An Approach for Generating Spectrum and Energy-Compatible Synthetic Accelerograms

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ABSTRACT

For the purpose of seismic performance verification of bridges in the process of seismic design, it is desirable to use spectrum-compatible accelerograms. However, it is well known that the correct evaluation of seismic response of structures depends on the well-suited seismic inputs. The appropriate seismic assessment of structures under earthquake loading is affected by the characteristics of accelerograms. For example, Aria Intensity, that is effective in presenting the damage potential of accelerograms. It is found that the Arias Intensity is capable of predicting the likelihood of damage of structures with short period (e.g., short-span bridges). Thus, in addition to being spectrum-compatible, there is a need to correct Arias Intensity of synthetic accelerograms to be energy-compatible in the time domain. Therefore, a simplified method that can generate synthetic accelerograms that are both spectrum-compatible and energy-compatible is necessary. This study proposed a method that can modify Arias Intensity when generating spectrum-compatible synthetic accelerograms for given seismic records. This method introduces an energy-compatible algorithm to the spectrum-compatible model, which makes the generated synthetic accelerograms match with the target response spectrum in the frequency domain and Arias Intensity in the time domain. The proposed method has been validated using various seismic records, its performance is satisfactory and its application is straightforward and quite useful in any seismic design of building new bridges or retrofitting old bridges.

Keywords: Arias Intensity; synthetic accelerograms; spectrum-compatible; energy-compatible; seismic design

1 INTRODUCTION

Earthquake may cause great damage to bridge structures, and a proper seismic load input of bridges has always been an important research direction in the field of earthquake engineering. Design response spectra are typically used in modern bridge codes or specifications to characterize the seismic load. For this reason, it is frequently important that the spectra of the input accelerograms are comparable to or envelope the specified target design spectra when nonlinear time history dynamic analysis are required. Spectrum-compatible accelerograms are the name given to this class of seismic inputs. For seismic design, spectrum-compatible accelerograms have become quite popular, and several spectrum-compatible models have been presented (e.g., Gasparini and Vanmarcke 1976; Zentner and Poirion 2012).

However, it cannot guarantee an accurate seismic evaluation when the accelerograms are only spectrum-compatible. Recently, the accurately reproduction of the natural characteristics (e.g., Peak Ground Acceleration (PGA), Cumulative Absolute Velocity (CAV), and Arias Intensity (AI)) of recorded accelerograms has been highlighted by researchers (Zentner and Poirion 2012). Arias (1970) proposed the intensity measure, Arias Intensity (AI), to depict the damage potential for accelerograms. It is found that AI is capable of predicting the possibility of damage to short-period structures (Travasarou et al. 2003), as the likelihood of seismic damage can be assumed as proportional to the energy per unit weight dissipated by the structures (Villaverde 2009). Cabañas et al. (1997) used AI as an intensity measure to relate the accelerogram energy to the structure damage occurrence for a more accurate seismic risk assessment. It is found that there is a strong correlation between AI and Local Medvedev-Sponheuer-Karnik (MSK). In addition to structure engineering, AI was also found to be an effective measure in geotechnical engineering, e.g., in the evaluation of rock falls, land slide occurrence, and liquefaction (Kramer and Mitchell 2006; Del Gaudio et al. 2003)

Recognizing the importance of AI in seismic analysis, it is necessary to maintain the AI after spectrally matched to the target response spectrum. In other words, in addition to be spectrum-compatible, the AI (i.e., energy-compatible) of accelerograms should also be sought. In this study, a straightforward method to correct the AI of the synthetic accelerograms are provided. This method combines an energy-compatible algorithm to the spectrum-compatible algorithm, which makes the generated synthetic accelerograms match with the target response spectrum in the frequency domain and Arias Intensity in the time domain. To validate the effectiveness of the proposed method, several accelerograms are generated to be compatible with the target response spectrum and the AI of the seed recorded accelerogram. It is found that the performance of this proposed method is satisfactory, and its application is straightforward and quite useful in any seismic design of building new bridges or retrofitting old bridges.

2 AN APPROACH FOR GENERATING SPECTRUM-COMPATIBLE ACCELEROGRAM

In this paper, the spectrum-compatible model proposed by Gasparini and Vanmarcke (1976) is adopted due to its simplicity and efficiency. This model generates artificial accelerograms $a(t)$ by a series of sine waves:

$$a(t) = g(t)\sum_{i=1}^{n} A_i\, sin(\omega_i + \varphi_i) \tag{1}$$

where $g(t)$ is a deterministic envelope function; A_i, ω_i, and φ_i are the amplitude, frequency, and phase angle of the ith sine wave. In order to modify the artificial accelerograms $a(t)$ to be compatible with the target response spectrum, A_i can be scaled up or down. In most cases, an iterative process is needed, and a straightforward linear correction can be implemented at the jth iteration:

$$A_{j+1} = \frac{PSA_T}{PSA_{calculated}} A_j \tag{2}$$

where PSA_T is the target response spectrum; $PSA_{calculated}$ is the calculated response spectrum of the synthetic accelerogram. In this study, a convergence criterion is adopted to determine the relative error between the target and the calculated results:

$$E = \frac{||V_T - V_{calculated}||}{||V_T||}\% \tag{3}$$

where E represents the relative error, V_T represents the target value, and $V_{calculated}$ represents the calculated value. It is found that a tolerance of $E \leq$ TOL = 15% is enough to produce an acceptable synthetic accelerogram. However, the tolerance can be decreased to get a better solution. This, of course, comes at the expense of increased computational effort.

3 AN APPROACH FOR ARIAS INTENSITY CORRECTION

Arias (1970) established the Arias Intensity (AI) in 1970, which can be mathematically described as:

$$AI = \frac{\pi}{2g}\int_0^{t_d} a^2(t)dt \tag{4}$$

where $a(t)$ represents the accelerogram; g is the gravitational acceleration; and t_d is the accelerogram duration. Past researchers (Li et.al 2017) find that the envelope function $g(t)$ has a great influence on the matching of AI to the seed recorded accelerogram in the time domain. Thus, in this paper, the envelope function $g(t)$ is modified based on the discrepancies between the target and the calculated energy distributions in order to correct AI in each iteration**.** In a manner similar to the spectrum matching method, the envelope function $g(t)$ can be modified at the *j*th iteration:

$$g(t)_{j+1} = \left(\frac{I_{s,T}(t)}{I_{s,calculated}(t)}\right) g(t)_j \tag{5}$$

where $I_{s,T}(t)$ and $I_{s,calculated}(t)$ are the smoothed energy distributions of the target seed recorded accelerogram and the synthetic accelerogram. In this paper, the Multiple-times Short-window Moving Averaging (MSMA) method was used to determine $I_s(t)$. More specifically, $I_s(t_i)$ at time t_i can be mathematically expressed as:

$$I_s(t_i) = \frac{I(t_{i-1})^2 + I(t_{i+1})^2}{2} \tag{6}$$

$$I(t_i) = a(t_i)^2 \tag{7}$$

The MSMA method can be applied several times until a smooth $I_{s,T}(t)$ is reached. The most important advantage of this method is that it will not cause much modification to the energy distribution of the accelerogram. To show the merit of the MSMA method, a recorded Kobe accelerogram is selected from the consortium of organizations for strong motion observation system (COSMOS), as is shown in Fig. 1.

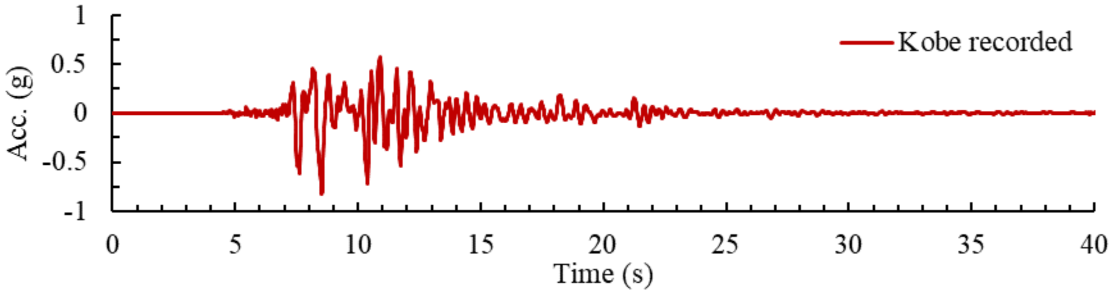


Figure 1: Original recorded Kobe accelerogram.

The energy distribution of the original recorded Kobe accelerogram was smoothed by using the MSMA method 500 times, as is shown in Fig. 2. It can be seen that the zigzagged original energy distribution (solid red line) was converted to a continuous smooth line (solid blue line). Fig. 3 illustrate the comparison in AI between the Kobe recorded accelerogram and the smoothed $I_s(t)$ in Fig. 2. As expected, the two resulting AIs have a close match with each other.

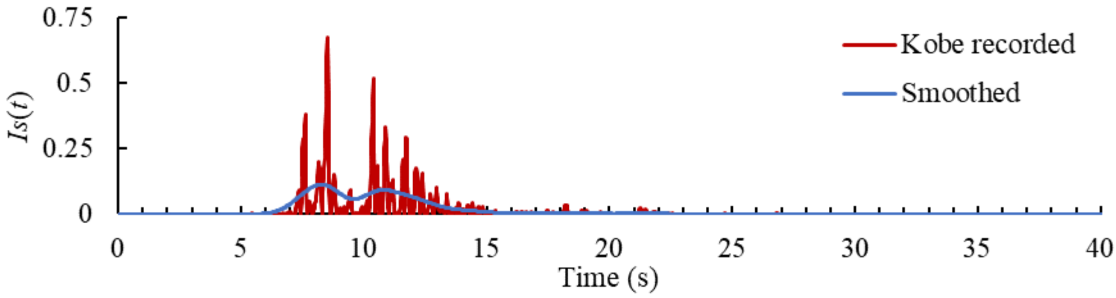


Figure 2: Energy distribution of the original recorded and smoothed Kobe accelerogram.

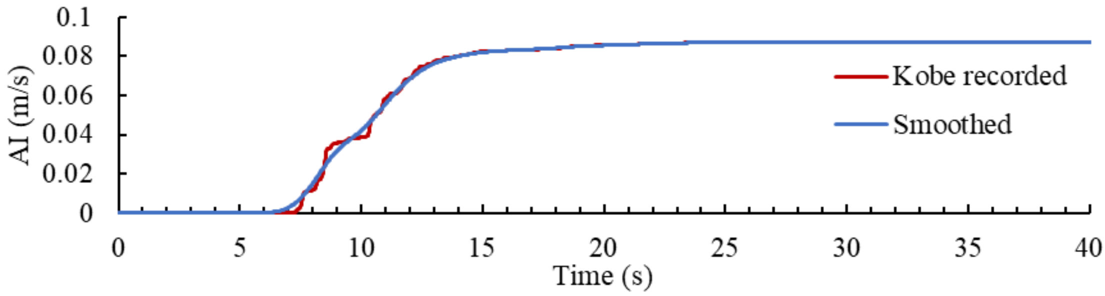


Figure 3: Comparison in AI.

4 THE PROPOSED METHOD

Fig. 4 illustrate the proposed method based on the theoretical basis in Sections 3 and 4.

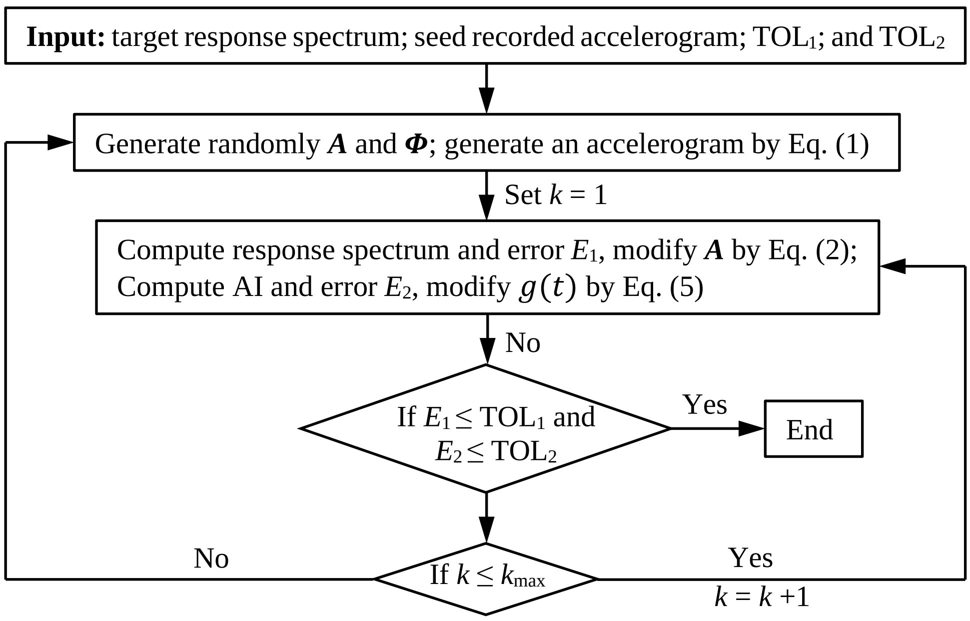


Figure 4: The proposed method.

This is a double iterative method used to modify the synthetic accelerogram to be both spectrum-compatible and energy-compatible. Initially, the target response spectrum, seed recorded accelerogram, tolerance TOL_1 on response spectrum and tolerance TOL_2 on energy distribution (i.e., AI) are provided. Then, an accelerogram generated by Eq. (1) with randomly amplitude $\boldsymbol{A}$ and phase angle $\boldsymbol{\Phi}$ is modified until the error E_1 on response spectrum and E_2 on energy distribution (i.e., AI) are less than the tolerance TOL_1 and TOL_2 simultaneously.

5 NUMERICAL EXAMPLE

In this study, a target response spectrum is determined through the Specifications for Seismic Design of Highway Bridges (JTG/T 2020) corresponding to a peak ground acceleration (PGA) equals to 0.82 g, corner period 0.45 s, and soil type II to verify the effectiveness of the proposed method. Eqs. (8) and (9) gives the expression of the code specified response spectrum.

$$PSA = \begin{cases} S_{max}(5.5T + 0.45) & T < 0.1s \\ S_{max} & 0.1s \leq T < T_s \\ S_{max}(\frac{T_g}{T}) & T > T_g \end{cases} \tag{8}$$

$$S_{max} = 2.25 C_i C_s C_d A \tag{9}$$

where T_g denotes the conner period; T is the natural period; S_{max} is the maximum value of horizontal design acceleration; C_i is the importance coefficient; C_s is the site coefficient; C_d is the damping coefficient; A is the PGA. The determined target response spectrum (damping ratio ξ = 5%) is schematically shown in Fig. 5.

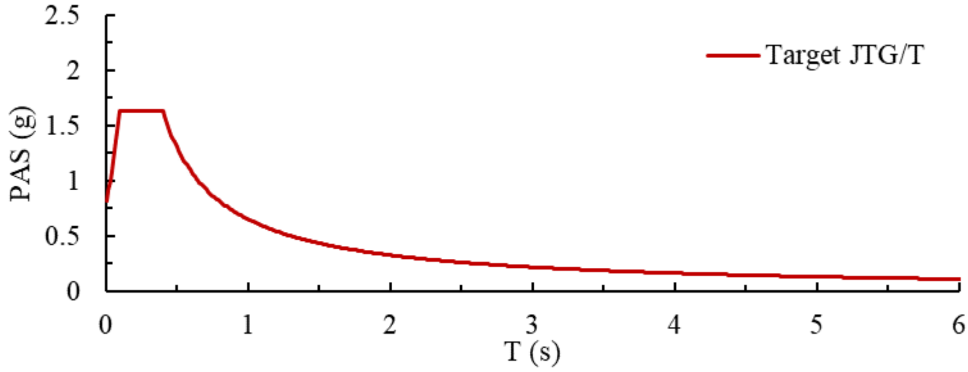


Figure 5: Target response spectrum.

The Kobe accelerogram presented in Section 3 is used as the seed records to spectrally match with the target response spectrum and the target energy distribution (i.e., AI) in the time domain. The convergence criteria for spectrum and energy matching (TOL_1 and TOL_2) are both set as 15%. Three accelerograms are generated using the proposed method. Fig. 6 shows the response spectrum comparison between the target response spectrum and the simulated accelerogram together with the original recorded Kobe accelerogram. The solid green line shows the response spectrum of the original recorded Kobe accelerogram, while the solid red line shows the target response spectrum. It can be seen that the Kobe response spectrum deviates a lot from the target response spectrum. The solid blue line presents the response spectrum of the simulated accelerograms. It is shown that the proposed method can generate accelerograms that are compatible with the target response spectrum. Further, the solid black line shows the mean response spectrum value of the simulated accelerograms. A good match is also detected.

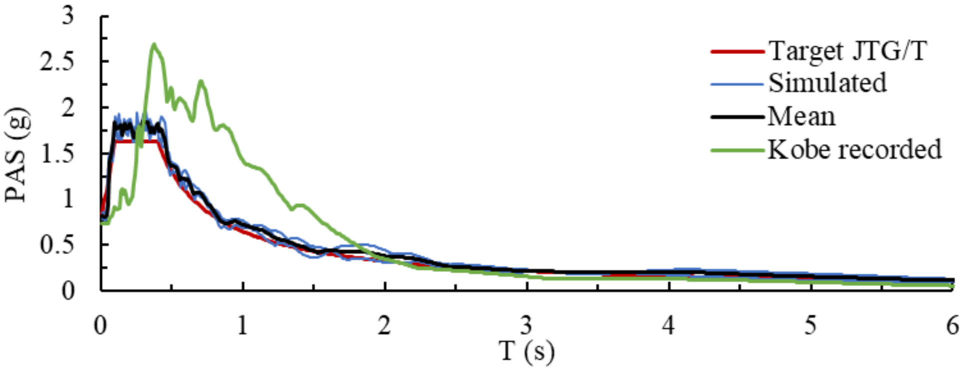


Figure 6: Comparison in response spectrum.

Fig. 7 gives the comparison in AI between the target recorded Kobe accelerogram and the three simulated accelerograms. It can be seen that a good match is reached between the target and the simulated accelerograms. The maximum value of AI for the target recorded Kobe accelerogram is 0.087 m/s in the end. The maximum values of AI for the three simulated accelerograms are 0.082 m/s, 0.079 m/s, 0.080 m/s, respectively, resulting a mean value of 0.081 m/s.

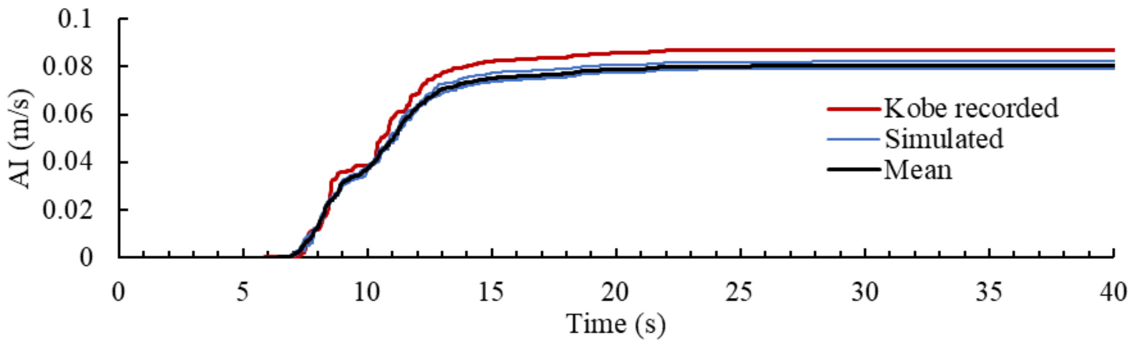
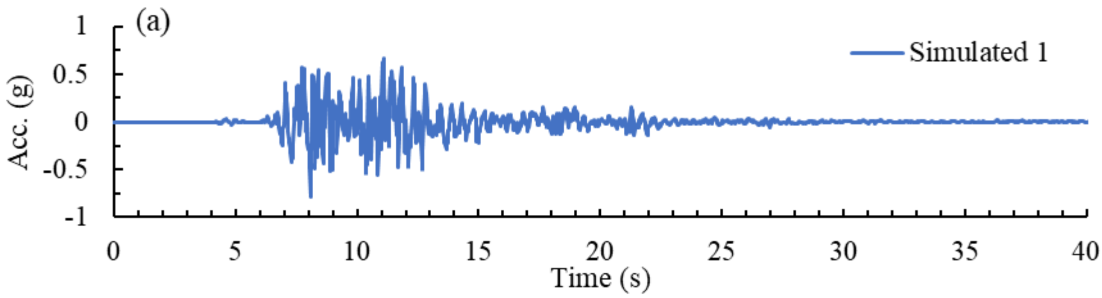


Figure 7: Comparison in AI.

Fig. 8 shows the three simulated spectrum- and energy-compatible accelerograms. Compare with the original recorded Kobe accelerogram shown in Fig. 1, it can be seen that the generated three accelerograms show the non-stationarity in the time domain, that quickly build up to a maximum value within a few seconds and then slowly decreases until it disappears into background noise. This is considered to be an aspect of significant importance, as the seismic design requires the real earthquake-like accelerograms.



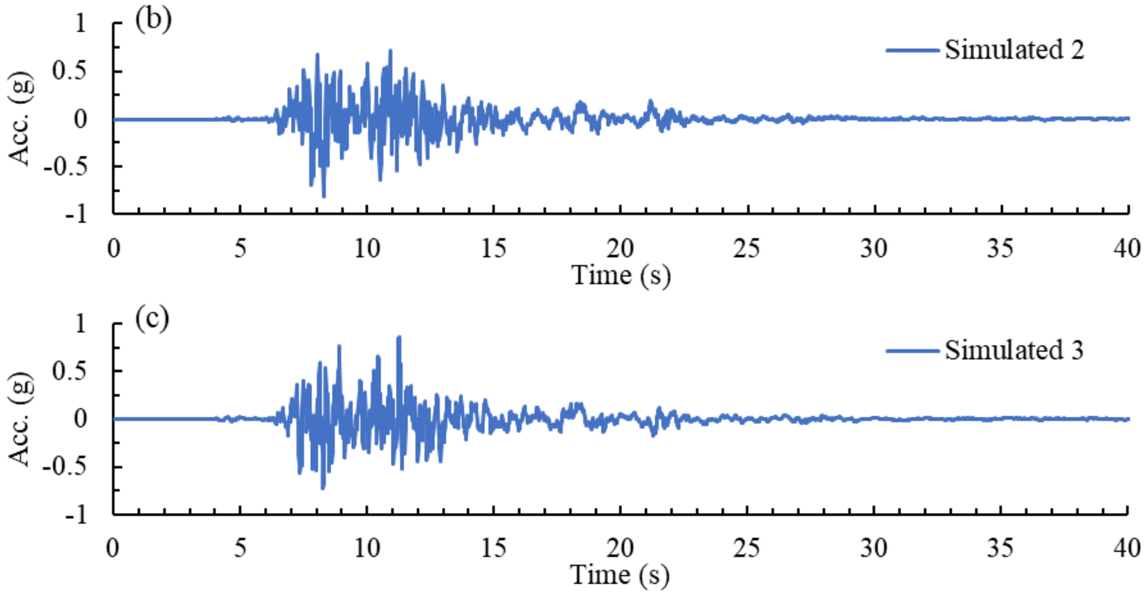


Figure 8: Simulated accelerograms.

6 CONCLUSION

In this study, a simplified method is proposed to generate both spectrum- and energy-compatible synthetic accelerograms for a given seed recorded accelerogram and code specified response spectrum. This method utilizes a double iterative procedure to modify the synthetic accelerograms. The effectiveness of the proposed method is validated using a target response spectrum determined through the specification of JTG/T 2020 and the recorded Kobe accelerogram. It is found the accelerograms generated using the proposed method shows the non-stationarity similar to the real earthquake accelerograms, indicating the appropriate application in earthquake engineering.

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