Seismological and engineering demand goodness of fit criteria for simulated and real ground motions

Shaghayegh Karimzadeh[1]

[1] Instructor, Doctor, Civil Engineering Department, Middle East Technical University, Ankara, Turkey.

ABSTRACT

For regions with sparse seismic networks or potential large earthquakes, ground motion simulation techniques have gained more attention in recent years. Simulated records are required to be generated using regional input dataset and then verified against existing recorded ground motions corresponding to past events. For verification of simulated motions, alternative goodness of fit criteria based on seismological measures have been tested so far. However, validation as well as applicability of simulated ground motions are issues of discussion not only in the seismological societies but also in the engineering communities. To use simulated motions in engineering applications, estimation of reliable structural demand parameters is essential. Since different characteristics of input excitations influence structural responses, it seems necessary to examine the closeness of the seismological goodness of fit scores to the ones obtained based on engineering demand parameters using the simulated and real ground motion datasets. To accomplish this, as a case study, goodness of fit scores for the real and simulated records of the 2009 L'Aquila, Italy earthquake with moment magnitude of 6.3 are investigated herein employing two alternative simulation methods (i.e.: Stochastic and Hybrid). In the first step, the scores are calculated using seismological measures (e.g.: peak values, duration and frequency as well as energy content of the time histories). In the next step, multi-degree-of-freedom reinforced concrete frames with different number of stories are selected and then structural responses in terms of inter-story drift ratios corresponding to the real and simulated ground motions are calculated. Then, the goodness of fit scores are estimated for structural responses. Results of this case study reveal good agreement between the seismological and engineering demand goodness of fit scores for the selected ground motion simulation approaches. Keywords: Ground motion, simulation, goodness of fit, seismology, engineering demand.

INTRODUCTION

Seismic behavior of different types of structures is generally affected by alternative characteristics of ground motion records including amplitudes, durations, energy, and their frequency content. For seismic structural response evaluation in details, the use of Nonlinear Time History Analysis (NLTHA) is recommended by most of the seismic design codes (e.g.: [1-2]). NLTHA requires full time series of ground motion records. In regions with sparse ground motion data or large earthquakes with long return periods, an alternative to real ground motion records is the use of regionally simulated ground motions. There are three main ground motion simulation techniques: Deterministic, stochastic, and hybrid methods (e.g.: [3-8]). Alternative ground motion simulation methods involve different computing costs and provide different levels of accuracy. Thus, several seismological measures are introduced to evaluate the Goodness Of Fit (GOF) between the recorded and simulated ground motion time histories (e.g.: [9-10]).

Although it is important to evaluate the GOF between the observed and simulated seismological parameters, a major research field that remains open is concerned with their use in earthquake engineering. Simulations have recently been of particular interest in earthquake engineering as they can practically reflect the physics of the earthquakes, the faulting mechanisms and the regional seismic parameters (e.g.: [11-15]). Recent studies reveal that the characteristics of input ground motions can affect engineering demand parameters. Therefore, before their use in earthquake engineering, it seems necessary to examine the closeness of the seismological GOF to the ones obtained based on engineering demand parameters for the simulated and real ground motion datasets. To accomplish this, as an initial trial in this study, the goodness of fit between the real and simulated records of the 2009 L'Aquila, Italy earthquake with a moment magnitude of 6.3 is investigated through two algorithms: Logarithmic misfit and GOF score introduced by Olsen and Mayhew [10]. For this purpose, the simulated records of two alternative simulation approaches (i.e.: Stochastic and Hybrid) are considered [13]. In the first part of this study, the seismological logarithmic misfits and GOF scores [10] are evaluated for certain seismological measures including peak values, duration, and frequency as well as the energy content of the time histories. In the next step, a total of nine Multi-Degree-Of-Freedom (MDOF) Reinforced-Concrete (RC) frames with different number of stories are selected and then structural responses in terms of maximum inter-story drift ratios corresponding to the real and simulated ground motion datasets are calculated. Finally, structural logarithmic misfits and GOF scores [10] are calculated in terms of the selected structural parameter (maximum inter-story drift ratio).

INPUT GROUND MOTION RECORDS

In this study, the observed and simulated time histories from two alternative approaches corresponding to the 2009 L'Aquila earthquake with Mw=6.3 are employed. The earthquake occurred in central Italy in the close vicinity of town L'Aquila on a normal fault. For GOF evaluation, a total of seven stations mostly located on rock sites [10] are selected. Table 1 presents information including the site classes, latitude, longitude, station code, epicentral distance (R_{EPI}), and observed Peak Ground Accelerations (PGAs) in both North-South (NS) and East-West (EW) directions.

In this study, the validated simulated records from two alternative ground motion simulation techniques by previous studies are employed [13, 16-17]. The investigated ground motion simulation methods are considered as the Hybrid Integral Composite (HIC) approach introduced by Gallovic and Brokesova [6] and the Stochastic Finite-Fault (SFF) approach of Motazedian and Atkinson [5]. The simulated ground motions based on the HIC and SFF approaches have been respectively validated by the studies of Ameri et al. [16] and Ugurhan et al. [17] against the real time histories of the 2009 L'Aquila earthquake. The HIC approach used in Ameri et al. [16] is based on the representation theorem with a k-squared slip distribution over the fault plane for simulation of the low-frequency band. However, this approach uses a composite application of Brune's source time functions with a proper seismic moment and corner frequency for simulation of the high-frequency band. Then, the ground motion amplitudes are combined in a cross-over frequency band. More details of simulations can be found in Ameri et al. [16]. On the other hand, the SFF method used in Ugurhan et al. [17] is based on a dynamic corner frequency approach to simulate the whole frequency band. In this approach, the fault plane is divided into smaller subfaults where their contribution is summed in the time domain to obtain the simulated time history. It is noted that the SFF approach provides only one horizontal component of simulated motion at each station. Details of simulations can be found in Ugurhan et al. [17]. The simulated PGAs corresponding to the horizontal time histories from the two methods are presented in Table 1.

Table 1. Information on the stations of the 2009 L'Aquila earthquake along with the real and simulated PGAs.

Station Code	Latitude (°)	Longitude (°)	Site Class (EC8 [1])	R_{EPI} (km)	Observed PGA-NS (cm/s^2)	Observed PGA-EW (cm/s^2)	Simulated PGA-NS HIC (cm/s^2)	Simulated PGA-EW HIC (cm/s^2)	Simulated PGA-SFF (cm/s^2)
AQA	42.376	13.339	B	4.6	347.59	350.46	196.96	341.18	254.94
CLN	42.085	13.521	A	31.64	76.57	73.49	50.72	23.75	75.59
FMG	42.268	13.117	A	19.32	24.53	20.12	30.38	28.44	61.10
GSA	42.421	13.519	B	18.05	139.02	131.88	103.31	195.26	157.36
LSS	42.558	12.969	A	39.02	7.61	9.21	6.21	5.41	24.04
MTR	42.524	13.245	A	22.35	51.65	42.17	16.21	14.44	54.66
SUL	42.090	13.934	C	56.53	24.53	27.04	8.37	5.41	32.96

SELECTED MDOF FRAME STRUCTURES

In this study, for structural response evaluation, a total of nine symmetric RC frame structures with varying fundamental periods are considered. Table 2 provides information regarding the number of stories, number of bays, total mass, and fundamental period of the selected frames. Among all frames, frames F1and F6 are selected from the existing structures in Bursa (Turkey). Frame F2 is the deficient form of frame F1 by minimizing reinforcement ratio, sectional sizes, and material strengths. Frames F3, F4, and F8 are designed according to the previous Turkish seismic design code [18]. Frames F5 and F7 are selected from the existing buildings of the Duzce damage database. Finally, frame F9 is designed based on the 1982 uniform building code in California [19]. All frames are modeled using nonlinear fiber-based beam-column elements along with Kent-Scott-Park concrete and steel with strain hardening ratio of 0.005.

Nonlinear time history analyses of the selected frames are conducted in OpenSees software [20]. OpenSees software uses finite elements in order to discretize and solve the equation of motion. Since all frames are symmetric, two-dimensional modeling is employed. During numerical analyses, contributions of dead and live loads to the total mass are assumed, respectively, as 100% and 25%. The fundamental period range resulting from the eigenvalue analyses of all frames varies between 0.47 and 1.3 seconds. During the NLTHA, the damping ratio of 5% is considered for the first mode of the selected frames. More details regarding the sectional and material properties, story masses, modal properties, and loads on beams for the nine frames can be found in Karimzadeh et al. [13].

Table 2. Information on the selected nine RC buildings.

Frame ID	Number of Stories	Number of Bays	Total Mass (t)	Fundamental Period (s)
F1	3	2	226.50	0.47
F2	3	2	226.50	0.72
F3	3	3	153.68	0.53
F4	4	3	212.22	0.69
F5	4	3	75.30	0.49
F6	5	2	260.20	0.78
F7	5	4	166.02	0.52
F8	7	3	365.59	1.05
F9	8	3	1816.10	1.30

SIMULATION RESULTS IN TERMS OF LOGARITHMIC MISFITS

In this study, logarithmic misfits are defined for evaluation of the observed and simulated ground motion record sets in terms of both seismological and structural measures. For this purpose, misfits are first evaluated in terms of different seismological parameters: Fourier Amplitude Spectrum (FAS), PGA, Peak Ground Velocity (PGV), PGV to PGA ratio (PGV/PGA), Arias Intensity (I_a), Cumulative Absolute Velocity (CAV), and Significant Duration (t_{eff}) defined as the time interval of 5% - 95% of the accumulated I_a. Next, misfits are investigated for a single structural demand parameter as the maximum inter-story drift ratio of selected buildings. It is noted that the maximum inter-story drift ratios for the selected frames are calculated from NLTHA for the real time histories and two alternative simulated ground motion record datasets.

Logarithmic misfits in terms of different aforementioned seismological and structural measures are evaluated using alternative formulas. The FAS misfits are calculated as follows:

$$Misfit_{FAS} = \frac{1}{n_f}\sum_{f=1}^{10}\left|log\,\frac{FAS_{simulated}(f)}{FAS_{real}(f)}\right| \tag{1}$$

where n_f is the total number of considered discrete frequencies within the interval of 0.1 to 10 Hz.

Misfits in terms of PGA, PGV, PGV/PGA, I_a, CAV, and t_{eff} are obtained using the following equation:

$$Misfit_R = log\left|\frac{R_{simulated}}{R_{real}}\right| \tag{2}$$

where R stands for the seismological parameter of interest.

Finally, misfits in terms of maximum inter-story drift ratios for all frames are calculated as follows:

$$Misfit_R = \frac{1}{n_s}\sum_{s=1}^{n_s}\left|log\,\frac{R_{simulated}\,(s)}{R_{real}\,(s)}\right| \tag{3}$$

where n_s is the total floor numbers of the frames. The terms $R_{simulated}(s)$ and $R_{real}(s)$ are, respectively, the simulated and real maximum inter-story drift ratios at story level s of the frame of interest.

Based on the formulas given above, all logarithmic misfits are calculated and the results are presented in Figures 1 and 2 for seismological and structural parameters, respectively. It is noted that each logarithmic misfit in terms of a certain parameter is obtained in terms of the geometric mean value of the NS and EW components at every station.

Figure 1 reveals that for all seismological parameters at the selected stations the logarithmic misfits are smaller than 1. However, the value of misfit varies depending on the parameter as well as the station of interest. Among all seismological parameters, the least misfit is obtained as 0 for PGA and t_{eff} at station CLN from the SFF method and for CAV at station GSA from the HIC method. On the other hand, the largest misfit is obtained as 1 for I_a at stations LSS from the SFF method and MTR from HIC method. When PGA, I_a, CAV, and t_{eff} are considered, it is seen that for most stations the SFF approach provides more accurate estimates than the HIC method. However, in terms of PGV and PGV/PGA parameters, the HIC method is more precise than the SFF approach at most stations. Overall, the average logarithmic misfits in terms of the selected seismological parameters are, respectively, calculated as 0.26 and 0.30 for the SFF and HIC approaches.

Next, results of structural logarithmic misfits are calculated for all frames and illustrated in Figure 2. Comparison of the results in Figure 2 with those obtained in Figure 1 reveals that similar to seismological logarithmic misfits, the values are less than 1 in logarithmic scale at all stations. When two alternative ground motion simulation methods are compared, it is seen that as the number of stories increases, at most stations the HIC method provides smaller misfits compared to the SFF approach. This can be due to the simulation of the broadband frequency range by the HIC ground motion simulation method. The minimum misfit from the SFF approach is calculated as 0.01 for the frame F8 at station SUL while from the HIC method this value is 0.02 for the frame F9 at station LSS. The maximum values of structural logarithmic misfits are calculated for frame F2 with values of 0.68 at station LSS from the SFF method and 0.66 at station MTR from the HIC method. The average logarithmic misfits in terms of the selected structural demand parameter are, respectively, calculated as 0.32 and 0.24 for the SFF and HIC approaches. This can be attributed to the inherent limitation of the SFF method in simulation of the low-frequency portion of the real time histories. Overall, it is seen that all seismological and structural logarithmic misfits are almost at the same level.

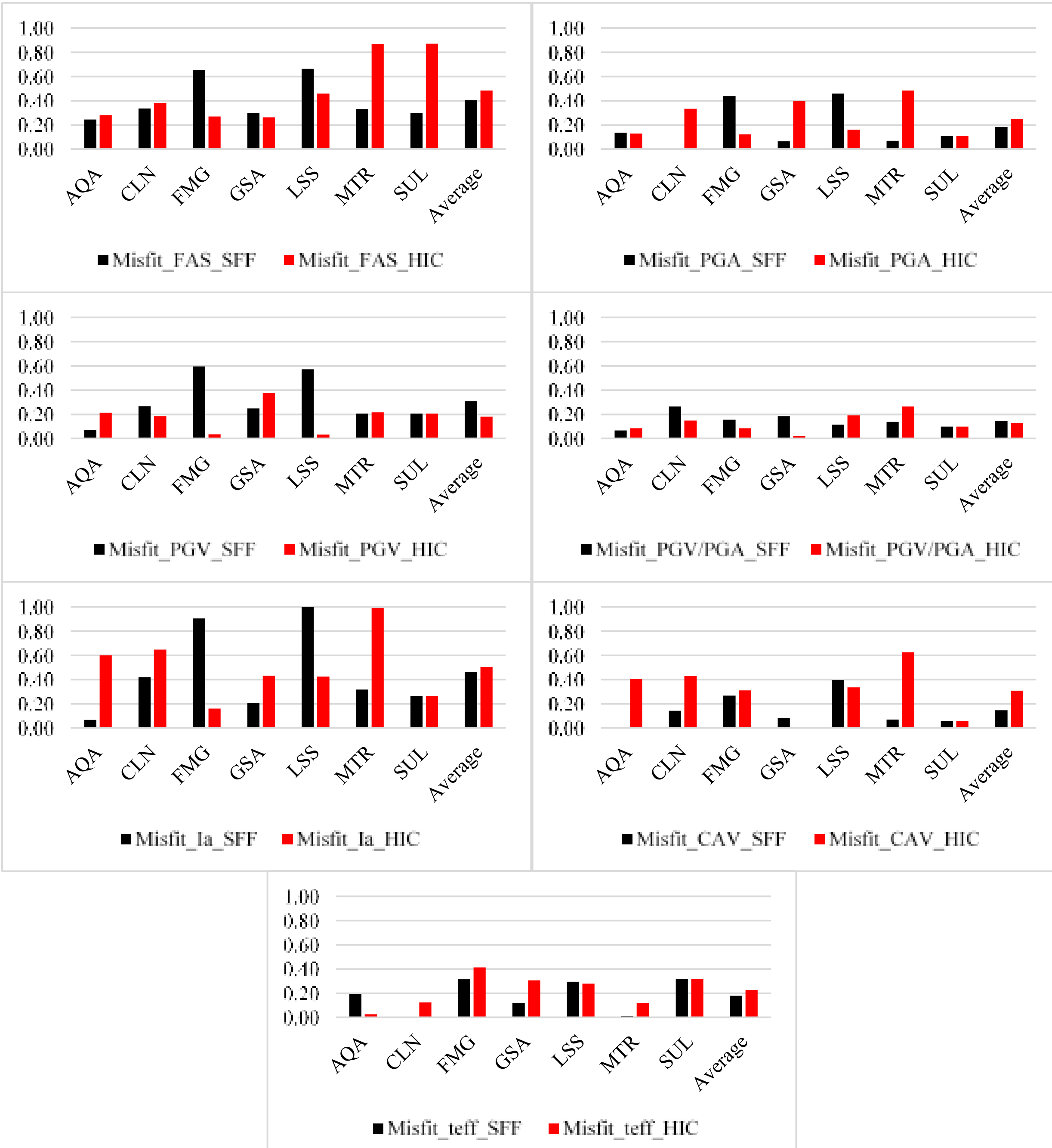


Figure 1. Seismological logarithmic misfits.

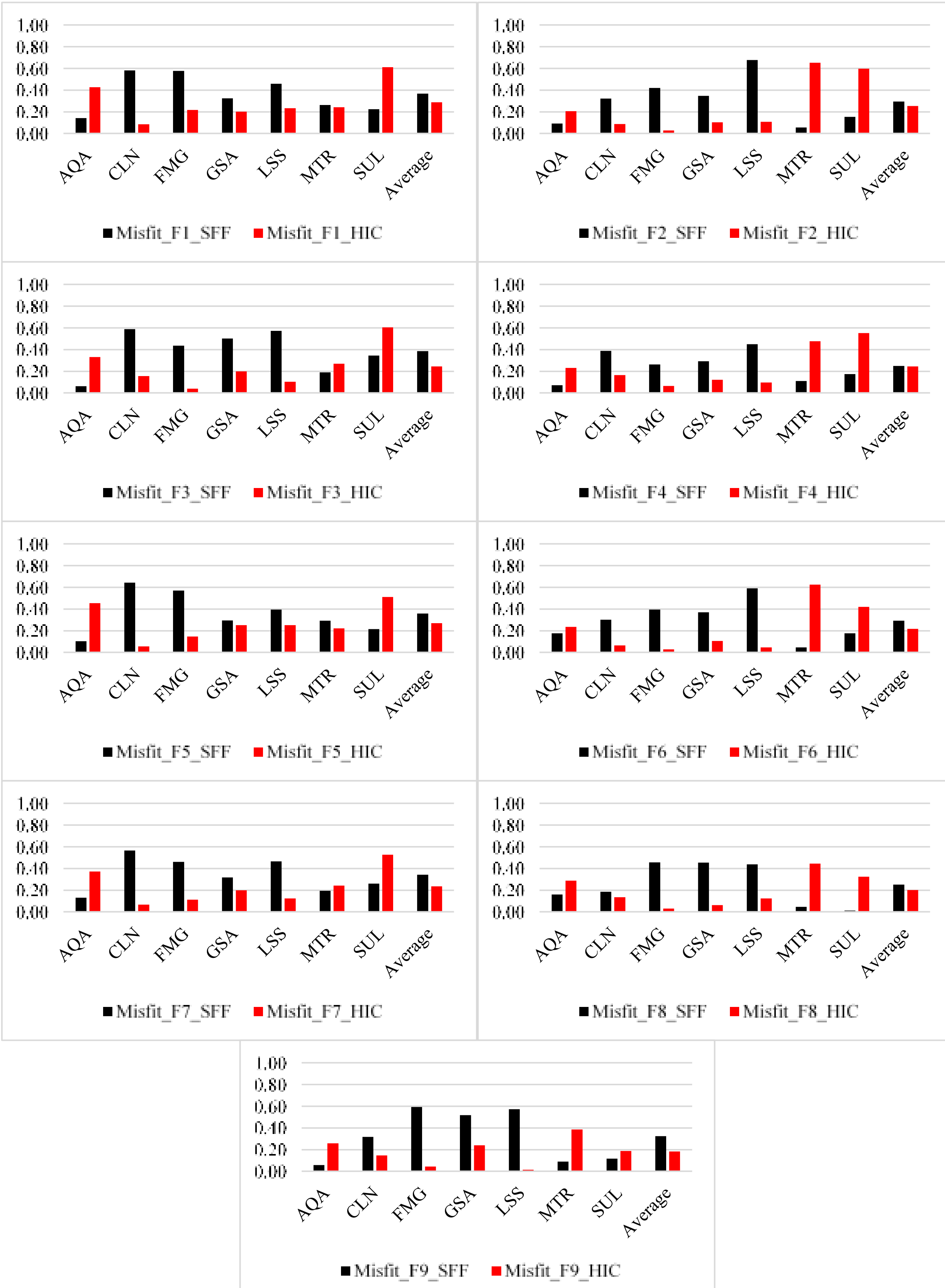


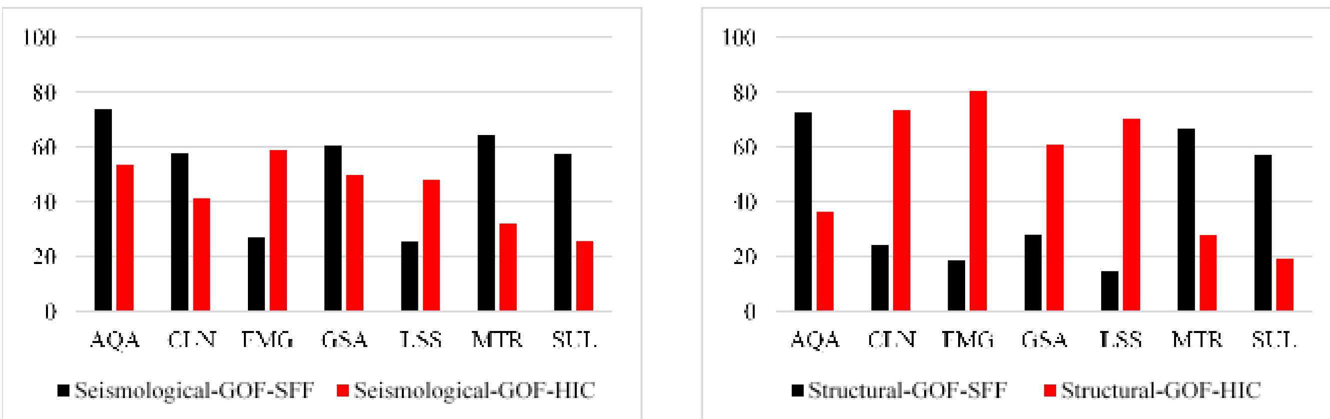
Figure 2. Structural logarithmic misfits.

SIMULATION RESULTS IN TERMS OF GOF SCORES

In this section, simulated motions from alternative approaches are evaluated through GOF score proposed by Olsen and Mayhew [10]. In that study, the final GOF score is obtained as the average score (from 0 to 100) by assumption of equal weights in order to combine the GOF scores corresponding to different parameters. The evaluation in terms of GOF scores herein is accomplished separately in terms of the previously mentioned seismological versus structural parameters. Figure 3 compares the station-wise GOF scores calculated based on the seismological and structural parameters from the SFF and HIC methods. The results reveal that the SFF simulation method provides higher seismological GOF scores than HIC method at stations AQA, CLN, GSA, MTR, and SUL, where a higher GOF implies a better performance. However, this observation is vice versa for the stations FMG and LSS where seismological GOF scores from the HIC method are greater than those corresponding to the SFF approach. This shows that at these stations the HIC method is more accurate than the SFF technique in simulation of the observed seismological parameters. Overall, the observations in terms of seismological GOF scores are in general (at most stations) consistent with those corresponding to the seismological logarithmic misfits.

Next, structural GOF scores are calculated for the engineering demand parameter of interest at all stations in order to compare them with the seismological GOF scores. Results reveal that the level of GOF scores are almost in the same range regardless of some discrepancies. The SFF simulation method provides higher structural GOF scores compared to the HIC method at stations AQA, MTR, and SUL. However, at stations CLN, GSA, FMG, and LSS, structural GOF scores from the HIC method are larger when compared to the results corresponding to the SFF method. Overall, the general trend for the structural GOF scores at all stations is consistent with the structural logarithmic misfits.

Finally, from this study it can be seen that there is generally consistency between the structural logarithmic misfits/GOF scores and seismological logarithmic misfits/GOF scores.



(a) (b)

Figure 3. (a) Seismological and (b) Structural GOF scores at the selected stations.

CONCLUSIONS

In this paper, the goodness of fit between the real and simulated ground motion records of the 2009 L'Aquila (Italy) earthquake (Mw=6.3) from two alternative methods is investigated. The goodness of fit criteria is evaluated for the real and simulated seismological measures versus engineering demand parameters. For evaluation, the previously validated simulated ground motion datasets from stochastic finite-fault and hybrid integral composite ground motion simulation methods are employed. To investigate the goodness of fit between the real and simulated motions two algorithms are employed: Logarithmic misfit and GOF score by Olsen and Mayhew [10]. The seismological goodness of fit is evaluated for alternative seismological parameters covering the frequency, energy, and intensity contents of the time histories. To investigate the structural goodness of fit, different multi-degree-of-freedom reinforced concrete structures with varying number of stories and fundamental periods are considered. The investigated structural response is taken as the maximum inter-story drift ratio.

Results of this study reveal that there is variability in terms of both seismological and structural logarithmic misfits when alternative seismological parameters or different structural types are investigated. Still, the maximum level of logarithmic misfits is similar for all parameters and structures considered herein. The smallest seismological logarithmic misfit is calculated for PGA and t_{eff} from SFF approach, while for CAV from HIC method. Based on both methods, the upper limit is obtained for arias intensity. Similarly, the simulated ground motions from both methods result in almost close values for the minimum and maximum structural logarithmic misfits.

Overall, a close trend is observed between the seismological and structural logarithmic misfit as well as GOF score. For most stations, as the seismological logarithmic misfit increases, the structural logarithmic misfit likewise takes larger value for most frames. In addition, as the seismological GOF score increases, the structural GOF score similarly goes up despite some discrepancies. Finally, in this study, goodness of fit is investigated not only between the observed and simulated seismological measures but also between the real and estimated engineering demand parameters of varying MDOF buildings. The proposed approach and similar ones can provide a means to investigate simulated time histories before their use in earthquake engineering for alternative applications.

REFERENCES

[1] EC8 (2004). Eurocode 8: *Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings*, European Norm, Management centere: Rue de Stassart 36, B-1050 Brussels, Belgium.
[2] ASCE/SEI 7-10 (2010). *American Society of Civil Engineers. Minimum design loads for buildings and other structures*.
[3] Olsen, K.B., Archuleta, R.J., and Matarese, J.R. (1995). "Three-dimensional simulation of a magnitude 7.75 earthquake on the San Andreas fault". *Science*, 270, 1628-1632.
[4] Beresnev, I.A., and Atkinson, G.M. (1998). "Stochastic finite-fault modeling of ground motions from the 1994 Northridge, California, earthquake. I. Validation on rock sites". *Bulletin of Seismological Society of America*, 88(6), 1392-401.
[5] Motazedian, D., and Atkinson, G.M. (2005). "Stochastic finite-fault modeling based on a dynamic corner frequency". *Bulletin of Seismological Society of America*, 95, 995–1010.
[6] Galloviç, F., and Brokešová, J. (2007). "Hybrid k-squared source model for strong ground motion simulations: Introduction". *Physics and Earth Planet*, 160, 34–50.
[7] Frankel, A. (2009). "A constant stress-drop model for producing broadband synthetic seismograms: comparison with the next generation attenuation relations". *Bulletin of Seismological Society of America*, 99(2A), 664-680.
[8] Aagaard, B.T., Graves, R.W., Schwartz, D.P., Ponce, D.A., and Graymer, R.W. (2010). "Ground-motion modeling of Hayward fault scenario earthquakes, part i: Construction of the suite of scenarios". *Bulletin of Seismological Society of America*, 100, 2927-2944.
[9] Anderson, J.G. (2004). "Quantitative measure of the goodness-of-fit of synthetic seismograms". *13th World Conference on Earthquake Engineering*, (243),775-784, Vancouver, B.C., Canada.
[10] Olsen, K.B., and Mayhew, J.E. (2010). "Goodness-of-fit criteria for broadband synthetic seismograms, with application to the 2008 Mw 5.4 Chino Hills, California, earthquake". *Seismological Research Letters*, 81(5), 715–723.
[11] Askan, A., Karimzadeh, S., Asten, M., Kılıç, N., Şişman, F.N., and Erkmen, C. (2015). "Assessment of seismic hazard in Erzincan (Turkey) region: construction of local velocity models and evaluation of potential ground motions". Turkish Journal of Earth Sciences, 24, 529-565.
[12] Sørensen, M.B., and Lang, D.H. (2015). "Incorporating simulated ground motion in seismic risk assessment: Application to the lower Indian Himalayas". *Earthquake Spectra*, 31(1), 71-95.
[13] Karimzadeh, S., Askan, A., Yakut, A., and Ameri, G. (2017a). "Assessment of Alternative Simulation Techniques in Nonlinear Time History Analyses of Multi-Story Frame Buildings: A Case Study". *Soil Dynamics and Earthquake Engineering*, 98, 38-53.
[14] Karimzadeh, S., Askan, A., and Yakut, A. (2017b). "Assessment of simulated ground motions for their use in structural engineering practice; a case study for Duzce (Turkey)". *Pure and Applied Geophysics*, 174 (9), 3325–3329.
[15] Karimzadeh, S., Askan, A., Erberik, M.A., Yakut, A. (2018). "Seismic damage assessment based on regional synthetic ground motion dataset: a case study for Erzincan, Turkey". *Natural Hazards*, 92(3), 1371–1397.
[16] Ameri, G., Gallovič, F., Pacor, F. (2012). "Complexity of the Mw 6.3 2009 L'Aquila (central Italy) earthquake: Broadband strong-motion modeling". Journal of Geophysical Research, 117, B04308.
[17] Ugurhan, B., Askan, A., Akinci, A., and Malagnini, L. (2012). "Strong ground motion simulation of the 6 April 2009 L'Aquila, Italy, Earthquake". *Bulletin of Seismological Society of America*, 102, 1429–1445.
[18] Turkish Ministry of Public Works and Settlement (1997). *Specification for structures to be built in disaster Areas*, Ankara. 1997.
[19] Uniform Building Code (1982). *International Conference on Building Officials (ICBO)*, Whittier, CA.
[20] OpenSees 2.4.5, Computer Software, University of California, Berkeley, CA. http://opensees.berkeley.edu.