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COMPARISON OF ENERGY-BASED RESPONSES OF STRUCTURAL SYSTEMS TO REAL AND SIMULATED GROUND MOTION RECORDS

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Abstract

Energy-based design and assessment approaches usually require use of ground motion datasets. Previous researchers attempted to use solely actual records, however, simulated records can also be used as an alternative in the absence of a homogenous ground motion database. The main objective of this study is to examine the differences in energy-based responses of structures subjected to real and simulated datasets. For this purpose, the obtained input energy spectra based on 'simulated' and 'real' records are compared. The simulated dataset is generated by the stochastic finite-fault method, considering the regional seismicity parameters that correspond to Duzce city located on the western segments of North Anatolian Fault zone in Turkey while the real dataset is formed by selection of regionally compatible records from NGA-West2 ground motion database. Next, time history analyses are performed for both elastic and inelastic SDOF structural systems to investigate the differences in terms of input energy, resulting from alternative ground motion datasets. The analysis results present variability in terms of energy-based structural demand parameters when alternative ground motion datasets, real or simulated records, are employed.

Keywords: Energy-Based Response, Single-Degree-of-Freedom Models, Time History Analysis, Stochastic Finite-Fault Method, Simulated Ground Motions.

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1 INTRODUCTION

Energy-based seismic design and analysis approaches have been investigated for many decades by previous studies [e.g.: 1-10]. All these studies have used actual ground motion records corresponding to worldwide past earthquakes. However, in general it is not simple to form a homogeneous ground motion dataset having well-distributed ground motion parameters that are compatible with the regional seismology of the study area. As an alternative, homogenous and well-distributed simulated ground motion datasets generated based on the regional seismological parameters for each study area can be utilized in order to estimate the energy-based seismic demand parameters of the structures.

The aim in this study is to investigate the efficiency of simulated ground motion records on the estimation of the elastic and inelastic input energy levels for single-degree-of-freedom (SDOF) structural systems. For this purpose, the 1999 Duzce (Western Turkey) earthquake (Mw=7.1) which occurred on the right-lateral strike-slip active North Anatolian fault zone is selected. In this study, first, the 1999 Duzce event is simulated using the previously validated source, path, and site parameters [11]. For simulations, the stochastic finite-fault methodology which can efficiently model the frequencies of engineering interest is employed [12]. Next, seismic input energy levels for elastic and inelastic SDOF systems with varying periods are assessed through time history analysis. Then, real and estimated input energy levels for both elastic and inelastic SDOF models are evaluated and compared under the real and simulated motions of the event at selected five stations. In the next part, a scenario event of magnitude 7.0 is simulated at different nodes with varying source-to-site distance levels in Duzce region. For all simulations soil class D is utilized, which is mostly compatible with the soil class of the study area. In addition to the simulated records, the real dataset is formed by the selection of regionally compatible records from the NGA-West2 ground motion database. In the selection process, the parameters of concern are considered as the soil class, moment magnitude, fault type and source-to-site distance. Then, time history analyses are performed for both elastic and inelastic SDOF structural systems using the real and simulated record sets to investigate the differences in terms of input energy levels.

2 INPUT GROUND MOTION DATASETS

In this study the seismic input energy levels are compared for two alternative sets of ground motion records: Simulated and real records. For this purpose, Duzce region, which is located in the western part of North Anatolian fault zone, is considered as the study area. In 1999, a major earthquake with Mw=7.1 occurred in Duzce region on the strike-slip fault zone. In the first part of this study, the real and simulated records of the 1999 Duzce event at a total of five stations are used in order to validate the simulated records of this event in terms of seismic input energy evaluation. The simulated records at these stations are prepared using the stochastic finite-fault ground motion simulation methodology based on a dynamic corner frequency approach [12]. It is noted that the stochastic finite fault simulation method simulates only one random horizontal component at each station. For ground motion simulation of the 1999 Duzce event at selected 5 stations, the validated source, path, and site parameters that were first proposed by [13] and then modified by [11] are used.

In the second part of this study, simulations are performed for a scenario event of magnitude 7.0 at a total of 370 blind nodes within the Duzce region with boundaries of 30°- 32° longitudes and 40°- 41° latitudes. For ground motion simulations at these nodes, the validated source, path, and site parameters that were first proposed by [13] and then modified by [11] are used. For simulation at all nodes, generic site amplification factors corresponding to NEHRP soil class D that are compatible with the study region are employed. The simulated record dataset is prepared for different Joyner and Boore distance (R_{JB}) intervals as 0-10 km, 10-20 km, and 20-40 km. Next, real ground motion dataset is constituted from the past earthquakes by considering the regional seismological characteristics of the study area (Duzce, Turkey). The seismological characteristics considered in selection process include the moment magnitude of Mw=7.0, fault mechanism of strike slip, source-to-site distance of 0-40 km, and NEHRP soil class of D. As a result, a suitable set of records are randomly selected for distance intervals of 0-10 km, 10-20 km, and 20-40 km.

Tables 1 and 2 illustrate the variations of peak ground acceleration (PGA) and peak ground velocity (PGV) with respect to R_{JB} for the selected real and simulated datasets. When the results in terms of the simulated ground motion intensity levels are compared with the real ones, generally more scatter is observed for the real record dataset. This is mostly due to the fact that the simulated record set is region-specific with less variation.

PGA	μ_{Real} [cm/s^2]	σ_{Real} [cm/s^2]	μ_{Syn} [cm/s^2]	σ_{Syn} [cm/s^2]
$0 \le R_{JB} < 10$	280.09	204.69	280.65	82.53
$10 \le R_{JB} < 20$	200.20	30.27	153.39	39.75
$20 \le R_{JB} \le 40$	90.99	33.31	93.98	19.85

Table 1: Mean and standard deviations of PGA distributions

PGV	μ_{Real} [cm/s]	σ_{Real} [cm/s]	μ_{Syn} [cm/s]	σ_{Syn} [cm/s]
$0 \le R_{JB} < 10$	37.84	27.08	36.29	12.37
$10 \le R_{JB} < 20$	20.40	8.65	20.55	5.85
$20 \le R_{JB} \le 40$	12.09	6.68	12.48	4.13

Table 2: Mean and standard deviations of PGV distributions

3 ASSESSMENT OF SEISMIC INPUT ENERGY

The governing differential equation of motion for a general nonlinear SDOF system excited at the base by a horizontal translation from earthquake ground motion is given by:

$$m\ddot{u}(t) + c\dot{u}(t) + f_r(u) = -m\ddot{u}_g(t) \tag{1}$$

where m and c are mass and viscous damping coefficients; $\ddot{u}$, $\dot{u}$ and u are acceleration, velocity and displacement relative to the moving base respectively, and the term $\ddot{u}_g$ corresponds to the horizontal ground acceleration at time t. The restoring force is denoted as f_r, and it can be computed as $f_r(u)=ku(t)$ for linear elastic systems. In case of nonlinear response, force-displacement relationship is determined by the hysteretic characteristics of the system. Through the numerical integration of Equation 1 in time domain, the energy balance equation is obtained and defined as follows:

$$E_k + E_\xi + E_a = E_i \tag{2}$$

where the three terms on the left-hand side of the formulation are kinetic energy E_k, viscous damping energy E_ξ, and absorbed energy E_a, respectively. Absorbed energy term represents the total amount of energy that structure absorbs either through recoverable elastic or unrecoverable inelastic deformations, thus it can be expressed as sum of the two where the former is called elastic strain energy E_s, and the latter is called hysteretic damping energy E_h. On the right-hand side of the formulation, the input energy, E_i is obtained. Throughout the ground motion excitation, the energy imparted to the structure is temporarily converted into the E_k and E_s, which eventually fades away, and is dissipated as either of the damping energy terms, E_ξ and E_h. In elastic systems, the only way to dissipate the input energy is the viscous damping since there are no inelastic deformations. Uang and Bertero [4] derived two alternative forms of energy balance equation (absolute and relative), where the definition of input energy and kinetic energy terms differ. Essentially, both formulations are mathematically equivalent, although their physical definitions are different. In fact, Uang and Bertero [4] demonstrated that the computed input energy values by the two formulations are nearly equal for a wide period range, 0.1 to 5 sec., which covers most of the building structures of engineering interest. Absolute input energy is evaluated based on the work done by the total base shear on ground displacement while the relative input energy is evaluated based on the work done by equivalent seismic load applied on the equivalent fixed-based system. In other words, the rigid body translation is not considered in calculation of the latter. In this study, the relative energy equation is utilized where the input energy is calculated as follows:

$$E_i^r = -\int m\ddot{u}_g(t)du \tag{3}$$

4 RESULTS

In the work presented herein, the main goal is to evaluate the efficiency of a simulated ground motion dataset by comparing with the corresponding observed ones in terms of seismic input energy demands in structures. Yet, the simulations must be verified before making such a comparison in order to avoid any bias. For this purpose, the input energy spectra are obtained first for both the real and synthetic records of the 1999 Duzce (Mw=7.1) earthquake at five stations as presented in Table 3 for the sake of comparison. Next, set of simulated records are compared with regionally compatible ground motion records from the NGA-West2 database. Recently, Karimzadeh et al. [13] have conducted a parametric study and discussed validity of the simulated dataset employed herein from the aspect of spectral characteristics for varying moment magnitude, source-to-site distances and soil conditions. All the dynamic analyses are performed on SDOF systems with 5% damping ratio. Two different structural models are considered; elastic linear model and piece-wise linear inelastic model that was proposed by Clough and Johnston [14] and exhibits stiffness degradation during cyclic behavior. In the latter model, the strength ratio, which is the normalized yield strength with respect to the weight, is considered as $\eta=0.1$. The reason for selecting a low level of strength ratio is due to the known fact that the building structures in the region are highly vulnerable to seismic action, which was unfortunately revealed by the massive destruction and death toll during the 1999 Duzce earthquake. In addition, low level of strength ratio means more inelastic action and a good base for comparing the inelastic input energies for real and synthetic ground motion records. The results are presented in terms of $E_i^r(T)$ per unit mass.

Station	**Code**	**Lat. (°)**	**Long. (°)**	**Site Class [NEHRP]**	**R_{epi} [km]**	**R_{JB} [km]**	**PGA-EW [cm/ s^2]**	**PGA-NS [cm/ s^2]**	**PGV-EW [cm/s]**	**PGV-NS [cm/s]**
Duzce	DZC	40.844	31.149	D	9.3	0.0	520.41	328.03	86.54	54.53
Mudurnu	MDR	40.442	29.717	D	34.1	38.5	20.06	21.25	1.97	2.27
Goynuk	GYN	40.396	30.783	D	55.2	34.3	22.17	25.79	5.84	4.49
Yarımca Petkim	YPT	40.764	29.762	D	116.9	67.9	16.15	23.47	4.08	8.38
Izmit	IZT	40.463	31.182	C	100.7	80.9	16.41	18.73	2.27	1.73

Table 3: Information on the strong motion stations that recorded the 1999 Duzce earthquake.

4.1 Verification of simulated seismic input energy levels for the 1999 Duzce (Turkey) earthquake (Mw=7.1)

Figure 1 shows the comparison of input energy spectra for linear elastic systems subjected to real and synthetic (labelled as Syn in the figures) ground motion records for the selected stations in Duzce. As it can be observed in the plots, station DZC is the only one that yields a significant amount of input energy when compared to the other stations due to the fact that it is the closest and the most affected station from the 1999 Duzce earthquake. It can also be stated that the input energy variations of real and synthetic ground motion records at both DZC station and the other four stations are in comparable grounds. The variations of the fits between the synthetic and the real records can be attributed to complex source, path and site effects.

Figure 2 shows the same input energy comparison for the inelastic SDOF systems using the Clough Johnston hysteresis model with a strength ratio η=0.1. The spectral variations at DZC station reveal that the input energy obtained from the synthetic ground motion lies in between the input energies obtained from the two horizontal components of the real ground motion records. In other stations, the variation is more due to the low levels of input energy. Actually, the elastic and the inelastic input energy plots for GYN, YPT and IZT stations in Figures 1 and 2 are the same due to the fact that the SDOF systems remains in the elastic range during the 1999 Duzce earthquake.

Overall, the results in Figures 1 and 2 indicate that the real input energy demand and the corresponding simulated values closely match. This observation confirms that simulated ground motions generated by stochastic finite-fault method are appropriate for this particular region and can be used in regions with similar characteristics for energy-based seismic design and assessment purposes.

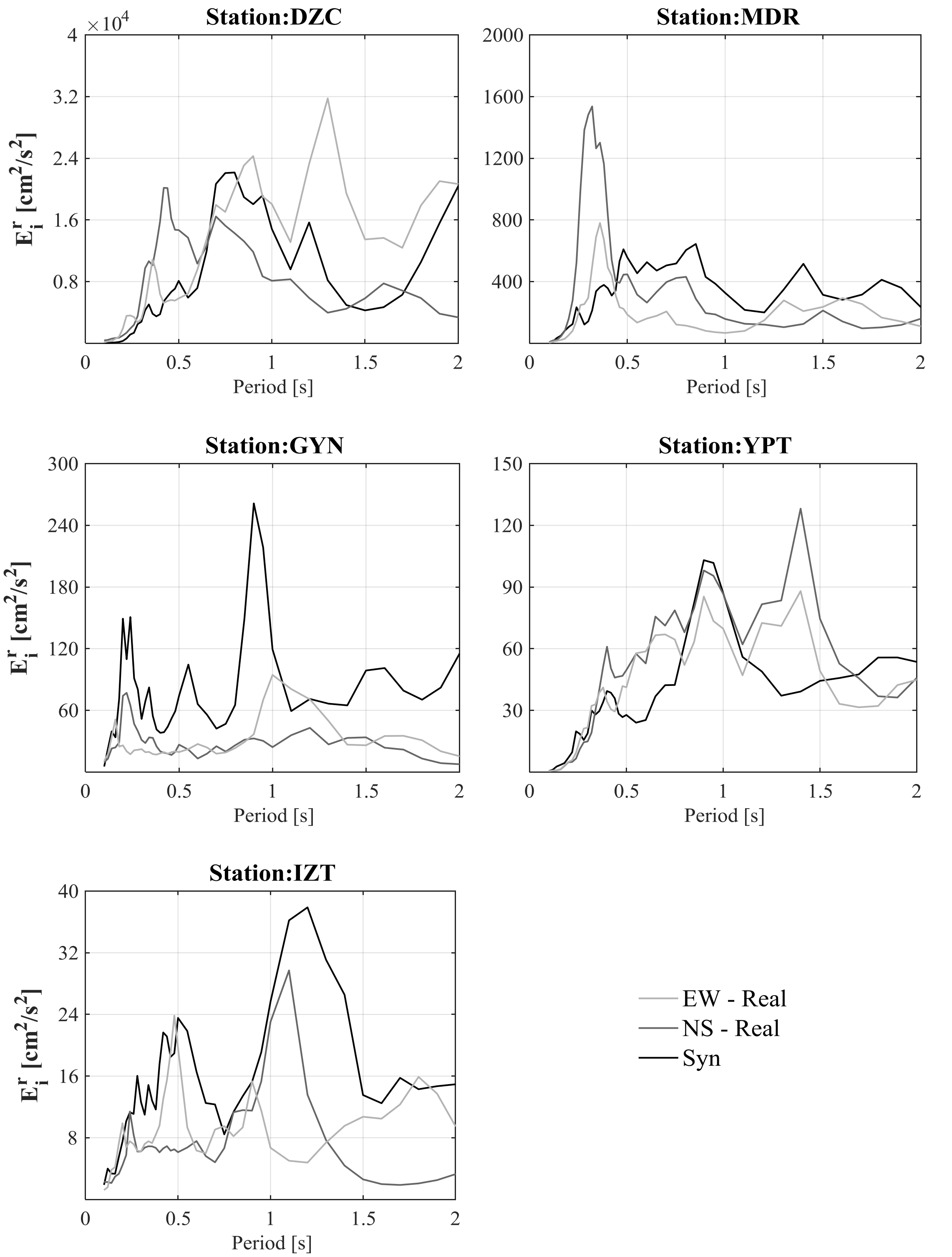

Figure 1. Comparison of elastic input energy spectra for real and simulated records of the 1999 Duzce (Turkey) earthquake (Mw=7.1)

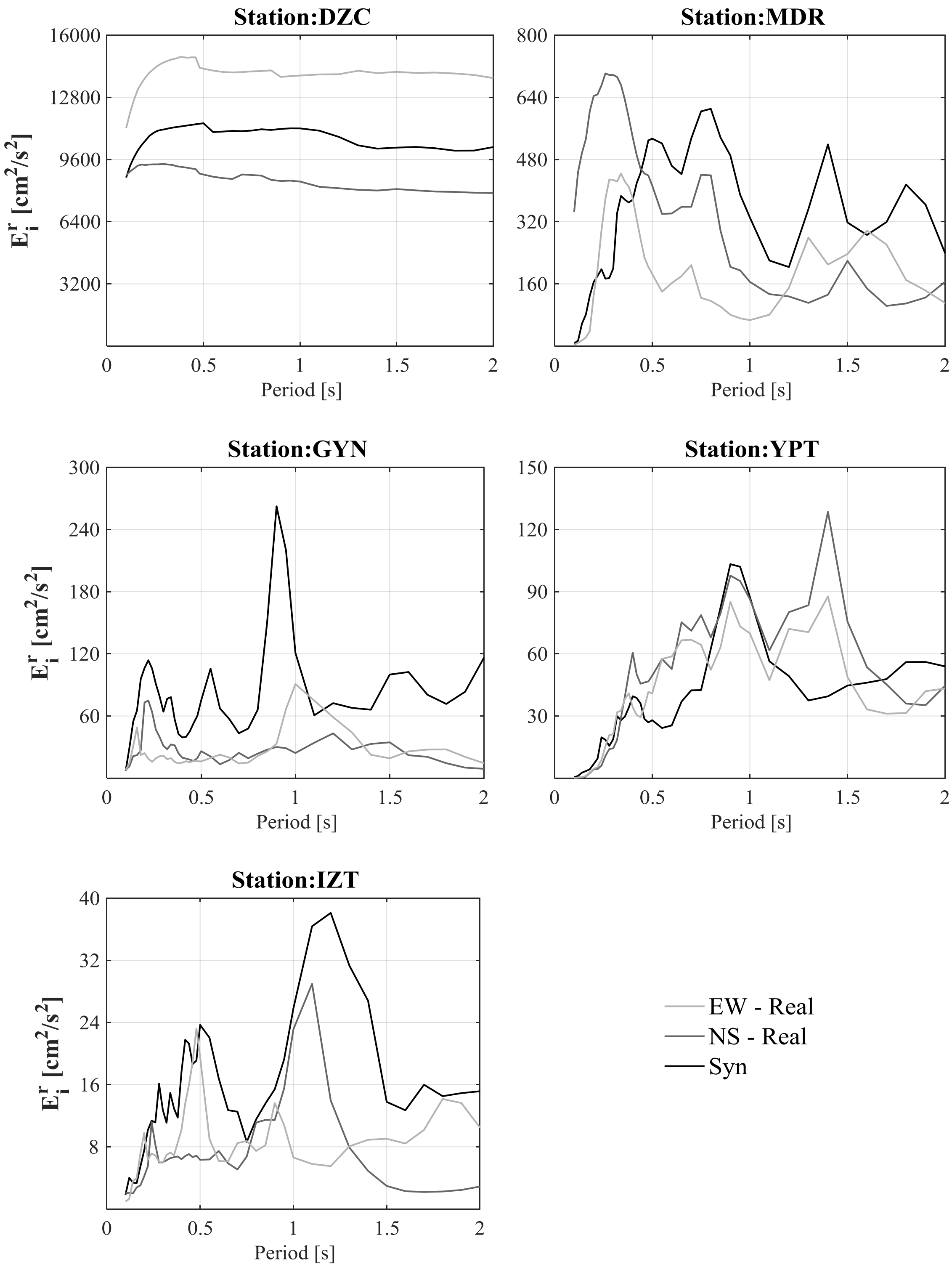

Figure 2. Comparison of inelastic input energy spectra for real and simulated records of the 1999 Duzce (Turkey) earthquake (Mw=7.1) using the Clough Johnston model

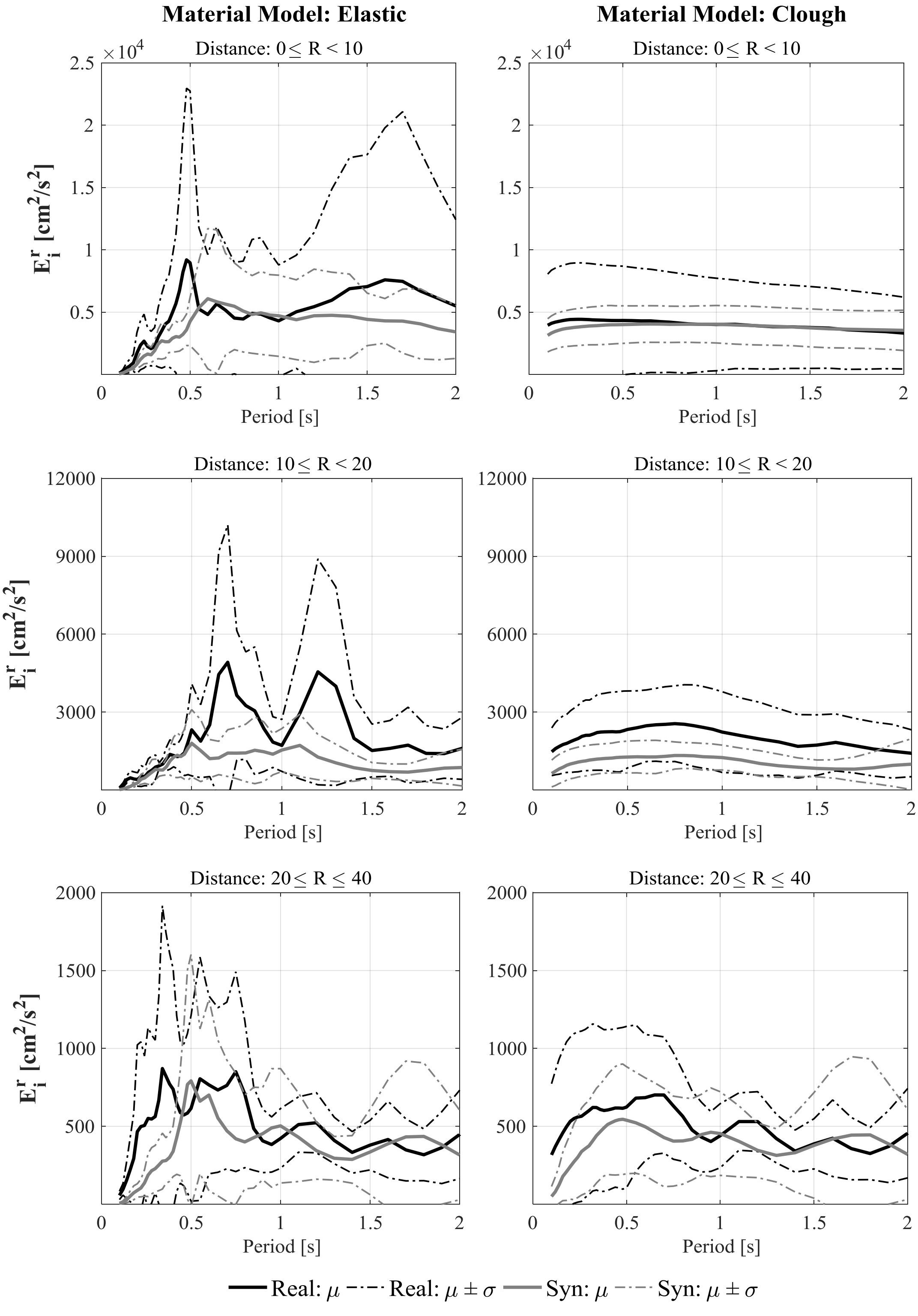

Figure 3. Comparison of input energy spectra for the selected real and simulated record sets

4.2 Comparison of input energy spectra for the selected real and simulated record sets

Figure 3 illustrates the mean elastic and inelastic input energy spectra together with their ±1 standard deviations for the aforementioned ground motion datasets using three different distance intervals. It is observed that the mean curves are generally closer to each other in the given period range. From the plots it also appears that the spectral variations are relatively more in the case of real ground motions for closer distance range. On the other hand, the variations for the real and synthetic record sets get smaller for longer distances due to the attenuation effects. These trends are also consistent with the values given in Tables 1-2 in terms of ground motion intensity parameters. Overall, it can be clearly seen that the mean elastic and inelastic spectra levels are consistent with the simulated ones for all distance ranges.

5 CONCLUSIONS

This study focuses on the efficiency of ground motion simulations for energy-based design and assessment purposes. For this purpose, the simulations are performed by considering the regional characteristics of Duzce city which is located in a shallow alluvial basin. The simulations are initially validated based on the observed event in the area in terms of both elastic and inelastic input energy spectra. It is observed that simulations provide mostly good fits. Next simulated records for a scenario event of Mw=7.0 are investigated against a selected number of real records set compatible with the regional seismicity. Results are compared in terms of the mean values together with the standard deviations from the mean. The following conclusions can be stated based on the results of this study:

- Validations for the selected case study reveal a good match for input energy variation in 5 different stations. This is due to the use of input parameters in the ground motion simulations of the 1999 Duzce event validated in terms of seismological parameters.
- Overestimation of the real responses can be observed in most of the cases, which encourages the use of ground motion simulations as an alternative conservative approach in seismic design.
- Selection of real records due to seismological parameters like magnitude, distance, soil condition and faulting type results in higher variations in terms of ground motion intensity parameters. This trend is also reflected in energy calculations. Hence region-specific ground motions should be used in order to minimize this variation in seismic design and analysis of structures at any specific site. The only way to achieve this is to employ simulated records which are extensively validated.

Finally, more investigations should be carried out using larger ground motion sets of real ground motions records. In addition, further evaluations should be performed for alternative scenario events before reaching to solid conclusions in this research field.

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