IMPROVED PROCEDURE FOR SPECTRAL ACCELERATION MATCHING IN DIFFERENT EARTHQUAKE SCENARIOS

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Abstract

The distinctive characteristics of near-field and far-field earthquake records have a critical influence on the seismic response of the structure, especially the frequency content and energy content. This study aimed at improving the ground motion linear scaling method, regarding the effect of near-field and far-field, for precise spectral matching between the response spectrum of real accelerations and the target elastic spectrum of TCVN 9386:2012. The common calibration methods are firstly presented and compared to evaluate the effectiveness of each one. The improvement of the Atkinson (ATK) linear scaling method by dividing the period range of interest is proposed and detailed by an application example. The results show that the proposed method is effective in matching the real ground motion to the target elastic spectrum.

Keywords: *Accelerograms; calibration of ground motion; response spectrum; response spectrum matching.*

1. Introduction

The time-history analysis method is preferred to investigate the seismic performance of structures based on its great advantages such as high accuracy, providing a detailed and complete time-history response of both linear and nonlinear structures subjected to earthquake. Further, in the current seismic-resistant design codes and standards [1-5], this approach is recommended to evaluate and confirm the analysis results of other methods in the final steps [1, 4-6]. However, the input materials of this method, i.e., time-history accelerograms, are lacking in moderate seismic regions such as Vietnam which provides a great challenge for engineers to ensure the appropriate ground motion data for seismic analyses.

The generation of ground motions compatible with a prescribed spectrum is attractive to engineers since it is considered an extension of stochastic simulations. In such a context, some authors [7, 8] have conducted research on creating artificial accelerograms. Artificial accelerograms have the inherent disadvantage of not fully reflecting the variability and randomness of the frequency content, energy content, and intensity of seismic waves. Currently, a linear scaling method is proposed to calibrate the

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DOI: 10.56651/lqdtu.jst.v3.n02.546.sce

available real and artificial accelerograms to match the target design spectrum according to TCVN 9386:2012 [9, 10]. In these results, the selection of a single calibrated period interval significantly reduces the matching of the calibrated earthquake response spectrum and the target elastic acceleration spectrum, especially for short vibration periods.

In addition, ground motions, that resulting from an earthquake, reflect characteristics of the seismic source such as the rupture process, the source to site travel path, and local site conditions. Therefore, the features of ground motions in the vicinity of an active fault are significantly different from the far-fault ones, which have an important effect on the structural seismic responses of these earthquakes [11-13]. There are disputes among the researchers in regard to the determination of a definite range as the near-field and far-field of the fault. Specifically, UBC-97 Code and Canadian code CNBC consider a distance less than 15 kilometers from the earthquake epicenter as the near-field range [2, 14].

Specifically, in the near-field zone, the ground motions have higher acceleration, short-duration impulsive motions, permanent ground displacement, and high-frequency content, which have attracted much attention as critical factors in the design of structures located in the near-field [12, 13, 15]. In the Fourier spectrum of near-field earthquakes, there is no spectrum in a large periodical range with maximum value but a spectrum that becomes maximal in a smaller range and definite period. The existence of such characteristics in near-field earthquakes leads to a case in which the behavior of the structure exits from a modular scenario. On the other hand, far-field ground motions, consist of dominant low-frequency components that significantly impact on high-rise buildings and long-span bridges. In such a context, it is necessary to consider the properties of ground motions in near-field and far-field through different earthquake scenarios in scaling and matching the accelerograms [16-18].

The main objective of the paper is to improve the linear scaling method of real accelerograms with multi-calibrated period intervals to increase the accuracy of the seismic response spectrum matching the target elastic spectrum. An overview study on the current commonly used accelerogram calibration methods is first outlined. The calculation of the elastic acceleration spectrum according to TCVN 9386:2012 is summarized. A comparison of calibration methods with earthquake conditions is conducted at a specific location in Vietnam. The proposed improvement to the linear scaling method of real accelerograms is performed with two different scenarios. In the numerical example study, the calibration results of the pairs of orthogonal accelerograms of two typical earthquakes are performed to evaluate the effectiveness of the proposed procedure.

2. Methods of ground motion scaling

To evaluate the accuracy of calibrated accelerations, several methods of scaling/matching the input ground motion are presented. Two common methods are mentioned including linear scaling using a single calibrated factor and scaling in the time-domain by using SeismoMatch software [19].

2.1. Linear scaling using a single calibrated factor

2.1.1. Peak Ground Acceleration (PGA) scaling

PGA method is one of the well-known and popular methods to correct the acceleration pattern based on the target elastic acceleration response spectrum. The fundamental methodology of this method, as its name implies, uses only a single factor calculated on the basis of the peak acceleration value of the accelerogram (PGA_g) and the target elastic acceleration spectrum. For the elastic acceleration spectra calculated according to the design standard (S_e), the value of PGA is determined by the value of the spectrum at period T = 0 [$S_e(0)$]. Therefore, the calibrated factor of this method (f_{PGA}) can be calculated according to the following formula:

$$f_{PGA} = S_e(0) / PGA_g \tag{1}$$

This method is easy to apply, but it ignores important properties of dynamic systems such as the frequency, the period, and the energy content of earthquake waves. Therefore, the difference between the response spectrum of the calibrated acceleration and the target spectrum is still significant.

2.1.2. S_e (T_1) scaling

In this method, the fundamental mode of structural vibration (corresponding to period T_1) is employed to determine the scaling factor, which is considered by the ratio of the elastic acceleration spectrum (S_e) and ground motion acceleration spectrum (S_g):

$$f_{S_e(T_1)} = S_e(T_1) / S_g(T_1) \tag{2}$$

Generally, this method is highly effective for simple structures, especially for single-degree-of-freedom (SDOF) systems since the calibration is directly performed with the fundamental vibration mode. However, for complex structures and/or nonlinear structural systems, analysis results are not very accurate when using accelerograms calibrated by such a method.

2.1.3. SI_a scaling

According to this method, the scaling factor is calculated in a period range of interest so that the area part of the target elastic spectrum is equal to the ground motion one. The scaling factor is determined as the following:

$$f_{SI_a} = \frac{\int_{T_i}^{T_j} S_e(T)\,dT}{\int_{T_i}^{T_j} S_g(T)\,dT} \tag{3}$$

where the period range of interest (from T_i to T_j) is the most significant parameter, which is determined based on the fundamental period of the structure T_1. Generally, this range is usually chosen from 0 s to $1.2T_1$. In addition, according to the recommendations of the American Society of Civil Engineering (ASCE), the calibration period can be calculated from $0.2T_1$ to $1.5T_1$.

This method is effective in calibrating the accelerograms for seismic analysis of structures, especially for multi-degree-of-freedom systems.

2.1.4. ATK scaling

This method is proposed in 2009 by Atkinson, including the following steps:

- Selection of the period range of interest.
- Selection of ground motion data for analysis.
- Calculation of the ratio of $S_e(T)/S_g(T)$ for each period step in the period range of interest.
- Calculation of the standard deviation of $S_e(T)/S_g(T)$, accelerograms with the smallest standard deviation will be chosen.
- Calibration of the selected accelerograms by the scaling factor, which is determined by the average of the ratio $S_e(T)/S_g(T)$ within the period range of interest.

According to the ATK method, the scaling factor is linearly calculated based on the difference between the response spectrum of ground motion and the target elastic acceleration spectrum. In addition, in the context of selecting accelerograms in an available earthquake database, this method provides an important advantage such that the selection of accelerograms is also covered through the choice of earthquake data with the smallest standard deviation. This method has been used in several recent researches [9, 10].

2.1.5. Mean Square Error (MSE) scaling

This method is proposed by the Pacific Earthquake Engineering Research Center (PEER). Accordingly, the scaling factor within the period range of calibration is determined by the following equation:

$$MSE = \frac{\sum w(T_i)\left\{\ln\left[S_e(T_i)\right] - \ln\left[f.S_g(T_i)\right]\right\}^2}{\sum w(T_i)} \tag{4}$$

where S_e is the target spectrum, S_g is the response spectrum of selected ground motion, $w(T_i)$ is the weight function, and f is the modification factor applied to the selected acceleration to minimize the MSE value between S_e and S_g.

Based on the mentioned method, a numerical analysis of earthquake El-Centro (19-05-1940) is performed to detail and evaluate of each method. The target elastic acceleration spectrum of Thanh Xuan, Hanoi is calculated according to TCVN 9386:2012 for soil type B. The results are shown in Fig. 1.

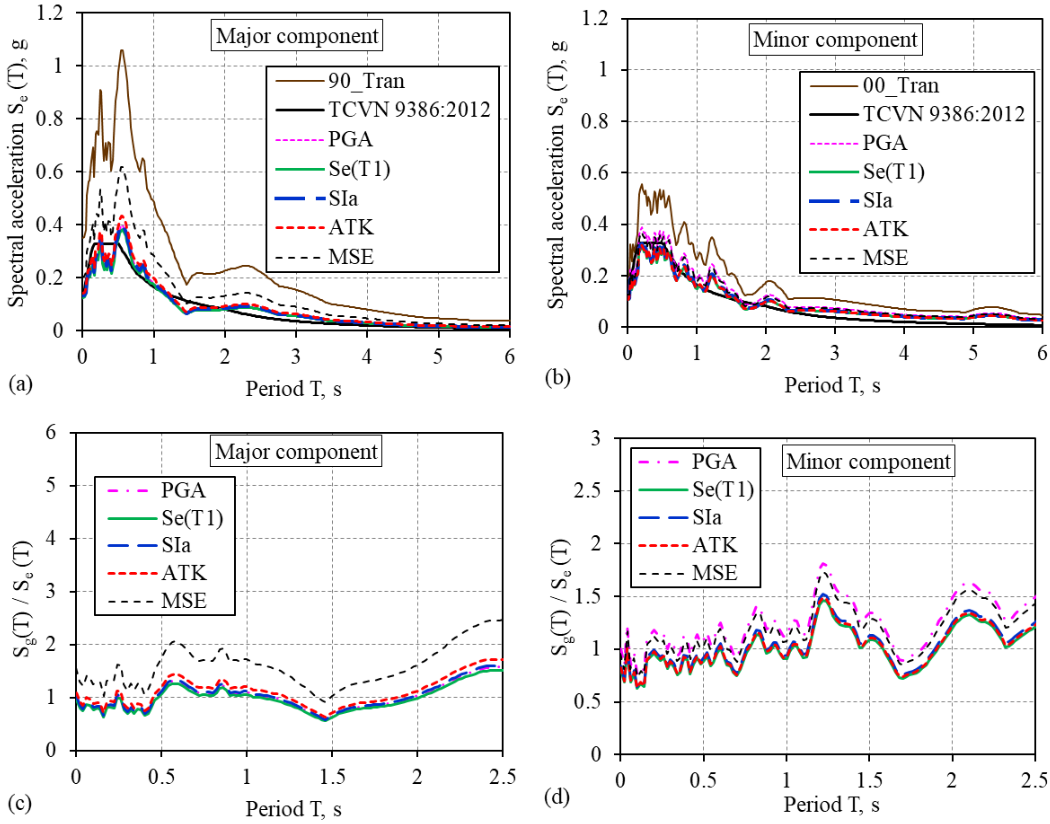

Fig. 1. Comparison of typical methods for linear scaling using a single calibrated factor, target spectrum of Thanh Xuan, Hanoi.

2.2. Ground motion scaling in time-domain

This method consists of matching the response spectrum of the ground motion to the target acceleration spectrum by compressing-stretch time steps over a period range including the fundamental period of the structure. In this method, the fundamental wavelets are added and/or subtracted from the original accelerogram. If the wavelet is selected well, the increase of displacement on the seismic waves is avoided. This procedure allows the reduction of the variance of the structural responses and provides a very good agreement of the response spectrum between the selected accelerogram and the target spectrum. However, trying to match the response spectrum by such a method, especially at short periods, results in a significantly changed energy distribution of the seismic waves. Particularly, the seismic records calibrated by this method have a magnitude significantly higher than the real earthquake signal scaled to match the target elastic response spectrum. In most cases, this method does not produce accelerograms representative of real earthquake records. This method proved to be more suitable for artificial accelerograms, or programs that generate accelerograms, rather than for real seismic records. Fig. 2 presents a comparison of the typical accelerogram (El-Centro Earthquake) calibrated by two methods, including linear scaling and calibration in time-domain using SeismoMatch. Accordingly, even the method using SeismoMatch provides a response spectrum that is closer to the target spectrum, the time-history acceleration calibrated by such a method is considerably higher than that of the linear scaling.

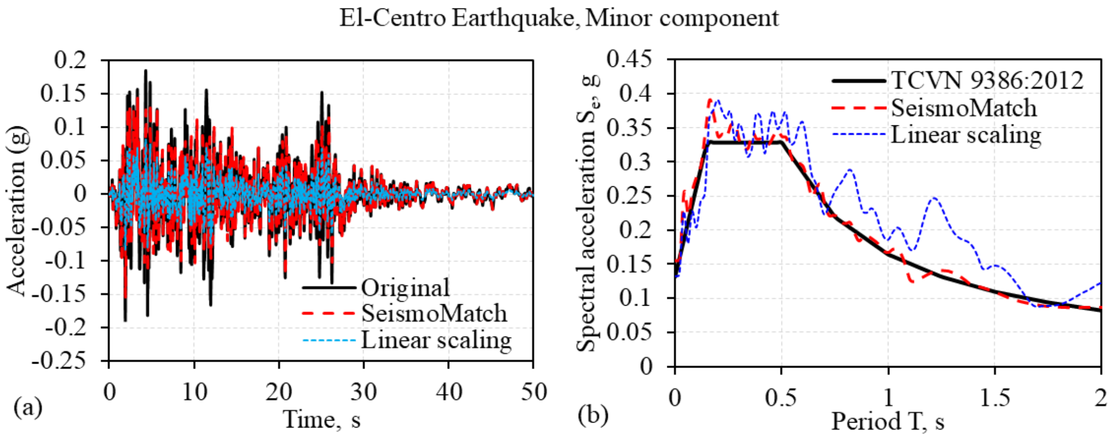

Fig. 2. Comparison of the linear scaling and calibration in time-domain (using SeismoMatch).

3. Improvements to the linear scaling of real acceleration by multi-scenarios

3.1. Methodology

The proposed procedure is performed based on the ATK scaling method, using a single factor that has been presented in previous publications [9, 10]. To do so, the real acceleration records are transformed in the principal directions in order to distinguish the major component and minor component (ensuring the suitable correlation value between the two components) as well as to ensure the independent condition. The detail of this procedure is referenced in the previous publication [10] and illustrated in Fig. 3.

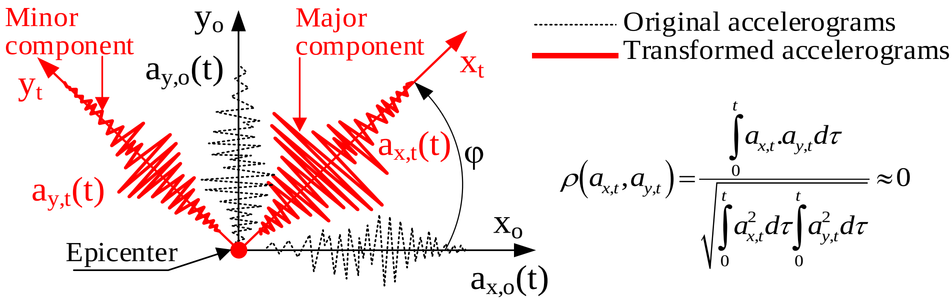

Fig. 3. Transformation of seismic waves into the principal directions [10].

The main improvement is as follows:

Based on the period range of interest (i.e., T_{min} and T_{max}), subdividing the calibrated period range (2 scenarios) ensures that there is interference around the fundamental period of the structure. The short period range is applied to calibrate the accelerograms in the near-field, and the longer one is used for the far-field, as illustrated in Fig. 4.

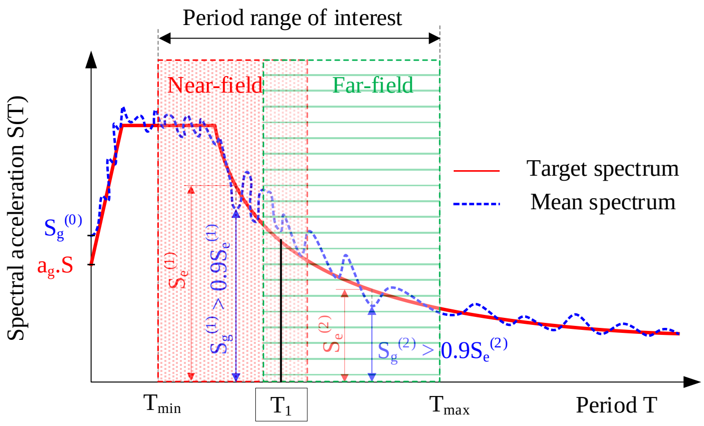

Fig. 4. Principle of the proposed calibration method.

The scaling factor for each scenario is determined from the average of S_e/S_g, which is performed over each period step of calibrated period intervals.

Finally, the response spectrum of calibrated accelerograms is verified and adjusted to satisfy the specified conditions in TCVN 9386:2012, including the condition of 90% matching and the condition of response spectrum at $T = 0$ s.

The seismic response of the structure can be evaluated by each scenario or by the combination of both scenarios where the final response is the average value of the results obtained from all the accelerograms used in the analysis [2, 20].

3.2. Application example

In order to detail the procedure of the proposed calibration method, an example is performed for the target elastic spectrum of Thanh Xuan district, Hanoi, calculated with seismic hazard for a probability of 10% in 50 years and 5% damping.

To determine the period range of interest, dynamic responses of a multi-story reinforced concrete building, with the fundamental period T_1 = 1.0 s, is considered [21]. Accordingly, the calibrated period range is T_{min} = 0.2 s, T_{max} = 2.0 s.

3.2.1. Horizontal elastic response spectrum according to TCVN 9386:2012

The elastic acceleration response spectrum of the horizontal components with period vibration less than or equal to 4 s is determined as the following:

$$\begin{aligned}
&0 \le T \le T_B : S_e(T) = a_g S\left[1+(2.5\eta-1)T/T_B\right]\\
&T_B \le T \le T_C : S_e(T) = 2.5 a_g S\eta\\
&T_C \le T \le T_D : S_e(T) = 2.5 a_g S\eta\left(T_C/T\right)\\
&T_D \le T \le 4s : S_e(T) = 2.5 a_g S\eta\left(T_C T_D/T^2\right)
\end{aligned} \tag{5}$$

The elastic displacement spectrum is calculated based on the spectral acceleration as follows:

$$S_{de}(T) = S_e(T).(T/2\pi)^2 \tag{6}$$

For vibration periods longer than 4 s, the elastic displacement spectrum is determined according to Eurocode 8 [1] as Eq. (7), and the elastic acceleration spectrum is calculated based on Eq. (6):

$$\begin{aligned}
&T_E \le T \le T_F : S_{de}(T) = 0.025 a_g S T_C T_D\left[2.5\eta + \left(\frac{T-T_E}{T_F-T_E}\right)(1-2.5\eta)\right]\\
&T_F \le T : \qquad S_{de}(T) = 0.025 a_g S T_C T_D
\end{aligned} \tag{7}$$

where T_B, T_C, T_D, T_E, and T_F are the parameters of spectral acceleration branch, S is the soil factor, a_g is the design ground acceleration on type A ground; η is the damping factor.

3.2.2. Selection of accelerograms

A suite of two typical earthquakes selected for the near-field and far-field is detailed in Tab. 1. Accordingly, El-Centro earthquake records (hypocenter distance of 12.2 km) represent for the near-field scenario and Kobe earthquake records (hypocenter distance of 19.9 km) are representative for the far-field scenario.

Tab. 1. Earthquake records for analyses

Earthquake	Station	Mw	Hypocenter distance (km)	PGA (g)	
				a_x	a_y
El Centro, 1940-05-19	CA - Array Sta 9; Imperial Valley Irrigation District	6.9	12.2	0.355	0.522
Kobe, 1995-01-16	Nishi-Akashi, Japan	6.9	19.9	0.503	0.509

After converting the accelerograms to the principle direction, the spectral acceleration of transformed records is shown in Fig. 5a and 5b for the minor components and the major components, respectively.

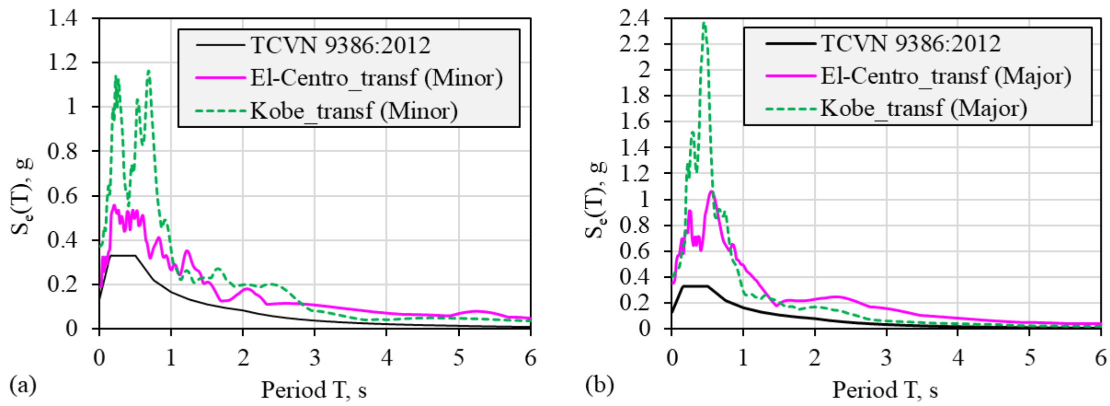

Fig. 5. Response spectral of transformed accelerograms:
(a) Minor components, (b) Major components.

3.2.3. Determined scaling factors by proposed method

Based on the period range of interest, two scenarios are chosen for analysis, ensuring the interference around the fundamental period. Specifically, scenario 1 corresponds to the period range of [0.2 s - 1.2 s] and scenario 2 corresponds to the period range of [0.8 s - 2.0 s]. For each scenario, the period step for calibration is ΔT = 0.02 s ensuring the number of calibration steps is not less than 20 [10].

In order to distinguish the characteristics of seismic waves in near-field and far-field, a parametric analysis through standard deviation was performed on both earthquake scenarios. The results are presented in Tab. 2. Accordingly, for scenario 1 with the period range from 0.2 s to 1.2 s, the standard deviation of the El-Centro earthquake is significantly lower than the Kobe earthquake. The opposite happens in scenario 2 where the period range of interest is considered from 0.8 s to 2.0 s. It shows that, in the shorter period ranges, the variation of the response spectrum of the accelerograms in the near-field (El-Centro earthquake) is considerably lower than that in the far-field and vice versa. The suitability of considered accelerograms for each scenario is therefore also identified with a smaller standard deviation.

Consequently, the scaling factors are also calculated for each scenario based on the average of S_e/S_g performed over each period step of the whole period range of interest. The obtained scaling factors are shown in Tab. 2. The calibrated factors are then multiplied by the original accelerograms (transformed components) to obtain the calibrated accelerograms.

Tab. 2. Standard deviation and scaling factor for selected scenarios

Earthquake components	Scenario 1 [0.2 s - 1.2 s]		Scenario 2 [0.8 s - 2.0 s]	
	Standard deviation	Scaling factor	Standard deviation	Scaling factor
El-Centro_major component	**0.065**	***0.369***	0.081	0.426
El-Centro_minor component	**0.075**	***0.608***	0.099	0.563
Kobe_major component	0.149	0.345	**0.072**	***0.533***
Kobe_minor component	0.195	0.431	**0.081**	***0.474***

To evaluate the effectiveness of the improvement method, a comparison between the linear scaling method using a single period range and using two period intervals (two earthquake scenarios) is performed. The results are presented in Fig. 6.

The difference of response spectrum of accelerograms calibrated by the two methods are plotted in Fig. 7.

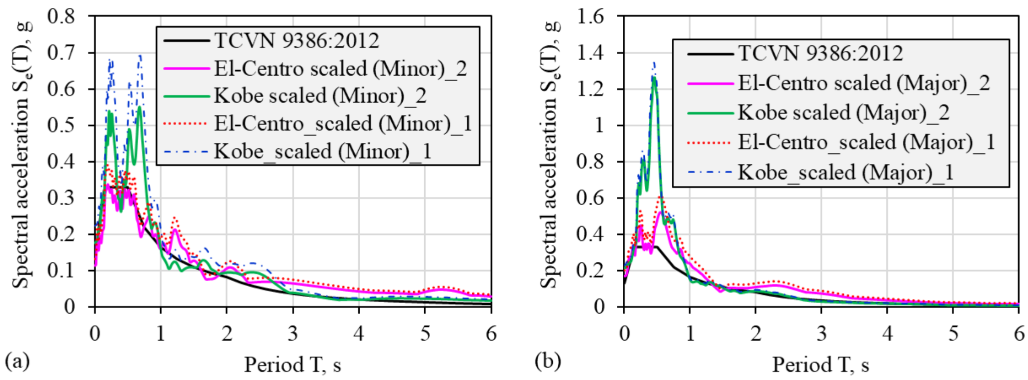

Fig. 6. Comparison of the single period range method (_1) and the method using two scenarios (_2): (a) Minor components, (b) Major components.

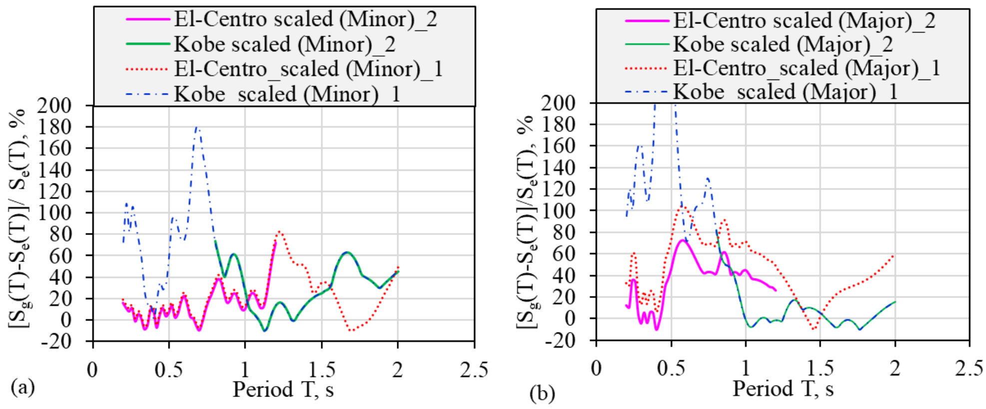

Fig. 7. Differences between the calibrated records, adopted the considered target spectrum: (a) Minor component, (b) Major component.

3.3. Discussion

The improvement method using multiple calibration period intervals provides better results when compared to the method using a single period range. It not only presents a smaller difference in the response spectrum of ground motion with the target spectrum but also eliminates their large difference at short period ranges. In addition, the analysis of the standard deviation of the response spectrum on considered scenarios is a simple but effective scientific argument, allowing evaluate the suitability of each accelerogram used for each corresponding earthquake scenario for analyses. Moreover, the proposed method arises from the need to analyze the difference in earthquake waves in the near-field and far-field zones with different earthquake scenarios.

4. Conclusion

Accelerogram plays an important role in the seismic analysis of structures, especially for dynamic time-history analysis. Selecting and scaling the accelerogram offer practical significance to address the challenge of ensuring earthquake data for moderate seismic regions such as Vietnam. The improvement method of linear scaling ground motion records is effective in matching the response spectrum while still ensuring the random variation over time of the real earthquake records. Further, the proposed method is conducted through simple calculation steps, easy to implement, so it is appropriate for engineers, providing an effective solution in calibrating the ground accelerations for seismic time-history analysis.

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CẢI TIẾN PHƯƠNG PHÁP HIỆU CHỈNH KHỚP PHỔ PHẢN ỨNG VỚI CÁC KỊCH BẢN ĐỘNG ĐẤT KHÁC NHAU

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Tóm tắt: *Sự khác nhau về tính chất của sóng động đất ở vùng gần và vùng xa có ảnh hưởng quan trọng đến phản ứng động đất của kết cấu, đặc biệt là nội dung tần số và năng lượng. Bài báo này nhằm nghiên cứu cải thiện phương pháp hiệu chỉnh tuyến tính gia tốc nền có kể đến ảnh hưởng của sóng động đất ở vùng gần và vùng xa, nhằm khớp phổ phản ứng của gia tốc động đất thực và phổ phản ứng đàn hồi theo TCVN 9386:2012. Đầu tiên, các phương pháp hiệu chỉnh phổ biến hiện nay được trình bày và so sánh nhằm đánh giá hiệu quả của mỗi phương pháp. Nội dung cải tiến phương pháp hiệu chỉnh tuyến tính ATK bằng cách chia nhỏ khoảng chu kỳ hiệu chỉnh được đề xuất và trình bày chi tiết trong ví dụ ứng dụng. Kết quả cho thấy phương pháp đề xuất có hiệu quả tốt trong việc khớp phổ phản ứng của gia tốc động đất thực và phổ phản ứng đàn hồi mục tiêu.*

Từ khóa: Giản đồ gia tốc; hiệu chỉnh gia tốc động đất; phổ phản ứng; khớp phổ phản ứng.

Received: 12/09/2022; *Revised:* 15/12/2022; *Accepted for publication:* 30/12/2022

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