



OPEN Filtering characteristics of isolation layer in base-isolated structures and shaking table test verification

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Base-isolated structures are extensively used in critical infrastructure and lifeline projects. Current response spectrum methodology for determining seismic actions has limitations in designing long-period base-isolated structures. Based on a two-degree-of-freedom (2DOF) model that accounts for the non-proportional damping characteristics of isolation bearings, this study analyzes the filtering characteristics of the isolation layers through spectral analysis of both original and attenuated ground motions. Theoretical and experimental results demonstrate that designing the superstructure using the "filtered response spectrum (FRS)" is more rational compared to conventional design response spectra (DRS). Shaking table tests under white noise and seismic excitations verify the filtering effect of isolation bearings: filtered acceleration time-history are reduced to 1/3–1/2 of the original peak values, with the FRS exhibiting decreased peaks, rightward shifts, and significantly shortened platform segments. The filtering principle, rather than period elongation alone, better explains the isolation layer's effectiveness, particularly for structures with inherently long natural periods. Current code-based design spectra inadequately capture the filtered seismic input, necessitating revisions to incorporate isolation-specific filtered spectra for rational and resource-efficient designs.

Keywords Isolation layer, Filtering characteristics, Non-proportional damping, Response spectrum, Shaking table test

Base-isolated structures have demonstrated excellent seismic performance, leading to their widespread application in critical infrastructure and lifeline engineering projects¹. Seismic isolation technology decouples the superstructure from ground motion by installing isolation devices with low lateral stiffness, high damping, and energy dissipation capacity at the base or intermediate levels of a structure. These devices absorb seismic energy, reducing energy transfer to the superstructure and mitigating earthquake damage². While response spectrum theory^{3,4} underpins current seismic design, it inadequately addresses long-period base-isolated structures due to limitations in long-period spectral regions^{5–13}. This critical limitation necessitates adopting a spectral filtering paradigm^{2,14,15}. The filtering principle posits that ground motions are attenuated into modified excitations after passing through isolation layers with low stiffness and high damping. Consequently, designing superstructures of base-isolated structures should incorporate filtered excitation input rather than original ground motions.

This study develops a two-degree-of-freedom (2DOF) analytical model^{16–18} integrating non-proportional damping^{19–30} to systematically evaluate isolation layer filtering characteristics through theoretical derivations and experimental verification. Comparative analysis between FRS and DRS establishes an enhanced methodological foundation for superstructure design optimization.

Isolation layer response spectra

Finite element model and numerical simulation

The prototype base-isolated structure is configured with the following principal parameters: seismic fortification intensity of 8 degree (0.20 g), Site Class II, Seismic Design Group III, comprising four principal above-grade stories with an auxiliary partial 5th level, yielding a total structural height of 18.9 m. A total of 34 isolation bearings — including LRB400 (Lead Rubber Bearing), LRB500, LNR500 (Natural Rubber Bearing), and LRB600 — are strategically positioned beneath each frame column in accordance with load distribution requirements. The ETABS finite element modeling of the structure is shown in Figure 1.

The base-isolated structure is simplified into a MDOF system model, with mass and stiffness values for each floor are obtained from ETABS calculations, and MATLAB is utilized for programming. Given the fundamental

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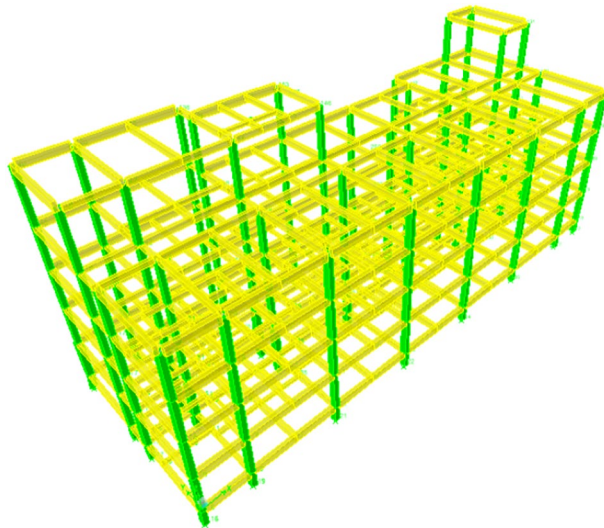


Figure 1. Computational model of the base-isolated structure.

objective of base isolation is to maintain the superstructure elasticity, the distinctions in the MDOF system model primarily focus on the isolation layer. Four distinct analytical cases are established:

- Case1:** Linear isolation layer with proportional damping + elastic superstructure
- Case2:** Linear isolation layer non-proportional damping + elastic superstructure
- Case3:** Nonlinear isolation layer with proportional damping + elastic superstructure
- Case4:** Nonlinear isolation layer with non-proportional damping + elastic superstructure

The non-proportional characteristics of the base-isolated structure are represented using a partitioned Rayleigh damping model, while isolation layer nonlinearity is described by Bouc-wen model³¹. The filtering effects of the isolation layer under these four cases are illustrated in Fig. 2. The results demonstrate that incorporating non-proportional damping and nonlinear characteristics in the isolation layer significantly enhances seismic energy dissipation, thereby achieving approximately 60% reduction in peak acceleration time-history amplitudes at the top of the isolation layer.

The filtered excitations that is attenuated ground motions (indicated by red dashed lines in Figures 2a–2 d) were implemented as seismic inputs to the superstructure. Compare the numerical calculations (MATLAB) with the time-history analysis results, as shown in Figure 3.

From Figure 3, it can be observed that the displacement at the first floor obtained from time history analysis is significantly reduced. This occurs because the time history analysis is conducted for base-isolated structures, while Cases 1–4 involve inputting filtered excitations into the superstructure. The figure further reveals that considering the nonlinear behavior of the isolation layer leads to numerical analysis results closely aligning with those from time history analysis. Crucially, the numerical results converge with time-history data when isolation layer nonlinearity is considered (Cases 3–4), achieving mean relative discrepancies of 32% and 26%, respectively. Conversely, neglecting nonproportional damping characteristics (Cases 1–2) leads to 82–84% deviations, particularly in top-story response predictions. These findings underscore the necessity of concurrently modeling both nonlinear mechanical behavior and nonproportional damping in base-isolation simulations.

Strong motion records^{17,32}

Extensive researches indicate that response spectra are directly influenced by site conditions^{33–35}. Seismic codes mandate that the site for base-isolated structures should be categorized into Site Classes I, II, and III. Near-field ground motions possess significantly different characteristics from far-field ground motions, exerting a more severe impact on buildings. Consequently, to enhance the adaptability of the response spectra obtained for base-isolated structures, 1217 strong ground motion records from the Pacific Earthquake Research Center (PEER) in the United States were selected and partitioned into nine groups, including Near-field pulse (NF), Near-field non pulse (NFN), and Far-field (FF) at Site Classes I, II, and III, respectively, as delineated in Table 1. The selection criteria for strong motion records are as follows: (1) The earthquake magnitude is 5.0 or above; (2) The peak acceleration is greater than 0.01 g; (3) The site conditions are consistent with the requirements for building sites when seismic isolation design is adopted for structures in the Chinese seismic design code; (4) The epicentral distance is within 100 km.

Isolation layer spectra

For base-isolated structures, the numerical analysis results obtained from both non-proportional damping linear and nonlinear models demonstrate negligible discrepancies compared to time history analysis results. Therefore, only the non-proportional damping characteristics of the base-isolated structure are considered when

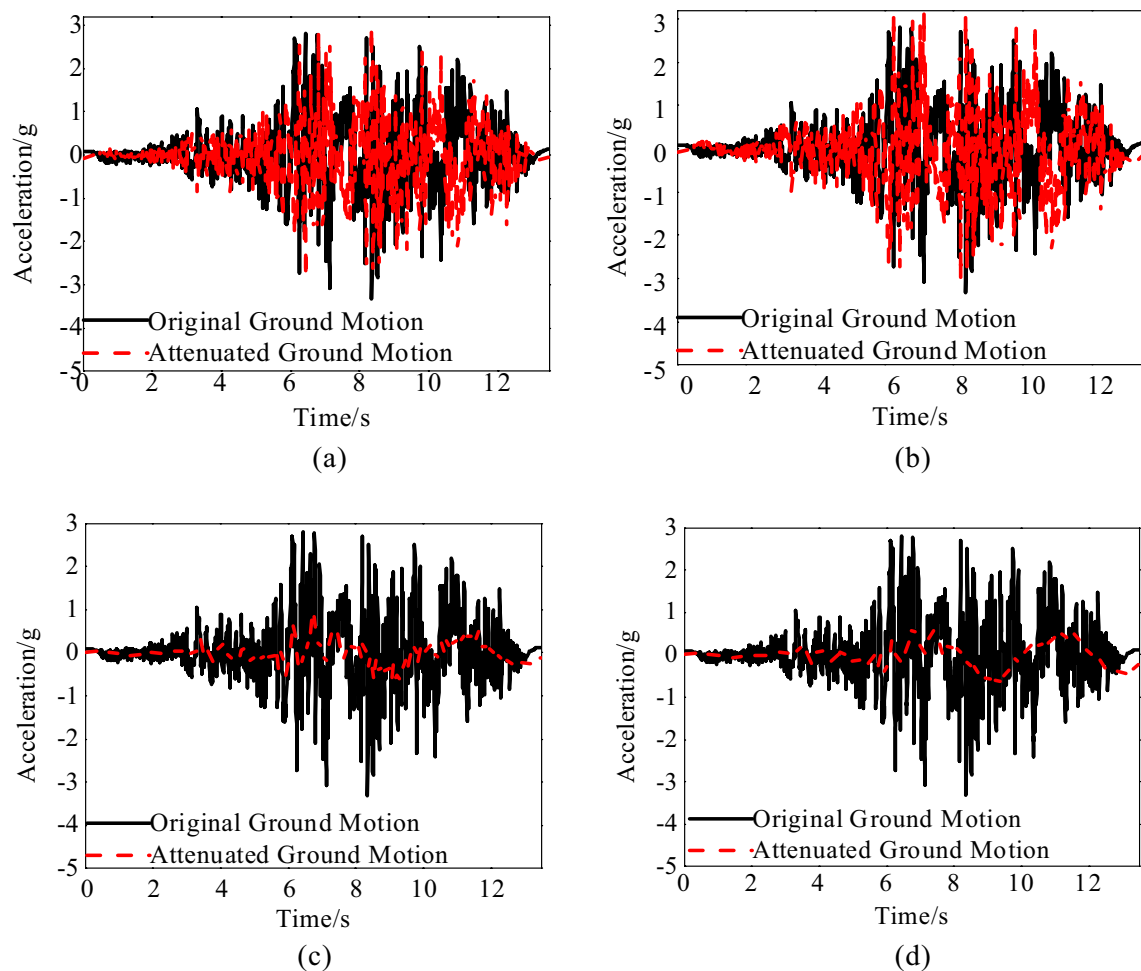


Fig.2. Comparison of filtering effects in base isolation layers.

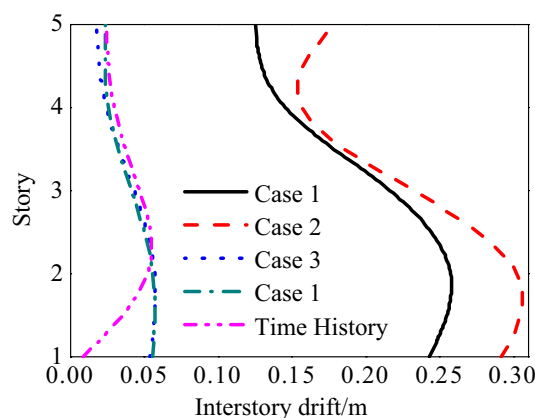
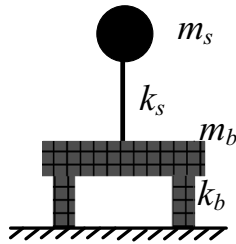


Fig.3. Comparison of numerical vs. time history analysis.

establishing the isolation layer spectra in this paper. To maintain generality across superstructure configurations and ensure broad applicability of the derived spectra, the structural system is simplified through a two-degree-of-freedom (2DOF) model following the methodology in Reference¹⁷. This idealized representation consists of a concentrated mass for the superstructure and a separate mass-spring-damper system for the isolation layer, as illustrated in Figure 4. The motion equation as follows:

$$[M] \{\ddot{X}\} + [C] \{\dot{X}\} + [K] \{X\} = -[M] \{\ddot{x}_g\} \quad (1)$$

Site classes	Class I	Class II	Class III
Near-field pulse (NF)	25	67	26
Near-field non pulse (NFN)	113	234	87
Far-field (FF)	207	289	169

Tab. 1. The selected strong ground motion records.**Fig.4.** DOF Simplified model.

Here, $[M]$, $[C]$, $[K]$ represent the mass matrix, damping matrix and stiffness matrix of the simplified model, respectively; $\{\ddot{X}\}$, $\{\dot{X}\}$, $\{X\}$ represent the acceleration, velocity, and displacement of the superstructure and isolation layer relative to the ground; $\{\ddot{x}_g\}$ is the ground motion acceleration.

In the base-isolated structures, the damping characteristics of the isolation system and the superstructure are quite different, using the partitioned Rayleigh damping model proposed in Reference²⁰, the damping matrix in the motion equation is expressed as:

$$[C] = [C_0] + [C_r] \quad (2)$$

$$[C_0] = \alpha_t [M] + \beta_t [K] \quad (3)$$

$$[C_r] = \begin{bmatrix} (\alpha_b - \alpha_t)m_b + (\beta_b - \beta_t)k_b & 0 \\ 0 & 0 \end{bmatrix} \quad (4)$$

Here, $[C]$ is the non-proportional damping matrix, $[C_0]$ is the proportional damping matrix, $[C_r]$ is the residual damping matrix of non-proportional damping.

$F_y = k_b x_y$ are the proportional damping coefficient between the superstructure and isolation layer:

$$\begin{Bmatrix} \alpha_b \\ \beta_b \end{Bmatrix} = \frac{2\xi_b}{\omega_1 + \omega_2} \begin{Bmatrix} \omega_1\omega_2 \\ 1 \end{Bmatrix}, \begin{Bmatrix} \alpha_s \\ \beta_s \end{Bmatrix} = \frac{2\xi_t}{\omega_1 + \omega_2} \begin{Bmatrix} \omega_1\omega_2 \\ 1 \end{Bmatrix} \quad (5)$$

Here, the damping ratios of the superstructure ($\xi_t = 0.05$) and isolation layer ($\xi_b = 0.20$). ω_1 , ω_2 are the first and second natural circular frequencies.

Thus, the motion equation (1) becomes::

$$\begin{bmatrix} m_b & 0 \\ 0 & m_t \end{bmatrix} \begin{Bmatrix} \ddot{x}_b \\ \ddot{x}_t \end{Bmatrix} + \begin{bmatrix} \alpha_b m_b + \beta_b k_b + \beta_t k_t & -\beta_t k_t \\ -\beta_t k_t & \alpha_t m_t + \beta_t k_t \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{x}_t \end{Bmatrix} + \begin{bmatrix} k_b + k_t & -k_t \\ -k_t & k_t \end{bmatrix} \begin{Bmatrix} x_b \\ x_t \end{Bmatrix} = - \begin{bmatrix} m_b & 0 \\ 0 & m_t \end{bmatrix} \{\ddot{x}_g\} \quad (6)$$

Here, m_b , m_t are the masses of the isolation layer and superstructure; k_b , k_t are the equivalent stiffness of the isolation layer and stiffness of the superstructure; $\ddot{x}_b$, $\dot{x}_b$, x_b are the relative acceleration, velocity, and displacement of the isolation layer under seismic action; $\ddot{x}_t$, $\dot{x}_t$, x_t are the relative acceleration, velocity, and displacement of the superstructure under seismic action; $\ddot{x}_g$ is the ground motion acceleration.

Using the state-space method, the equation of motion is formulated as:

$$\{\dot{x}\} = [A] \{x\} + \{B\} \ddot{x}_g \quad (7a)$$

$$\{y\} = [C_y] \{x\} + \{D\} \ddot{x}_g \quad (7b)$$

$$\text{Here, } [A] = \begin{bmatrix} [0] & [I] \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix} \quad \{B\} = \begin{Bmatrix} \{0\} \\ -\{\delta\} \end{Bmatrix} \quad [C_y] = \begin{bmatrix} [I] & [0] \\ [0] & [I] \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix}$$

$$\{D\} = \begin{Bmatrix} \{0\} \\ \{0\} \\ \{0\} \end{Bmatrix} \quad \{x\} = \begin{Bmatrix} \{X\} \\ \{\dot{X}\} \\ \{\ddot{X}\} \end{Bmatrix} \quad \{y\} = \begin{Bmatrix} \{X\} \\ \{\dot{X}\} \\ \{\ddot{X}\} \end{Bmatrix} = \begin{Bmatrix} x_b \\ x_t \\ \dot{x}_b \\ \dot{x}_t \\ \ddot{x}_b \\ \ddot{x}_t \end{Bmatrix}$$

Here, $[I]$ is the identity matrix, $\{\delta\}$ is the unit vector, $\{y\}$ is the output vector.

The isolation layer spectra characterizes the relationship between the maximum response of the isolation layer and the natural period of the base-isolated structure. By solving the state-space equations and adjusting the control vector $\{D\}$, the isolation layer spectra can be derived as either the absolute acceleration spectra or displacement spectra of the isolation layer. Mathematically, it is expressed as:

$$S_a = \max |\ddot{x}_b(t)| \quad (8)$$

$$S_d = \max |x_b(t)| \quad (9)$$

Filtering characteristics of the isolation layer

The analytical procedure comprises three distinct phases. First, time-history analysis is conducted on the base-isolated structure, where the filtered absolute acceleration at the isolation layer top serves as spectral input (Spectra 1). This filtered spectra characterizes the superstructure's peak acceleration response accounting for isolation effects. Subsequently, conventional spectral analysis using original ground motions generates a 5% damped response spectra (Spectra 2), compliant with Ref.³⁶ specifications. In the final phase, considering the significantly higher damping ratio typical of base-isolated structures, the original ground motions are again used for spectral analysis to derive a 20% damped spectra (Spectrum 3). This spectra assumes rigid-body superstructure motion, directly coupling isolation layer response with structural dynamics. To evaluate which response spectra (Spectra 1, 2, or 3) provides the most rational basis for superstructure design, 1,217 ground motions are selected as inputs. The relationship between the maximum response and the natural vibration period of the structure under different conditions is analyzed, as illustrated in Figure 5.

Figure 5a demonstrates notable attenuation in the filtered acceleration spectra compared to conventional DRS across damping ratios (5% or 20%). Substituting isolation layer responses (Spectra 3) for superstructure dynamics (Spectra 1) induces 18–22% overestimation, creating material overdesign despite structural conservatism. The displacement spectra comparison (Figure 5b) reveals fundamental limitations: neither code-specified response spectra nor simplified SDOF isolation models adequately capture superstructure displacement responses, necessitating filtered displacement spectrum implementation for accurate base-isolation assessments.

Seismic design of superstructures in base-isolated structures typically incorporates "spectral reduction factors (RF)" per Ref.³⁶, where DRS ordinates are systematically attenuated (Table 2).

According to the *Code for Seismic Design of Buildings*, the horizontal seismic action on the post-isolation structure can be reduced by **three tiers** compared to non-isolated structures. The post-isolation time-history analysis directly adopts the maximum horizontal seismic coefficient $\alpha_{\max}$, which undergoes three-stage reduction: $0.75\alpha_{\max}$ (RF=0.5), $0.50\alpha_{\max}$ (RF=1.0), and $0.25\alpha_{\max}$ (RF=1.5), corresponding to the reduced-intensity spectra in Figure 6.

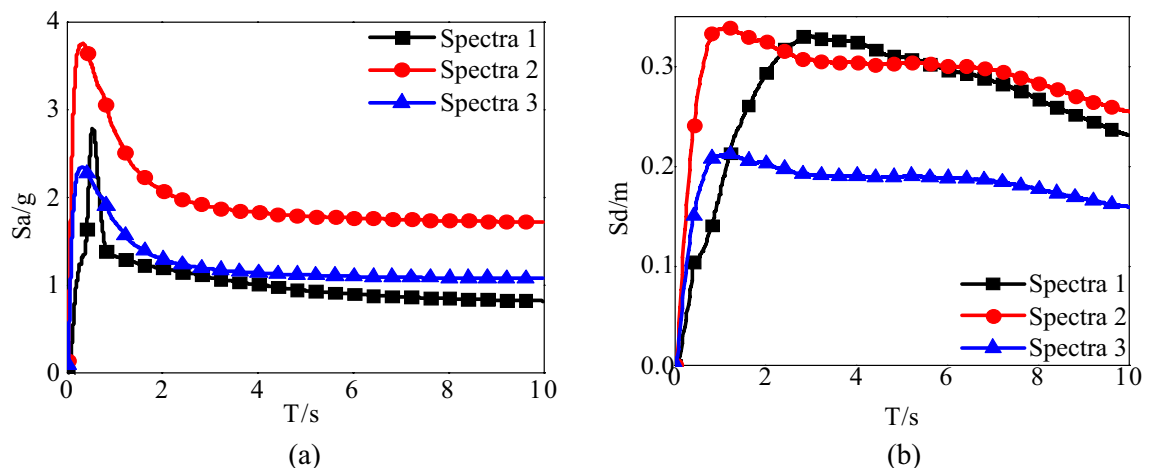


Fig.5. Spectral modalities.

Seismic action	Intensity 6	Intensity 7	Intensity 8	Intensity 9
Frequent earthquake	0.04	0.08 (0.12)	0.16 (0.24)	0.32

Tab. 2. Maximum values of horizontal seismic influence coefficient.

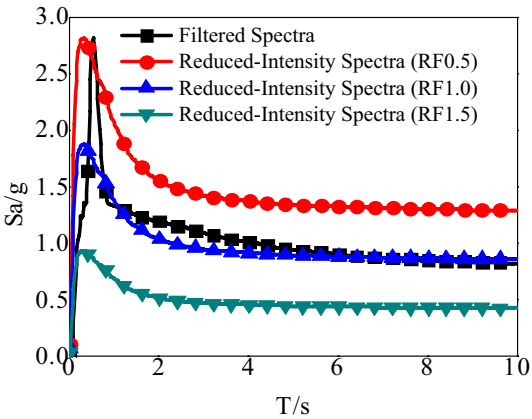


Fig.6. Comparison of filtered spectra and reduced-intensity spectra.

Comparative analysis reveals critical limitations:

- 0.5-stage reduction (RF=0.5) overestimates responses across all periods;
- Full-stage reduction (RF=1.0) achieves spectral convergence for $T > 4.0$ s but underestimates 0.05–0.40 s range responses (conventional building period domain);
- 1.5-stage reduction (RF=1.5) induces complete spectral divergence, violating code compliance requirements.

The analytical findings conclusively demonstrate that implementing filtered spectra in base-isolated structural systems provides superior convergence between seismic performance and material efficiency compared to conventional reduced-intensity spectra. This methodology shift eliminates the inherent conservatism of code-specified spectral reduction approaches while maintaining requisite structural reliability.

Shaking table test verification

The prevailing theory attributes the seismic isolation mechanism of base-isolated structures is structural period elongation to diminishes seismic demands. Specifically, the isolation layer increases the natural vibration period of the original structure, leading to lower spectral values in the DRS compared to the non-isolated structure, thereby diminishing seismic effects. However, if the structure’s inherent natural period is already large, the post-isolation period extension may not significantly alter the seismic influence coefficient on the response spectra curve, yet the vibration reduction effect remains substantial. In such cases, the filtering principle provides a more coherent explanation. Section"Shaking table test verification"subsequently quantifies these filtering phenomena through controlled shaking table tests.

Overview of the experimental model

The experimental program employed a 1:4 scaled base-isolated structural system, comprising laminated isolation bearings, an isolation interface slab, upper counterweight mass, and substructure columns (Figure 7a). Shaking table specifications (capacity: 6DOF/50kN), construction protocols, and material constitutive relationships are detailed in Ref.³⁷. and excluded for brevity.

Test matrices were categorized by two principal variables:

- Ground motions (NF vs. FF)
- Substructure column height configurations (H=1.0 m vs. 1.5 m)

Each case was further stratified by:

- PGA levels (0.05 g–0.40 g, corresponding to Chinese intensity scales VI-IX)
- White Noise and Excitation directions (X, X+Y, or X+Y+Z)

Complete test case taxonomies are codified in Ref. [131] Tables 5.11–5.14, with experimental instrumentation schematics provided in Figure 7.



Fig.7. Shaking table test model.

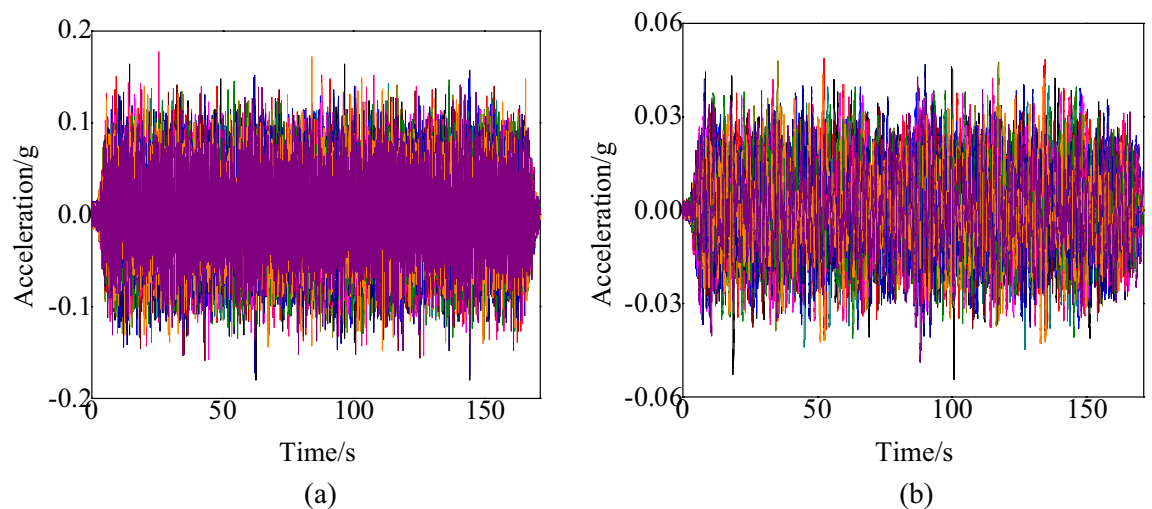


Fig.8. White noise.

Experimental analysis of filtering characteristics in the isolation layer

The experimental investigation focused on quantifying base-isolation layer spectral filtering characteristics through Column A (Case M2 A).

The study proceeded as follows:

- 1) Acceleration time histories at the shaking table platform and shaking table platen under white noise inputs were analyzed to evaluate the isolation layer's filtering behavior.
- 2) Acceleration time histories at the shaking table platform and shaking table platen were examined using NF and FF ground motions to assess filtering under realistic seismic conditions.
- 3) The filtered spectra was generated to quantify the isolation layer's frequency-dependent attenuation effects

White noise shaking table test analysis

The dynamic properties of the experimental specimen—including equivalent-period characteristics, Fourier spectral densities, and frequency response functions (FRF)—were rigorously validated in Ref.³⁷. Modal decomposition analyses established first-mode dominance (modal participation factor: 82.7%), thereby precluding the need for additional verification in this study.

Acceleration time histories the shaking table platform and shaking table platen under white noise excitation (0.05 g–0.40 g PGA) are presented in Figure 8, comparing input signals at the shaking table platform with filtered outputs at the shaking table platen.

Pre-isolation slab acceleration magnitudes reached ± 0.20 g (Figure 8a), whereas post-isolation measurements demonstrated 70% peak attenuation (0.06 g maximum absolute value) through spectral filtering mechanisms.

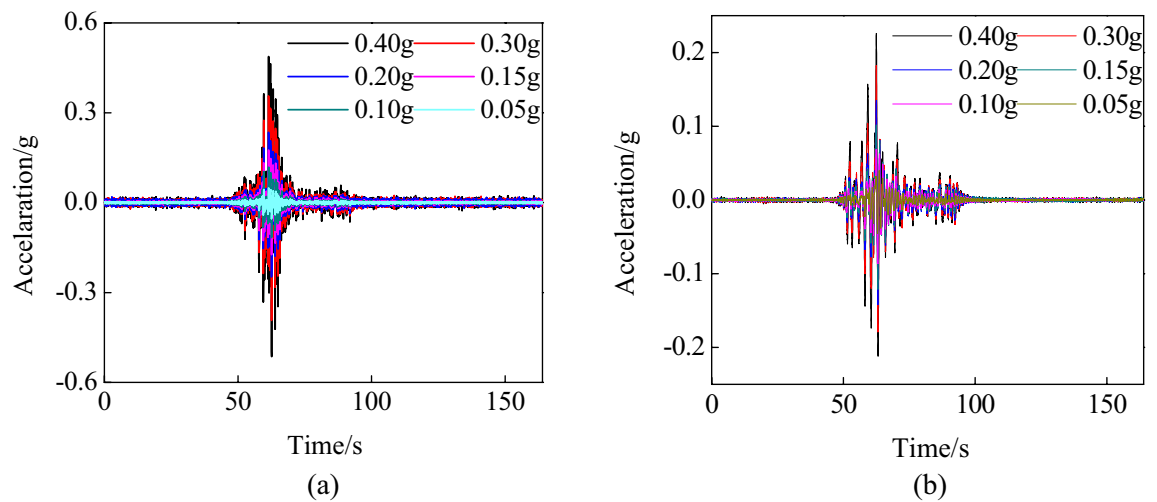


Fig. 9. NF ground motions.

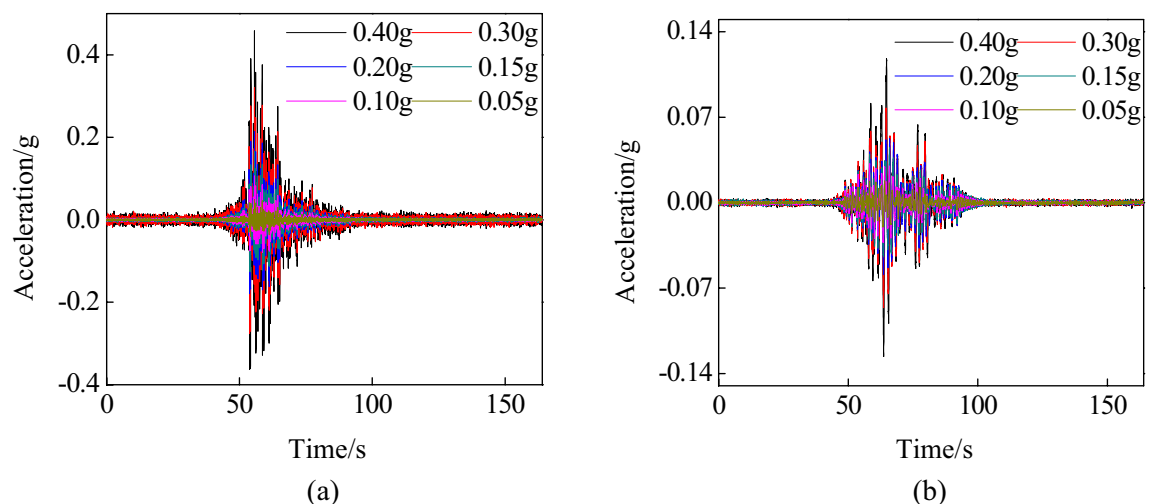


Fig.10. FF ground motions.

Therefore, the base-isolation system demonstrates marked spectral filtering efficacy, achieving 70% attenuation efficiency for seismic excitations traversing its low-stiffness interface. This energy dissipation mechanism reduces transmitted peak accelerations to 30% of input levels while curtailing 85% of input energy flux to the superstructure, thereby enhancing structural safety.

Ground motions shaking table test analysis

The spectral filtering mechanism fundamentally transforms input ground motions (Figures 9a–Fig. 10a) into attenuated ground motions (Figures 9b–Fig. 10b) through base-isolation layer transmission. This input-output relationship was empirically validated through white noise excitation protocols.

The plotted data in Fig. 9 reveal PGA of NF ground motions attenuation demonstrated 17.7–58.7% reduction efficiency ($\mu=42.5\%$) across input levels (0.05 g–0.40 g), exhibiting intensity-dependent nonlinear filtering behavior. The plotted data in Fig. 10 reveal PGA of FF ground motions attenuation maintained 63.7–75.8% reduction efficiency ($\mu=71.9\%$) across input levels (0.05 g–0.40 g), revealing energy dissipation characteristics. The isolation layer exhibits ground motions attenuation, with varying efficacy depending on seismic record types (near-field vs. far-field).

“Filtered spectra”

The superstructure’s dynamic response is predominantly dictated by filtered (attenuated) ground motions. Consequently, seismic design of the superstructure should employ filtered response spectra (FRS) derived from the modified records, which differ from the code-prescribed spectra in Ref.³⁶. Current reliance on conventional

spectra persists in practice, yielding suboptimal in base-isolated structures designs. The FRS which derived from the filtered seismic records is necessary.

Figures 11 and 12 present comparative analyses of original versus filtered spectra derived through numerical simulations, considering two critical parameters: seismic excitation typology (NF vs. FF) and PGA levels (0.05 g–0.40 g).

For both NF and FF ground motipns, after filtering through the isolation bearings and transmission to the isolation layer's top (Shaking table platen), the FRS exhibits reduced peak values and a rightward peak shift (lengthened predominant periods).

- 1) NF ground motipns: 18% peak attenuation at 0.05 g PGA due to limited acceleration reduction. For other PGAs, the DRS and FRS share similar shapes, converging at $T > 4$ s.
- 2) FF ground motipns: Across all six PGAs (0.05 g–0.40 g), filtered spectra show significant peak reductions (63.7–75.8%) and rightward shifts. Spectral shapes remain consistent, with DRS and FRS converging beyond 4 s.

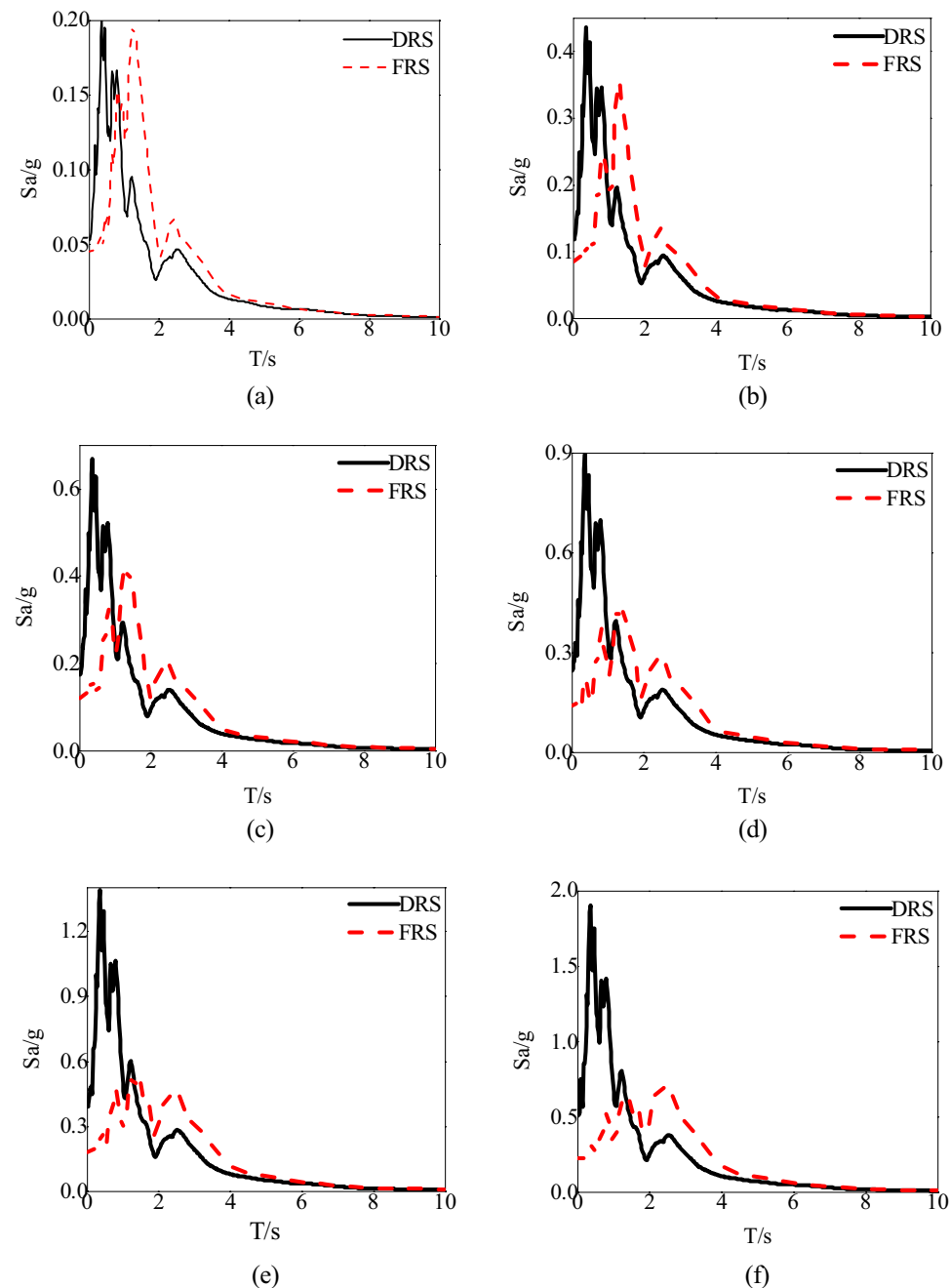


Fig.11. DRS vs. FRS of NF ground motions.

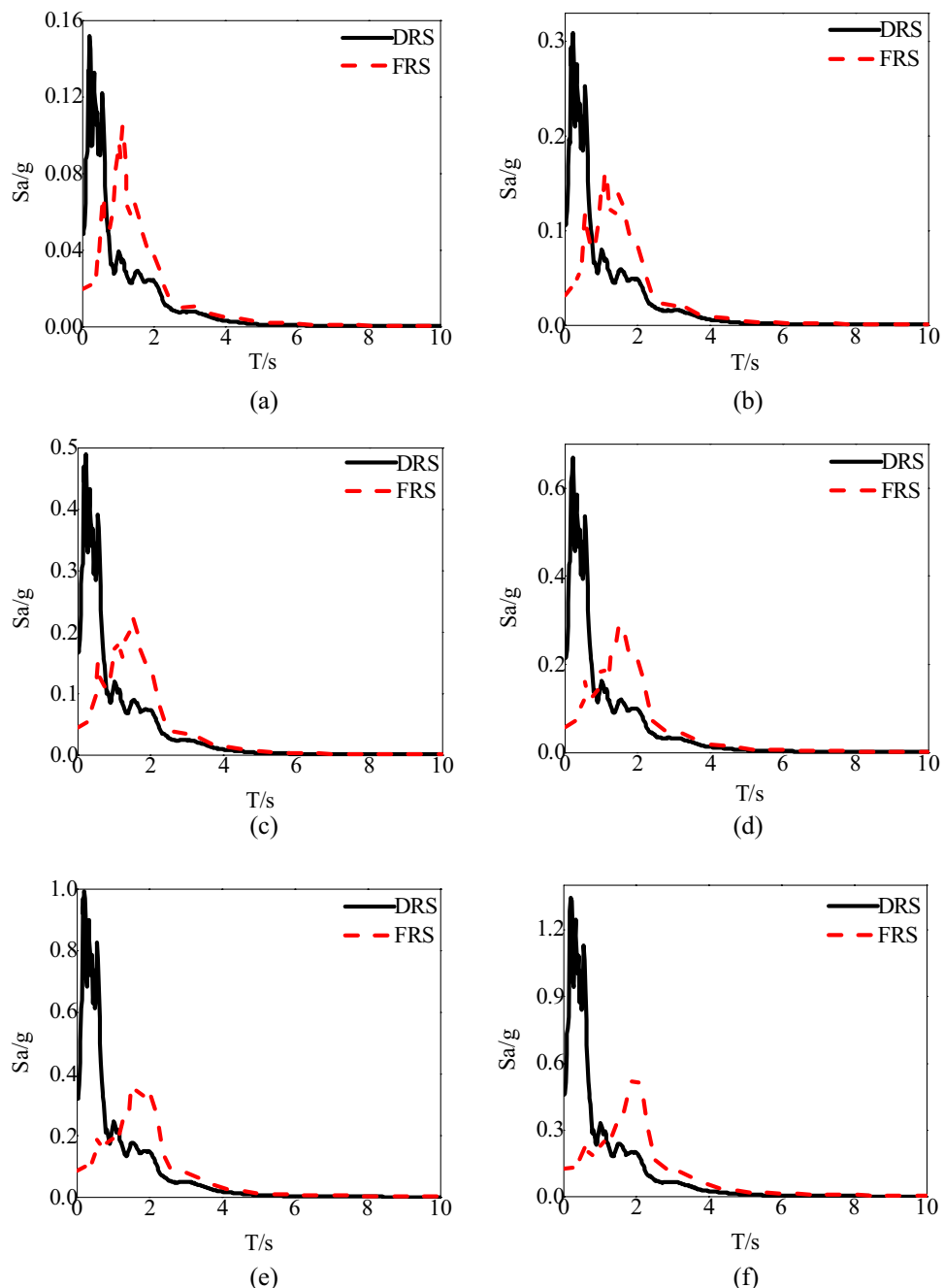


Fig.12. DRS vs. FRS of FF ground motions.

Conclusions

(1) By comparing four analytical cases with time history results, it is demonstrated that non-proportional damping characteristics of the isolation layer and nonlinear mechanical behavior of isolation bearings must be incorporated in MATLAB-based simplified models of base-isolated structures. This dual consideration achieves optimal convergence with time-history benchmarks (mean relative error: 26%).

(2) For seismic design of the superstructure in base-isolated systems: neither the SDOF simplified response spectra nor the code-prescribed "reduced-intensity" DRS adequately represents the true filtered response of the superstructure.

Within the natural vibration period ranges of short-period: $T < 1$ s and medium-period: 1–4 s, whether under the action of far-field or near-field earthquake records, the FRS is smaller than the DRS. When designing base-isolated structures, using FRS can structural ensure safety compliance and material utilization optimization. For the long-period range where $T > 4$ s, FRS is greater than DRS. Only by using FRS for the design of base - isolated structures can the structures be safer.

(3) Under both white noise excitation and seismic actions, the isolation layer's filtering effect: 17.7–75.8% PGA attenuation.

(4) Owing to the isolation bearings' filtering properties, seismic actions on the superstructure are substantially attenuated. The filtered spectra---characterized by reduced peaks and rightward-shifted predominant periods---is more suitable for seismic design of the superstructure than conventional spectra.

Data availability

The raw seismic record data that support the findings of this study were obtained from the PEER Ground Motion Database (https://ngawest2.berkeley.edu/users/sign_in?unauthenticated=true) The experimental data that support the findings of this study are available from the author Tianni Xu(835434235@qq.com) but restrictions apply to the availability of these data, which were used under license from the Institute of Earthquake Protection and Disaster Mitigation (Lanzhou University of Technology) for the current study, and so are not publicly available. Data are, however, available from the author upon reasonable request and with permission from the Institute of Earthquake Protection and Disaster Mitigation (Lanzhou University of Technology). Data sets generated during the current study are available from the corresponding author Yiming Wang (wangyiming198601@163.com) on reasonable request.

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Declarations

Competing interests

The authors declare no conflict of interest.

Additional information

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