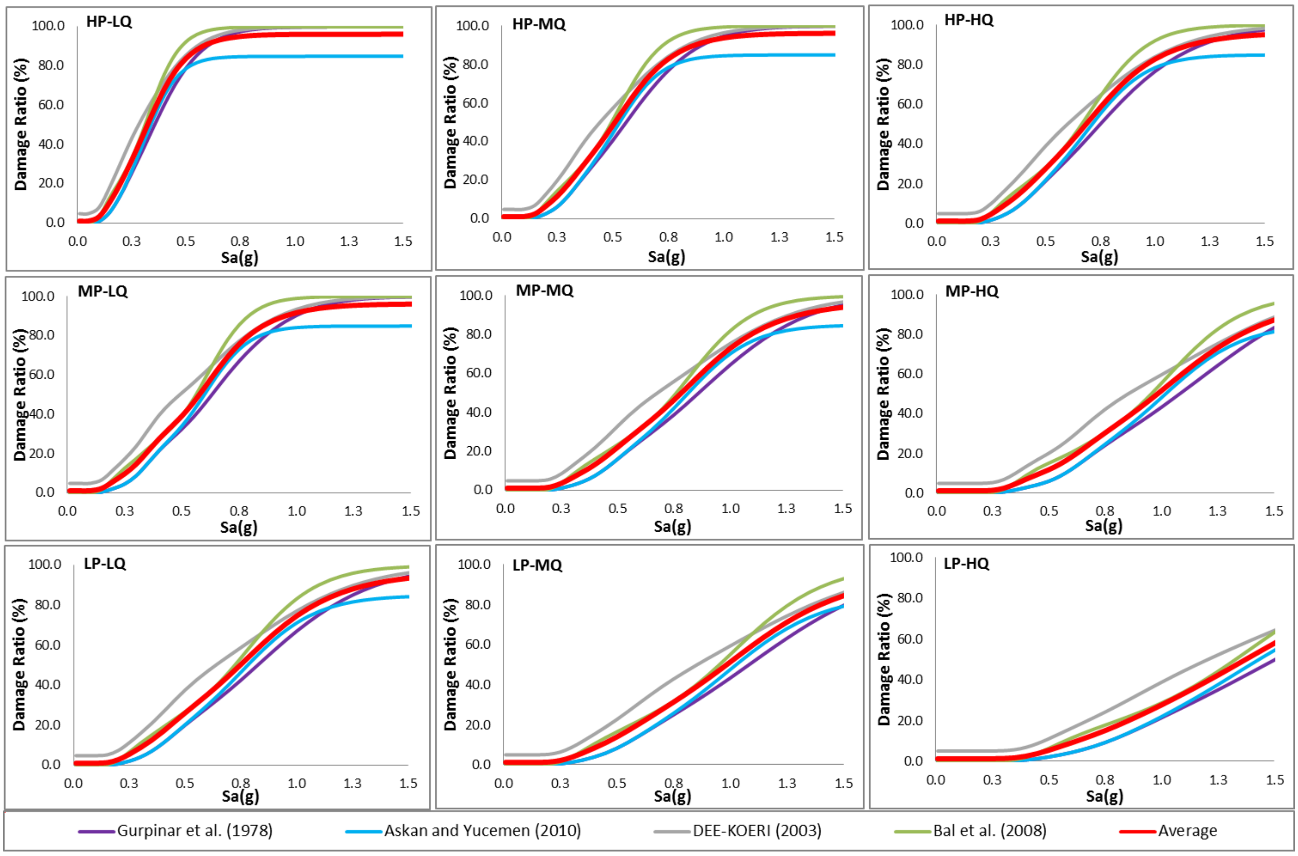


Fig. 3 The vulnerability curves computed using different CDR factors

states that may occur in the structure after an earthquake (Demartino and Monti 2020). CDR factors are used based on the relationship between the damage states defined in the fragility curves and DR. Subsequently, vulnerability functions are calculated using the probability of occurrence the damage state in the fragility curves and the CDR factor. CDR factors, which are an important link between earthquake damage and economic loss, are utilized in establishing the instant decision-making mechanism in critical structures and facilities. In this study, considering the region's building stock, seismicity, and engineering practices, four different CDRs expressed in Table 3 were used.

The mathematical expression of the derivation of vulnerability curves is given in Eq. (2).

$$Damage\ Ratio(S_{ae,j}) = \sum_{DS} P(DS_i|S_{ae,j}) \times CDR(DS_i) \quad (2)$$

Using Eq. (2), vulnerability curves of nine sub-classes are obtained as a function of spectral acceleration for four different CDRs (see Fig. 3).

In Fig. 3, vulnerability functions are shown for each sub-class, considering four different consequence models and their averages. In general, at low spectral acceleration values, the probability of damage occurrence is highest for DEE-KOERI (2003) model, while at increasing spectral acceleration values, higher values are obtained for Bal *et al.* (2008) model. For the Gurpinar *et al.* (1978) and Askan and Yucemen (2010) models, the probabilities of damage occurrence are lower than the average curve. In Askan and Yücemen's consequence model (Table 3), since the central damage ratio of the collapse damage state is defined as 85%, it is seen that the probability of damage ratio occurring in the sub-classes remains constant above 85%. It is clearly seen that for any seismic hazard level considered, the highest probability of occurrence of damage ratios is observed in the HP-LQ building class, while the lowest occurrence probabilities are observed in the LP-HQ building class. For example, the results obtained for 0.6 g Sa(g) value are given in Fig. 4.

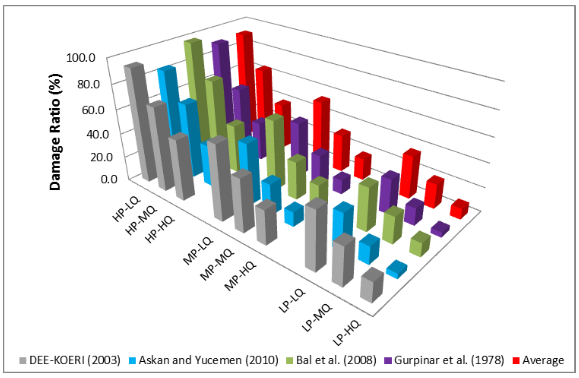


Fig. 4 Probability distribution of damage occurrence, Sa(0.6g)

Damage ratios of building classes were evaluated comparatively based on Sa (0.6 g). It is seen that there are

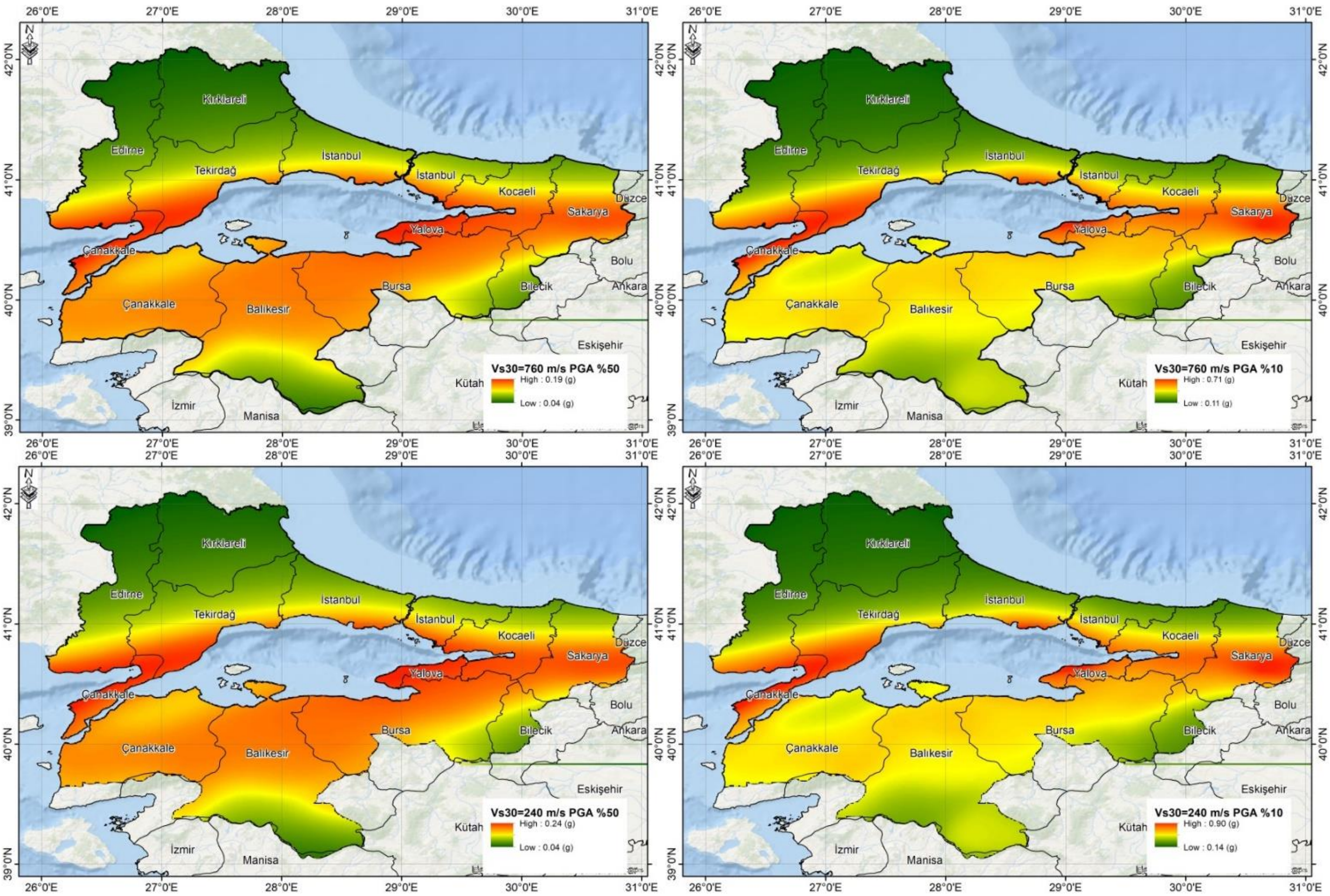


Fig. 5 PGA(g) distribution for different soil conditions and earthquake recurrence periods

significant differences in single-story RC precast building sub-classes. For instance, while the average damage ratio value is 91.30% for the HP-LQ sub-class, this value is 8.96% for the LP-HQ sub-class. For the quality parameter, while the probability of average damage occurrence was 91.30% in HP-LQ building class, this value was calculated as 39.34% in HP-HQ building class. Similarly, for the period parameter, the damage ratio values for HP-MQ and LP-MQ sub-classes are 64.84% and 20.52%, respectively. It should be noted that the different capacities of these building classes will cause the EDP values to change. Therefore, earthquake demand values are needed for earthquake risk assessment of the structures.

3.2 Seismic hazard analysis

Probabilistic seismic hazard analysis (PSHA) for the Marmara region was performed with OpenQuake software. Epistemic and random uncertainties in the source and ground motion models were considered.

OpenQuake software was developed as a component of the Global Earthquake Model (GEM) to model, research, and manage earthquake hazards and risks. It is written in Python and an open-source web-based platform (Silva *et al.* 2013). This program provides seismic risk assessment for any region based on deterministic or probabilistic hazard analysis. It is being tested by various institutions and research projects worldwide, notably the SHARE project funded by the European Commission (Pinho 2012).

As the first step of PSHA, the seismic area source, line source, and background source models defined within the European FP7 SHARE project were considered source models (Woessner *et al.* 2015). For the PSHA of the active shallow tectonic zone, seismic source models and ground motion prediction equation models (GMPEs) were combined with the logic tree approach. PSHA was conducted by considering PGA and Sa(g) as earthquake ground motion intensity parameters. In this study, the attenuation relations presented by Akkar and Bommer (2010), Cauzzi and Faccioli (2008), Chiou and Youngs (2008), Zhao *et al.* (2006) were considered.

PSHA was performed for two different soil conditions, soil dependent (Vs,30=240 m/s) and soil independent (Vs,30=760 m/s). Regarding the soil classification stated in the Turkish Building Seismic Design Code 2018 (TBSDC-2018), these Vs,30 parameter values represent soft soil (ZD) and stiff soil (ZB) classes, respectively.

PGA and Sa distributions in the Marmara region were calculated with four different GMPEs with different weights. In this study, only the PGA distributions obtained by considering 72 and 475 years recurrence periods of ground motion for two different soil conditions are given in Fig. 5.

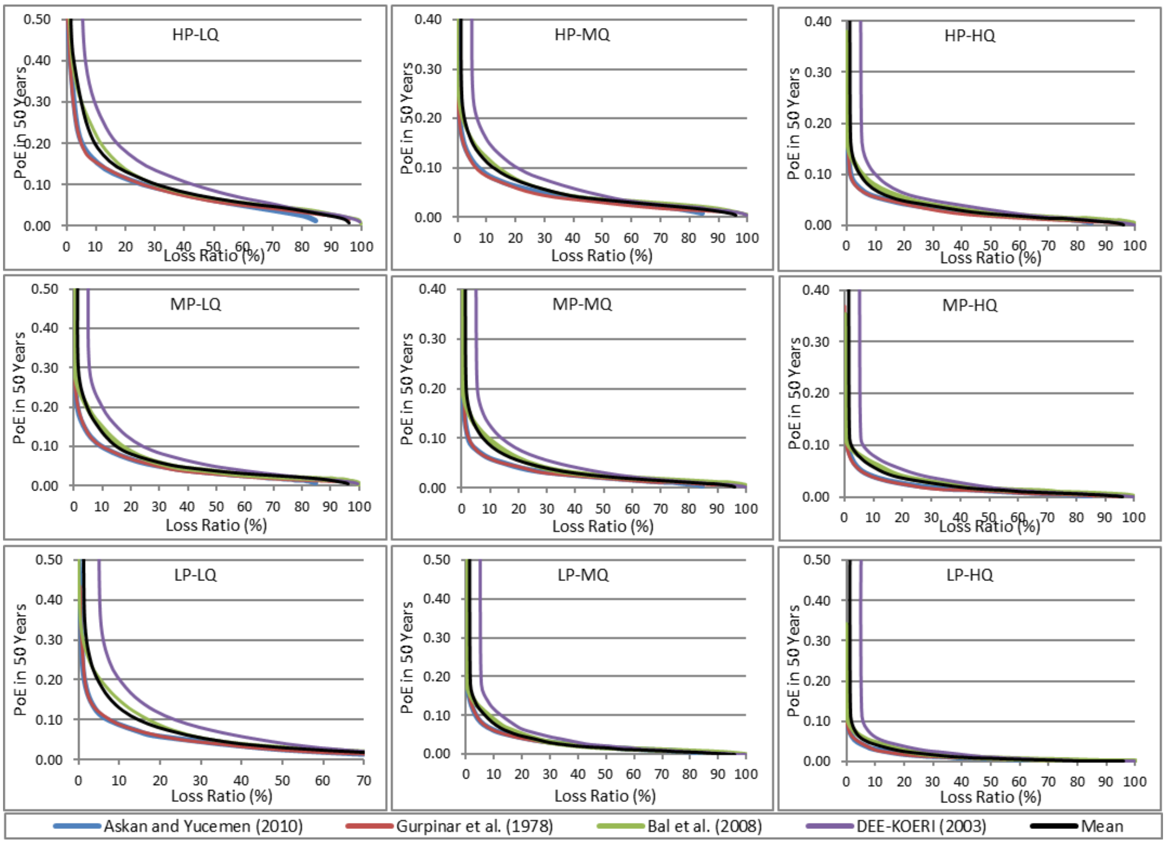


Fig. 6 Loss curves of nine sub-classes for stiff soil condition

3.3 Loss curves

Loss curves, which enable the calculation of the loss ratio of the structure in terms of different earthquake hazard levels, are one of the highly beneficial tools for determining the priority of risky structures in the considered region. These curves were obtained by following the steps in the flowchart presented in Fig. 2. The loss curves for nine single-story RC precast sub-classes, which computed the loss ratio values for any earthquake hazard level, are presented in Fig. 6 for stiff soil and Fig. 7 for soft soil, respectively.

When Figs. 6 and 7 are evaluated as a whole, it is seen that consequence models (CDR) are highly effective on the loss ratios. In general, for any earthquake hazard level, the highest loss ratio values are obtained for KOERI (2003) model, while the lowest loss ratio values are obtained for Gurpinar *et al*. (1978) and Askan and Yucemen (2010) models. It is also seen that the loss curves obtained by considering Bal *et al*. (2008) models are quite compatible with the average loss curve.

When the loss curves considering the stiff soil condition and MP-LQ sub-class are analyzed, the loss ratio values for Gurpinar *et al.* (1978), Askan and Yucemen (2010), Bal *et al.* (2008), and KOERI (2003) models are obtained as 9.8%, 9.8%, 16.9%, and 24.2% for the earthquake hazard level with a 10% probability of exceedance in 50 years (see Fig. 6). Considering the soft site condition for the same sub-class, these values were obtained as 34.6%, 36.2%, 46.2%, and 53.7%, respectively (see Fig. 7).

4. Evaluation of the effect of parameters on loss ratio

In order to avoid the effect of consequence model uncertainties on the loss curve, average loss curves are considered. The effects of quality, period, and site condition parameters on the loss ratio are evaluated using the average loss curve. The results are shown in Figs. 9-10, respectively.

The loss ratio values are comparatively analyzed for the earthquake hazard level with a 10% probability of exceedance in 50 years. The effect of the quality parameter in building classification on the loss ratio is analyzed for the HP building class based on both soil conditions. The loss ratios for the stiff soil condition for HQ, MQ, and LQ sub-classes are 4.3%, 14%, and 32%, respectively. Similarly, the loss ratios for the soft soil condition are calculated as 23%, 40%, and 74%, respectively (see Fig. 8).

Fig. 9 shows the effect of different period values on the loss ratio. The period effect is analyzed considering the MQ building class. Loss ratios are calculated at 7% for the LP sub-class, 7.4% for the MP sub-class, and 12.6% for the HP sub-class for stiff soil conditions, while 21.3%, 27.2%, and 38.5% are calculated for soft soil conditions, respectively.

Finally, in Fig. 10, the effect of different soil conditions on the loss ratio is evaluated separately for nine sub-classes. The LP-LQ building class's loss ratio is calculated as 15.4% for stiff soil conditions, while the loss ratio is calculated as 41.0% for soft soil conditions.

Damage distributions for quality and period parameters are evaluated based on Figs. 8-10. In this evaluation, three

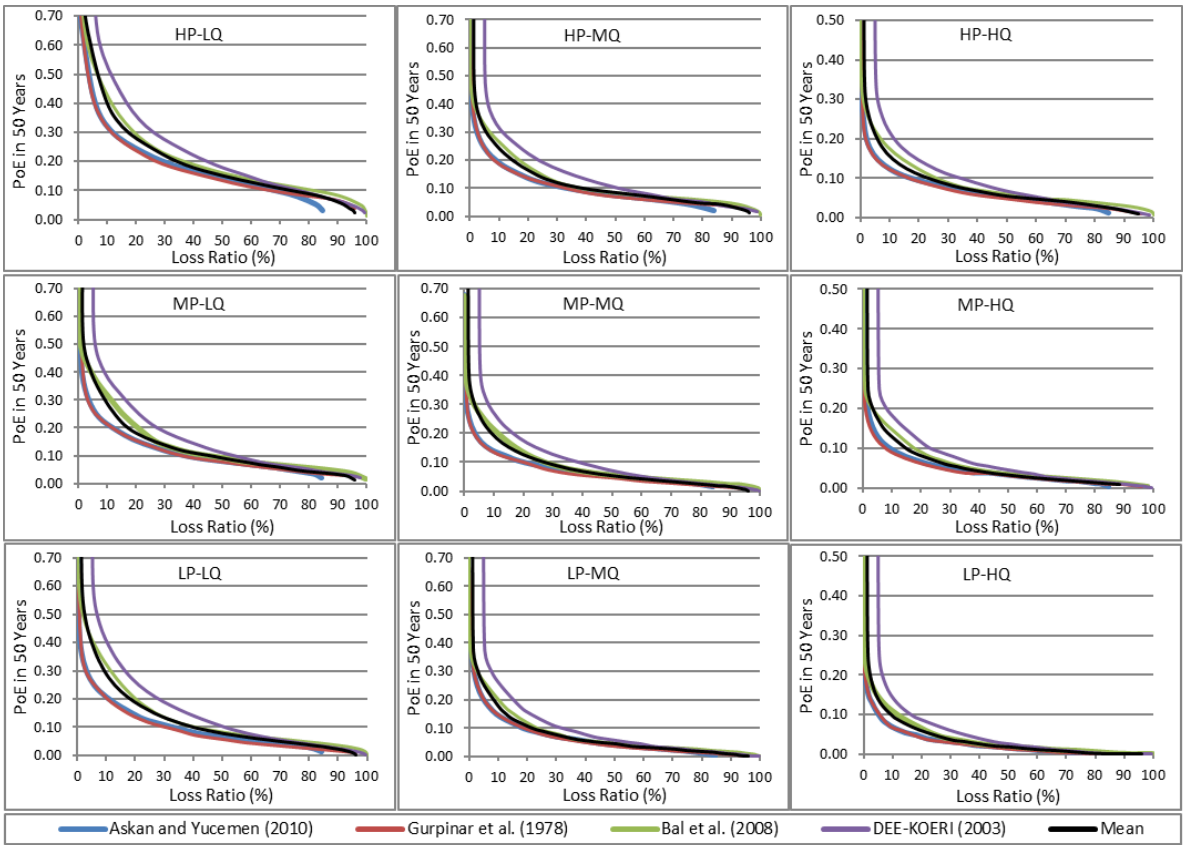


Fig. 7 Loss curves of nine sub-classes for soft soil condition

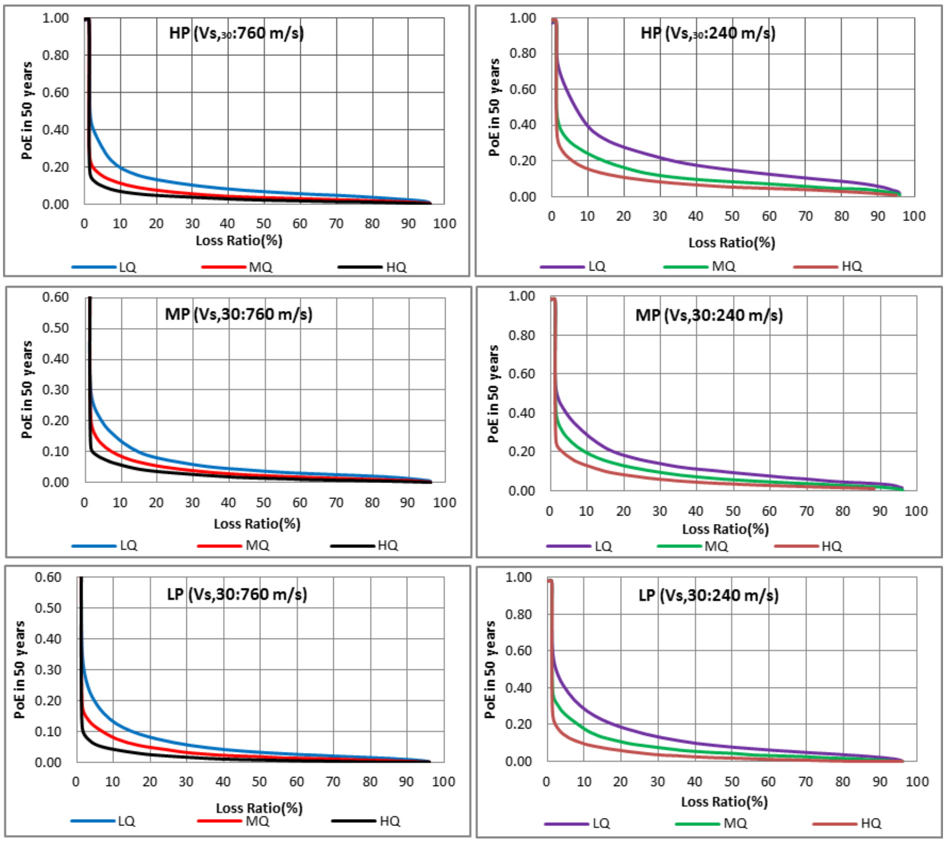


Fig. 8 Effect of quality on loss curve with stiff (left) and soft (right) site conditions

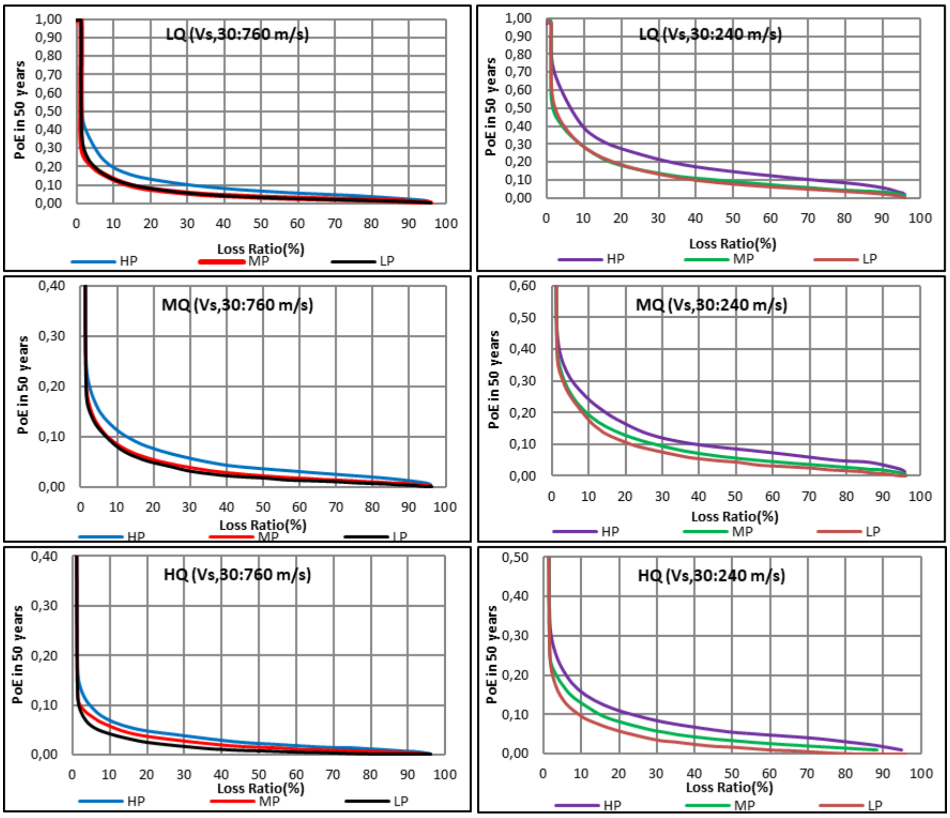


Fig. 9 Comparison of the effect of period parameters on average loss curves with stiff (left) and soft (right) soil conditions

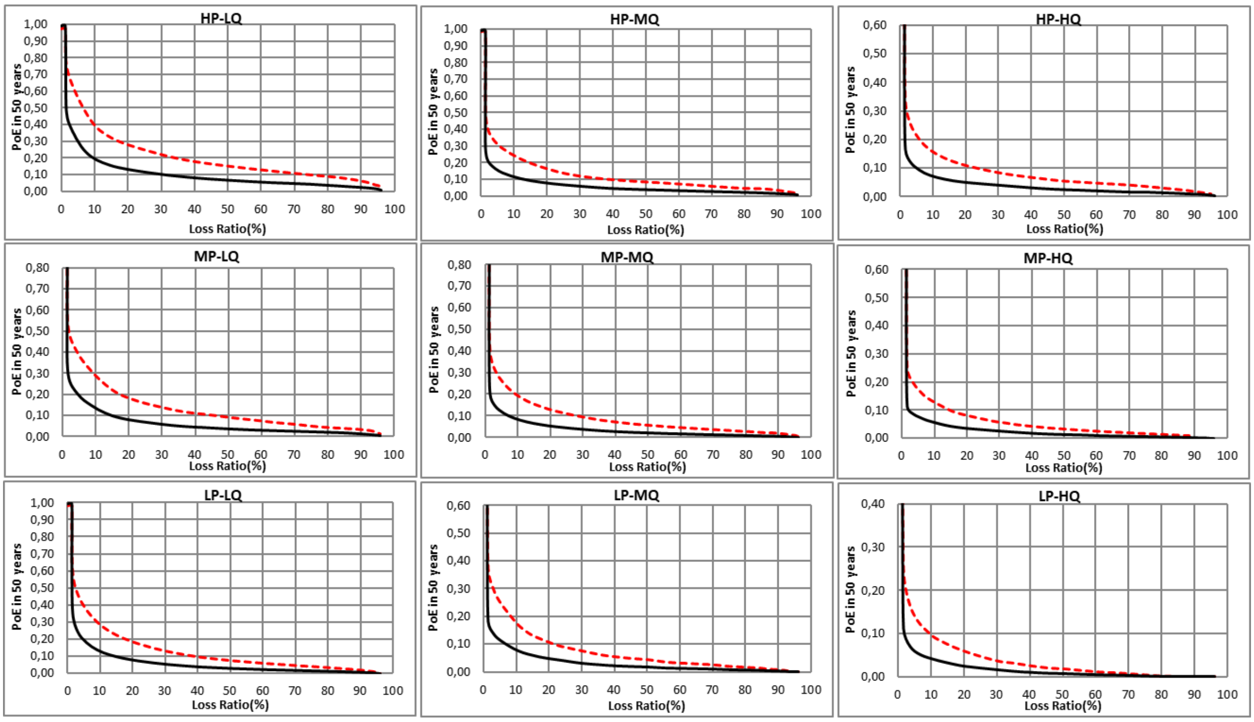


Fig. 10 Investigation of the effects of soil condition parameters on loss curves for nine sub-classes; red dashed line (soft soil), black solid line (stiff soil)

different earthquake intensity levels are employed. Regarding TBSDC-2018, the DD-1 earthquake intensity level (2475 return period-the largest earthquake ground motion), DD-2 earthquake intensity level (475 return period-design earthquake ground motion), and DD-3 earthquake intensity level (72 return period-frequent earthquake ground motion) are recognized. The limit values presented by Yesilyurt *et al*. (2021b) for damage states are

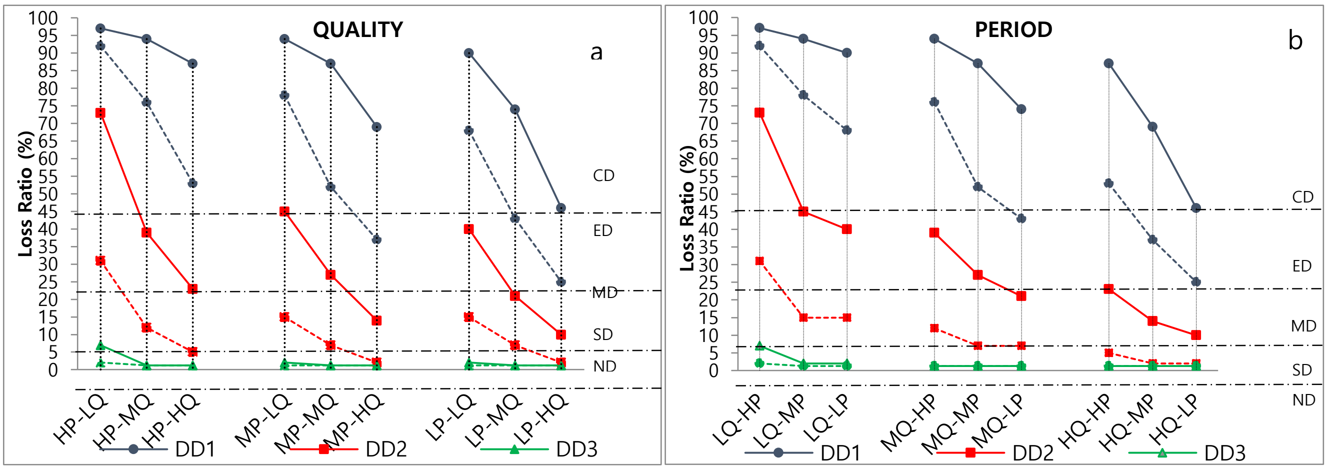


Fig. 11 Investigation of structural damage state for three different earthquake intensity levels, (a) Quality (left) and (b) Period (right)

considered. Horizontal dashed lines in Fig. 11 indicate these threshold values for each damage state. In Fig. 11, the damage state distributions of the nine sub-classes are analyzed for both soil conditions at three different earthquake intensity levels. Continuous lines represent the results for soft soil conditions, while dashed lines represent stiff soil condition results.

First, in Fig. 11(a), it is evident that the quality parameter is more effective on the damage state. On the other hand, it is seen that the damage state variation between moderate and low period sub-classes is limited, and the damage state increases more sharply in the transition to high period sub-class Fig. 11(b). In general, for the DD1 earthquake intensity level, most of the sub-classes are in the Collapse Damage (CD) state, while for the DD3 earthquake intensity level, the sub-classes are in the None Damage (ND) state.

For the DD1 earthquake intensity level, HQ-LP building class is in the "Extensive Damage (ED)" state in soft soil conditions and the "Moderate Damage (MD)" state in stiff soil conditions. The damage state degrades one or two levels due to stiff and soft soil conditions. It is also found that there is a sharp change in the damage states due to the quality parameter. For example, the HP-LQ sub-class is in the "Collapse Damage (CD)" state for DD2 earthquake intensity level in stiff soil conditions, while the HP-HQ sub-class is in the "None Damage (ND)" state in the same conditions. It is observed that the evaluation for the period parameter degrades the structural damage states by one level. For example, for DD2 intensity level with soft soil conditions, the MQ sub-class is in "Moderate Damage (MD)" for LP and MP, while it is "Extensive Damage (ED)" for HP. Similar evaluations can be made for different hazard levels and soil conditions.

5. Conclusions

Single-story precast RC industrial building class is defined as nine sub-classes regarding quality and period parameters. Considering the seismic risk methodology presented in the study, probabilistic seismic risk analysis is performed for stiff and soft soil conditions. The results obtained depending on the period, and quality parameters are presented comprehensively through the loss curve. The results are compared, and the critical findings are briefly summarized.

Considering the loss ratio values and damage state distributions for different earthquake intensity levels, it is evident that quality is much more effective on damage state than period compared to results of vulnerability and fragility curves. The main reason is the change in EDP value depending on the building capacity. In this respect, loss curves provide more accurate estimations in earthquake risk assessment. Considering three different period intervals, it is evaluated that the damage states do not change much for LP and MP sub-classes, while the damage states change sharply in HP sub-classes. It is determined that the effect of soil conditions on building damage state differs in each sub-class. It is found that the change in soil condition causes the change in the structural damage state from None to Moderate damage state or from Slight to Extensive damage state.

Seismic risk and loss estimation studies are crucial for managing the loss of life, risk reduction actions, emergency planning, and financial commitments related to economic losses. Furthermore, the results are valuable for insurance companies to evaluate their solvency and price insurance at the various hazard levels. At this stage, the loss curves presented in this study are efficient in direct loss estimation and rapid earthquake risk calculations.

Obviously, if a similar procedure used in this work were applied to other building classes, it would contribute to the more rational implementation of insurance activities and be a valuable reference in the preliminary risk assessment phase.

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