A NONSTATIONARY STOCHASTIC GROUND MOTION MODEL BASED ON SPECIFIED EARTHQUAKE SCENARIOS

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ABSTRACT

A spectral based stochastic ground motion model is presented in this work, using a user-specified earthquake scenario description as input, defined in terms of magnitude $M_w$, closest-to-site distance $R_{rup}$ and local average shear-wave velocity $V_{S30}$, and resulting in fully nonstationary acceleration time-histories at a site of interest. A bimodal analytical evolutionary Kanai-Tajimi (K-T) model lies at the core of the suggested predictive stochastic model, capable of modeling strong nonstationarities of the seismic ground motion. The stochastic K-T model parameters are linked to the used ground motion physical predictors, $M_w$, $R_{rup}$, and $V_{S30}$ at the site of interest, through mixed-effects regression models with random effect terms. Finally, the simulation of sample ground motion realizations based on the specified earthquake scenario is facilitated by the Spectral Representation Method. A freely available executable file with a simple graphical user interface is also presented in order to facilitate uncomplicated use of the developed model. In an effort to evaluate the performance and assess the versatility of the formed predictive model, results are compared with well-established GMPE models. Non-linear response-history analyses are also conducted comparing the seismically induced structural demand of a considered system when subjected to sets of both recorded and associated simulated ground motions. Overall, derived results and comparisons verify the reliability, efficiency and robustness of the predictive stochastic simulation framework in generating ground motions that can be readily used towards the earthquake response characterization of structural systems.

Keywords: Nonstationary stochastic ground motion; specified earthquake scenarios; Spectral Representation Method; evolutionary bimodal Kanai-Tajimi power spectrum; predictive simulation framework

1. INTRODUCTION

In current structural analysis practice, the input ground motion time-histories are often selected from actual ground motions recorded in past earthquake events. Naturally, these motions have to at least possess some similar characteristics with the possible future earthquakes that may affect the structure under consideration and this is unfortunately not possible in numerous cases and design scenarios. Due to this reason, engineers are frequently forced to scale the recorded motions or to modify their spectral content. This procedure is thus mainly motivated by necessity and some concerns have been raised about the fact that records are not only selected from locations unrelated to the site of the project but are also modified, making the recordings susceptible to potentially unrealistic ground motion representations.

Another alternative, instead of using modified recorded time histories, is to use simulated ground motions with uniquely defined, representative characteristics of possible earthquake ground motions at a site of interest. ASCE 7-16 refers to this option as well by a general remark that “appropriate simulated ground motions” can be used. This work focuses on this approach and proposes a method that could realize this option. Apart from overcoming the concerns related to selecting and scaling

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recorded ground motions, simulated earthquake waveforms based on stochastic representations have the extra advantage that can be directly used in a stochastic dynamic analysis. In addition, a description of the earthquake hazard in the form of simulated waveforms provides a meticulous characterization of seismic risk beyond capabilities of individual Ground Motion Prediction Equation models (GMPEs).

A spectral based stochastic ground motion model is presented in this work, using a user-specified earthquake scenario description as input, defined in terms of magnitude $M_w$, closest-to-site distance $R_{rup}$ and local average shear-wave velocity $V_{S30}$, and resulting in fully nonstationary acceleration time-histories at a site of interest. Among the most recent works in this direction (Rezaeian & Der Kiureghian, 2010) and (Yamamoto & Baker, 2013) developed time-domain and wavelet-based stochastic ground motion models respectively. A detailed overview of relevant stochastic ground motion models of this type, differences and similarities can be found in (Vlachos et al., 2018a). A bimodal analytical evolutionary Kanai-Tajimi (K-T) model, as introduced in (Vlachos et al., 2016), lies at the core of the suggested predictive stochastic model. The functional forms that describe the temporal evolution of the K-T model parameters are capable of modeling strong nonstationarities of the seismic ground motion. The stochastic K-T model parameters are linked to the used ground motion physical predictors, $M_w$, $R_{rup}$, and $V_{S30}$ at the site of interest, through mixed-effects regression models with random effect terms. An extensive Californian subset of the (NGA-West2, 2013) database is used to develop and calibrate the regression models. Model parameter realizations are obtained through fitting the K-T model to the selected Californian database records, and their resulting marginal distributions are effectively described by simple probability models. The sample parameters are subsequently translated to the standard normal space for computational and simulation efficiency. The random effect terms in the developed regression models can effectively model the correlation among ground motions of the same earthquake event, in parallel to taking into account the location dependent effects of each site. The covariance structure of the normal model parameters is estimated and together with the developed regression models form a multivariate normal probability model, that can be easily simulated for a given earthquake scenario. The sample model parameters are translated back to their physical space through their fitted marginal distribution models. Finally, the simulation of sample ground motion realizations based on the specified earthquake scenario is facilitated by the Spectral Representation Method (Vlachos et al., 2018a). A freely available executable file with a simple graphical user interface is also presented in order to facilitate uncomplicated use of the developed model. To evaluate the performance and assess the versatility of the formed predictive model, the simulation-based attenuation of important scalar ground motion engineering metrics is studied and compared with the results of well-established GMPE models. Furthermore, median and median plus/minus one standard deviation elastic response spectra of simulated time-histories are compared against the NGA-West2 GMPE models for a variety of earthquake scenarios. Non-linear response-history analyses are also conducted comparing the seismically induced structural demand of a considered system when subjected to sets of both recorded and associated simulated ground motions. Overall, derived results and comparisons verify the reliability, efficiency and robustness of the predictive stochastic simulation framework in generating ground motions that can be readily used towards the earthquake response characterization of structural systems.

2. EVOLUTIONARY BIMODAL POWER SPECTRUM AND ASSOCIATED PARAMETERS

This section presents the fully nonstationary parametric K-T ground motion model, as developed and explained in detail by (Vlachos et al., 2016). The used bimodal K–T model is the first fully analytical model to date that can directly describe multi-modal evolutionary power spectral densities. The developed model consists of two distinct spectral modes, based on the superposition of two classical unimodal K-T expressions. Incorporating a high-pass filter is deemed essential, since it suitably diminishes the spectral energy levels in the lower-frequency range of the simulated ground motions. The used model is thus expressed as:
\[ S_{xx}(f,t) = | HP(f) |^2 \sum_{k=1}^{2} S_{\theta}^{(i)}(t) \left\{ 1 + \left[ \frac{2 \zeta_{g}^{(i)}(f / f_{g}^{(i)}(t))}{f / f_{g}^{(i)}(t) - \left( 1 - \left( f / f_{g}^{(i)}(t) \right)^2 \right)} \right] + \left( \frac{2 \zeta_{g}^{(i)}(f / f_{g}^{(i)}(t))}{f / f_{g}^{(i)}(t) - \left( 1 - \left( f / f_{g}^{(i)}(t) \right)^2 \right)} \right)^2 \right\} \]  

where \( S_{xx}(f,t) \) is the model evolutionary power spectrum, \( HP(f) \) is a deterministic 4th-order high-pass Butterworth filter with corner frequency \( f_c = 0.2 \text{Hz} \), and \( \{ f_{g}^{(i)}(t), \zeta_{g}^{(i)}(t), S_{\theta}^{(i)}(t) \} \) are the dominant frequency, apparent damping ratio and participation factor with respect to the \( k \)th mode respectively.

The selected subset of the (NGA-West2, 2013) ground motion database used in this work consists of 1,410 exclusively Californian earthquake ground acceleration records. The nonstationary spectral estimation of the database records is performed by using the Short-Time Multiple-Window estimation technique, as explained in (Vlachos et al., 2018a). Having estimated the nonstationary spectral content of an acceleration signal \( x(t) \) together with the analytical K-T model in Equation 1, the required spectral parameters are identified at every time-instant of the considered signal through matching the analytical and numerically estimated power spectra in the least-squares sense over the entire frequency domain.

The analysis space, where the analytical expressions that describe the temporal-variation of the model parameters are formed, is the non-dimensional cumulative energy domain instead of the typically used time domain, and a new energy-based amplitude modulating function is developed. Based on this modeling choice, the representation of the spectral energy distribution becomes more accurate in the strong motion part of the seismic signal, since the effects of the prolonged preceding or trailing weak motion parts are effectively reduced. The adopted energy domain definition is given as:

\[ \varepsilon(t) = \int_0^T x^2(\tau) d\tau / \int_0^T x^2(\tau) d\tau, \quad I_x = \int_0^T x^2(\tau) d\tau \]  

where \( T \) is the record total duration and \( \varepsilon(t) \in [0,1] \). An analytical form is required in order to describe the energy accumulation over time and express the entirety of the developed functional forms in the time domain, thus facilitating the simulation of the evolutionary ground motion model. The following parametric expression is proven to effectively describe the energy accumulation over time of the selected records:

\[ \varepsilon(t) = e^{\left( \frac{(t/T_{d})^{-\gamma}}{\gamma} \right)} / e^{\left( \frac{1}{\gamma} \right)^{-\delta}} \]  

where \( \{ \gamma, \delta \} \) are scale and shape parameters respectively.

Certain choices in the selection of the functional forms result in non-uniform amplitude modulation of the power spectral intensity. In order to remedy this adversary effect, the model power spectrum in Equation 1 is converted to unit-variance at each time-instant, followed by the introduction of an amplitude modulating function \( z(t) \) as follows:

\[ S_{xx}(f,t) = z^2(t) | HP(f) |^2 \sum_{k=1}^{2} S_{\theta}^{(i)}(t) \left\{ 1 + \left[ \frac{2 \zeta_{g}^{(i)}(z(t)) f / f_{g}^{(i)}(z(t))}{f / f_{g}^{(i)}(z(t)) - \left( 1 - \left( f / f_{g}^{(i)}(z(t)) \right)^2 \right)} \right] + \left( \frac{2 \zeta_{g}^{(i)}(z(t)) f / f_{g}^{(i)}(z(t))}{f / f_{g}^{(i)}(z(t)) - \left( 1 - \left( f / f_{g}^{(i)}(z(t)) \right)^2 \right)} \right)^2 \right\} \]  

It can be easily shown that the amplitude modulating function \( z(t) \) is directly proportional to the temporal derivative of the energy accumulation function \( \varepsilon(t) \) (Vlachos et al., 2016).

The strongly nonstationary character of the seismic ground motion is directly related to both the non-
coinciding arrival times and the differences in the attenuation nature of the body and surface seismic waves. Local soil conditions may also significantly alter the spectral energy distribution of the resulting ground motion. Therefore, a versatile analytical expression is selected to model the inherent frequency nonstationarities of the ground motion and is given as:

$$f_\varepsilon^{(k)}(\varepsilon) = Q_k \left( \frac{1}{2} + \varepsilon \right) a_k \left( \frac{3}{2} - \varepsilon \right)^{\beta_k}$$  \quad (5)

for $k = 1, 2$ and $\{Q_k, a_k, \beta_k\}$ being the parameters of the analytical form with respect to the $k^{th}$ mode.

Aiming to a sophisticated but also concise model, the modal damping ratio $\zeta_g$ is modeled as the averaged identified damping in the central 90% of the signal’s energy for each considered spectral mode. As far as the participation factors in Equation 4 are concerned, advantage was taken of their connection and their logarithmic ratio $R^{(2)}(\varepsilon) = \log_{10} \left[ S_o^{(2)}(\varepsilon) / S_o^{(1)}(\varepsilon) \right]$ is modeled by a Gaussian expression. A more detailed presentation of the modeling process can be found in (Vlachos et al., 2016). Overall, the required model parameters collectively form an 18-parameter model set $P$:

$$P = \left[ \gamma_k, \delta_k, Q_1, Q_2, a_1, a_2, b_1, b_2, \frac{\varepsilon^{(1)}}{\varepsilon_0}, \frac{\varepsilon^{(2)}}{\varepsilon_0}, F^{(1)}, \mu^{(1)}, \sigma^{(1)}, F^{(2)}, \mu^{(2)}, \sigma^{(2)}, I_s, T_d \right]^T \quad (6)$$

In Figure 1, the seismic record with the sequence No. 215 (component 70) in the NGA database is shown, from the Livermore-01 1980 earthquake and the San Ramon Fire Station recording. This actual earthquake scenario recording is described by $M_w$: 5.8, $R_{rup}$: 17.93km and $V_{S30}$: 384.47(m/s). The estimated evolutionary power spectrum $S_{XX}^{(e)}(\tau)$ of the signal based on the Short-Time Multiple-Window technique is also shown, together with the fitted $S_{XX}$ spectrum of Equation 4 for this particular time history. Demonstrative plots of the expressions in Equations 3 and 5 and the $R^{(2)}$ ratio for this particular case are also presented in Figure 1.

Figure 1. Top: Livermore-01 recording (Left); Estimated power spectrum (middle); Fitted power spectrum model of Equation 4. Bottom: Energy accumulation (left); Dominant frequencies (middle); Logarithmic normalized participation factor.
3. GROUND MOTION SIMULATIONS BASED ON THE EVOLUTIONARY K-T MODEL

The Spectral Representation Method (SRM) can be used for the simulation of a nonstationary Gaussian stochastic process (Shinozuka & Jan, 1972; Deodatis, 1996; Liang et al., 2007). The SRM relies on the theory of evolutionary spectral representation developed by (Priestley, 1965), in which a complex-valued, in general, zero-mean, nonstationary stochastic process \( x_0(t) \) admits the following representation:

\[
x_0(t) = \int_{-\infty}^{\infty} A(\omega, t) e^{i\omega t} dZ(\omega)
\]

where \( A(\omega, t) \) is a deterministic modulation function of both frequency and time and \( Z(\omega) \) is a spectral process with orthogonal increments. The properties of \( Z(\omega) \) are:

\[
E[dZ(\omega)] = 0, \quad E[|dZ(\omega)|^2] = S(\omega)d\omega
\]

where \( E[\cdot] \) is the expectation operator and \( S(\omega) \) is the power spectrum of the associated stationary stochastic process. It can be easily shown that the mean value of the process \( x_0(t) \) is zero, \( E[x_0(t)] = 0 \), and the autocorrelation function can be expressed as:

\[
R_{x_0x_0}(t, t+\tau) = E[x_0^*(t)x_0(t+\tau)] = \int_{-\infty}^{\infty} |A(\omega, t)A(\omega, t+\tau)S(\omega)e^{i\omega \tau} d\omega
\]

where the asterisk denotes the complex conjugate. For \( \tau = 0 \), Equation 9 yields the following result:

\[
\sigma_{x_0}^2(t) = E[x_0^2(t)] = R_{x_0x_0}(t, t) = \int_{-\infty}^{\infty} |A(\omega, t)|^2 S(\omega)d\omega
\]

If the stochastic process \( x_0(t) \) is a physical process and thus real-valued, the autocorrelation function of Equation 9 can be rewritten as:

\[
R_{x_0x_0}(t, t+\tau) = \int_{-\infty}^{\infty} S_{x_0x_0}(\omega, t)S_{x_0x_0}(\omega, t+\tau)e^{i\omega \tau} d\omega
\]

where \( S_{x_0x_0}(\omega, t) = |A(\omega, t)|^2 S(\omega) \) is the two-sided evolutionary power spectrum of the nonstationary process \( x_0(t) \). For \( \tau = 0 \), Equation 11 yields:

\[
\sigma_{x_0}^2(t) = E[x_0^2(t)] = R_{x_0x_0}(t, t) = \int_{-\infty}^{\infty} S_{x_0x_0}(\omega, t)d\omega
\]

The analytical nature of the model power spectrum in Equation 4 facilitates the simulation of ground motion realizations through the SRM. The time-domain is discretized and the associated energy domain is given by Equation 3. The evolutionary spectral characteristics are calculated through use of the energy-based forms in Section 2 and samples \( \Phi \) of the model set \( P \) shown in Equation 6. Consistent with Equations 7, 8 and 11-12, the SRM is then engaged in a straightforward manner for the simulation of fully nonstationary ground motion sample realizations \( x^{(s)}(t) \) as:

\[
x^{(s)}(t) = 2 \sum_{n=0}^{N-1} [2S_{x_0}(f_n, t, \Phi) \pi M]^{1/2} \cos(2\pi f_n t + \Phi_n^{(s)})
\]

where \( \Phi^{(s)} \) is a set of \( N \) independent random phase angles uniformly distributed in \([0,2\pi] \).
The connection between the stochastic K–T model parameters and the earthquake scenario, specified in terms of $M_{w}$, $R_{rupt}$ and $V_{S30}$ (often written also as $M$, $R$, $V$ in the text, for simplicity), is based on predictive linear random-effect regression relations and the selected Californian NGA-West2 ground motion database. Sample observations of the stochastic K-T model parameters $\mathbf{P}$ are obtained by fitting the developed model to the database records. The resulting marginal distributions of the model parameters are effectively described by appropriate probability distribution models (Vlachos et al., 2018a). These parameter samples are then translated to the standard normal space in order to perform their statistical modeling with computational and simulation efficiency. The random effect terms in the selected linear mixed regression models can effectively model the correlation of ground motions pertaining to the same seismic event, while considering at the same time the fact that each different site is expected to have its own effect on the resulting ground motion.

The linear random-effect model linking the transformed normal model parameter $Z_i$ with the selected earthquake and local site ground motion predictors is of the form:

$$Z_i = E[Z_i | M, R, V, \beta_i] + \omega_i$$

(14)

where $E[\cdot]$ is the expectation operator and $\beta_i$ is the regression coefficient vector describing the conditional mean response of $Z_i$ for the given earthquake and local site characteristics. The zero-mean error term $\omega_i$ is characterized by a parametrized covariance structure including the contribution of the random effect terms as explained earlier. The optimization method used for the unbiased estimation of both the coefficient vectors $\beta_i$ and the covariance parameters is the Restricted Maximum Likelihood Method. A single functional form for the predictive regression equations of all transformed normal model parameters has been chosen in an effort to perform their statistical modeling in a unified and consistent way, while facilitating at the same time their simulation process. The developed predictive regression relation for the transformed standard normal model parameters is given as:

$$Z_i = \beta_{0i} + \beta_{1i} \left( \frac{M}{6} \right) + \left( \beta_{2i} + \beta_{3i} \frac{M}{6} \right) \ln \left( \frac{R + 5}{30} \right) + (\beta_{4i}I_S + \beta_{5i}I_M + \beta_{6i}I_H) \ln \left( \frac{V}{450} \right) + \eta_{ei} + \eta_{si} + \eta_{res,i}$$

(15)

where $\mu_i (M, R, V, \beta_i)$ is the estimated conditional mean response of the normal parameter $Z_i$ for the specified earthquake scenario. The indicator variables $\{I_S, I_M, I_H\}$ receive a value of one when the local site soil is considered soft, medium or hard respectively, otherwise their respective values are set to zero. The random effect terms $\eta_e$ and $\eta_s$ represent the inter-event and site-to-site variability respectively, and $\eta_{res}$ is a residual error term. All three terms are independent zero-mean normal variables with variances $\sigma_{ei}^2$, $\sigma_{si}^2$ and $\sigma_{res}^2$, respectively, and the total regression variance of $Z_i$ is given as:

$$\sigma_{tot,i}^2 = \sigma_{ei}^2 + \sigma_{si}^2 + \sigma_{res,i}^2$$

(16)

The complete covariance matrix $\Sigma$ of the 18 normal parameters $Z$ is estimated next through correlation analysis of the total regression error terms, allowing for the quantification of their complete joint stochastic nature. The whole process is explained in detail in (Vlachos et al., 2018a) together with the calculated coefficients $\beta_i$ and the covariance matrix $\Sigma$. The estimated regression coefficients provide interesting insight regarding the attenuation of the normal model parameters. Indicatively, the total duration $T_d$ tends to increase with magnitude and decrease with site stiffness. Assuming that the scaling factors $Q_1$ and $Q_2$ can be considered as proxies for the magnitude of the two dominant modal frequencies, it is observed that both frequencies tend to decrease with magnitude and distance, whereas they tend to increase with site stiffness. Finally, both modal apparent damping ratios of the seismic ground motion tend to increase with magnitude and decrease with distance.
5. STOCHASTIC SIMULATION OF GROUND MOTIONS FOR SPECIFIED EARTHQUAKE SCENARIOS

Given the earthquake scenario description in terms of $M_w$, $R_{rup}$ and $V_{s30}$ at a site of interest, the conditional mean $\mu_i$ of the associated normal model parameters $Z_i$ are calculated through Equation 15 forming the conditional mean vector $\mu = [\mu_1, \ldots, \mu_8]$. The joint stochastic structure of the normal model parameters $Z_i$ is thus expressed by the following multivariate normal probability model as:

$$Z \sim \mathcal{N}(\mu, \Sigma)$$

(17)

A sample normal parameter vector $z^{(s)}$ can be easily simulated from this multivariate normal model. This sample normal vector is next translated back to its physical space through the fitted marginal probability models (Vlachos et al., 2018a), resulting in the sample physical parameter vector $p^{(s)}$. Given the physical-space sample vector, the construction of the sample evolutionary power spectrum $S_{XX}(f, t, p^{(s)})$ is easily performed, as already explained, and fully nonstationary ground motion samples are generated by the SRM, as shown in Equation 13.

In Figure 2, demonstrative plots of sample power spectra and associated ground motion simulations are provided for an earthquake scenario described by $M_w: 5.8$, $R_{rup}: 17.93\text{km}$ and $V_{s30}: 384.47\text{(m/s)}$. This is the same earthquake scenario with the one in Figure 1 from the Livermore-01 earthquake. The generated power spectra and ground motions of Figure 2 however are not related to any specific recorded event but are instead representative of possible future seismic records for this specified earthquake scenario.

A freely available executable file with a simple graphical user interface is currently under development in order to facilitate uncomplicated use of the developed model for specified earthquake scenarios. The program will become available at the webpage of the first author. Detailed instructions for its use are provided in Figure 3, while Figure 4 showcases a representative output. Based on a user-defined earthquake scenario and its description by $M_w$, $R_{rup}$ and $V_{s30}$, the program generates sample evolutionary power spectra, each one of which is used to generate a number of seismic ground-acceleration realizations. Ground motion velocity and displacement time histories are also provided,

Figure 2. Sample evolutionary power spectra and associated ground motion simulations for an earthquake scenario described by $M_w: 5.8$, $R_{rup}: 17.93\text{km}$ and $V_{s30}: 384.47\text{(m/s)}$. Each sample power spectrum is related to the sample ground motion below it.
by numerical integration of the acceleration time histories, together with the 5%-damped acceleration elastic response spectrum. The random seed information can be selected by the user, a parallel processing option to speed up the simulation process is available, and results can be saved in multiple formats.
6. VALIDATION

The attenuation of important scalar ground-motion engineering metrics corresponding to simulated ground motions generated by the developed stochastic model are compared with the associated predictions obtained from pertinent Ground Motion Prediction Equations (GMPEs), including the Arias intensity $I_A$ (Foulser-Piggott & Stafford, 2012; Stafford et al., 2009; Travasarou et al., 2003), the significant duration $T_{5.95}$ (Bommer et al., 2009; Kempton & Stewart, 2006), and the spectral based mean period $T_m$ (Rathje et al., 1998; Rathje et al., 2004) of the earthquake ground acceleration record. The spectral-based mean period $T_m$ is defined as the weighted-average period of the ground acceleration record in the Fourier spectral domain, weighting each period by the square of its Fourier amplitude. Figure 5 illustrates comparisons of the distance attenuation of median Arias intensity $I_A$, the magnitude attenuation of median significant duration $T_{5.95}$, and the magnitude attenuation of median spectral-based mean period $T_m$, as obtained by ensembles of 500 simulated ground motions and the associated predictions from the considered GMPE models, as mentioned before. As can be observed, results are in very good agreement. More details are provided in (Vlachos et al., 2018b).

In an effort to further assess the performance of the developed predictive stochastic model, the statistics of elastic response spectra from simulated ground motions are compared with the associated predictions from the state-of-the-art NGA-West2 GMPEs (Bozorgnia & et.al, 2014) for a number of different earthquake scenarios (Vlachos et al., 2018b). In Figure 6, the median plus/minus one logarithmic standard deviation elastic response spectra of ensembles of 1,000 simulated accelerations are compared and found in very close agreement with the associated predictions, for the cases of increasing moment magnitude $M_w$, increasing closest-to-site distance $R_{rup}$, and increasing local site soil shear wave velocity distance $V_{S30}$.

![Figure 5. Attenuation of median Arias intensity $I_A$ (upper), median significant duration $T_{5.95}$ (middle), and median spectral-based mean period $T_m$, as obtained by simulated ground motions and associated predictions from the considered GMPE models.](image-url)
Going beyond the linear range, the nonlinear seismic demands of a 2D MDOF frame structure are assessed, when subjected to sets of both recorded and associated simulated ground motions (Vlachos et al., 2018b). Two representative collections of 128 NEHRP Class D and 86 Class C far field Californian strong ground motions are selected from the NGA-West2 database. All 214 earthquake ground motion records originate from events of magnitude greater than 6.5 and are obtained from smaller to moderate source-to-site distances. Simulated ground motions are subsequently generated by the developed predictive stochastic model, where each simulated motion is associated with earthquake and local-site characteristics, $M$, $R$, and $V$, identical with those from each different recording in the two aforementioned selected earthquake ground acceleration collections.

In the current work, it is assumed that fragility curves can be expressed in the form of two-parameter lognormal distribution functions. They are developed as functions of spectral acceleration $S_a$ representing the earthquake ground motion intensity measure. They are estimated based on the maximum likelihood method, as described in (Shinozuka et al., 2003) and further explained in (Andriotis & Papakonstantinou, 2018) as the ordinal case with probit link.

The considered structure is an existing typical 6-story steel moment resisting frame of a hospital building located at Woodland Hills, California. Its geometry together with the associated structural layout and modeling details in OpenSees can be seen in (Vlachos et al., 2018b). The structural material is Grade A36 steel, characterized by a yield stress of 36 ksi, elastic modulus of 29,000 ksi, and post-yield strain hardening ratio of 3%. The first three natural periods of the steel frame are calculated to be 0.98 sec, 0.38 sec, and 0.23 sec respectively. Rayleigh damping is assumed by imposing 2% damping ratio on the first and third modes.
Figure 7. IDR demand fragility curves of the 2D steel moment resisting frame, based on the selected earthquake record datasets and the associated ensembles of simulated ground motions, for IDR demand states: \( IDR_{\text{lim}} (\%) = \{0.5, 1.0, 1.5\} \).

Figure 7 provides comparisons in terms of inter-storey drift ratio (IDR) demand fragility curves for the ensembles of both recorded and simulated ground motions, associated with the two selected local site categories, NEHRP Classes D and C respectively. The specified set of IDR demand thresholds is \( IDR_{\text{lim}} (\%) = \{0.5, 1.0, 1.5\} \). The obtained results are in very good agreement illustrating the capabilities of the developed predictive stochastic model in generating ground motion sample realizations that can be used towards the effective characterization of the probabilistic nonlinear earthquake response of MDOF structural systems, subjected to diverse sets of earthquake ground motions.

7. CONCLUSIONS

A developed predictive stochastic ground motion model is presented in this paper using a user specified earthquake scenario description in terms of moment magnitude \( M_w \), closest distance \( R_{\text{rup}} \) and average site shear-wave velocity \( V_{S30} \) and resulting in fully nonstationary acceleration time-histories at a site of interest. A bimodal analytical fully nonstationary Kanai-Tajimi (K-T) model lies at the core of the predictive stochastic model. The K–T model parameters are linked with the selected set of earthquake and local-site ground motion physical predictors through use of linear random-effect regression models and an extensive Californian NGA-West2 strong motion database. The simulation of sample ground motion realizations based on the user-specified earthquake scenario is performed by the Spectral Representation Method (SRM). A freely available executable file with a simple graphical user interface is also explained in order to facilitate uncomplicated use of the developed model for specified earthquake scenarios.

In an effort to evaluate the efficiency and assess the versatility of the developed predictive stochastic ground motion simulation framework, the attenuation of a number of important scalar ground motion metrics, as obtained by simulated fully nonstationary ground acceleration time histories, is studied and compared against the results of well-established GMPE models. The statistics of linear elastic response spectra from ensembles of simulated ground motion time-histories are next compared with the associated predictions of the state-of-the-art NGA-West2 GMPE models, for a wide spectrum of earthquake scenarios. Finally, nonlinear response-history analyses are conducted for a typical 2D MDOF frame structure comparing the seismically induced demands of the considered system when subjected to sets of both of both recorded and associated simulated ground motions.

Overall, the results obtained by the developed predictive stochastic model are found to be in excellent agreement with the associated GMPE predictions, illustrating the fitness of the suggested stochastic simulation framework in effectively modeling both important scalar ground-motion intensity measures and response-spectral ordinates, based on given seismological scenarios. In addition, the fragility results based on the earthquake record datasets and the associated ensembles of simulated ground motions are found to be of very similar nature, validating the reliability and robustness of the predictive stochastic simulation framework in generating ground motions that can be readily used towards the earthquake response characterization of nonlinear MDOF structural systems.
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9. REFERENCES


