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DETERMINATION OF DRIFT HAZARD CURVES OF STEEL MOMENT-RESISTING FRAMES FOR TERRITORY OF TEHRAN CITY

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ABSTRACT

The principal result of probabilistic seismic demand analysis, an integral part of performance based design methodologies, is a structural demand hazard curve, which means annual frequency that the displacement-based demand exceeds a given value. The main aim of this article is the determination of drift hazard curves of steel moment-resisting frames for territory of Tehran city. For this purpose, the calculated seismic hazard curves from a probabilistic seismic hazard analysis are combined with the mean drift demand, predicted through the selected demand model. In this article in order to select the best probabilistic seismic demand model, 6 different models with one and two intensity measure parameter are statistically evaluated, using a Bayesian approach. Based on the estimated standard deviation of these models, the results show there is not a certain demand model with same accuracy for all frames, hence using a unique model for all structures may not be rational. Also the results show that in case of using one-parameter model, the estimated seismic demand depends on the selected demand model. This problem can be solved by using two-parameter demand models, which need much more calculation to estimate the demand.

Introduction

Probabilistic Seismic Demand Analysis (PSDA), an integral part of Performance Based Design (PBD) methodologies, is an approach to estimate the mean annual probability of exceeding a specified seismic demand for a given structure at a designated site (Cornell 1996). Analogous to a ground motion hazard curve estimated by Probabilistic Seismic Hazard Analysis (PSHA), the principal result of PSDA is a structural demand hazard curve, which means annual frequency that the displacement-based demand (here maximum inter-story drift) exceeds a given value. The main aim of this article is the determination of drift hazard curves of Steel Moment-Resisting Frames (SMRFs) for territory of Tehran city, which is the capital city of Iran and located in a high level seismic risk zone.

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To estimate the seismic demand of a structure at a designed site, the randomness and uncertainties in the ground motion records and nonlinear structure response must be considered. Although there are some different approaches for this purpose (Tothong and Cornell 2006), nowadays the approach suggested by Cornell and co-workers (Bazzurro 1998 and Luco 2002) is the main method in PBD. In this new approach by introducing an intermediate parameter known as the ground motion Intensity Measure (IM), the PSDA problem is simplified by decoupling the ground motion hazard and Nonlinear Dynamic Analysis (NDA). In short, PSDA by using an application of total probability theorem combines a ground motion hazard curve of IM parameter for the designated site, with the demand results from NDA of the given structure under a suite of earthquake ground motion records. With *DR* denoting maximum inter-story drift and *IM* a selected ground motion intensity measure, PSDA is expressed mathematically as follows:

$$\lambda_{DR}(z) = \int_0^\infty G_{DR|IM}(z \mid x).\,| d\lambda_{IM}(x) | \tag{1}$$

In this equation the drift hazard, which means the mean annual frequency of *DR* exceeds the value *z*, is denoted $\lambda_{DR}(z)$ and IM hazard is denoted $\lambda_{\mathrm{IM}}(x)$ (evaluated at *x*), typically computed through PSHA . The term $G_{DR|IM}(z|x)$, which is customarily estimated using NDA results for a suite of earthquake records, denotes the probability of DR exceeding the value *z* given (i.e., conditioned on knowing) that *IM* equals *x.* This conditional term is usually named Probabilistic Seismic Demand Model (PSDM).

In some studies, instead of using one IM, a vector of two ground motion parameters, IM1 and IM2 is used to estimate the drift (Baker and Cornell 2006). In this case the Eq.1 changes to:

$$\lambda_{DR}(z) = \int_0^\infty \int_0^\infty G_{DR|IM1,IM2}(z \mid x, y).f_{IM2|IM1}(y \mid x)\,| d\lambda_{IM1}(x) | \tag{2}$$

In this new equation the term $f_{IM2|IM1}$ $(y|x)$ denotes the conditional probability density function of IM2 given IM1 and the other terms are similar to Eq.1.

In this article, the hazard drift curves of SMRFs in Tehran are calculated by using both one and two-parameter PSDM. The following parts of this article are assigned to determination of different terms of Eq.1 and Eq.2. After introducing the structural model and chosen ground motion records, based on the results of NDA, the best one and two-parameter PSDM are selected. In order to calculate the hazard curves of selected IM, a PSHA is done for various points of Tehran and an Incremental Dynamic Analysis (IDA) is used to participate the effects of collapse cases in estimation the model parameters. Finally the drift hazard curves of SMRFs are determined for different SMRFs and various seismic zones of Tehran with selected one and two-parameter models. Also, in order to consider both the randomness and uncertainty associated with seismic events and structural responses, a Bayesian regression analysis, which is strong tool to simultaneous modeling of randomness and uncertainty, is used to all required estimations.

Definition of Used Generic Steel Moment-Resisting Frames

In this article, NDA is carried out using a family of two-dimensional single-bay generic

SMRFs with number of stories equal to 3, 6, 9, 12 and 15, and first mode periods equal to 0.3, 0.6, 0.9, 1.2 and 1.5 second respectively. Some main characteristics of this family of frames are as follows, more details can be found in (Medina and Krawinkler 2005):

- Relative stiffness are turned so that the first mode is straight line
- Plasticization just occurs at the end of the beams and the bottom of the first story columns
- Frames are designed so that simultaneous yielding at all plastic hinge locations is attained under a parabolic (NEHRP, k=2) load pattern.
- Moment-rotation hysteretic behavior is modeled by using rotational springs with peak-oriented hysteretic rules and cyclic deterioration parameter equal to 30 and 3% strain hardening.

Selection of Ground Motion Records

An appropriate estimation of seismic demand through NDA requires a suitable selection of ground motion records which must represent the seismic hazard condition of target territory at different return periods. In this article, using a bin strategy, 80 records are selected from the PEER Center Ground Motion Database (http://peer.berkeley.edu/smcat/) and are classified into four magnitude-distance bins for the purpose of time history analysis of SMRFs (Medina and Krawinkler 2003). The record bins are designated as follows:

- Large Magnitude-Short Distance Bin, LMSR, (6.5 < Mw < 7.0, 13 km < R < 30 km),
- Large Magnitude-Long Distance Bin, LMLR, (6.5 < Mw <7.0, 30 km < R < 60 km),
- Small Magnitude-Short Distance Bin, SMSR, (5.8 < Mw < 6.5, 13 km < R < 30 km), and
- Small Magnitude-Long Distance Bin, SMLR, (5.8 < Mw < 6.5, 30 km < R < 60 km).

Selection of PSDM Based on NDA Results

A demand model is a mathematical expression relating the structural demand at the component level to the demand at system level. In the other word, a PSDM relates structure specific demand to the specific IM. The selection of PSDMs is based on several inherent properties such as practicality, sufficiency, effectiveness and efficiency (Mackie and Stojadinovic 2002). In this section, based on the NDA results of SMRFs under chosen ground motion records, the best PSDMs are selected.

Generally, the following mathematical form is adopted for a demand model:

$$D(IM,\theta,\sigma) = d(IM,\theta) + \sigma.\varepsilon \qquad (3)$$

In the above expression, D is the demand parameter, d is the selected deterministic model and ε is a standard normal random variable. As mentioned before IM is the ground motion intensity measure parameter (may be one or more parameters), also θ is the vector of model parameters and σ is the standard deviation of model error. The vector of θ and amount of σ must be calculated based on the results of NDA. In this article, in order to select the best model, 6 different PSDMs, consist of different one-parameter and two-parameter models, are evaluated. In These models, listed below, DR denoting maximum inter-story drift, PGA is the peak ground acceleration and S_{a1} and S_{a2} denote first and second mode spectral acceleration.

Model No: 1 $\ln(DR) = a.\ln(PGA) + w + \sigma.\varepsilon$

Model No: 2 $\ln(DR) = a.\ln(S_{a1}) + w + \sigma.\varepsilon$

Model No: 3 $\ln(DR) = a.\ln(S_{a2}) + w + \sigma.\varepsilon$

Model No: 4 $\ln(DR) = a.\ln(PGA) + b.\ln(S_{a1}) + w + \sigma.\varepsilon$

Model No: 5 $\ln(DR) = a.\ln(S_{a1}) + b.\ln(S_{a2}) + w + \sigma.\varepsilon$

Model No: 6 $\ln(DR) = a.\ln(\sqrt{S_{a1}^2 + S_{a2}^2}) + w + \sigma.\varepsilon$

All of the parameters and standard deviation of the defined models, based on the results of NDA, are estimated by using of the well-known Bayesian updating rules. The efficiency of models, defined the amount of variability of a demand parameter given an IM, can be a suitable criterion to select the best PSDM. The measure used to evaluate efficiency is the dispersion, defined as the standard deviation of the model error (Shome 1999). Fig. 1 shows the estimated amount of standard deviation for all models and SMRFs graphically.

The results show that the defined models have totally different dispersion in different number of stories. As a general rule, the two-parameter models have smaller standard deviation and their standard deviation is nearly independent from number of stories, but it must be noted that using these model to estimate the drift requires much more calculation. Between one-parameter models, although model No: 2, which is widely used for SMRFs (Cornell et al. 2002), has a small dispersion in low-rise fames, its standard deviation highly increase by increasing the number of stories. This situation is reversed in model No: 3 and the standard deviation of this model decrease by increasing the number of stories. It seems the dispersion of model No: 1 is nearly independent of number of stories. Also, based on the amount of standard deviation of models, model No: 5 seems to be the best model in 2-parameter models and all models. In this article, by consideration of all results, in order to determinate the drift demand of SMRFs, model No: 2 is selected as one-parameter PSDM and model No: 5 is selected as two-parameter PSDM.

Probabilistic Seismic Hazard Analysis for Territory of Tehran City

IM hazard function, generally calculated via PSHA, is an integrate part of seismic demand estimation. Also, the spectral acceleration at the first mode period, S_{a1}, is the selected parameter as IM in this study, so the hazard function of this parameter at periods of 0.3, 0.6, 0.9, 1.2 and 1.5 second, the first mode periods of modeled SMRFs, must be calculated for different seismic zones of Tehran city. In this study a well-known PSHA method is used to calculate the hazard functions at mentioned periods (Cornell 1977). The applied spectral attenuation relation in this calculation is a valid relation for Tehran territory, represented by Ambraseys, Simpson & Bommer in 1996.

In this Article, territory of Tehran is defined as an area between 50.8°E to 52.2°E longitude and 35.5°E to 36.2°E latitude. By division of this territory to a grid of points, spacing of 0.1 degrees in latitude and longitude and hazard analysis for all points, a map of peak ground acceleration is generated with 475 years return period. This map, shown in Fig. 2, is used to divide the Tehran territory in 3 seismic zones with different seismic hazard levels. Then, by using selected spectral attenuation relation and PSHA method, the hazard functions of five mentioned periods at all points of every seismic zone are determined. The S_{a1} hazard function of each zone is defined as the average of S_{a1} hazard function of every point in that zone. As shown in Fig. 3 these hazard curves can be regressed by a power equation as follows:

$$\lambda_{Sa}(x) = k.(x)^t \tag{4}$$

This approximation can simplify the integrations in Eq.1 and 2 with no decreasing in the accuracy. The required parameters of this relation for different zones are listed in Table 1.

Although these hazard function are enough to estimate the seismic drift demand by using one-parameter PSDM, applying two-parameter PSDM No: 5 needs determination of conditional probability density function of S_{a2} given S_{a1} additional to these hazard curves. By assuming a normal distribution for dispersion of S_{a2} given S_{a1}, this function can be defined as:

$$f_{IM2|IM1}(y \mid x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2\sigma^2}(y-\mu(x))^2} \tag{5}$$

The required parameters of this distribution (σ and $\mu(x)$) are estimated by using Bayesian regression analysis based on S_{a2} and S_{a1} amounts of 80 selected ground motion records. The estimated parameters are listed in Table 2 for 3 and 15-story SMRFs.

Consideration of Collapse Probability by Using IDA to Calibrate PSDMs

The selected ground motion records in this study are not strong enough to cause collapse or even severe nonlinear behavior in modeled SMRFs. Besides, as the results of PSHA in Tehran show, there is a possibility that the seismic hazard level in Tehran reach a limit, which may lead to collapse of structures. Collapse is considered here as the ultimate limit state in which dynamic sideway instability in one or several stories of structural system is attained. So the selected records cannot represent the real behavior of SMRFs in this territory. In order to conquest this shortage, an Incremental Dynamic Analysis (IDA) is used to scaled the S_{a1} of the records to reach a high limit. This limit is defined the spectral acceleration with the probability of exceeding equal to 0.0001. This limit for S_{a1} at 0.3, 0.6, 0.9, 1.2 and 1.5 second is calculated 2.1g, 1.35g, 0.95g, 0.6g and 0.55g respectively in Tehran. Each record scaled from S_{a1} =0.05g to the defined high limit with 0.05g steps and used to NDA of SMRFs. By following this process, at each level, 80 pairs of (S_{a1} and *DR)* data points are produced. Some of these data are lead to collapse of structures, some of them are not. In order to contribute all data points in estimation of drift, the following modification is applied to calculate the term $G_{DR|IM}(z|x)$:

$$G_{DR|IM}(z \mid x) = (1 - P_{Collapes|IM}(x)).[1 - \Theta(\frac{\ln(z) - d(x,\theta)}{\sigma})] + P_{Collapes|IM}(x) \tag{6}$$

In this equation, Θ is denoted cumulative normal distribution function and $d(x, \theta)$ and σ are the deterministic part (or mean) and standard deviation of the selected demand model respectively. The resulted data points from IDA, which do not lead to collapse of SMRFs, are used in a Bayesian regression analysis to estimate model parameters (θ) and standard deviations of the demand model. The results for model No: 2 and model No: 5 are listed in Table 3. The remained data points, which lead to collapse of SMRFs, are used to calculate the probability of collapse at the given IM level, $P_{Collapes|IM}(x)$. This probability is defined as the number of scaled record, which leads to collapse, divided to the number of all records, 80, at any given IM level. Fig. 4 shows such a probability calculation for 3 and 15-story SMRFs. As Seen in this figure, a linear model like follows can be used to predict the probability of collapse:

$$0 \le P_{Collape|IM}(x) = \alpha x + \beta \le 1 \qquad (7)$$

The estimated model parameters, α and β, by using a Bayesian regression analysis for different SMRF models are also listed in Table 3. These models are plotted in Fig. 4 along with real data.

Determination of Drift Hazard Curves of SMRFs for Territory of Tehran City

In Fig. 5 the determined drift hazard curves of SMRFs for territory of Tehran city in three different seismic zones are shown. These curves are calculated by using one-parameter PSDM No: 2 and the probabilities of collapse are considered in the calculations. In order to study the effects of using two-parameter model instead of one-parameter on estimated demand, the drift hazard curves of 3 and 15-story frames are calculated by using PSDM No: 5 and the results are shown in Fig. 6. In comparison with using model No: 2, for 3-story frame, except the saturated region of curves, the estimated drifts by applying one and two-parameter model are almost similar in all ranges. Because of similar standard deviation of the model No: 2 and the model No: 5 in case of 3-story frame, these results are expected, but in the case of 15-story frame, as seen in Fig. 6, the estimated drift demand by using these two models are totally different. The main reason of such a large dissimilarity in estimated drift of 15-story frame is the large difference in estimated standard deviations of model No: 2 and Model No: 5. Results of this comparison state that the selection of a suitable demand model is a matter of concern and different models may lead to unlike estimation of seismic demand. Also it seems that the behavior of structure is an important factor in selection of a suitable demand model.

Conclusion

In this article, in order to determine the drift hazard curves of steel moment-resisting frames for territory of Tehran city, the calculated seismic hazard curves from a probabilistic seismic hazard analysis are combined with the mean drift demand, predicted through the selected demand model. Also in this article, in order to select the best probabilistic seismic demand model, 6 different models with one and two IM parameter are evaluated. The results show that the models have various behaviors in different type of structures hence using a certain demand model for all stiff and deformable frames may not be reasonable. Study the estimated standard deviation in different models shows that although the widespread demand model, which estimates the drift demand based on first mode spectral acceleration, has enough accuracy in low-rise frames, in the case of mid and high-rise frames this accuracy decreases and other models may lead to better results. In the case of 15-story frame, using different one-parameter demand models lead to different estimation of demand, but a reliable estimated demand must be independent from selected demand. By using two parameter demand models one can solve this problem, because their standard deviations is lower than on parameter models and are generally independence of number of stories, but in this case, to estimate the demand much more calculations are required.

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Table 1. Calculated parameters for seismic hazard curves of Eq. 4 in 3 different seismic zones

spectral acceleration	High Level Hazard		Medium Level Hazard		Low Level Hazard	
	k	t	k	t	K	t
$S_a(0.30)$	1.890 E-3	-2.653	8.422 E-4	-2.683	1.861 E-4	-2.888
$S_a(0.60)$	5.653 E-4	-2.131	2.661 E-4	-2.191	6.416 E-5	-2.510
$S_a(0.90)$	1.787 E-4	-2.005	8.947 E-5	-2.105	2.311 E-5	-2.367
$S_a(1.20)$	7.460 E-5	-2.021	3.444 E-5	-2.140	7.434 E-6	-2.451
$S_a(1.50)$	5.356 E-5	-2.021	2.473 E-5	-2.140	5.337 E-6	-2.451

Table 2. Estimated parameters for conditional probability density function of S_{a2} given S_{a1}

	conditional probability density function	Mean $\mu(x)$	Standard Deviation σ
3-Story	$f(S_a(0.1) \mid S_a(0.3))$	$\mu(x) = 0.6973x + 0.0506$	0.128065
15-story	$f(S_a(0.6) \mid S_a(1.5))$	$\mu(x) = 2.0902x + 0.0881$	0.181576

Table 3. Estimated Parameters for demand and collapse models, using Bayesian regression

Model No:2	$\ln(DR) = a.\ln(S_{a1}) + w + \sigma.\varepsilon$					
Estimated parameter		3-Story	6-Story	9-Story	12-Story	15-Story
a	mean	1.01998	1.02264	1.00849	0.98621	0.95189
	standard deviation	0.05315	0.06143	0.08431	0.10851	0.13280
w	mean	-5.88245	-4.95632	-4.30291	-3.77650	-3.41315
	standard deviation	0.05068	0.05844	0.08627	0.11983	0.15555
σ	mean	0.16381	0.18065	0.26602	0.35727	0.45031
	standard deviation	0.02439	0.02890	0.04745	0.06830	0.09234
Model No:5	$\ln(DR) = a.\ln(S_{a1}) + b.\ln(S_{a2}) + w + \sigma.\varepsilon$					
a	mean	0.96173	0.77403	0.52078	0.36159	0.22376
	standard deviation	0.07783	0.07215	0.08867	0.09898	0.10836
b	mean	0.05878	0.25040	0.49720	0.64776	0.78133
	standard deviation	0.07383	0.06619	0.08268	0.09200	0.10030
w	mean	-5.86930	-5.02383	-4.60756	-4.29345	-4.14392
	standard deviation	0.05356	0.05059	0.07677	0.09822	0.11617
σ	mean	0.16173	0.12547	0.14521	0.15568	0.17399
	standard deviation	0.02350	0.01984	0.14521	0.03050	0.03516
Collapse model:	$0 \le P_{Collape\|IM}(x) = \alpha x + \beta \le 1$					
α		0.381	0.051	0.076	0.121	0.311
β		-0.679	-0.061	-0.049	-0.036	-0.088

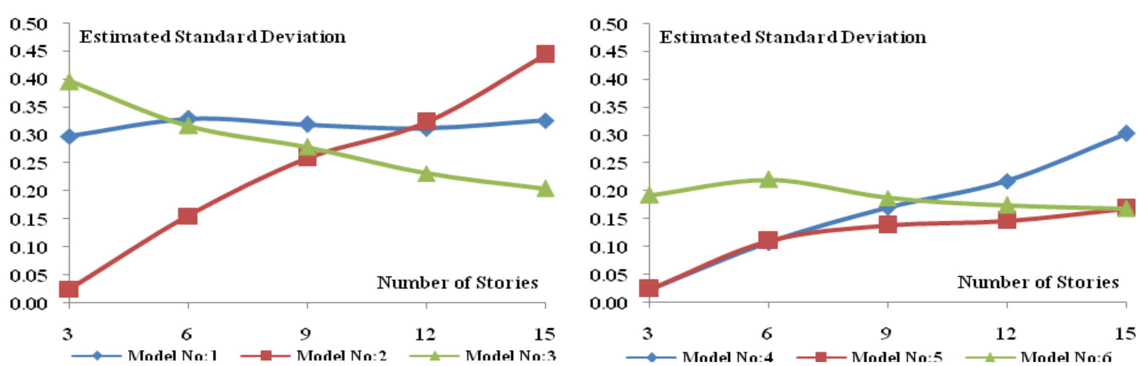

Figure 1. Estimated standard deviation of 6 defined demand model, using Bayesian regression

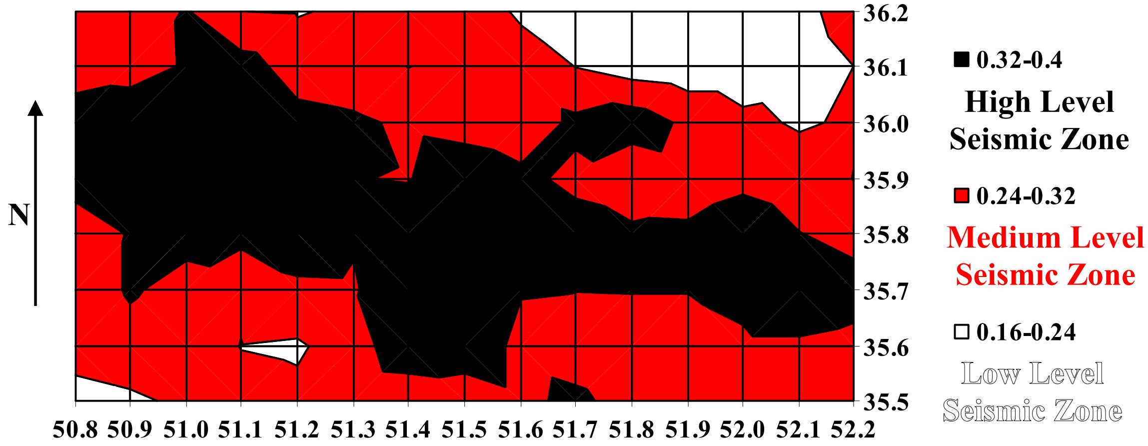

Figure 2. The map of Peak Ground Acceleration (g) calculated for territory of Tehran city with 475 years return period and 3 defined seismic zones based on the PGA.

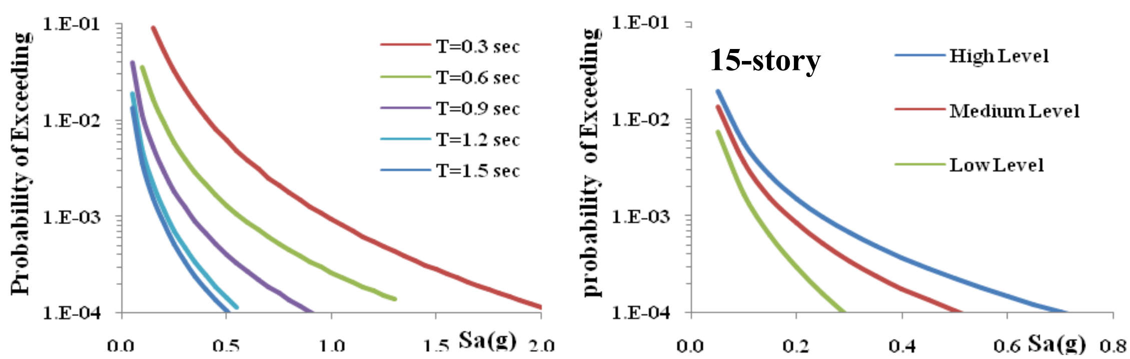

Figure 3. Calculated seismic hazard curves for different spectral acceleration and different seismic zones in territory of Tehran city.

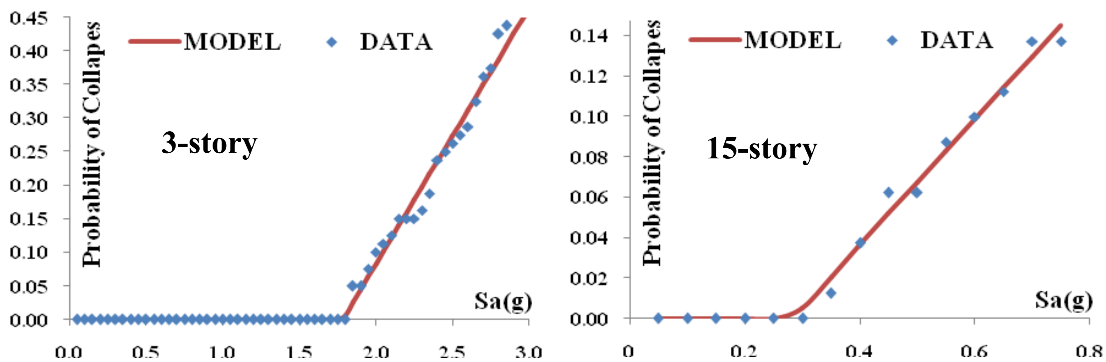

Figure 4. Calculated probability of collapse at the given S_{a1} for 3 and 15-story SMRFs. The red line shows the defined collapse model in Eq. 7 and Table 3.

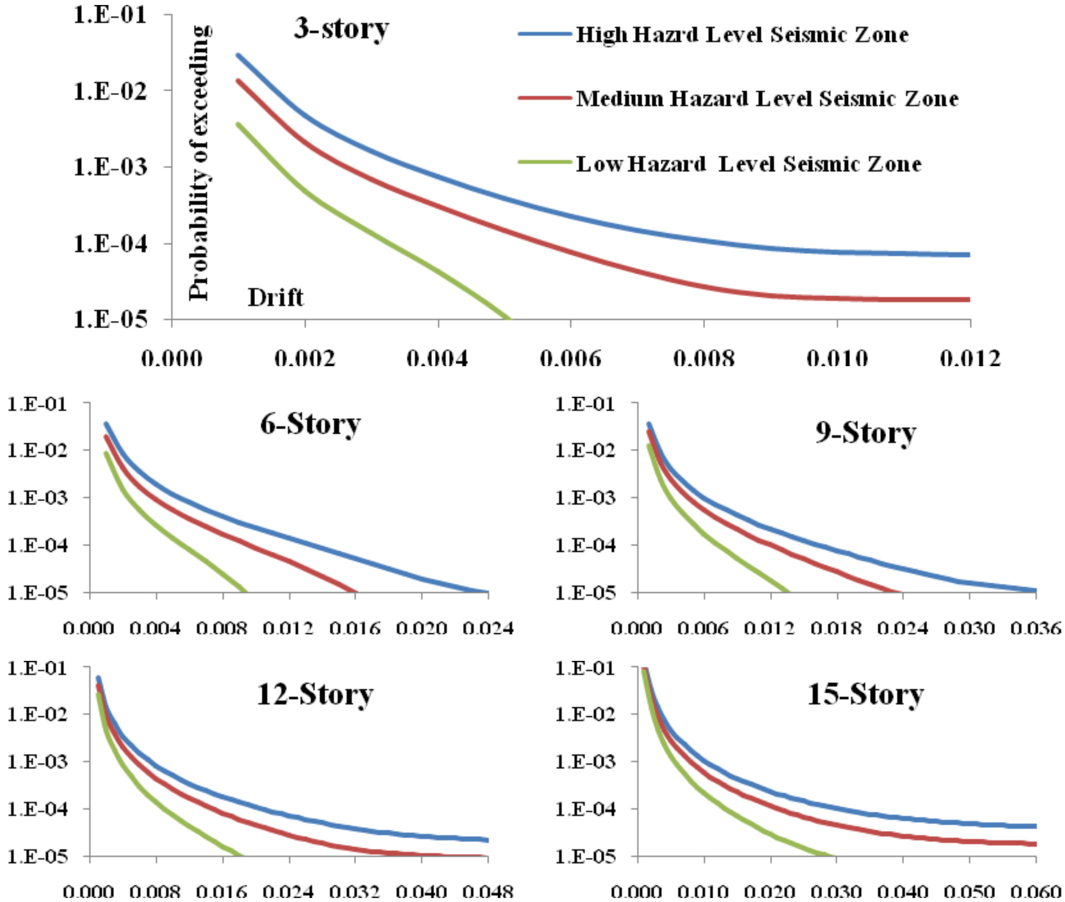

Figure 5. Determined drift hazard curves of SMRFs for territory of Tehran city in three different seismic zones using one-parameter PSDM No: 2.

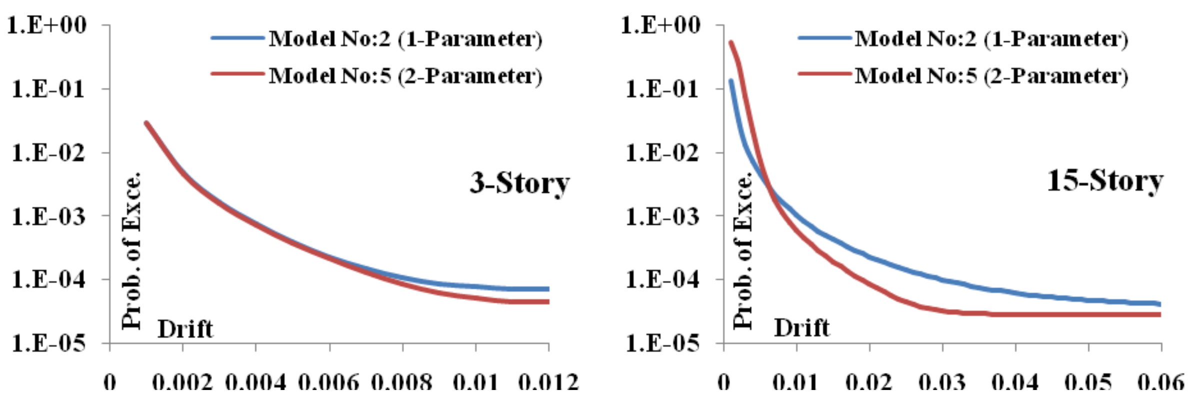

Figure 6. Comparison of estimated seismic drift demand using demand model No: 2 and No: 5