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Statistical evaluation of drift demands of rc frames using code-compatible real ground motion record sets

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Abstract. Modern performance-based design methods require ways to determine the factual behavior of structures subjected to earthquakes. Drift ratio demands are important measures of structural and/or non-structural damage of the structures in performance-based design. In this study, global drift ratio and interstory drift ratio demands, obtained by nonlinear time history analysis of three generic RC frames using code-compatible ground motion record sets, are statistically evaluated. Several ground motion record sets compatible with elastic design spectra defined for the local soil classes in Turkish Earthquake Code are used for the analyses. Variation of the drift ratio demands obtained from ground motion records in the sets and difference between the mean of drift ratio demands calculated for ground motion sets are evaluated. The results of the study indicate that i) variation of maximum drift ratio demands in the sets were high; ii) different drift ratio demands are calculated using different ground motion record sets although they are compatible with the same design spectra; iii) the effect of variability due to random causes on the total variability of drift ratio demands is much larger than the effect of variability due to differences between the mean of ground motion record sets; iv) global and interstory drift ratio demands obtained for different ground motion record sets can be accepted as simply random samples of the same population at %95 confidence level. The results are valid for all the generic frames and local soil classes considered in this study.

Keywords: drift ratio demands; ground motion record sets; nonlinear time history; statistical evaluation

1. Introduction

Performance-based design is currently popular design philosophy in which design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard (Ghobarah 2001). In SEAOC Vision 2000 (SEAOC Vision 2000 Committee 1995), one of the basic documents on performance-based design concept, possible design approaches are involved including various elastic and inelastic analysis procedures such as: (1) conventional force and strength methods; (2) displacement-based design; (3) energy approaches; and (4) prescriptive design approaches. Among the approaches, displacement-based design has been widely adopted and structural response parameters such as maximum

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displacement, global drift ratio, interstory drift ratio, maximum ductility demands, etc. commenced to be utilized for design targets (Priestley, Calvi *et al.* 2007). Similar parameters are also utilized to identify different performance levels and limit conditions for the seismic performance evaluations of existing buildings (ATC-40 1996, FEMA-440 2005). It can be said that global or interstory drift ratio demands are the principal considerations in performance-based design.

The most comprehensive and accurate method to compute displacement or drift ratio demands in order to assess the behavior of structures subjected to earthquake is the nonlinear time history analysis of three-dimensional structural models. Recently, increasing processing power of computers and the developments in the software industry have resulted in more common nonlinear time history analyses. However, due to the complexity and difficulty of nonlinear time history analysis of three-dimensional structural models, the simpler two-dimensional frames (Akkar, Yazgan *et al.* 2005, Miranda 1999, Gupta and Krawinkler 2000, Medina and Krawinkler 2005, Garcia and Miranda 2006, Hatzigeorgiou and Liolios 2010, Garcia and Miranda 2010, Ghaffarzadeh, Talebian *et al*. 2013), and single degree of freedom systems (Riddell, Garcia *et al*. 2002, Bazzurro and Luco 2005, D'Ambrisi and Mezzi 2005, Garcia and Miranda 2007, Lin and Miranda 2009, Hatzigeorgiou and Beskos 2009) are also be preferred as structural analysis models to predict and evaluate the structural response to seismic excitation. In these studies, based on the objective of the study, maximum displacement, maximum drift, maximum interstory drift, etc. can be used as structural response parameter. Furthermore, different criteria are used in selection of ground motion records for nonlinear time history analyses.

Since digital databases containing ground motion records have become easily accessible, real ground motion records have increasingly preferred for time history analysis. As known, ground motion records differ based on characteristics such as the magnitude of the earthquake, faulting type, local soil properties, duration of ground motion, the distance between the epicenter and the recording station, etc. Ground motion records to be used in the analyses directly affect the displacement and/or drift demands that would be obtained from the nonlinear time history analyses. Thus, selection of ground motion records based on the seismicity of the region and the local soil conditions that a structure is in is important for accurate prediction of the seismic behavior of that structure in a possible earthquake (Iervolino, De Luca *et al*. 2010a, Kayhan, Korkmaz *et al.* 2011, Han and Seok 2014).

In order to select ground motion records for nonlinear analyses, various techniques can be used (Haselton, Baker *et al.* 2009, Katsanos, Sextos *et al*. 2010). Selecting ground motion records with response spectra matching the target spectrum is one of the widely used approaches. Target response spectra may include most commonly the Uniform Hazard Spectrum that corresponds to spectral accelerations with equal probabilities of exceedance at all periods (McGuire 2004). Recently developed the Conditional Mean Spectrum (Baker 2011) and the related Conditional Spectrum (Lin, Haselton *et al.* 2013a, 2013b, Jayaram, Lin *et al.* 2011) are alternatives to the Uniform Hazard Spectrum that can be used as targets for ground motion selection. The Conditional Mean Spectrum considers the entire spectrum on spectral acceleration at a single user defined period and then calculates the mean values of spectral acceleration at all other periods. The Conditional Spectrum differs from The Conditional Mean Spectrum only in that also considers the variability in response spectra at periods other than user defined period.

In most of the modern seismic codes including the Turkish Earthquake Code (TEC 2007) time history analysis is accepted as one of the analysis method for design or seismic performance evaluation, and required conditions are defined (FEMA-368 2001, EUROCODE-8 2004, ASCE 07-05 2006, GB 2010). In these codes, seismic hazard is defined in terms of the Uniform Hazard

Spectrum. Seismic loads are generally represented by design spectra that are compatible with local soil conditions or ground motion records selected for time history analyses. In order to simulate the seismic actions to be used as dynamic loading, relatively similar procedures are described. Synthetic, artificial, or real ground motion records could be used as long as they are compatible with regional design spectra defined in the seismic codes within a stated period range. Modern seismic codes usually require at least three ground motion records to be used. The mean of the structural responses are used for design and/or seismic performance evaluation if at least seven ground motion records are selected, otherwise the maximum of structural responses is considered (Bommer and Ruggeri 2002, Beyer and Bommer 2007, Katsanos, Sextos *et al*. 2010).

Recent studies showed that it is possible to obtain different code-compatible ground motion record sets by selecting and scaling from hundreds of ground motion records available in digital databases (Iervolino, Maddaloni *et al*. 2008, Kayhan, Korkmaz *et al*. 2011, Kayhan 2012). As mentioned earlier, ground motion records to be used in the analyses directly affect the displacement and drift ratio demands that would be used for design or seismic performance evaluation. Hence, the mean of structural responses could be accepted as random variables that changes according to ground motion record sets, compatible with any target spectrum, used for nonlinear time history analyses.

The aim of this study is to evaluate the discrepancy of structural response parameters obtained by nonlinear time history analysis using different code-compatible ground motion record sets. For this aim, three generic RC frames having 3-, 5- and 7-story are selected and nonlinear analyses of the frames are performed. Global drift ratio and interstory drift ratio demands are selected as structural response parameters. Ground motion record sets compatible with design spectra defined for local soil classes Z1, Z2 and Z3 in TEC are used for nonlinear analyses. For each local soil classes, four different ground motion record sets are used. Ground motion records are selected from European Strong Motion Database (Ambraseys, Douglas *et al.* 2004). Performing nonlinear analysis of the frames, maximum global drift ratio and maximum interstory drift ratio demands are calculated for each of the ground motion records in the sets. Then, the mean of global and interstory drift ratio demands are calculated for each set.

Results of the study demonstrated that the analysis of the RC frames yielded different global and interstory drift ratio demands for different ground motion record sets although they are compatible with the same design spectrum. Furthermore, maximum drift ratio demands obtained from the records in any ground motion set have a large scattering around the mean drift ratio demands of that set. The difference between the mean drift ratio demands of ground motion record sets are evaluated by one-way analysis of variance (Gamst, Meyers *et al*. 2008). Analysis of variance results showed that the differences between the mean of the structural responses calculated for different ground motion records sets are not statistically meaningful at 5% level of significance. In other words, it can be said that global and interstory drift ratio demands in ground motion sets are accepted as simply random samples of the same population at %95 confidence level. The results are valid for all the frames and local soil classes considered in this study.

2. Structural models

Seismic design codes like Eurocode-8 and TEC apply to the design and construction of buildings and civil engineering works in seismic regions. Their purpose is to ensure that in the event of earthquakes: human lives are protected; damage is limited; and structures important for

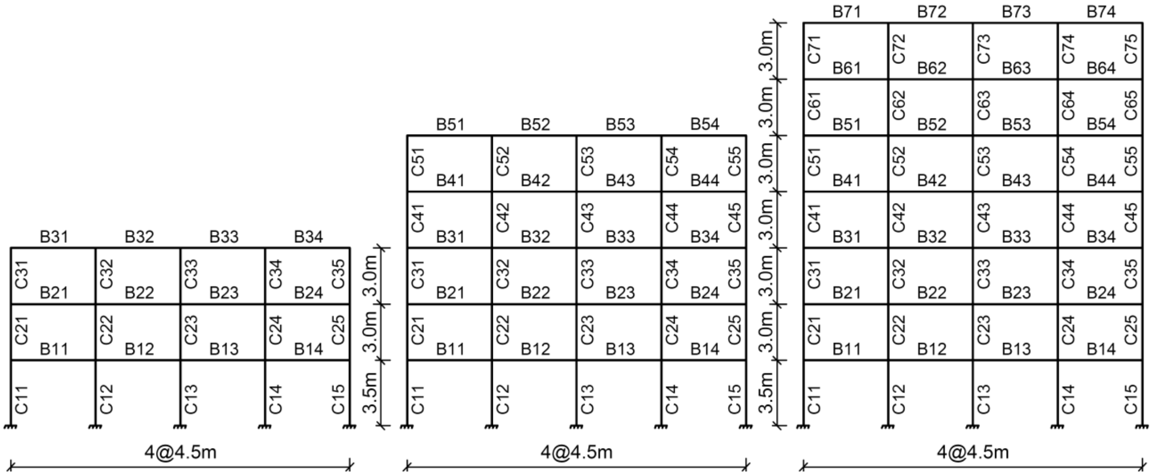

Fig. 1 Two-dimensional frames used for nonlinear analysis

civil protection remain operational.

The requirements on seismic design and details for seismic moment frames are also specified in Eurocode-8 and TEC. Seismic moment frames are used as one of the seismic force-resisting systems in buildings that are designed to resist earthquakes. Beams, columns, and beam-column joints in seismic moment frames are proportioned and detailed to resist flexural, axial, and shearing actions that result as a building sways during strong earthquake ground shaking. The proportioning and detailing requirements for special moment frames are intended to ensure that inelastic response is ductile. According to both Eurocode-8 and TEC, similar three main goals for seismic moment frames are: (a) to achieve a strong-column/weak-beam design; (b) to avoid shear failure in frame members; and (c) to provide details that enable ductile flexural response in yielding regions. In this study, generic RC frames designed satisfying the criteria defined in TEC about seismic moment frames are used.

2.1 Description of generic RC frames

Three generic beam-column frames, 3-, 5- and 7-story, are selected for nonlinear analyses. The labels of the frame members and geometrical properties of the frames can be shown in Fig. 1. Base floor height is 3.50 m and the height of the other floors is 3.00 m of the frames. All the beams in the frames have 30×60 cm cross sectional dimensions. All the columns in 3- and 5-story buildings have 30×60 cm and all the columns in 7-story building have 40×70 cm cross sectional dimensions.

The RC frames are analyzed considering both vertical and seismic loads according to TEC. In order to calculate seismic loads, design ground acceleration is taken as 0.40 g and local soil class is assumed as Z3 (similar to soil class C defined in EUROCODE-8). Material properties are accepted to be f_c=25 MPa for concrete compressive strength and f_y=420 MPa for the yield strength of longitudinal and transverse reinforcement. Considering analyses results, the RC frames are designed and reinforcement details of columns and beams are determined. Then, the nonlinear models of the frames are prepared using gravity loads, outcome member size and reinforcement details of the frame members.

Typical cross sections of the columns are given in Fig. 2. In Fig. 2, the number before "ϕ" is the

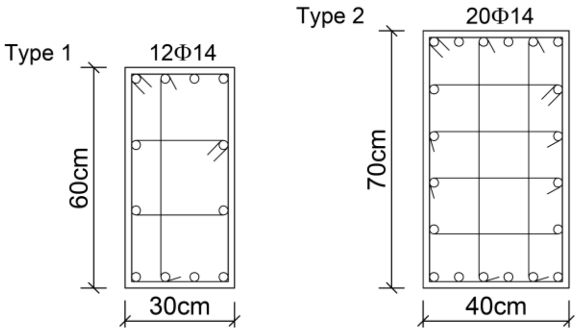

Fig. 2 Typical cross section of columns in 3-, 5- and 7-story frames

Table 1 Longitudinal reinforcing area at ends of the beams (cm^2)

Frame	Story	B1				B2				B3				B4			
		Left		Right		Left		Right		Left		Right		Left		Right	
		Top	Bot	Top	Bot	Top	Bot	Top	Bot	Top	Bot	Top	Bot	Top	Bot	Top	Bot
3 Story	1	7.67	4.52	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	7.67	4.52
	2	5.65	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	5.65	3.39
	3	4.52	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	4.52	2.26
5 story	1	12.92	9.86	9.16	4.28	9.16	4.28	10.29	6.79	10.29	6.79	9.16	4.28	9.16	4.28	12.92	9.86
	2	10.74	6.90	7.92	3.80	7.92	3.80	9.45	6.06	9.45	6.06	7.92	3.80	7.92	3.80	10.74	6.90
	3	8.80	4.52	7.92	3.39	7.92	3.39	7.92	4.52	7.92	4.52	7.92	3.39	7.92	3.39	8.80	4.52
	4	6.54	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.54	3.39
	5	4.52	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	4.52	2.26
7 story	1	13.16	9.86	10.29	6.88	10.29	6.88	11.68	8.55	11.68	8.55	10.29	6.88	10.29	6.88	13.16	9.86
	2	12.92	8.29	10.29	6.79	10.29	6.79	11.68	8.55	11.68	8.55	10.29	6.79	10.29	6.79	12.92	8.29
	3	11.68	6.90	9.45	6.06	9.45	6.06	10.46	7.35	10.46	7.35	9.45	6.06	9.45	6.06	11.68	6.90
	4	10.29	5.41	9.05	4.81	9.05	4.81	9.05	6.06	9.05	6.06	9.05	4.81	9.05	4.81	10.29	5.41
	5	7.92	4.28	6.79	3.39	6.79	3.39	7.92	4.52	7.92	4.52	6.79	3.39	6.79	3.39	7.92	4.28
	6	5.65	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	6.79	3.39	5.65	3.39
	7	4.52	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	6.79	2.26	4.52	2.26

number of bars and after "ϕ" is the diameter of bar in mm. All columns in 3- and 5-story frames have Type-1 cross section and all columns in 7-story frame have Type-2 cross section.

Longitudinal reinforcing areas at both left and right ends of the beams in 3-, 5- and 7-story frames are given in Table 1. For each of the left and right ends, the reinforcing areas at the top and bottom of the beams are given in Table 1, separately. Diameter and spacing of transverse reinforcement of the RC members are 8 mm and 100 mm, respectively.

2.2 Modeling approach and capacity curves of the frames

3-, 5-, and 7-story generic frames are modeled for nonlinear analysis using abovementioned loading, dimensions and reinforcing details of the frame members. SAP2000 (SAP2000 2009), structural analysis program, is used to perform nonlinear static and dynamic analysis of the frames.

Columns and beams of the frames are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of them. User-defined plastic hinge properties are used for the frame members. In order to define plastic hinge properties, moment-curvature analyses are performed considering section properties and axial load level for each of the columns and beams. Axial loads were assumed as zero for beams, and, were calculated by adding 30% of live loads to dead loads for columns according to TEC. Modified Kent-Park model (Park, Priestley *et al.* 1982) for confined and unconfined concrete and Mander stress-strain model (Mander, Priestley *et al.* 1988) with strain hardening for steel are used in moment-curvature analysis.

In SAP2000, moment-rotation relationship is used to nonlinear behavior of frame members instead of moment-curvature relationship. The required moment-rotation relations are determined using moment-curvature analysis results and plastic hinge length. According to TEC, the plastic hinge length can be taken as half of the section height.

When modeling a frame for structural analysis, it is important to consider the effective stiffness of the frame members, because it affects the resulting period of the frame, story drift and internal force distributions. For this reason, the effective stiffness values to be used for the frame members are defined in modern seismic design codes. For example, ACI 318-08 (2008) recommends the following options for estimating member stiffness for the determination of lateral deflection of building systems subjected to factored lateral loads: a) 0.35EI for beams and 0.70EI for columns; or b) 0.50EI for all compression and flexural members. According to EUROCODE-8, the effective stiffness of the load carrying elements of the frames should also be considered in structural analysis model. Unless a more accurate analysis is performed, the flexural and shear stiffness of structural elements may be taken as one half of the corresponding stiffness of the uncracked elements. According to TEC, effective stiffness values are 0.4EI for beams, and, these values vary depending on axial load level for columns (Eq. (1)). In Eq. (1), N and A_c are axial load and area of cross section of columns, respectively, and f_c is compressive strength of concrete. Linear interpolation is made for values of the $N/(A_c\, f_c)$ between 0.10 and 0.40. In this study, the initial effective stiffness values for each of the frame members are considered in nonlinear models.

$$\begin{aligned} &0.4EI \quad \text{for } N/(A_c f_c) \le 0.10 \\ &0.8EI \quad \text{for } N/(A_c f_c) \ge 0.40 \end{aligned} \tag{1}$$

As known, low concrete strength and insufficient amount and detail of transverse reinforcement can cause shear failures in RC frame members during an earthquake. For this type of structures, shear hinges also should be defined in order to take into consideration shear failures of the members. As mentioned before, the frames used in this study are seismic moment frames. For this reason, all the beams, columns and beam-column joints in the frames are designed to avoid shear failure considering capacity-design rules defined in TEC. Thus, shear hinges are not defined for the columns and beams.

In Table 2, total height (H), natural vibration period using initial effective stiffness (T) and seismic weight (W) of the frames are given. Modal participating mass ratio (α_1) and modal participation factors (PF_1) for the first mode are also given in Table 2.

Pushover analyses are performed and capacity curves of the frames are obtained considering gravity loads and lateral load pattern. The first mode shape is used for lateral load pattern. In Fig. 3, capacity curves obtained for the frames are given. P-Delta effect is also considered for pushover analysis. Generally capacity curves are given using lateral load-lateral top displacement form (V_t-Δ).

Table 2 Some information about the RC frames

RC frame	H (m)	T (s)	W (kN)	α_1	PF_1
3-story	9.50	0.538	2258.36	0.914	1.245
5-story	15.50	0.839	3876.62	0.869	1.277
7-story	21.50	0.938	5674.66	0.840	1.288

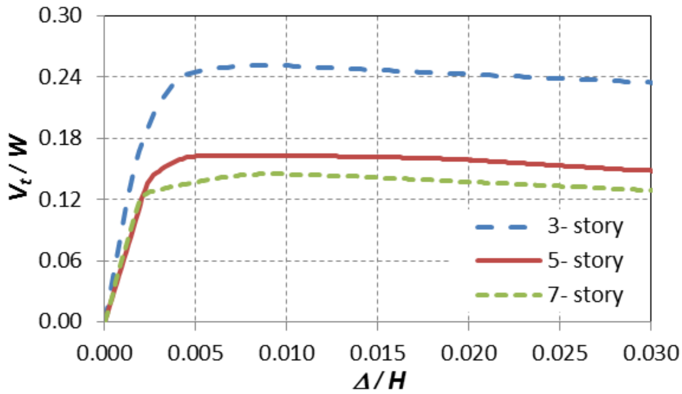

Fig. 3 Capacity curves of the RC frames

In this study, lateral strength ratio (V_t/W) and global drift ratio (Δ/H) are used for vertical and horizontal axis of the capacity curves, respectively. According to Fig. 3, maximum lateral strength ratio of the 3-, 5- and 7- story frames are about 25%, 16% and 14%, respectively, and decreasing with increasing drift ratio. In TEC, it is assumed that the frame members do not lose their moment carrying capacity during the nonlinear analysis. For this reason, when the plastic hinge information is defined for the frame elements, the limit values for the collapse that the moment carrying capacity terminates are not given in TEC. When plastic hinge information is defined, this fact is taken into account in this study. As a result, a decrease in lateral strength ratio is not observed in capacity curves of the frames given in Fig. 3.

3. Ground motion record sets

In most of the modern seismic codes including the Turkish Earthquake Code (TEC 2007) time history analysis is accepted as one of the analysis method for design and/or performance evaluation, and required conditions are defined (FEMA-368 2001, EUROCODE-8 2004, ASCE 07-05 2006, GB 2010). According to these codes, code-compatible ground motion records can be used for time history analysis. It was expected that the average response spectra of the selected ground motion records should be compatible with the regional design spectra defined in the seismic codes within a stated period range.

In this study, TEC compatible ground motion records sets are used to perform nonlinear time history analysis. For each considered local soil class defined in TEC, four different ground motion record sets are used. Ground motion records are selected from European Strong Motion Database (Ambraseys, Douglas *et al.* 2004). There are seven ground motion records in each set.

3.1 Time history analysis requirements in TEC

According to TEC, artificially generated, previously recorded or simulated ground motions with appropriate source and wave propagation characteristics can be used in linear or nonlinear time history analysis of buildings and building-like structures. Local site conditions should be appropriately considered in using recorded or simulated ground motions. It is required to use at least three ground motion records and these selected records should meet the following conditions:

- The duration of strong motion part shall not be shorter than 5 times the fundamental period of the building in the considered direction and 15 seconds;
- Mean spectral acceleration of ground motion records for zero period shall not be less than A_0g;
- Mean spectral accelerations of ground motion records for 5% damping ratio shall not be smaller than 90% of design spectral accelerations in the period range between 0.2T and 2.0T with respect to dominant natural period T of the building in the considered earthquake direction.

In linear and nonlinear calculations, the maximum of structural responses shall be considered for the design and/or seismic evaluation if three ground motion records are used; and when at least seven ground motions are utilized, the mean of structural responses can be considered.

3.2 Ground motion database and record sets

According to the current seismic zoning map (http://www.deprem.gov.tr), prepared by the Ministry of Public Works and Settlement, 96% of Turkey's land is located on different level of seismic hazard. There are five seismic zone is defined according to seismic hazard level: Zone 1st, 2nd, 3rd, 4th, and 5th degree. According to TEC, design ground acceleration is 0.4 g, 0.3 g, 0.2 g and 0.1 g for the Zone 1st, 2nd, 3rd and 4th degree, respectively. Zone 5th degree is accepted as non-seismic zone and design ground acceleration is zero for this zone. In TEC, four different local soil classes are defined in Section 6.2: Z1, Z2, Z3, and Z4. The ordinates and shape of the elastic design spectrum, to be determined seismic loads, depend on the seismic zone and local soil class. Fig. 4 demonstrates the variation on Spectral Acceleration Coefficient $A(T)$ that would be used for the residential buildings, which are located in Zone 1st degree, based on the TEC specifications.

For selection and scaling of code-compliant ground motion record sets, initially, the following criteria of epicentral distance (R), magnitude (M) and peak ground acceleration (PGA) are used to obtain a catalog from the European Strong Motion Database (Ambraseys, Douglas *et al*. 2004): R be in the range of 10-50 km; M be greater than 5.5; and PGA be 0.10 g or higher.

The catalog of 542 strong ground motion records were grouped based on the local soil classes that they were recorded on. It was observed that there are 190 horizontal components of 95 ground motion records for soil class A; 236 horizontal components of 118 ground motion records for soil class B; and 116 horizontal components of 58 ground motion records for soil class C in the catalog (according to EUROCODE-8 definition of local soil classes). It should be noted that soil class D and E are ignored for the selection of ground motion records for the catalog because there are not sufficient number of records in the database satisfying the abovementioned criteria. Soil Z1, Z2, and Z3 defined in the TEC are compatible with soil class A, B and C defined in EUROCODE-8, respectively. For this reason, ground motion records recorded on soil class A, B and C, are considered to obtain record sets for Soil Z1, Z2 and Z3, respectively, and Soil Z4 is ignored.

The scaling coefficient is constrained to be in the range of 0.50-2.00. In order to satisfy

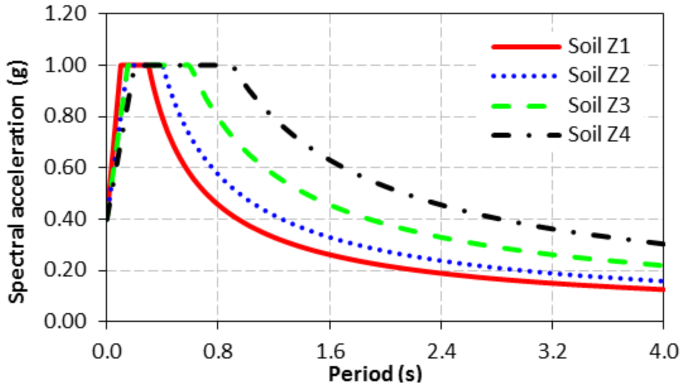

Fig. 4 Spectral acceleration coefficient for local soil classes

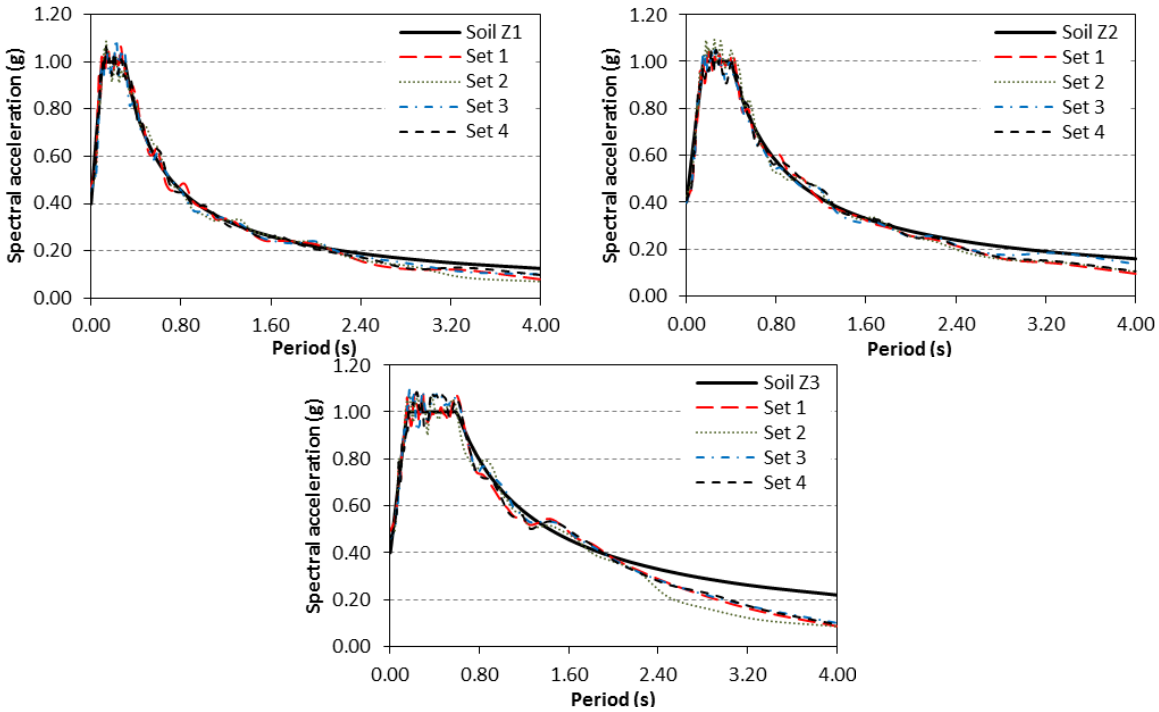

Fig. 5 Average spectrum of ground motions sets and target spectrum

compatibility between the mean spectrum of the ground motion record sets and design spectrum, the range of 0.08s-2.40s of the period is considered.

Four different ground motion record sets are obtained for each soil classes Z1, Z2 and Z3 considering only those ground motion records recorded on matching soil class sites, i.e. on sites with soil classes A, B and C, respectively. The detailed information about ground motion selection procedure used in this study can be found in Kayhan *et al*. (2011) and Kayhan (2016). Totally 12 ground motion record sets are obtained. Each of the sets has seven horizontal components of the ground motion records. In Fig. 5, mean spectra of obtained ground motion record sets and corresponding target spectra are given. The information about ground motion record sets used in

Table 3 Ground motion record sets compatible with TEC

Soil Class	Set 1		Set 2		Set 3		Set 4	
	Record	Scale	Record	Scale	Record	Scale	Record	Scale
Soil Z1	5270-Y	1.014	646-Y	0.816	5272-Y	1.440	6272-X	1.848
	410-X	1.782	383-Y	1.449	6331-X	1.132	5272-Y	1.698
	292-X	1.344	362-X	1.475	382-X	1.448	6327-Y	1.151
	362-X	1.554	292-X	0.971	5655-X	0.787	605-X	0.924
	7158-X	0.632	1243-X	0.789	6270-Y	0.894	368-X	0.851
	6272-Y	1.224	5272-Y	1.664	292-X	0.818	383-Y	0.993
	6327-Y	0.519	6331-X	1.166	362-Y	0.972	467-Y	1.277
Soil Z2	645-Y	1.394	1859-X	0.992	6496-Y	1.721	6447-Y	1.919
	352-Y	1.275	946-Y	1.786	1735-X	0.835	352-Y	0.592
	548-X	0.711	6496-Y	1.803	532-Y	1.061	232-Y	1.273
	6422-X	1.600	645-Y	1.182	595-X	0.910	142-Y	1.023
	946-Y	0.903	1720-Y	0.636	760-X	0.870	760-X	1.054
	760-Y	1.467	595-X	0.819	142-Y	1.523	1735-X	1.688
	572-Y	1.747	142-Y	1.501	352-Y	0.982	6496-Y	1.309
Soil Z3	360-X	0.704	601-Y	1.008	141-X	1.988	6962-X	1.998
	374-Y	0.672	648-Y	0.743	151-X	0.923	7104-X	0.728
	602-X	0.999	360-X	0.831	7010-X	1.378	375-Y	0.904
	6962-Y	1.355	6606-Y	1.105	1230-X	0.540	1230-X	0.693
	6978-Y	0.622	1230-X	0.548	6606-Y	1.301	360-X	1.044
	6606-Y	0.582	6975-Y	1.096	6978-Y	0.819	6978-Y	0.757
	1230-X	0.788	375-Y	0.600	6962-Y	1.984	7010-Y	1.913

this study is presented in Table 3. The table includes ground motion record numbers, horizontal component indices and scaling coefficients. Detailed information about the ground motion records is given in Appendix A.

4. Dynamic analysis results

The maximum global lateral displacement demands (Δ_{max}) and the maximum interstory lateral displacement demands (δ_{max}) are obtained for the generic frames by nonlinear time history analysis using ground motion records in the sets. In this study, global and interstory drift ratios are selected as structural response parameters for statistical evaluation. Thus, maximum global drift ratio demand (Δ_{max}/H) and maximum interstory drift ratio demands (δ_{max}/h) are also calculated for each frames and each ground motion record in the sets.

According to TEC, the mean of structural response parameters can be considered for design or seismic performance evaluation if at least seven ground motion records are used for time history analysis. In this study, there are seven ground motion records in ground motion record sets. The mean of global drift ratio ($m_{\Delta/H}$) and interstory drift ratio ($m_{\delta/h}$) demands for each set are calculated

Table 4 Mean and standard deviation values of global drift ratio for the RC frames

Frames	Sets	Soil Z1		Soil Z2		Soil Z3	
		$m_{\Delta/H}$	$s_{\Delta/H}$	$m_{\Delta/H}$	$s_{\Delta/H}$	$m_{\Delta/H}$	$s_{\Delta/H}$
3-story	Set 1	0.0049	0.0028	0.0068	0.0045	0.0110	0.0106
	Set 2	0.0050	0.0035	0.0071	0.0041	0.0107	0.0057
	Set 3	0.0053	0.0029	0.0062	0.0029	0.0104	0.0059
	Set 4	0.0063	0.0033	0.0072	0.0053	0.0097	0.0073
5-story	Set 1	0.0053	0.0031	0.0077	0.0059	0.0095	0.0074
	Set 2	0.0059	0.0041	0.0063	0.0034	0.0105	0.0066
	Set 3	0.0055	0.0036	0.0074	0.0027	0.0106	0.0048
	Set 4	0.0057	0.0034	0.0076	0.0035	0.0114	0.0118
7-story	Set 1	0.0041	0.0024	0.0059	0.0046	0.0077	0.0060
	Set 2	0.0046	0.0035	0.0056	0.0035	0.0081	0.0048
	Set 3	0.0046	0.0031	0.0062	0.0026	0.0083	0.0044
	Set 4	0.0046	0.0028	0.0057	0.0019	0.0082	0.0074

using Eq. (2) and Eq. (3), respectively. In Eq. (2) and Eq. (3), *i* and *j* represent the ground motion record label in a set and the story number of the frame, respectively.

$$m_{\Delta/H} = \left[\sum_{i=1}^{7} \left(\Delta_{\max} / H \right)_i \right] / 7 \tag{2}$$

$$m_{(\delta/h)_j} = \left[\sum_{i=1}^{7} \left(\delta_{\max,j} / h_j \right)_i \right] / 7 \tag{3}$$

For evaluation of the scattering of drift ratio demands obtained from ground motion records, coefficient of variance (*CoV*), the ratio of standard deviation (*s*) to mean (*m*), is also calculated for each of the sets.

The mean ($m_{\Delta/H}$) and standard deviation ($s_{\Delta/H}$) of maximum global drift ratio demands calculated for the sets are given in Table 4. It can be shown that different $m_{\Delta/H}$ values are obtained for each of the frames using different ground motion sets although they are compatible with the same local soil class. For example, when Soil-Z1 is considered, $m_{\Delta/H}$ values of four ground motion sets are equal to 0.0049, 0.0050, 0.0053 and 0.0063 for the 3-story frame. $m_{\Delta/H}$ values of the sets for the same frame are 0.0068, 0.0071, 0.0062 and 0.0072 for Soil-Z2, and 0.0110, 0.0107, 0.0104 and 0.0097 for Soil-Z3. Similar results are also valid for 5- and 7-story frames. These results are compatible with the knowledge that there is variability in structural responses due to the nature of earthquake-induced ground motions, structural properties and design assumptions.

$CoV_{\Delta/H}$ values calculated for ground motion record sets considering global drift ratio demands are given in Fig. 6. It can be seen in Fig. 6, $CoV_{\Delta/H}$ values are remarkably high. For example, $CoV_{\Delta/H}$ values of the four ground motion record sets calculated for the 3-story frame are ranging from 0.53 to 0.70 for Soil-Z1; from 0.46 to 0.73 for Soil-Z2; from 0.53 to 0.96 for Soil-Z3. It means that the dispersion of the $\Delta_{\max}/H$ values in a set around the $m_{\Delta/H}$ value calculated for that set is high. Significantly high $CoV_{\Delta/H}$ values are also calculated for the 5- and 7-story frames. As can

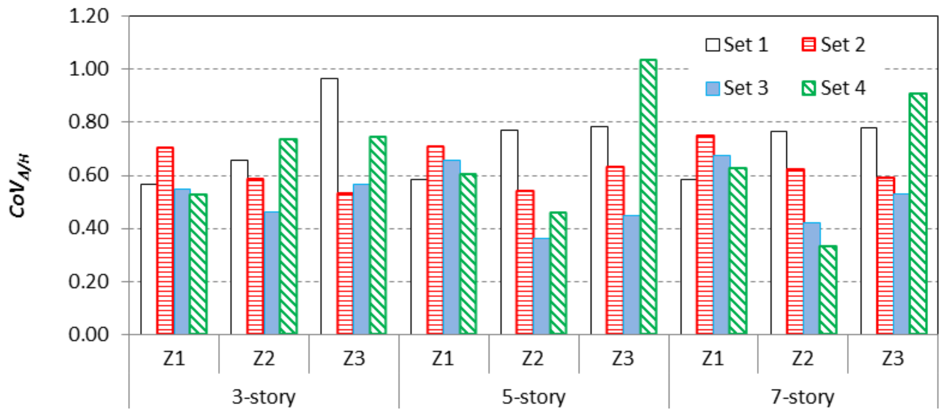

Fig. 6 *CoV* values for global drift ratio demands

Table 5 Mean and standard deviation values of interstory drift ratios for 3-story frames

Story	Sets	Soil Z1		Soil Z2		Soil Z3	
		$m_{\delta/h}$	$s_{\delta/h}$	$m_{\delta/h}$	$s_{\delta/h}$	$m_{\delta/h}$	$s_{\delta/h}$
3	Set 1	0.0036	0.0026	0.0049	0.0031	0.0064	0.0045
	Set 2	0.0035	0.0023	0.0048	0.0029	0.0077	0.0044
	Set 3	0.0036	0.0022	0.0039	0.0020	0.0071	0.0041
	Set 4	0.0043	0.0022	0.0049	0.0038	0.0063	0.0042
2	Set 1	0.0058	0.0031	0.0077	0.0045	0.0122	0.0114
	Set 2	0.0059	0.0038	0.0080	0.0042	0.0117	0.0057
	Set 3	0.0062	0.0031	0.0072	0.0030	0.0115	0.0062
	Set 4	0.0073	0.0036	0.0082	0.0055	0.0120	0.0099
1	Set 1	0.0060	0.0035	0.0083	0.0056	0.0147	0.0159
	Set 2	0.0063	0.0048	0.0090	0.0055	0.0130	0.0070
	Set 3	0.0064	0.0036	0.0077	0.0036	0.0129	0.0076
	Set 4	0.0077	0.0041	0.0087	0.0065	0.0131	0.0120

be seen in Fig. 6, $CoV_{\Delta/H}$ values for the 5-story frame are changing between 0.59 and 0.71 for Soil-Z1; 0.36 and 0.77 for Soil-Z2; 0.45 and 1.03 for Soil-Z3. For the 7-story frame, $CoV_{\Delta/H}$ values are varying from 0.59 to 0.75 for Soil-Z1; 0.33 to 0.77 for Soil-Z2; 0.53 to 0.90 for Soil-Z3. According to the results given in Fig. 6, it can be said that Δ_{max}/H values obtained from ground motion records in the sets have large dispersion about the $m_{\Delta/H}$ values of the sets.

One of the structural parameters considered in this study is the interstory drift ratio demand. Maximum interstory drift ratio (δ_{max}/h) is calculated by nonlinear time history analysis using each ground motion record in the sets for each of the generic frames used in the study. Then, mean interstory drift ratio ($m_{\delta/h}$) values of the sets are calculated.

The mean ($m_{\delta/h}$) and standard deviation ($s_{\delta/h}$) of maximum interstory drift ratio demands calculated for the 3-story frame are given in Table 5. According to Table 5, similarly $m_{\Delta/H}$, various $m_{\delta/h}$ values are calculated for each story of the frames using different ground motion records sets although they are compatible with the same local soil class. For example, at the 3rd story, $m_{\delta/h}$

Table 6 Mean and standard deviation values of interstory drift ratios for 5-story frames

Story	Sets	Soil Z1		Soil Z2		Soil Z3	
		$m_{\delta/h}$	$s_{\delta/h}$	$m_{\delta/h}$	$s_{\delta/h}$	$m_{\delta/h}$	$s_{\delta/h}$
5	Set 1	0.0028	0.0016	0.0032	0.0018	0.0036	0.0026
	Set 2	0.0025	0.0014	0.0029	0.0010	0.0044	0.0029
	Set 3	0.0027	0.0010	0.0030	0.0007	0.0039	0.0021
	Set 4	0.0027	0.0012	0.0038	0.0019	0.0050	0.0061
4	Set 1	0.0051	0.0026	0.0064	0.0038	0.0077	0.0055
	Set 2	0.0051	0.0030	0.0058	0.0021	0.0086	0.0051
	Set 3	0.0053	0.0023	0.0062	0.0014	0.0082	0.0037
	Set 4	0.0054	0.0028	0.0070	0.0030	0.0092	0.0095
3	Set 1	0.0069	0.0036	0.0095	0.0065	0.0115	0.0076
	Set 2	0.0077	0.0051	0.0079	0.0037	0.0123	0.0067
	Set 3	0.0073	0.0043	0.0091	0.0025	0.0127	0.0052
	Set 4	0.0077	0.0044	0.0096	0.0038	0.0127	0.0108
2	Set 1	0.0075	0.0039	0.0110	0.0086	0.0141	0.0116
	Set 2	0.0087	0.0063	0.0094	0.0052	0.0148	0.0092
	Set 3	0.0081	0.0057	0.0107	0.0039	0.0157	0.0067
	Set 4	0.0083	0.0048	0.0098	0.0055	0.0165	0.0159
1	Set 1	0.0065	0.0037	0.0102	0.0093	0.0135	0.0139
	Set 2	0.0073	0.0062	0.0084	0.0056	0.0141	0.0102
	Set 3	0.0070	0.0056	0.0095	0.0051	0.0149	0.0080
	Set 4	0.0067	0.0041	0.0103	0.0049	0.0166	0.0190

values of four ground motion record sets are equal to 0.36%, 0.35%, 0.36% and 0.43% for Soil Z1. At this story, $m_{\delta/h}$ values of the sets are equal to 0.49%, 0.48%, 0.43% and 0.49% for Soil Z2 and, equal to 0.64%, 0.77%, 0.71% and 0.63% for Soil Z3. Similar results are found for 1st and 2nd stories as well. Table 5 shows that $m_{\delta/h}$ values for all soil classes and sets are higher at the 1st story when compared to the other stories. It is also observed that a change in local soil class is effective on $m_{\delta/h}$ values. $m_{\delta/h}$ increase when local soil class changes from Z1 to Z3.

For the 5-story frame, the mean ($m_{\delta/h}$) and standard deviation ($s_{\delta/h}$) of maximum interstory drift ratio demands are given in Table 6. According to Table 6, various $m_{\delta/h}$ values are also calculated for each story of the frames using different ground motion records sets. For example, at the 1st story, $m_{\delta/h}$ values of four ground motion record sets are equal to 0.65%, 0.73%, 0.70% and 0.67% for Soil Z1, to 1.02%, 0.84%, 0.95% and 1.03% for Soil Z2 and to 1.35%, 1.41%, 1.49% and 1.66% for Soil Z3. Table 6 indicates that $m_{\delta/h}$ values are the highest at the 1st and 2st story for all soil classes and record sets. Local soil classes also affect $m_{\delta/h}$ values for the 5-story frame.

The mean ($m_{\delta/h}$) and standard deviation ($s_{\delta/h}$) of maximum interstory drift ratio demands calculated for the 7-story frame are given in Table 7. According to Table 7, similarly 3-story and 5-story frames, various $m_{\delta/h}$ values are calculated for each story of the 7-story frame using different ground motion records sets. For the 7-story frame, the highest are calculated at the 2nd and 3rd story. At the 2nd story, $m_{\delta/h}$ differ between 0.62%-0.69% in this story for Soil-Z1 increase

Table 7 Mean and standard deviation values of interstory drift ratios for 7-story frames

Story	Sets	Soil Z1		Soil Z2		Soil Z3	
		$m_{\delta/h}$	$s_{\delta/h}$	$m_{\delta/h}$	$s_{\delta/h}$	$m_{\delta/h}$	$s_{\delta/h}$
7	Set 1	0.0021	0.0012	0.0026	0.0018	0.0028	0.0018
	Set 2	0.0019	0.0010	0.0027	0.0013	0.0036	0.0022
	Set 3	0.0020	0.0008	0.0028	0.0011	0.0035	0.0016
	Set 4	0.0023	0.0013	0.0024	0.0013	0.0029	0.0018
6	Set 1	0.0037	0.0020	0.0042	0.0024	0.0049	0.0027
	Set 2	0.0033	0.0018	0.0045	0.0019	0.0060	0.0030
	Set 3	0.0034	0.0014	0.0048	0.0016	0.0061	0.0027
	Set 4	0.0039	0.0019	0.0042	0.0015	0.0049	0.0028
5	Set 1	0.0050	0.0027	0.0057	0.0032	0.0075	0.0039
	Set 2	0.0048	0.0027	0.0060	0.0028	0.0088	0.0041
	Set 3	0.0049	0.0022	0.0063	0.0020	0.0088	0.0042
	Set 4	0.0054	0.0028	0.0060	0.0020	0.0075	0.0042
4	Set 1	0.0058	0.0034	0.0073	0.0046	0.0106	0.0072
	Set 2	0.0063	0.0042	0.0071	0.0037	0.0109	0.0055
	Set 3	0.0062	0.0036	0.0078	0.0026	0.0112	0.0052
	Set 4	0.0065	0.0039	0.0078	0.0025	0.0107	0.0081
3	Set 1	0.0063	0.0034	0.0086	0.0061	0.0122	0.0092
	Set 2	0.0071	0.0057	0.0081	0.0044	0.0119	0.0066
	Set 3	0.0071	0.0051	0.0091	0.0034	0.0121	0.0053
	Set 4	0.0071	0.0044	0.0088	0.0026	0.0127	0.0106
2	Set 1	0.0062	0.0034	0.0089	0.0071	0.0125	0.0109
	Set 2	0.0069	0.0060	0.0083	0.0052	0.0118	0.0080
	Set 3	0.0066	0.0056	0.0090	0.0043	0.0125	0.0079
	Set 4	0.0068	0.0038	0.0084	0.0027	0.0129	0.0123
1	Set 1	0.0044	0.0027	0.0075	0.0071	0.0093	0.0109
	Set 2	0.0048	0.0048	0.0065	0.0051	0.0095	0.0081
	Set 3	0.0047	0.0045	0.0067	0.0047	0.0108	0.0102
	Set 4	0.0048	0.0029	0.0054	0.0022	0.0102	0.0129

with the change in soil class and differ between 1.18%-1.29% for Soil-Z3.

In order to evaluate the scattering of δ_{max}/h values calculated for ground motion records in the sets around the $m_{\delta/h}$ values of the sets, $CoV_{\delta/h}$ values were calculated. The minimum and maximum values of $CoV_{\delta/h}$ calculated for four different sets are given in Table 8. Considering only maximum values, it can be shown that $CoV_{\delta/h}$ values are at least 0.541 and some of them are even bigger than 1.00. The lowest $CoV_{\delta/h}$ values of the sets for 3-, 5-, and 7-story frame are 0.425, 0.225 and 0.296, respectively.

Results given in Fig. 6 and Table 8 indicate that the scattering of global and interstory drift ratio demands obtained from ground motion records around the mean drift ratio demands

Table 8 The range of $CoV_{\delta/h}$ values calculated for ground motion record sets

Story		7-story frame			5-story frame			3-story frame		
		Soil Z1	Soil Z2	Soil Z3	Soil Z1	Soil Z2	Soil Z3	Soil Z1	Soil Z2	Soil Z3
1	Minimum	0.603	0.403	0.853	0.572	0.473	0.534	0.538	0.469	0.536
	Maximum	1.005	0.955	1.260	0.849	0.911	1.146	0.757	0.748	1.080
2	Minimum	0.543	0.320	0.633	0.524	0.363	0.430	0.498	0.425	0.486
	Maximum	0.879	0.795	0.956	0.731	0.783	0.963	0.636	0.668	0.929
3	Minimum	0.548	0.296	0.438	0.525	0.279	0.410	0.520	0.510	0.574
	Maximum	0.801	0.706	0.829	0.655	0.691	0.849	0.731	0.776	0.713
4	Minimum	0.585	0.317	0.466	0.427	0.225	0.449			
	Maximum	0.671	0.628	0.755	0.591	0.600	1.027			
5	Minimum	0.447	0.312	0.470	0.358	0.231	0.543			
	Maximum	0.564	0.566	0.565	0.568	0.565	1.205			
6	Minimum	0.400	0.336	0.436						
	Maximum	0.541	0.569	0.560						
7	Minimum	0.416	0.402	0.457						
	Maximum	0.561	0.725	0.665						

calculated for the sets are not negligible. Similar results are obtained by Katsanos, Sextos *et al*. (2010) using EUROCODE-8 compatible ground motion record sets. Iervolino, De Luca *et al.* (2010b) also note that the dispersion of the inelastic response of the same structural model was significantly greater in ground motion sets.

It can be suggested that this fact should be taken into consideration in calculating the possibility of exceedance of pre-determined limit values for structural responses. To take the uncertainties in structural responses into consideration more realistically, it could be argued that studies to determine the probability distribution of structural response parameters using more ground motions for nonlinear time history analyses are required as well.

5. Statistical evaluation of the analysis results

5.1 Analysis of variance

Analysis of variance (ANOVA), developed by Fisher (Gamst, Meyers *et al*. 2008), method was used to analyze the differences among mean global and drift ratio demands of four ground motion record sets calculated for each of the frames. ANOVA is used to test whether or not the samples in two or more groups are drawn from populations with the same mean values.

The simplest model for ANOVA is one-way ANOVA since the mean of a random variable depends only on a single factor. Consider k independent groups drawn different populations being compared, each of size n, and the members of the groups are normally distributed with unknown mean μ and unknown variance σ^2. The relevant null hypothesis is all the population means are equal (Eq. (4)).

$$H_0 : \mu_1 = \mu_2 = \mu_3 \ldots \mu_k \tag{4}$$

Table 9 *k* random samples for the one-way ANOVA

	Set 1	Set 2	Set 3	Set 4
	X_{11}	X_{21}	X_{31}	X_{41}
	X_{12}	X_{22}	X_{32}	X_{42}
	X_{13}	X_{23}	X_{33}	X_{43}
	X_{14}	X_{24}	X_{34}	X_{44}
	X_{15}	X_{25}	X_{35}	X_{45}
	X_{16}	X_{26}	X_{36}	X_{46}
	X_{17}	X_{27}	X_{37}	X_{47}
Total	T_{1+}	T_{2+}	T_{3+}	T_{4+}
Mean	X_1	X_2	X_3	X_4

In this study, the H_0 is the mean of populations represented by drift ratio demands are equal. Global and interstory drift ratio demands obtained using ground motion records in each sets are assumed as separate groups drawn from populations. For example, considering 3-story frame and Soil-Z1, there are four ground motion sets and each of them has seven ground motion records. Therefore, four separate groups that contain seven Δ_{max}/H values for considered abovementioned frame and local soil class. Similarly, there are four separate groups that contain seven δ_{max}/h values for each story of the frames and local soil class.

In Table 9, typical model used in this study for one-way ANOVA is given. There are k=4 different ground motion sets and each of the ground motion sets has n=7 ground motion records. Obtained drift ratio demands for each ground motion record is represented by X_{ij} (i and j are the label of ground motion set and ground motion record in the set, respectively). T_{1+}, T_{2+}, T_{3+} and T_{4+} refer the total of seven X_{ij} values in the sets and T_{++} refers the total of all the X_{ij} values. X_i, the sample mean of the X_{ij} values in each set, and X, the mean of all the X_{ij} values, is also given in Table 9.

To test H_0, first, the variance within groups (s_0^2) is calculated as the error sum of squares divided by its degrees of freedom (Eq. (5)). Second, the variance between groups (s_M^2) is calculated as the group sum of squares divided by its degrees of freedom (Eq. (6)). s_0^2 and s_M^2 measure the variability due to random causes and the variability due to differences between the mean of groups, respectively. The test statistic for one-way ANOVA is F, the ratio of the variance between groups to the variance within groups (Eq. (7)).

$$s_0{}^2 = \frac{\sum\sum X_{ij}^2 - \sum(T_{i+}^2/n_i)}{\sum n_i - k} \tag{5}$$

$$s_M^2 = \frac{\sum_{i=1}^{k} \frac{T_{1+}^2}{n_i} - \frac{T_{++}^2}{N}}{k-1} \tag{6}$$

$$F = \frac{s_M^2}{s_0^2} \tag{7}$$

The calculations often summarized in a tabular format as displayed in Table 10.

Table 10 Analysis of variance for the one-way ANOVA

Source of variation	Sum of squares	Degrees of freedeom	Variance	Computed F
Treatments	$\sum \frac{T_{i+}^{2}}{n_1} - \frac{T_{++}^{2}}{N}$	k-1	s_M^2	$\frac{s_M^2}{s_0^2}$
Error	$\sum\sum X_{ij}^{2} - \sum \frac{T_{i+}^{2}}{n_1}$	N-k	s_0^2	
Total	$\sum\sum X_{ij}^{2} - \frac{T_{++}^{2}}{N}$	N-1		

Table 11 F values calculated for global drift ratio demands

Soil	Frames		
	3-story	5-story	7-story
Soil Z1	0.296	0.032	0.041
Soil Z2	0.070	0.164	0.053
Soil Z3	0.036	0.069	0.012

Table 12 F values calculated for interstory drift ratio demands

Story number	Soil Z1			Soil Z2			Soil Z3		
	3-story	5-story	7-story	3-story	5-story	7-story	3-story	5-story	7-story
1	0.225	0.032	0.014	0.074	0.129	0.194	0.041	0.068	0.028
2	0.281	0.056	0.026	0.069	0.109	0.038	0.010	0.058	0.014
3	0.155	0.054	0.055	0.189	0.209	0.065	0.160	0.035	0.015
4		0.025	0.052		0.216	0.073		0.075	0.012
5		0.092	0.074		0.518	0.070		0.199	0.227
6			0.170			0.168			0.406
7			0.233			0.088			0.389

If F is lower than F-critical value, H_0 is accepted. F-critical value is 3.01 for the test with significance level α=0.05 and degrees of freedom k-1=3 and Σn_i-k=24.

Using $\Delta_{\max}/H$ values, F values are calculated for each RC frame and local soil class and compared with F-critical value. Similarly, using $\delta_{\max}/h$ values, F values are calculated for each RC frame, story and local soil class and compared with F-critical value. F values calculated for $\Delta_{\max}/H$ and $\delta_{\max}/h$ are given in Table 11 and Table 12, respectively. As can be shown in Table 11 and Table 12, all the F values are much lower than F-critical (3.01). Maximum F value calculated for global and interstory drift ratio demands is lower than even 0.60. Accordingly, H_0 is accepted for both global and interstory drift ratio demands. Thus, it can be said that global and interstory drift ratio demands in ground motion sets are drawn from populations with equal mean. This result is valid for all the RC frames and local soil classes considered in this study.

As mentioned before, s_0^2 and s_M^2 measure the variability due to random causes and the variability due to differences between the mean of groups, respectively. These values are used to calculate F (Eq. (7)). The lower F values state that the effect of variability due to random causes on the total variability is larger than the effect of variability due to differences between the mean of groups. The results of one-way ANOVA show that variance within groups is so larger than variance between groups that differences between the mean of groups are accepted as statistically insignificant.

5.2 Sampling distributions of mean of drift ratio demands

According to ANOVA results, for each of the frames considered in this study, global and interstory drift ratio demands obtained using different ground motion record sets that are compatible with a particular design spectrum can be accepted as random samples selected from the same populations. In the circumstances, it is possible to draw some conclusions about the distribution of populations by analyzing related drift ratio demands.

When it is impossible to observe the entire set of populations, it is generally calculated a statistic from a sample, a subset of population, selected from the population, and from these statistics various statements are made concerning the values of population parameters. A statistic is a random variable that depends on the sample. Therefore, it must have a probability distribution. The sample mean (m) and the sample variance (s^2) of the probability distribution are two important statistics. The sampling distribution of the mean is the probability distribution of mean (m), and identifies the variability of sample means m around the population mean μ.

In this study, it is considered the problem of obtaining interval estimates. In this case, rather than specifying a certain value as estimate of μ, it is specified an interval for a certain degree of confidence that μ lies within. An interval estimate of the population parameter μ is an interval of the form $l \le \mu \le u$, where l and u depend on the numerical value of the sample mean m for a particular sample. Different values of m will be calculated considering different samples. Thus, l and u will be different values of random variables, L and U, respectively. The values of L and U can be determined from the sampling distribution of the sample mean m such that the probability statement given in Eq. (8) is true.

$$P(L \le \mu \le U) = 1 - \alpha \qquad 0 < \alpha < 1 \tag{8}$$

The resulting quantities l and u are known as lower and upper confidence limits, respectively, and the interval (l, u) is called a 100(1-α)% confidence interval for the parameter μ. The 1-α is defined as the confidence coefficient. If an infinite number of random samples are obtained and a 100(1-α)% confidence interval for μ is calculated from each sample, 100(1-α)% of these intervals will contain the true value of μ.

Suppose that a random sample of n observations is taken from a population normally distributed with mean μ and variance σ^2. Because of the value of the sample mean m is calculated using the values of the random variables in the sample, m is also a random variable. It is expected that value of the sample mean is the population mean μ and sample variance is 1/n times the population variance σ^2 (Eq. (9)). Thus, it is concluded that m is also centered about the population mean μ, but its spread decreases when the sample size increases.

$$E\left[m\right] = \mu \quad \text{and} \quad Var\left(m\right) = \frac{\sigma^2}{n} \tag{9}$$

For a large sample of size n from a population with mean μ and variance σ^2, the Central Limit

Table 13 90% confidence interval (l, u) for $\mu_{\Delta/H}$ (%)

Frames	Soil Class	Mean	SE Mean	l	u
3-story	Soil Z1	0.5364	0.0322	0.4606	0.6121
	Soil Z2	0.6841	0.0214	0.6338	0.7344
	Soil Z3	1.0456	0.0273	0.9815	1.1098
5-story	Soil Z1	0.5586	0.0122	0.5299	0.5873
	Soil Z2	0.7246	0.0311	0.6515	0.7977
	Soil Z3	1.0506	0.0403	0.9558	1.1453
7-story	Soil Z1	0.4477	0.0115	0.4208	0.4747
	Soil Z2	0.5869	0.0143	0.5532	0.6206
	Soil Z3	0.8087	0.0118	0.7808	0.8365

Theorem specifies that sample mean m is approximately normal with mean μ and variance σ^2/n. Moreover, the sample standard deviation s may be close to σ. If the population is approximately normal, m can be accepted approximately normal even when the sample size is small. But, if the sample size is small, s may not be close to σ. In this situation, the Student's t distribution can be used to calculate confidence intervals for a population mean μ. For a random sample of size n, a 100(1-α)% confidence interval on μ is given by Eq. (10). In Eq. (10), $t_{\alpha/2,n-1}$ is the upper 100α/2 percentage point of the t distribution with n-1 degrees of freedom and $s/\sqrt{n}$ is standard error of sample means.

$$m - t_{\alpha/2,n-1}\frac{s}{\sqrt{n}} \le \mu \le m + t_{\alpha/2,n-1}\frac{s}{\sqrt{n}} \tag{10}$$

In applied practice, confidence intervals are typically stated at the 90% or 95% confidence level. In this study, 90% confidence level was used for representative calculation. 90% confidence interval (l, u) for the mean of the populations of global drift ratio demands ($\mu_{\Delta/H}$) and interstory drift ratio demands ($\mu_{\delta/h}$) are calculated for each frame and local soil classes. In Tables 4-7, four different mean values of the global and interstory drift ratio demands ($m_{\Delta/H}$, $m_{\delta/h}$) for the frames and local soil classes are given, before. Thus, n and $t_{\alpha/2,n-1}$ are used as 4 and 2.35, respectively, for the calculation of the confidence interval of the population means.

In Table 13, confidence interval (l, u) for the mean of the populations of global drift ratio demands are given. The central tendency and standard error of mean of sample means of global drift ratio demands are also given in Table 13.

According to Table 13, considering the 3-story frame, central tendency of the sample means is 0.54% for soil Z1, 0.68% for soil Z2 and 1.05% for soil Z3. As can be shown, central tendency of sample means increase if the soil class changes from Z1 to Z3. For the same frame, 90% confidence interval of $\mu_{\Delta/H}$ is (0.46%, 0.61%) for soil Z1. Hence, it can be said that the resultant interval indeed contains $\mu_{\Delta/H}$ with confidence 90%. Namely, if different ground motion record sets compatible with design spectrum defined for local soil class Z1 in TEC are used for nonlinear analysis of the 3-story frame, the mean global drift ratio demands calculated for each set are between the abovementioned lower and upper confidence limits with 90% probability. Considering the same frame, 90% confidence interval of $\mu_{\Delta/H}$ is (0.63%, 0.73%) for soil Z2, and

Table 14 90% confidence interval (l, u) for $\mu_{\delta/H}$ (%)

Story number	Soil Class	7-story frame			5-story frame			3-story frame		
		Mean	l	u	Mean	l	u	Mean	l	u
Story-1	Soil Z1	0.4675	0.4453	0.4897	0.6875	0.6464	0.7286	0.6600	0.5715	0.7485
	Soil Z2	0.6525	0.5508	0.7542	0.9600	0.8571	1.0629	0.8425	0.7765	0.9085
	Soil Z3	0.9950	0.9144	1.0756	1.4775	1.3195	1.6355	1.3425	1.2422	1.4428
Story-2	Soil Z1	0.6625	0.6261	0.6989	0.8150	0.7563	0.8738	0.6300	0.5492	0.7108
	Soil Z2	0.8650	0.8237	0.9063	1.0225	0.9344	1.1106	0.7775	0.7264	0.8286
	Soil Z3	1.2425	1.1888	1.2962	1.5275	1.4045	1.6505	1.1850	1.1485	1.2215
Story-3	Soil Z1	0.6900	0.6430	0.7370	0.7400	0.6950	0.7850	0.3750	0.3316	0.4184
	Soil Z2	0.8650	0.8156	0.9144	0.9025	0.8108	0.9942	0.4650	0.4063	0.5238
	Soil Z3	1.2225	1.1825	1.2625	1.2300	1.1635	1.2965	0.6875	0.6105	0.7645
Story-4	Soil Z1	0.6200	0.5854	0.6546	0.5225	0.5049	0.5401			
	Soil Z2	0.7500	0.7082	0.7918	0.6350	0.5763	0.6938			
	Soil Z3	1.0850	1.0539	1.1161	0.8425	0.7680	0.9170			
Story-5	Soil Z1	0.5025	0.4716	0.5334	0.2675	0.2527	0.2823			
	Soil Z2	0.6000	0.5712	0.6288	0.3225	0.2751	0.3699			
	Soil Z3	0.8150	0.7268	0.9032	0.4225	0.3505	0.4945			
Story-6	Soil Z1	0.3575	0.3251	0.3899						
	Soil Z2	0.4425	0.4088	0.4762						
	Soil Z3	0.5475	0.4693	0.6257						
Story-7	Soil Z1	0.2075	0.1874	0.2276						
	Soil Z2	0.2625	0.2424	0.2826						
	Soil Z3	0.3200	0.2720	0.3680						

(0.98%, 1.11%) for soil Z3. Considering the 5-story frame, central tendency of the sample means is 0.56% for soil Z1, 0.72% for soil Z2 and 1.05% for soil Z3. 90% confidence intervals of $\mu_{\Delta/H}$ are (0.53%, 0.59%) for soil Z1, (0.65%, 0.80%) for soil Z2, and (0.96%, 1.15%) for soil Z3. Confidence intervals of $\mu_{\Delta/H}$ calculated for the 7-story frame are also given in Table 13.

The central tendency of mean of sample means of interstory drift ratio demands and confidence interval (l, u) for the mean of the populations of interstory drift ratio demands are given in Table 14. Considering each story of the frames separately, the minimum and maximum central tendency of the sample means are calculated for soil Z1 and Z3, respectively, as expected.

It should be noted that the variance of the sample mean is $1/n$ times the population variance σ^2. Correspondingly, if the sample size (the number of ground motion record sets used for nonlinear analysis) are increased the spread of sample means and corresponding %90 confidence interval of $\mu_{\Delta/H}$ and $\mu_{\delta/H}$ becomes more reduced.

6. Results

In this study, global drift ratio and interstory drift ratio demands, obtained by nonlinear time history analysis of three generic RC frames using different real ground motion record sets compatible with TEC, are statistically evaluated. Ground motion record sets compatible with elastic design spectra defined for local soil classes Z1, Z2 and Z3 in TEC are used for the analyses. Performing nonlinear time history analysis of the frames, maximum global drift ratio ($\Delta_{\max}/H$) and maximum interstory drift ratio ($\delta_{\max}/h$) demands are calculated for each of the ground motion records in the sets. Then, the mean of global and interstory drift ratio demands ($m_{\Delta/H}$ and $m_{\delta/h}$) are calculated for each of the sets, separately. In order to evaluate the scattering of the drift ratio demands obtained from ground motion records around the mean of the sets, coefficient of variation (*CoV*) values are also calculated. The significance of the difference between the mean drift ratio demands obtained calculated for different ground motion sets is tested using one-way analysis of variance at 95% confidence level. Finally, 90% confidence interval is calculated for global and interstory drift ratio demands, separately, for each of the frames. The results of the study could be summarized as follows:

- *CoV* values calculated for ground motion record sets indicate that the scattering of both $\Delta_{\max}/H$ and $\delta_{\max}/h$ values within the sets were high.
- Calculated *CoV* values for both Δ_{mak}/H and δ_{mak}/h values were randomly distributed independent of ground motion record sets, local soil class and frames considered in this study. In other words, it could not be argued that a higher or lower value of *CoV* was not related to local soil class, ground motion record sets and frames.
- It was observed that the $m_{\Delta/H}$ values of four ground motion record sets calculated for a frame were different. Therefore, $m_{\Delta/H}$ values can be accepted as random variables with their distribution parameters (such as mean and variance). Similar result was also obtained for the $m_{\delta/h}$ values.
- The variance of the maximum drift ratio demands obtained from the ground motion records in the sets was quite larger than the variance of the mean drift ratio demands of the sets. This is valid for both global and interstory drift ratio demands. In the circumstances, one-way analysis of variance results showed that the samples represented by $m_{\Delta/H}$ values of different ground motion record sets for a frame can be accepted as simply random samples of the same population at 95% confidence level. This result is valid for $m_{\delta/h}$ values obtained for any stories of a frame.
- The results listed above are valid for all the generic frames and local soil classes considered in this study.
- Since it is accepted that drift ratio demands calculated for the frames using code-compatible ground motion record sets are random samples of the same population, it can be drawn some conclusions about the population as a whole using the corresponding drift ratio demands. For example, confidence interval can be estimated for the population mean at the desired level of confidence. Furthermore, using large number of ground motion sets, and then evaluating the nonlinear analyses results, detailed information about distribution of the population can be obtained. Hence, using code-compatible different ground motion sets for nonlinear analyses of a structure it is possible to obtain about the distribution of the population of the mean drift ratio demands which are used for design or assessment of that structure according to modern seismic codes.

In this study, TEC compatible ground motion record sets are used to perform nonlinear analyses. It should be noted that many of modern seismic codes (FEMA-368 2001, EUROCODE-8 2004, ASCE 07-05 2006, GB 2010) describe relatively similar procedures for defining seismic hazard in terms of the uniform hazard spectrum. In addition, they require spectral matching between the design spectrum and the response spectrum of a selected record set within a stated period range. Therefore, it is possible to obtain similar results of the study when the ground motion sets compatible with the abovementioned seismic codes are used for nonlinear analyses.

Based on these results, it could be argued that there is a significant requirement for the consideration of variability in structural responses. Reliability based approaches and/or using stochastic distribution models of structural response parameters may become the future direction of taking the variability of structural responses into consideration numerically. Finally, considering various options such as different structural systems with single or multiple degrees of freedom, ground motion record sets containing larger number of records, and larger number of ground motion record sets, etc. would provide more remarkable results in the future studies.

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Appendix A. The information about the ground motion records used for time history analyses

Record	Earthquake Name	Date	Magnitude	Station Code
141-X	Friuli	15.09.1976	6.0	ST12
142-Y	Friuli	15.09.1976	6.0	ST14
151-X	Friuli	15.09.1976	6.0	ST33
232-Y	Montenegro	24.05.1979	6.2	ST77
292-X	Campano Lucano	23.11.1980	6.9	ST98
352-Y	Biga	05.07.1983	6.1	ST131
360-X	Umbria	29.04.1984	5.6	ST41
362-X	Umbria	29.04.1984	5.6	ST137
368-X	Lazio Abruzzo	07.05.1984	5.9	ST143
374-Y	Lazio Abruzzo	07.05.1984	5.9	ST148
375-Y	Lazio Abruzzo	07.05.1984	5.9	ST149
382-X	Lazio Abruzzo	11.05.1984	5.5	ST140
383-Y	Lazio Abruzzo	11.05.1984	5.5	ST153
410-X	Gölbaşı	05.05.1986	6.0	ST161
467-Y	Chenoua	29.10.1989	5.9	ST181
532-Y	Racha	15.06.1991	6.0	ST202
548-X	İzmir	06.11.1992	6.0	ST43
572-Y	Patras	14.07.1993	5.6	ST178
595-X	Umbria Marche	26.09.1997	5.7	ST83
601-Y	Umbria Marche	26.09.1997	5.7	ST224
602-X	Umbria Marche	26.09.1997	6.0	ST224
605-X	Umbria Marche	26.09.1997	5.7	ST84
645-Y	Umbria Marche	14.10.1997	5.6	ST83
646-Y	Umbria Marche	14.10.1997	5.6	ST234
648-Y	Umbria Marche	14.10.1997	5.6	ST332
760-X	Umbria Marche	26.09.1997	6.0	ST265
946-Y	Potenza	05.05.1990	5.8	ST103
1230-X	İzmit	17.08.1999	7.6	ST576
1243-X	İzmit	13.09.1999	7.6	ST561
1720-Y	Dinar	01.10.1995	6.4	ST543
1735-X	Adana	27.06.1998	6.3	ST581
1859-X	NW Kefallinia	27.02.1987	5.7	ST1303
5270-Y	Mt. Vatnafjoll	25.05.1987	6.0	ST2486
5272-Y	Mt. Vatnafjoll	25.05.1987	6.0	ST2487
5655-X	NE of Banja Luka	13.08.1981	5.7	ST2950
6270-Y	South Iceland	17.06.2000	6.5	ST2556
6272-X	South Iceland	17.06.2000	6.5	ST2568
6327-Y	South Iceland	21.06.2000	6.4	ST2552
6331-X	South Iceland	21.06.2000	6.4	ST2486
6422-X	İzmit	13.09.1999	5.8	ST3135
6447-Y	İzmit	11.11.1999	5.6	ST3140
6496-Y	Düzce	12.11.1999	7.2	ST3135
6606-Y	İzmit	11.11.1999	5.6	ST2571
6962-X	İzmir	13.09.1999	5.8	ST3271
6975-Y	İzmit	13.09.1999	5.8	ST3272
6978-Y	İzmir	13.09.1999	5.8	ST3273
7010-X	İzmit	11.11.1999	5.6	ST772
7104-X	İshaklı	03.02.2002	5.8	ST856
7158-X	Firuzabad	20.06.1994	5.9	ST3293