Alternate approach for calculating the optimum viscous damper size

Elif Cagda Kandemir

This study explores the optimal viscous damper size required to prevent a five-story building from colliding with a rigid wall. It comprises two parts, both based on the novel application of the wavelet coherence method (WCoh). In the first, impact incidents were estimated using the WCoh method, and in the second, an approach based on WCoh for optimizing the viscous damper size was proposed. A validation model was used to verify the proposed method and good agreement among total damper sizes was observed. Nonlinear viscous dampers have also investigated due to their lower damping force than viscous dampers produce. This study has shown that wavelet coherence can be used to identify seismic pounding.

Key words:
seismic pounding, viscous damper, continuous wavelet transform (CWT), wavelet coherence (WCoh), near-fault ground motions

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Alternativni pristup za izračunavanje optimalne veličine viskoznog prigušivača

Ovaj rad istražuje optimalnu veličinu viskoznog prigušivača potrebnu za sprječavanje sudara pterokatnice s krutim zidom. Sastoji se od dva dijela, oba temeljena na novoj primjeni metode wavelet koherencije (WCoh). U prvom su dijelu slučajevi udara procijenjeni metodom WCoh, a u drugom je predložen pristup temeljen na metodi WCoh za optimizaciju veličine viskoznog prigušivača. Za provjeru predložene metode korišten je validacijski model i primijećeno je da se ukupne veličine prigušivača dobro slažu. Nelinearni viskozni prigušivači imaju omjer prigušenja koji je identičan onom linearnih viskoznih prigušivača, ali imaju nižu silu prigušivanja, čime štite konstrukciju i prigušivač pri velikim brzinama konstrukcija. Ovo je istraživanje pokazalo da se wavelet koherencija može koristiti za identifikaciju seizmičkog sudara.

Ključne riječi:
seizmički sudar, viskozni prigušivač, kontinuirana wavelet transformacija (CWT), wavelet koherencija (WCoh), gibanja tla u blizini rasjeda
1. Introduction

Migration from villages to cities for better living conditions not only increases population in cities but also reduces the amount of land that can be used for residential development. Hence, metropolitan areas often have adjacent buildings with little space separating them. In Figure 1, adjacent buildings with no seismic gap can be seen on one of the main arteries in Izmir, which is the third largest city in Turkey. The city lies in an active seismic zone; hence, it has experienced severe earthquakes in the past, and in 2020, it was exposed to the Aegean Sea earthquake.

Adjacent buildings are susceptible to serious damage during earthquakes because of the aforementioned insufficient gaps and unsynchronised behaviour of neighbouring structures. For decades, researchers have investigated issues related to seismic events in all aspects: optimal gaps between neighbouring structures [1–5], analytical models for seismic forces [6–13], methods for mitigating the effects of earthquakes [14–19], and so on. Although there is a considerable interest in the subject [20–24], there are issues for which researchers have not reached a consensus and their solutions remain undetermined.

Recently, signal processing methods have attracted attention from researchers who are familiar with structural engineering subjects. Wavelet transform, which provides the frequency content of a time signal, has better window function scaling and shifting than Fourier transforms [25]. Mohebi et al. [26] used complex Morlet mother wavelet to perform continuous wavelet transform (CWT) and detect damage due to seismic forces. Xing et al. [27] performed a wavelet transform on the acceleration responses of a single-degree-of-freedom (SDOF) structure colliding with a rigid barrier to detect pounding and acceleration responses of a single-degree-of-freedom (SDOF) forces. Xing et al. [27] performed a wavelet transform on the acceleration responses of a single-degree-of-freedom (SDOF) structure colliding with a rigid barrier to detect pounding and acceleration responses of a single-degree-of-freedom (SDOF) forces.

This study presents a promising method for determining the optimal damper size required to prevent pounding. First, the wavelet coherence approach for evaluating pounding behaviour based on the CWT was exhibited. This procedure was followed by optimization viscous dampers to prevent pounding. For the optimisation, the objective function is assigned as minimized total damper coefficient. Considering that the structure becomes elastic after dampers are added, the linear elastic behaviour of the building was considered [31, 32]. Two models were employed in this study: one proposed by Lavan and Levy [32] for validating the proposed method and another by Kandemir-Mazanoglu and Mazanoglu [33] for parametric analysis under various gap distances and earthquake motions. Linear and nonlinear viscous damper sizes were implemented for a five-storey building, and the results were compared.

2. Problem formulation

This section presents the objectives, methodology, and optimization approach of the proposed method. The aim of this study is to determine the viscous damper size for a five-storey building that prevents one-sided impact on a rigid wall. The dampers were implemented horizontally between consecutive floors considering a uniform damper size distribution. This study uses the frequency changes of system responses to evaluate pounding and viscous damper sizes. Within the scope of this study, wavelet transform, which is a powerful technique for detecting the frequency information of a signal, was used after the wavelet coherence method.

Figure 1. Adjacent buildings in Izmir
2.1. WCoh method and structural pounding relation

Impact forces acting on a structure are activated when a seismic gap is closed at an unpredictable moment. Owing to the randomness of impact forces, structural responses are nonlinear in a structure’s elastic range. The equation of motion for a multi degree-of-freedom model subjected to one-sided pounding is

\[ \mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = -\mathbf{M}\ddot{\mathbf{1}} \times g, \]

where \( \mathbf{M} \) is the mass matrix, \( \mathbf{C} \) is the damping coefficient matrix, and \( \mathbf{K} \) is the stiffness matrix while \( \mathbf{X}, \dot{\mathbf{X}}, \ddot{\mathbf{X}}, \mathbf{F}_p \) are the acceleration, velocity, and displacement responses of the structure, respectively. \( \{\mathbf{F}_p\} \) includes the pounding forces of each floor that has active and passive states associated with closed and open gaps, respectively. A passive state occurs when there is no pounding. If there is pounding, that is, an active state, the value of the force depends on the selected model. In related literature, there are many models that can be used to simulate gap elements that produce impact forces \([34-37]\). Gap-activated stiffness and/or damping are added to the structure, and the natural frequency changes during impact. At this point, wavelet transform can be used after the wavelet coherence method and to observe frequency differences between structures with and without an adequate seismic gap.

Recently, signal processing techniques, including wavelet-based approaches, have become significant in structural engineering \([38-40]\). Before discussing the WCoh method, we first briefly introduce the wavelet transform. Wavelet transforms are more suitable for providing simultaneous frequency-time information for non-stationary signals than Fourier transforms owing to its adaptive windowing technique. It decomposes the signal into basic functions of dilated (scaled) and translated (shifted) versions of the mother wavelet function. There are two types of wavelet transforms: discrete and continuous. The discrete wavelet transform (DWT) uses only a subset of scale and shifting parameters while CWT computes wavelet coefficients at each scale in discrete time. Despite its heavy computational load, the latter has been used in this study owing to its adaptive windowing capability to provide frequency information. Wavelet coefficients, \( C(a,b) \), as functions of \( a \) and \( b \), are computed by multiplying the original signal with appropriately scaled and shifted wavelets as follows \([41]\):

\[
\begin{align*}
C(a,b) &= \int_{-\infty}^{\infty} f(t) \cdot \psi^\ast(a,b,t) \, dt \\
\psi(a,b,t) &= \frac{1}{\sqrt{a}} \psi^\ast \left( \frac{t-b}{a} \right)
\end{align*}
\]

Where \( \psi(a,b,t) \) is the main wavelet and \( t, a, b \) are time, scale, and shifting factors, respectively. \( \psi^\ast \) is a complex conjugate of the wavelet. The scale parameter \( a \) is inversely proportional to the frequency. Consequently, the correlation coefficient of the scaled wavelet with the signal is plotted on the frequency–time plane. The scalogram of CWT shows the correlation between the scaled \( (a) \) and shifted \( (b) \) wavelet and signal. Abrupt variations in the signal can be detected with high frequency, while slower ones can be detected with low frequency. Wavelets have different forms, such as Haar, Morlet, Daubechies, and Mexican Hat. The Morlet wavelet, which was used in this study, is a complex function that has been shown to be effective for frequency extraction for signals diagnosis, \([42, 43]\). It has also been applied in seismic signal detection \([44, 45]\).

Wavelet coherence is a method that represents the frequency synchronisation of two time series in a certain time range. The coherency coefficients (WCoh) are calculated using the following equations:

\[
W_{Coh} = \frac{\left| \mathbf{S}\{ \mathbf{C}_x \ast(a,b) \mathbf{C}_y(a,b) \} \right|^2}{\mathbf{S}\{ \mathbf{C}_x(a,b) \}^2 \cdot \mathbf{S}\{ \mathbf{C}_y(a,b) \}^2}
\]

\[
\Delta \varphi(t,a) = \tan^{-1} \frac{\text{Im} \left[ W_{CXY}(t,a) \right]}{\text{Re} \left[ W_{CXY}(t,a) \right]}
\]

where \( \mathbf{C}_x(a,b) \) and \( \mathbf{C}_y(a,b) \) represent the CWTs of the \( x \) and \( y \) signals at \( a \) scales and \( b \) positions. The superscript * is the complex conjugate and \( S \) is the operator for smoothing the time and scale parameters. In the formulation, the cross-wavelet term \( \mathbf{C}_x \ast(a,b) \mathbf{C}_y(a,b) \) is included in the numerator. \( \Delta \varphi \) denotes the phase of the wavelet. The coefficients are plotted in the frequency–time space while the phase is indicated by arrows. Wavelet coherence takes values between zero and one to represent dissimilarity and similarity, respectively. For WCoh, zero and one represent completely different and exactly matching frequency content, respectively. For detailed information about the subject, please refer to Torrence and Compo \([25]\) and Grinsted et al. \([46]\).

In this study, the wavelet coherence method has been applied to acceleration responses due to earthquake ground motion when the structure has adequate and inadequate seismic gaps. A WCoh value different from one indicates different frequency contents of responses; thus, pounding occurs. After installing viscous dampers between the consecutive floors in the building structure, as no pounding is expected, the frequency contents of the seismic responses become equivalent to those when the system has an adequate seismic gap, that is, no pounding state, resulting one for WCoh value. The equation of motion was solved using Newmark’s step-by-step method with a constant average acceleration and time step of 0.001 s. This was done to obtain the acceleration responses of structures with and without pounding.

2.2. WCoh-based optimization of viscous damper size

This section describes the procedure for determining the optimum viscous damper size that prevents pounding. The
wavelet coherence method explained in the previous section stores the coefficients in a matrix with the size of period \times duration. For a complete signal coherency, all coherence coefficients must be equal to one at each period. Therefore, a new parameter, called the average wavelet coherence coefficient (AWC), was introduced. AWC is calculated according to Eq. (5), where \( T \) is the duration of the signal, \( i \) is the period, and WCoh coefficient is the corresponding period.

\[
AWC_i = \frac{\sum_{i=1}^{T} \text{Wcoh coefficient}_i}{T}
\]  

(5)

The procedure followed in this paper is given by the flowchart in Figure 2. The objective function is the minimum total damper coefficient \((Cd = \Sigma c_j)\). An inequality constraint applies lower \((lb)\) and upper \((ub)\) bounds to the damper coefficient \(c_j\) of each damper installed at each floor \((lb \leq c_j \leq ub)\). \(lb\) is zero for the case without and damper and \(ub\) is \(3 \times 10^6\) Ns/m. The equality constraint is that the average wavelet coherence must be one \((AWC = 1)\). The optimization process can be summarized as follows:

**Step 1.** Input the structural data as mass, stiffness, and damping matrices. The damping matrix is generated by the Rayleigh damping method with a damping ratio of 5\% for the first and last modes.

**Step 2.** Input the additional damping ratio of viscous dampers (at first, zero is assigned for no damper state).

**Step 3.** Time response analysis is performed, and the acceleration responses of each floor are obtained.

**Step 4.** The WCoh method is applied to the CWT of the acceleration responses of the structure with and without pounding. Then, the AWC of each floor is calculated.

**Step 5.** If all AWCs are equal to one, time response analysis is performed to determine pounding forces using the Kelvin–Voigt model (or any other model given in literature). If there is no pounding at any floor, the algorithm is terminated, and no viscous damper is required.

**Step 6.** If one of the AWCs in Step 5 is not equal to one, the additional damping ratio \((x_d)\) is gradually increased (in steps of 0.01 in this study) and the viscous damper coefficients \((cd)\) of each floor between the inequality constraints are computed and introduced into the corresponding location of the structural damping matrix \((C)\). Dampers are placed from the first floor onwards.

**Step 7.** Steps 3 and 4 and are repeated by gradually increasing \(x_d\) until the equality constraint AWC is equal to one and no pounding occurs at all floors.

Additional damping ratio \((x_d)\) formulation for interstorey linear viscous dampers is given in FEMA 273 [52] as follows:

\[
\varepsilon_d = \frac{T_j \sum_{j} cd(\alpha_j \cos^2{(\phi_j - \phi_{j-1})})^2}{4\pi \sum_{i} m_i \phi_i^2}
\]  

(6)

where \(T_j\) is the fundamental natural period, \(cd(\alpha_j)\) is the damping coefficient with a denoting the velocity exponent, \(q_i\) is zero if the damper is horizontal, and \(m_i\) indicates the mass of one floor. \((\phi_j, \phi_{j-1})\) indicates the relative horizontal modal displacements between consecutive floors at the first mode. Subscript \(i\) is used for indexing the floor while \(j\) is the floor where dampers are added. This optimization algorithm was run for two cases for the gap distances of 10 and 15 cm between the structure and rigid wall under different near-fault earthquakes.

3. Ground motions

Selected ground motions are the examples of near-fault earthquake ground motions. The earthquakes were scaled according to the acceleration design spectrum of the Kocaeli province (latitude 40.696536°, longitude 29.811293°) in Turkey, for which the spectral accelerations are 2.059 and 0.694 at 0.2 and 1 s periods and the soil class is ZC (very dense soil and soft rock) [47]. Table 1 shows the properties of the selected earthquakes.
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4. Structural model

The structure discussed in this study is a five-storey shear frame and has been idealized as the lumped mass-stiffness model. The mass and stiffness of each floor were $1 \times 10^5$ kg and $6.8 \times 10^7$ N/m, respectively [33]. The natural period of the first mode was 0.85 s. Inherent damping of 5% was used for the first and last modes to construct a Rayleigh damping matrix. The structure was evaluated for gap distances ($d$) of 10 and 15 cm. Figure 3 shows the model.

![Lumped mass-stiffness model of the structure and rigid wall](image)

**Figure 3. Lumped mass-stiffness model of the structure and rigid wall**

5. Results

The results of this study are presented under two headings. The first presents the seismic pounding detected by the WCoH method, and the second presents the optimization results. Model setup and time response analysis under earthquake motion and wavelet analysis were performed in MATLAB [48].

5.1. Estimation of seismic pounding using WCoH method

In this section, the acceleration responses for the structure with and without sufficient seismic gap were compared using the wavelet coherence method; this comparison was performed to detect frequency differences. The results of the Chi-Chi and Northridge earthquakes were examined because they had the largest impact values. The computed WCoH coefficients of roof accelerations with and without pounding were plotted against time. In the default spectrum, yellow is for high coherence and blue for low coherence. The white-dashed line shows the cone of influence without edge effects. Arrows in wavelet coherence graphs have various meanings: arrows pointing to the right indicate signals that are in phase, arrows to the left indicate a phase difference of 180°, and arrows pointing up and down indicate a phase difference of 90°. The direction of the arrows does not affect the coherence coefficients.

To verify coherence plots, pounding forces modelled using the Kelvin–Voigt model (linear spring-damper) were computed using the following equation [7]:

$$F_p(t) = k_p \delta(t) + c_p \dot{\delta}(t)$$

(7)

$$c_p = 2\xi_p \sqrt{k_p \frac{m_1 m_2}{m_1 + m_2}}$$

(8)

$$\xi_p = \frac{-\ln \epsilon}{\sqrt{\pi^2 + (\ln \epsilon)^2}}$$

(9)

<table>
<thead>
<tr>
<th>Earthquake name, year</th>
<th>Station</th>
<th>Component</th>
<th>PGA [g]</th>
<th>Scale factor</th>
</tr>
</thead>
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<tr>
<td>Chi-Chi, 1999</td>
<td>TCU065</td>
<td>E</td>
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<td>0.667</td>
</tr>
<tr>
<td></td>
<td>TCU065</td>
<td>N</td>
<td>0.575</td>
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</tr>
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<td>0.781</td>
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<tr>
<td></td>
<td>Array #7</td>
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<td>0.905</td>
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<td></td>
<td>Takatori</td>
<td>90</td>
<td>0.671</td>
<td></td>
</tr>
<tr>
<td>Kocaeli, 1999</td>
<td>Duzce</td>
<td>180</td>
<td>0.312</td>
<td>1.226</td>
</tr>
<tr>
<td></td>
<td>Duzce</td>
<td>270</td>
<td>0.364</td>
<td></td>
</tr>
<tr>
<td>Landers, 1992</td>
<td>Lucerne</td>
<td>260</td>
<td>0.725</td>
<td>1.034</td>
</tr>
<tr>
<td></td>
<td>Lucerne</td>
<td>345</td>
<td>0.789</td>
<td></td>
</tr>
<tr>
<td>Northridge, 1994</td>
<td>Rinaldi</td>
<td>228</td>
<td>0.874</td>
<td>0.689</td>
</tr>
<tr>
<td></td>
<td>Rinaldi</td>
<td>318</td>
<td>0.472</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Selected earthquake motions
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Figure 4. Wavelet coherence plots between acceleration responses with and without pounding and corresponding pounding force-time diagrams

where $F_p(t)$ is the pounding force as a function of time ($t$, $k_p$ is the stiffness, and $c_p$ is the damping coefficient of the impact model. $\delta(t)$ and $\dot{\delta}(t)$ are the relative displacement and velocity between two colliding structural members, respectively. $\xi_\delta$ is the impact damping ratio and $e$ is the coefficient of restitution. Masses of colliding members are denoted as $m_1$ and $m_2$, which are the masses of the floor of the structure ($1 \times 10^5$ kg) and rigid wall ($1 \times 10^5$ kg) corresponding to the adjacent building floor, respectively. In the present study, $k_p$ was assumed to be 20 times the storey stiffness coefficient, as suggested by Anagnostopoulos [7]. Moreover, $\xi_\delta$ of 0.14 ($e = 0.65$) was used for concrete surfaces, as suggested by Azevedo and Bento [49]. The linear spring and dashpot are activated when the gap between structures is closed, thereby generating pounding force.

Figure 4 shows the wavelet coherence and their corresponding pounding force-time graphs. The formations in the form of blue lines, which appear between 0 and 0.5 s in both earthquakes, show the collision moments. A more intense shade of blue represents a greater pounding force. The corresponding pounding force-time graphs verify the results obtained from WCoh plots. The graphs show blue areal formations in addition to the previously mentioned linear vertical formations. For example, between 0.4 and 1.5 s, areal non-coherence coefficients are observed for both gap distances during the Rinaldi earthquake. These incoherences can be said to be due to the phase difference between the behaviours after impact. Note that the arrows pointing to the right in different angles to the horizontal (up and down) indicate positively correlated signals.

5.2. Optimized total damper size

This section presents the processing of the wavelet coherence coefficients obtained in the previous section. After the WCoh analysis of acceleration responses in MATLAB, the coefficients are stored as a matrix of size period × duration. Consequently, the average values of WCoh coefficients at each period of the structure [50] were calculated as given in Eq. (5) and defined as an equality constraint in the optimization process. Figure 5 depicts the AWC-period relation for each earthquake motion in 0 to 5 s.
Figure 6 shows the average AWC with time considering all the earthquakes. The largest coherency occurs in the range 1.5 to 2 s whereas the lowest occurs in the range 4.5 to 5 s for the investigated ground motions and structures. The decrease in the average AWC with the period implies that the behaviour in higher periods is totally different when the structure has an inadequate seismic gap.

5.2.1. Validation model

The model in the study by Lavan and Levy [32] presented in Figure 7 was used to verify the proposed method. The model is a two degree-of-freedom system in which each floor mass is 25 ton. The stiffnesses of the first and second floors are 37500 and 25000 kN/m, respectively, while inherent damping coefficients are 48.609 and 32.411 kNs/m, respectively. The ground motion used is the NS component of the 1940 El-Centro earthquake scaled by 2.01.

Table 2 shows the comparative results of the total damper sizes. The total damper size calculated by the proposed method was 8.1 % less than the cited reference, whereas the maximum drifts of the first and second floors were 5 % and 3.3 % less.

Although the employed reference has no information regarding an additional damping ratio, a supplemental damping ratio of 25 % was obtained in this study. A good correlation was obtained by the proposed method.

5.2.2. Five-storey building model

A five-storey building has been investigated for different gap distances and ground motions. Linear (LVD) and nonlinear viscous dampers (NVD) were implemented on the structure. NVDs produce a lower damping force between damper ends than LVDs for the same structural velocity response. This situation is due to the velocity exponent ($\alpha$). The velocity exponent takes values between 0 and 1. Different damper types and their forces based on the velocity exponent are given in Figure 8.

Equation 10 was used to calculate the damping coefficient of NVDs [53].

<table>
<thead>
<tr>
<th>Total damper coefficient [kNs/m]</th>
<th>Lavan and Levy (2005)</th>
<th>Proposed method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum drifts (first and second floors)</td>
<td>9.0 and 9.0 mm</td>
<td>8.5 and 8.7 mm</td>
</tr>
</tbody>
</table>
Where $c_d(1)$ is the linear damper coefficient, $\omega_1$ is the first natural frequency of the building, $x_0$ is the maximum drift, and $\beta$ is calculated as follows:

$$\beta = \frac{2^{1+\alpha} \Gamma^2 (1+\alpha/2)}{\pi \Gamma(2+\alpha)}$$  \hspace{1cm} (11)

Where $\Gamma$ is the gamma function. In this study, the velocity exponent ($\alpha$) was assumed to be 0.5. Table 3 demonstrates the supplemental damping ratios ($\xi_d$) and linear $c_d(1)$ and nonlinear $c_d(0.5)$ viscous damper sizes.

The structures with viscous dampers have additional damping without additional rigidity because of these devices. This feature results in the same frequencies for the structure for an adequate seismic gap after the installation of viscous dampers with a sufficient damping coefficient. Therefore, the wavelet coherence approach is adequate for determining the viscous damper size that prevents pounding using the acceleration responses of the structure with and without an appropriate separation.

Table 3 shows the optimum damper sizes and ratios under various earthquake motions. Damper sizes are not available for the Imperial Valley (Array #5) and Landers (Lucerne 345) earthquakes for both gap distances and Kocaeli (Duzce 180) earthquakes for the gap of 15 cm because there is no pounding. The maximum damper coefficient was obtained in the Northridge earthquake (Rinaldi 228). The total damper size decreased as the gap size increased. Nonlinear dampers reduce the damping coefficients by 22.6 and 5.23 % when the gap distances are 10 and 15 cm, respectively. This rate is the same for all earthquakes. An examination of Eq. 10 shows that the maximum drift ($x_0$) is the only variable when the NVD size is calculated from LVD. Therefore, in this study, as the building collides with a rigid wall, maximum drift ($x_0$) is equal to the separation distance for each ground motion.

### 6. Conclusions

Signal processing tools are becoming important and being applied in seismic engineering. Knowledge gained through the convolution of seismic signals, such as ground motions or structural responses, can provide insight into the dynamic behaviour of seismic activity. The proposed method is not only an alternative to existing methods but it also has a lower computational load and is easier to understand. This study has shown that wavelet coherence can be used to identify seismic pounding. In addition, optimum damper sizes for preventing pounding during seismic activity were obtained by simulating seismic responses with and without pounding and obtaining their frequency properties. The conclusions of this study can be summarized as follows:

- When a structure is exposed to collisions, wavelet coherence coefficients for shorter periods are low, indicating the low coherence between acceleration responses with and without pounding verifying that pounding is present.
- Wavelet coherence analysis can be used to identify the exact moment of pounding. In addition, the more blue the coherence spectrum, the more severe is the pounding force. Thus, WCoh plots can be used to obtain pounding force information without using one of the various models in the literature.
- The wavelet coherence method is a promising tool for obtaining viscous damper size using only seismic responses. It has a high computation speed and is easy to understand.
- Nonlinear viscous dampers have a damping ratio that is identical to that of linear viscous dampers while having a lower damping force, thereby protecting the structure and damper device at high structural velocities.
REFERENCES


