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Research Article

The Impact of Isolation Parameters on Structural Responses due to Strong Earthquake Motion Processed by DWT

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ABSTRACT

The parameters of the base isolation system play a significant role in structural responses as they directly affect the interaction between the structure and seismic excitation. This study focuses on investigating the impact of base isolation parameters on structural behavior under decomposed earthquake effects. The period and damping ratio of the isolator, which are inherently effective in determining characteristics such as stiffness and damping coefficients, were parametrically varied to discern their effects on the seismic behavior of the structure. Displacement of the base mat on the isolators and roof acceleration responses were obtained through time response analyses. To examine seismic input across different frequency ranges, discrete wavelet transformation was used to decompose the earthquake acceleration. A five-level decomposition was applied. Subsequently, time response analyses were conducted for the original earthquake acceleration scenario and the corresponding approximation coefficients. Decomposition levels yielding responses similar to those obtained under the original earthquake were identified. Additionally, the correlation between acceleration responses and the earthquake and approximation coefficients was calculated to figure out the effect of the frequency ranges of seismic excitation on the seismic behavior of the building. The adequate decomposition levels for the base-isolated structure have been presented. This analysis illustrates how various frequency ranges of seismic excitation impact the structural response by highlighting which decomposition levels are most representative of the original earthquake effects.

Introduction

The base isolation system parameters are of great importance since they directly affect how the structures respond to seismic forces. The stiffness and damping coefficient parameters directly influence a building's ability to withstand earthquakes by controlling flexibility and energy dissipation. The efficacy of base isolation has been extensively studied and validated through both theoretical and experimental works. Notable references in this field include works by Kelly [1] and by Soong and Constantinou [2], providing insights into the behavior of isolation systems under various seismic conditions. These studies enrich our understanding of base isolation as a robust seismic mitigation strategy in structural engineering.

Utilizing advanced mathematical tools are helpful to analyze the system behavior and apply the right choice from a vast of options in the designing process that understands the structural behavior and responding the necessities in terms of durable structure. Wavelet transform pioneered by Mallat [3], offers a powerful means of analyzing signals with versatility, scaling, and translating to different resolutions. They capture both high and low-frequency information by applying low-pass and high-pass filters respectively. Unlike Fourier analysis, which focuses solely on frequency, Wavelet transform allows for adjusting window size to achieve both time and frequency details. This adaptability is facilitated by a range of wavelet functions such as Symlet, Coiflet, and Daubechies, which can expand or compress over time and amplitude. Consequently, wavelets have become effective tools in fields of engineering, economics, biomedical research etc. Discrete Wavelet Transform (DWT) has been firstly introduced by Mallat [4], demonstrating its efficacy in analyzing nonstationary signals like earthquake motions. Subsequent advancements, including Daubechies wavelets introduced by Ingrid Daubechies [5], have expanded the applicability of wavelet analysis by offering orthogonality and regularity. The evolution of the technique stills goes on to shape signal processing and analysis methodologies across diverse domains.

This study conducts a comprehensive examination of base isolation parameters, particularly focusing on stiffness and damping coefficient, and their influence on structural behavior, which is essential in determining the overall seismic performance of structures. To distinguish their impact, the isolator's period systematically varied from 2 sec to 3 sec while the damping ratio is changed from %30 to %40. Time response analyses yield structural responses focusing on displacement of base mat above isolators and acceleration at the top of the building. Additionally, DWT, utilizing the Haar wavelet function, is employed to decompose earthquake accelerations into five levels. The low-frequency contents, i.e., approximation coefficients, are then applied to analyze the dynamic behavior of the structure. This decomposition strategy facilitates a thorough investigation of seismic inputs across different frequency bands, to clarify the interaction between structures and ground motion. Subsequently time response analyses are conducted for original earthquake acceleration and its corresponding approximation coefficients. Adequate levels of decomposition which address similar responses obtained by those under original earthquake have been achieved. Furthermore, the correlation between the acceleration responses and the earthquake acceleration as the original and its approximations has been computed to clarify the effectiveness of frequency ranges of the seismic excitation on the seismic behavior of the building.

This research aims to uncover the relationship between structural dynamics, isolation parameters and seismic excitation characteristics. Ultimately, it contributes to a deeper understanding of which level is adequate for decomposition of earthquake acceleration under varying base isolation parameters.

Literature

Wavelet analysis is utilized effectively in denoising earthquake acceleration signals. In the examination of earthquake data, various wavelet decomposition techniques have been employed by researchers. Kamgar et al. [6] conducted a comparative study of Meyer and Daubechies 4 wavelets to identify the most suitable transformation for ground motions. In this study, the findings revealed that Daubechies 4 (db4) is superior to the alternatives.

In another investigation, Kamgar et al. [7] utilized a three-level decomposition with db4 wavelet. Kaloop and Hu [8] chose a two-level decomposition using Daubechies wavelet. Heidari et al. [9] and Heidari et al. [10] took a different approach by employing five decomposition levels to characterize strong earthquake parameters. Nonlinear response spectra were generated for each decomposed signal to show the behavior under decomposed earthquake motions. Kandemir [11] and Kandemir and Jankowski [12] studied viscous dampers between adjacent structures using continuous wavelet transform. In a related study, Yamamoto and Baker [13] proposed that a six to seven decomposition level is suitable for describing ground motions, contributing additional insights to the discourse on optimal decomposition strategies in earthquake analysis.

Additionally, there are valuable studies in the related literature that focus on optimization and application to base-isolation system parameters [14-16].

In this study, earthquake acceleration and its approximations have been applied to the base isolated building to clarify the effect of frequency content on the seismic behavior of the structure.

Discrete Wavelet Transform

The Discrete Wavelet Transform (DWT) focuses on a subset of scales and translations, unlike continuous version, resulting in a discrete representation of the signal through wavelet coefficients at various resolution levels. Unlike the Fourier transform, which only provides frequency information, the DWT captures both time and frequency characteristics, making it ideal for analyzing non-stationary signals, such as earthquakes. The most similar signal processing method to DWT is the Short-Time Fourier Transform (STFT). STFT also provides time-frequency analysis by applying a sliding window to perform Fourier transforms across the signal. However, STFT offers a fixed time-frequency resolution based on the window size, whereas DWT's multi-resolution approach adapts to different scales.

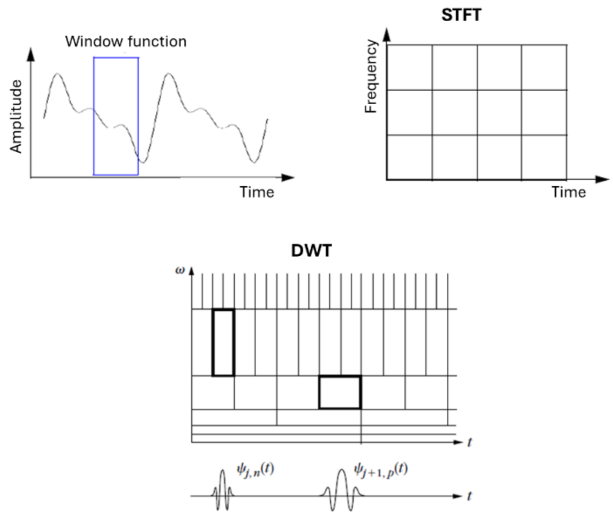

Figure 1. Decomposition of earthquake acceleration signal by discrete wavelet transform (Misiti et al., 2004; Arı et al., 2008)

Losses in frequency or time information occur due to the fixed window function in STFT [17]. Figure 1 illustrates how STFT scans the signal using a window function with a fixed time interval that cannot be stretched or compressed, resulting in a frequency-time graph of the signal within a certain time and frequency band [18]. To overcome these limitations, wavelet transform has been developed as an effective method for decomposing the frequency information of a signal. Using a wavelet function that can be both scaled and shifted, frequency information can be obtained for multiple time intervals [19]. High-frequency information is obtained in narrow time intervals, while low-frequency information is captured in wider time intervals.

In each decomposition level of DWT, a high-pass filter eliminates low-frequency components, and a low-pass filter removes high-frequency components. This procedure results in detail and approximation coefficients, respectively [4]. The DWT of a signal is expressed as,

$$DWT(j,k) = \sum_n f(n) \cdot \psi_{j,k}(n) \quad (1)$$

where j represents the scale parameter indicating the level of resolution or frequency band, and k represents the translation parameter indicating the time location, $\psi_{j,k}(n)$ represents the scaled and translated version of the mother wavelet function $\psi(t)$ used to analyze the signal. It is defined as:

$$\psi^*(t) = \begin{cases} 1 & 0 \leq t < 0.5 \\ -1 & 0.5 \leq t < 1 \\ 0 & otherwise \end{cases} \quad (2)$$

The decomposition process is achieved through a series of low-pass and high-pass filters, often referred to as scaling and wavelet functions, respectively [4]. Subsequently, the signal is downsampled by a factor of two, as illustrated in Figure 1. This downsampling process reduces the number of samples (N) by half while retaining the essential features at different scales.

Iteratively, the decomposition process is applied to the approximation coefficients, resulting in a multi-level representation of the signal. Each level of decomposition provides information at a different scale as shown in Figure 2. In this paper, approximation coefficients, which capture the low-frequency contents of seismic ground accelerations, have been utilized.

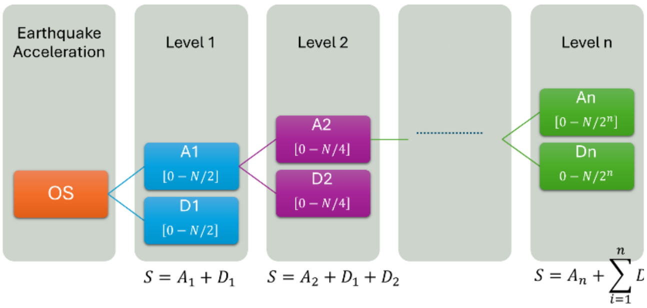

Figure 2. Decomposition of earthquake acceleration signal by discrete wavelet transform

Considered Ground Motion and Its Decompositions

A devastating earthquake struck the southwestern region of Turkey on February 6th, 2023, causing widespread destruction and significant seismic activity. Acceleration records from the seismic event in Kahramanmaras in 2023 are employed for analysis in this study. Specifically, the acceleration record from Elbistan station (TK4612) is utilized due to its high peak ground acceleration. Details regarding the seismic record of the station are provided in Table 1.

Table 1. Selected ground motion

Earthquake-Station	Component	Magnitude	PGA (g)
Kahramanmaraş-Elbistan	NS	7.6	0.648

The wavelet transform is a valuable tool for understanding the characteristic frequency contents that define the presentation of the original earthquake signal. The identification of these frequencies varies depending on the number of decomposition levels used. To quantify and understand these frequency characteristics, one can calculate the frequency ranges and corresponding time intervals of a given time series as given in Table 2 for the earthquake.

Table 2. Frequency ranges and corresponding time intervals of the ground motion

Level	Frequency range (Hz)	Time interval (s)
1	0.097656-0.19531	52.50-104.99
2	0.19531-0.39063	26.25-52.50
3	0.39063-0.78125	13.12-26.25
4	0.78125-1.5625	6.56-13.12
5	1.5625-3.125	3.28-6.56
6	3.125-6.25	1.64-3.28
7	6.25-12.5	0.82-1.64
8	12.5-25	0.41-0.82
9	25-50	0.21-0.41
10	50-100	0-0.21

Figure 3 illustrates the original acceleration signal and its decomposition into five levels (details and approximations) for Elbistan earthquake. Notably, the first, second and third level approximations (A1, A2 and A3, respectively) exhibits the most significant similarity in shape with the original signal. This is because, most of the energy from the initial signal is stored in the approximations, providing a coarse representation while retaining essential features at a lower resolution. As the decomposition progresses to higher levels, the detail coefficients capture finer details and high-frequency components, but may introduce more noise and less relevant information [4].

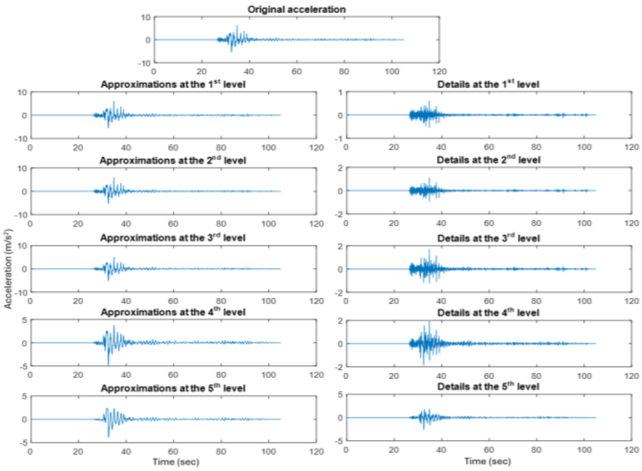

Figure 3. Decomposition of earthquake acceleration signal by discrete wavelet transform

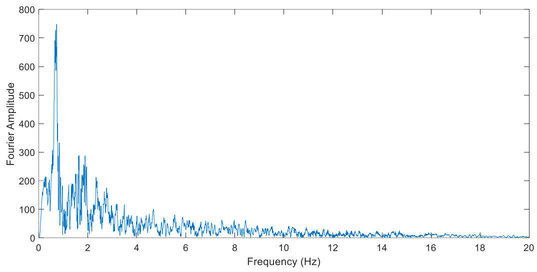

Figure 4. Fourier spectrum of the earthquake

Figure 4 illustrates that the Fourier spectrum of the earthquake record exhibits a notable amplitude for frequencies up to 3 Hz. Therefore, it is verified that for this earthquake, the DWT method performs better due to its frequency content being dominated by low-pass frequencies.

Numerical Outcomes

The examination is conducted on a 3-story base isolated building exposed to the original earthquake acceleration signal (denoted as OS) and its approximations up to five levels (A1, A2, A3, A4, A5). The building is idealized as lumped mass-stiffness model. The design of base-isolated structures aims to ensure that the structure's dynamic behavior remains elastic [20]. To achieve this, the base isolation system is designed to interrupt the transmission of seismic waves, thereby ensuring that the superstructure behaves linearly. Consequently, base-isolated structures typically exhibit linear behavior.

In the current section, the displacement responses of the base mat and acceleration response of the top story under the selected earthquake acceleration are provided. The study investigates the effects of varying isolator periods, specifically 2, 2.5, and 3 seconds, alongside damping ratios of 30% and 40%. The resulting time responses for each scenario have been derived and analyzed.

The results of the time response analyses focus on the acceleration response of the top story, divided by the peak ground acceleration (PGA). Table 3 presents peak responses for various isolator periods and 30% damping ratio. It is observed that as the period increases, the acceleration response decreases, while the displacement response increases. Additionally, upon examining the decomposed signal of ground acceleration, it is noted that the building exhibits consistent behavior when exposed to OS, A1, A2, and A3 scenarios, similar to the time histories given in Figure 2. However, the behavior significantly alters under A4 and A5 scenarios. This highlights the importance of determining the optimal decomposition level for both the structure and earthquake under consideration.

Table 3. Peak Acceleration and Displacement Responses for the Varied Isolator Period of Tb =2 to 3 sec and ξb =30%

Isolator parameters	OS	A1	A2	A3	A4	A5
Tb =2 sec	0.797	0.797	0.797	0.794	0.785	0.733
ξb =30%	39.251	39.251	39.250	39.115	38.715	37.282
Tb =2.5 sec	0.597	0.597	0.596	0.594	0.586	0.562
ξb =30%	44.247	44.240	44.220	44.138	43.801	42.511
Tb =3 sec	0.437	0.437	0.436	0.434	0.427	0.420
ξb =30%	46.929	46.920	46.890	46.766	46.274	44.458

Table 4 also demonstrates consistent results across various isolator periods, maintaining a damping ratio of 40%. Notably, a distinct trend emerges compared to the 30% damping scenario, the acceleration response increases, while the displacement response decreases. This underscores the critical influence of the damping ratio on structural behavior during seismic events. Employing first-level decomposition produces precise results, with A2 and A3 also yielding outcomes near those obtained by OS. However, it's important to acknowledge that A4 and A5 scenarios yield significantly different outcomes, especially for displacement responses, highlighting the sensitivity of structural response to seismic input decomposition levels.

Table 4. Peak Responses for the Varied Isolator Period of Tb =2 to 3 sec and ξb =40%

Isolator parameters	OS	A1	A2	A3	A4	A5
Tb =2 sec	0.750	0.750	0.748	0.743	0.727	0.666
ξb =40%	32.695	32.691	32.667	32.571	32.319	30.976
Tb=2.5 sec	0.590	0.589	0.5890	0.588	0.582	0.541
ξb =40%	36.715	36.713	36.697	36.633	36.369	35.281
Tb =3 sec	0.457	0.457	0.457	0.456	0.451	0.425
ξb =40%	43.423	43.413	43.384	43.266	42.805	41.105

Structures designed with base isolators of 2 and 3 second periods corresponded to natural frequencies of 0.5 Hz and 0.33 Hz, respectively. These frequencies fell between the first and third decomposition levels used in the earthquake analysis (see Table 2). The appropriate decomposition level was identified as A1, A2 and A3; and it was observed that the seismic response results closely matched the preliminary predictions.

The correlation between the acceleration responses and the approximations up to seven levels of decomposition has also been investigated using the following equation,

$$Ratio_C = \frac{\sum_i (A_i)_n (\ddot{x}_i)_n}{\sqrt{\sum_i (A_i)_n}^2 \sqrt{\sum_i (\ddot{x}_i)_n}^2} \quad (3)$$

where i is the time step, n is level of decomposition ($n = 1, \dots, 7$) and A is approximation coefficients while $\ddot{x}$ is the acceleration response of the structure. In this section, the analyses are performed up to seven levels of decomposition to capture the highest rate of correlation. The results are presented in Tables 5 and 6.

Table 5. Correlation for Tb =2 to 3 sec and ξb =30%

Isolator parameters	A1	A2	A3	A4	A5	A6	A7
Tb =2 sec ξb =30%	-0.030	0.005	0.082	0.254	0.539	0.888	0.485
Tb =2.5 sec ξb = =30%	-0.071	-0.039	0.032	0.194	0.454	0.819	0.681
Tb =2.5 sec ξb =30%	-0.057	-0.027	0.039	0.188	0.419	0.761	0.792

Table 6. Correlation for Tb =2 to 3 sec and ξb =40%

Isolator parameters	A1	A2	A3	A4	A5	A6	A7
Tb =2 sec ξb = 40%	0.127	0.167	0.254	0.443	0.717	0.948	0.396
Tb =2.5 sec ξb = 40%	0.054	0.092	0.176	0.361	0.626	0.912	0.587
Tb =3 sec ξb = 40%	0.036	0.072	0.152	0.328	0.575	0.869	0.710

Figures 5 and 6 illustrate the correlation values for seven-level decomposition. The lowest correlation occurs for the first three decomposition levels, while the highest peaks, indicating a larger correlation between acceleration response and approximation, occur at the sixth-level decomposition. At high decomposition levels, where low-frequency components prevail (see Table 2), the correlation increases due to the base isolator lowering the structure's overall frequency.

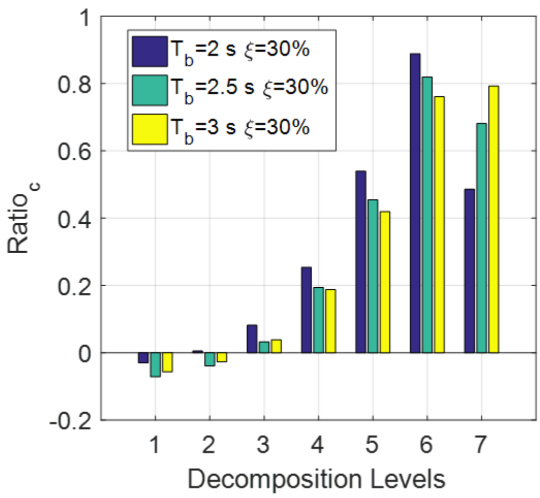

Figure 5. Correlation values between acceleration response and approximations for ξb = 30%

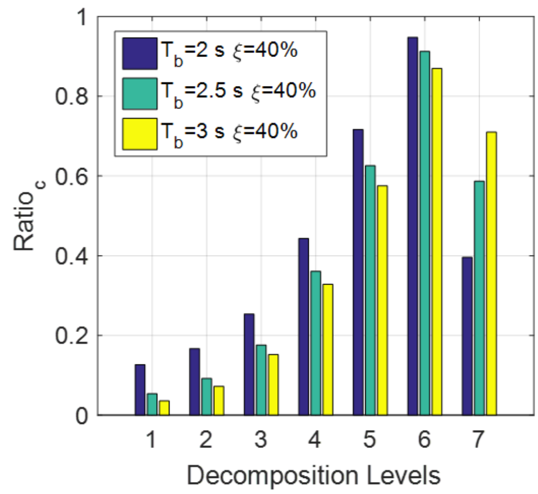

Figure 6. Correlation values between acceleration response and approximations for ξb = 40%

To further validate the results and enhance the study, a 4-story benchmark building given in the study of Kandemir and Mortazavi [15] has been examined through DWT. The optimal parameters identified in their study are a 2.507-second isolator period and 30% damping ratio. For the 1994 Northridge earthquake record (SYL360), Kandemir and Mortazavi [15] reported the base displacement of 36.215 cm and PGR/PGA ratio of 0.400. Table 7 shows the comparative responses obtained from the original signal and its approximations up to the fifth level. We identified the appropriate decomposition levels as A1, A2, and A3, and observed that the results closely aligned with the previous outcomes given by Table 3 and 4.

Table 7. Peak Responses for the Varied Isolator Period of Tb =2.507 sec and ξb =30%

OS [15]	A1	A2	A3	A4	A5
0.400	0.395	0.385	0.355	0.329	0.300
36.215	36.209	36.149	35.904	34.942	31.286

Conclusions

The study investigates the dynamics of structural response under seismic loading conditions, with a focus on the displacement response of the base mat and the acceleration response of the top story in a 3-story base isolated building. It explores the effects of varying isolator periods and damping ratios, considering both the original earthquake acceleration (OS) and its approximations (A1, A2, A3, A4, A5). The outcomes of the study can be listed as follows:

- As the analysis progresses by changing the isolator parameters, a noticeable pattern emerges: an increase in isolator period correlates with a decrease in acceleration response and a simultaneous increase in displacement response. This trend underscores the tangled relationship between isolator periods and structural dynamics, highlighting their crucial role in mitigating seismic forces.
- Regardless of base isolation parameters, the adequate decomposition levels for the corresponding earthquake and the structure are achieved as A1, A2 and A3 where the responses are similar to those obtained for the original acceleration.
- The frequencies of structures designed using base isolators with periods of 2 and 3 seconds correspond to 0.5 Hz and 0.33 Hz, respectively. These frequency ranges fall between the first- and third-decomposition levels of the decomposed earthquake levels. In this context, the appropriate decomposition level was carefully identified, and it was found that the results of seismic response closely aligned with the preliminary outcomes given in Table 2. This alignment demonstrates the effectiveness of the decomposition approach in accurately capturing the seismic behavior of the structures at these frequencies.
- The computational time for the time response analyses conducted using A1, A2, and A3 was reduced to approximately half, one-quarter, and one-eighth of the original time, respectively.
- The relation between the ground motion and the acceleration responses increases while the damping of the isolator increases. However, the dynamic behavior of the base-isolated structure shows low degree of correlation proportional to the resonance experienced in the low frequency band of the earthquake.

In summary, the discrete wavelet transform proves to be a beneficial tool for deriving seismic responses with reduced acceleration record length, thereby resulting in low computational cost.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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