Uncertainty in the seismic performance of semi-active base isolation systems

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ABSTRACT

In a conventional base isolation system, minimizing the seismic responses of the superstructure is always at the cost of increasing the isolator's response. The semi-active control of the isolator has been considered an effective solution to such a dilemma. It tunes the real-time properties of the isolator according to preset rules to further reduce the superstructure's seismic responses without increasing that of the isolator or vice versa. However, the number of ground motion records used to design and validate the controller, i.e., the preset rules, in existing studies is usually very small and therefore is questionable if it is adequate to address the significant uncertainty in the shaking of future earthquakes. This paper critically reviews the performance of the proportional-integral-derivative (PID), linear-quadratic regulator (LQR), and fuzzy controllers in semi-active base isolation systems with magnetorheological (MR) dampers subjected to highly uncertain ground motion inputs through numerical simulations. The results show that the control performance of the controllers varies significantly with the increasing number of input records, suggesting the necessity of using at least 50 ground motion records to appropriately assess the performance uncertainty of semi-active base isolation systems. More importantly, the superior performance of the optimized controllers is not guaranteed if the system is subjected to ground motions that are new to the controller, even if the controller has been optimized for thousands of existing ground motions. It highlights the need of improving the adaptability of the semi-active systems for uncertain ground motion inputs.

1. Introduction

Base isolation is among the most effective techniques for protecting building structures from earthquake damage. A basic principle of base isolation is to limit the earthquake forces by inserting a laterally flexible isolator at the base to elongate the fundamental period of the system, thereby, reducing the seismic responses of the superstructure (Davas and Alhan, 2019). However, the flexible isolator needs to accommodate large lateral drifts, which may even exceed the size of the seismic gap and pose pounding risks when the system is subjected to near-fault earthquakes (Su et al., 1989; Skinner et al., 1993; Heaton et al., 1995). Additional damping in the form of metallic or oil dampers may help suppress the isolator's drift but at the cost of sacrificing the flexibility of the system and increasing the superstructure's responses, especially the floor acceleration response (Kelly, 1999; Jangid and Kelly, 2001). Minimizing the floor acceleration and the base drift in a base isolation system has been recognized as an irreconcilable conflict (Kelly, 1999).

In light of these issues, researchers attempted to introduce passive (Wang et al., 2018, 2022a), semi-active (Lu and Lin, 2009; Wang et al., 2020) and active control (Chang and Spencer, 2010) to base isolation systems from the 1990s. Semi-active base isolation systems can alter the damping properties of the auxiliary dampers to withstand external dynamic forces without requiring very high power to operate (Singh et al., 1997; Yamada and Kobori, 2001), thus have become one of the most exciting areas of research in structural control (Symans and Constantinou, 1999; Casciati et al., 2012). Nonlinear response history analyses are usually performed with several selected ground motions to evaluate the control performance of a semi-active base isolation system in comparison with the passive counterpart (Johnson et al., 1998; Yoshida and Dyke, 2004). Since the structural seismic responses depend...
on the ground motion characteristics, which are highly uncertain (Lee and Mosalam, 2005), the results of many pieces of research have shown significant dispersion in the performance of semi-active systems subjected to different ground motion inputs (Ramallo et al., 2002; Yoshioka et al., 2002; Zamani et al., 2018).

Notwithstanding, it seems to have become a common practice to use only a very small number of ground motions in developing semi-active control systems for seismic protection. We collected 174 published papers on active or semi-active systems for seismic protection, and summarize the numbers of ground motion records that the authors used in their research in Fig. 1. Among them, 94.3% adopted no more than 16 records, and there is a strong tendency to use the same ‘benchmark’ suites for ease of comparison (Fig. 1(a)). For example, 14 pieces of research used the same ground motion suite consisting of four records first established by Johnson et al. (1998). 28 used the same pair of suites first established by Nagarajaiah and Narasimhan (2006), each of which consists of seven records. Such benchmark suites of ground motions lay a common ground for a fair comparison of the performance of different control strategies, but the small numbers of records in these benchmark suites raise questions on whether the control strategies are reliable in front of the significant uncertainty of earthquake ground shaking yet to come.

The awareness of such worries is illustrated by the clear tendency of using more ground motion records in semi-active research through the years. The average number of records used in individual research has grown from merely three in the early 1990s to more than ten in 2020 (Fig. 1(b)). This trend has been fueled by convenient access to the fast-growing database of high-quality ground motion records over the world. However, there is still a lack of consensus on how many records are adequate in designing and testing a semi-active system.

In this study, we assess the seismic performance of an archetype base isolation system semi-actively controlled by three types of most commonly-used controllers, namely, the PID, LQR, and fuzzy controllers. The assessment adopted nearly 4 000 ground motion records to optimize and/or validate the controllers. The optimized controllers were then tested by the three benchmark suites of ground motions to provide insight into the adaptability of the controllers for uncertain ground motion inputs.

2. Ground motion suites

Four ground motion suites are taken as a common basis for assessing the performance of the semi-active control strategies throughout the paper. Three of them, namely the Johnson, NN-1 and NN-2 suites, are small suites consisting of only a handful of ground motion records and are most frequently used in the field of semi-active control research. The other suite is exhaustive and consists of nearly 4000 records.

The Johnson suite was firstly established by Johnson et al. (1998) and has since then been adopted in more than 14 subsequent papers on active or semi-active control research. It consists of four horizontal ground motion records obtained in four different earthquakes in the US and Japan, including the most widely used El Centro NS component in the 1940 Imperial Valley earthquake.

The NN-1 and NN-2 suites were firstly established by Nagarajaiah and Narasimhan (2006), and have since then been used in no less than 28 papers on active or semi-active control research. Each suite consists of seven unidirectional records from four different earthquakes. The records in the two suites constitute seven pairs of horizontal records in the orthogonal directions. They were originally used together for bidirectional loading, but nowadays the two suites are usually used individually (Zamani et al., 2018).

The information of the ground motion records in the three small suites is listed in Table 1, where $M_{w}$ is the moment magnitude of the earthquake, PGA is the peak ground acceleration of the ground motion, and FN, FP, NS and EW denote the fault-normal, fault-parallel, North-South and East-West directions, respectively.

In addition to the three small benchmark suites, an exhaustive suite of 3 986 unidirectional ground motion records is established for comparison purposes. The suite consists of all the individual records in the NGA growing database of high-quality ground motion records over the years. The average number of records used in individual research has grown from merely three in the early 1990s to more than ten in 2020 (Fig. 1(b)). This trend has been fueled by convenient access to the fast-growing database of high-quality ground motion records over the world. However, there is still a lack of consensus on how many records are adequate in designing and testing a semi-active system.

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Table 1

<table>
<thead>
<tr>
<th>Suite</th>
<th>Earthquake Year</th>
<th>$M_{w}$ Station Direction</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Johnson</td>
<td>Imperial Valley, US 1940</td>
<td>7.1 El Centro</td>
<td>NS</td>
</tr>
<tr>
<td>Tokachi-oki, Japan 1968</td>
<td>7.9 Hachinohe</td>
<td>NS</td>
<td>0.229</td>
</tr>
<tr>
<td>Northridge, US 1994</td>
<td>6.7 Sylmar</td>
<td>NS</td>
<td>0.843</td>
</tr>
<tr>
<td>Kobe, Japan 1995</td>
<td>6.9 KJMA</td>
<td>NS</td>
<td>0.834</td>
</tr>
<tr>
<td>NN-1</td>
<td>Imperial</td>
<td>1979</td>
<td>6.5 El Centro</td>
</tr>
<tr>
<td>Northridge, US 1994</td>
<td>6.7 Newhall</td>
<td>FN</td>
<td>0.736</td>
</tr>
<tr>
<td>Northridge, US 1994</td>
<td>6.7 Sylmar</td>
<td>FN</td>
<td>0.875</td>
</tr>
<tr>
<td>Imperial</td>
<td>1979</td>
<td>6.5 El Centro</td>
<td>FN</td>
</tr>
<tr>
<td>Chi-Chi, China 1999</td>
<td>7.6 TCU068</td>
<td>NS</td>
<td>0.512</td>
</tr>
<tr>
<td>Erzincan, Turkey 1992</td>
<td>6.8</td>
<td>Turkey</td>
<td>NS</td>
</tr>
<tr>
<td>NN-2</td>
<td>Northridge, US 1994</td>
<td>6.7 Newhall</td>
<td>FP</td>
</tr>
<tr>
<td>Northridge, US 1994</td>
<td>6.7 Sylmar</td>
<td>FP</td>
<td>0.604</td>
</tr>
<tr>
<td>Imperial</td>
<td>1979</td>
<td>6.5 El Centro</td>
<td>FP</td>
</tr>
<tr>
<td>Northridge, US 1994</td>
<td>6.7 Newhall</td>
<td>FP</td>
<td>0.656</td>
</tr>
<tr>
<td>Northridge, US 1994</td>
<td>6.7 Sylmar</td>
<td>FP</td>
<td>0.604</td>
</tr>
<tr>
<td>Imperial</td>
<td>1979</td>
<td>6.5 El Centro</td>
<td>FP</td>
</tr>
<tr>
<td>Chi-Chi, China 1999</td>
<td>7.6 TCU068</td>
<td>EW</td>
<td>0.369</td>
</tr>
<tr>
<td>Erzincan, Turkey 1992</td>
<td>6.8</td>
<td>Turkey</td>
<td>EW</td>
</tr>
</tbody>
</table>


Fig. 1. (a) Number of ground motion records used in published papers and (b) The average number of records per paper over time.
West2 database of the Pacific Earthquake Engineering Research (PEER) Center (Ancheta et al., 2014) that satisfy the following three criteria: (1) PGA is larger than 40 cm/s² and peak ground velocity (PGV) is larger than 5 cm/s²; and 10 cm/s for the 1999 Chi-Chi and the 2011 Tohoku earthquakes to limit the number of records from these two record-rich earthquakes; (2) Information of the site shear wave velocity and the fault distance is present; and (3) The effective period is larger than 6 s. The suite is referred to as the ‘Big suite’ hereinafter. The fault distance, magnitude and average shear-wave velocity in the upper 30 m ($\text{s}_{30}$) of the selected ground motions are depicted in Fig. 2.

Regarding the seismic input, all the individual records in the aforementioned four suites of ground motions were normalized to have a PGV of 50 cm/s before they were used in the analysis to provide a consistent level of the earthquake intensity. The average spectra of the normalized motions are compared with the design spectrum at the major earthquake level in China (2% in 50 years probability of exceedance) in Fig. 3 for the Johnson, NN-1 and NN-2 ground motion suites.

3. Archetype building and numerical modeling

A nine-story base-isolated building model is taken as the archetype building throughout the paper. It served as a practical design example for passively base-isolated buildings in the Recommendation for the Design of Seismically Isolated Buildings published by the Architectural Institute of Japan (AIJ, 2013). A lumped mass model is used for its analysis and seismic design (Fig. 4). The superstructure of the building is assumed to remain elastic owing to the protection provided by the base isolation. The lumped mass and lateral stiffness of the superstructure are listed in Table 2. The fundamental period of the fixed-base superstructure is 0.76 s.

Laminated rubber bearings are used as the isolator. Its lateral stiffness $k_0$ and the mass of the base mass $m_0$ are also given in Table 2. The isolation period, which ignores the stiffness of the damper in the isolation layer, is 3.91 s, more than 5 times longer than that of the fixed-base superstructure. 5% Rayleigh damping is assumed for the first and third modes of the base-isolated structure without dampers in the isolation layer. In the original passive design, steel dampers of a total lateral stiffness $239 \text{kN}$ is adopted in the isolation layer to mitigate the drift of the superstructure. If the initial stiffness $k_0$ is considered, the fundamental period of the system is reduced to 1.25 s.

To convert the system into a semi-active one, the steel dampers are replaced by MR dampers, one of the most popular semi-active devices in earthquake engineering (Yoshioka et al., 2002). Each MR damper is modeled as a combination of a Bouc-Wen element, linear dashpots, and springs proposed by Dyke et al. (1996) (Fig. 5), in which the restoring force of an MR damper $f_{\text{d,MR}}$ is the summation of the forces of the Bouc-Wen element, the dashpot of $c_0$ and the springs of $k_1$ and $k_0$ as shown in Eq. (1). A total of 40 large-scale MR dampers, each with a 1 000 kN capacity and a ±200 mm stroke (Jung et al., 2003), is used in the isolation layer to provide a wide range of control force from 18% to 180% of the yield strength of the steel dampers in the passive counterpart. The total damper force $f_{\text{d,MR}}=40f_{\text{d,MR}}$

$$f_{\text{d,MR}} = aw + c_0(x - y) + k_0(x - y) + k_1x$$  \hspace{1cm} (1)

where $w$ is an evolutionary variable usually referred to as the hysteretic displacement and is governed by (Wen, 1976)

$$w = -p\omega([\dot{x} - \dot{y}])|w|^{\alpha - 1} - \beta(\dot{x} - \dot{y})|w|^\alpha + A(\dot{x} - \dot{y})$$  \hspace{1cm} (2)

and by force equilibrium, one has

$$\dot{y} = \frac{1}{c_1 + c_0}[aw + c_0\dot{x} + k_0(x - y)]$$  \hspace{1cm} (3)

According to Jung et al. (2003), the parameters $n = 2, \gamma = \beta = 164 \text{m}^{-2}$, and $A = 1 107.2$ determine the size and shape of the hysteresis loop, $k_0 = 2 \text{N/m}$ is used to control the stiffness at large velocities and $k_1 = 9.7 \text{N/m}$ is the stiffness of the accumulator (Dyke et al., 1996). In the model, the parameter of the Bouc-Wen element $a$ and the damping coefficients of the two dashpot $c_0$ and $c_1$ are assumed to depend on the input voltage $V$ by the following equations (Spencer et al., 1996; Jung et al., 2003).

$$a = 46.2 + 41.2v [\text{kN/m}]$$  \hspace{1cm} (4)

$$c_0 = 110 + 114.3v [\text{kNs/m}]$$  \hspace{1cm} (5)

$$c_1 = 8 359.2 + 7 482.9v [\text{kNs/m}]$$  \hspace{1cm} (6)

where $v$ is the output of a first-order filter given by

$$\dot{v} = -100(v - V)$$  \hspace{1cm} (7)

Assuming that the base-isolated system remains elastic except for the dampers, the equation of motion of the archetype structure subject to earthquake ground acceleration $\ddot{x}_g$ can be written as:

$$M\ddot{x} + C\dot{x} + Kx + D_d\dot{u} = -MI\ddot{x}_g$$  \hspace{1cm} (8)

where $x, \dot{x}$ and $\ddot{x}$ are the $n \times 1$ vectors of relative displacement, velocity and acceleration vectors, respectively, $n=10$ is the number of degrees of

Fig. 2. Distribution of properties of ground motion records in Big Suite.
\[ \dot{z} = Az + Bf_d + D\ddot{x}_g \]  

(9)

where \( z = \{x, \dot{x}\} \) is the \( 2n \times 1 \) state vector; \( A \) is the \( 2n \times 2n \) system matrix; \( B \) and \( D \) are \( 2n \times 1 \) vectors denoting the locations of dampers and external excitations in the state-space, respectively.

4. Control algorithms

The performance uncertainties of three of the most popular feedback controllers in civil engineering applications are investigated, namely the PID, LQR, and fuzzy controllers, representing the most fundamental and widely used algorithms in classical control, optimal control, and intelligent control, respectively. Among the 174 published papers that we mentioned in the Introduction, 109 adopted one of these three controllers. Their implementations in the archetype base-isolated buildings are introduced as follows.

4.1. PID control

The PID control is the most widely used classical control algorithm in industrial control systems and smart structures. In a PID controller, the control force \( f_c \) is the weighted sum of a proportional term, an integral term and a derivative term of the error \( e \) between the structural output and the desired reference (Equa. (10)).

\[
f_c(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt}
\]

(10)

where \( K_P, K_I \) and \( K_D \) are the weight coefficients for the three terms.

In the present problem, we chose the relative velocity \( \dot{x}_0 \) of the isolation layer as the input variable according to the suggestion of Etedali et al. (2013) and assume an ideal zero-velocity \( \dot{x}_0 = 0 \) as the control target. Therefore, the error is \( e = - \dot{x}_0 \). The discrete position PID controller in MATLAB/Simulink toolbox is adopted. The discrete transfer function is:

\[
H(z) = K_P + K_I \frac{1}{Z - 1} + K_D \frac{N}{Z^{N+1}}
\]

(11)

where \( Z \) is the transfer function operator, \( T_d \) is the time interval of the discrete system and \( N=1000 \) is the parameter of the low-pass filter for derivation (Miyamoto et al., 2016).

Since the force of the MR dampers \( f_{d} \) can only be commanded indirectly by manipulating the voltage \( V \) applied to the current driver for the MR dampers, the clipped optimal control proposed by Dyke et al. (1996) is adopted to induce the MR dampers to approximately track the desired control force \( f_c \). The control law is essentially a secondary bang-bang controller and can be concisely stated as Eq. (12).
\[ V = V_{\text{max}} H(f_c - f_d) \]  
\[ H(x) \]  
where \( H(\cdot) \) is the Heaviside step function.

The block diagram that consists of a PID controller and the clipped-optimal control algorithm for the semi-active base-isolated building is presented in Fig. 6. The \( K_I, K_P \) and \( K_D \) coefficients of the PID controller are to be optimized and will be discussed later.

### 4.2. LQR control

An LQR controller determines the optimal control force \( f_c \) by minimizing the quadratic objective function \( J \):

\[ J = \int_{0}^{\infty} \left[ z^T Q z + f_c^2 \right] dt \]  
where \( Q \) and \( R \) are the symmetric state cost and control cost matrices, respectively, and can be determined in terms of scalars \( q \) and \( r \) as in Equa. (14) for this single-variable control problem (Ou, 2003).

\[ Q = \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \]  
\[ R = r \]  

The optimal control force \( f_c \) is then determined by

\[ f_c = -Gz \]  
where \( G \) is the feedback gain matrix obtained by solving the Riccati equation of \( Q \) and \( R \), and is dependent solely on the ratio of \( q/r \).

### 4.3. Optimization by genetic algorithm

The control variables \( PV \), that is, \([K_I, K_P, K_D]\) for the PID controller and \( q/r \) for the LQR controller, are optimized to achieve the objective of minimizing the seismic responses of the superstructure without increasing the isolator’s drift as compared to the passive counterpart. The control performance is evaluated in terms of the degrees of reduction in the isolator’s drift, the floor velocity, and the floor acceleration responses in the semi-actively controlled isolation systems as compared to the passive counterpart denoted as \( R_D, R_V \) and \( R_A \), respectively, and defined in Equa. (16).

\[ R_D = \frac{x_0; \text{MR}}{x_0; \text{steel}}, R_V = \frac{\text{PFV}_{\text{max,MR}}}{\text{PFV}_{\text{max, steel}}}, R_A = \frac{\text{PFA}_{\text{max,MR}}}{\text{PFA}_{\text{max, steel}}} \]  
where \( x_0 \) is the peak lateral drift of the isolator; \( \text{PFV}_{\text{max}} \) and \( \text{PFA}_{\text{max}} \) are the maximum peak floor velocity and peak floor acceleration over the floors of the superstructure, respectively; the subscripts ‘MR’ and ‘steel’ denote the semi-active and passive isolation cases, respectively. By these terms, the objectives of semi-active control are defined by Equa. (17).

\[ \min_{PV} R_V + R_A \leq 1 \]  
\[ \text{s.t.} \ x_0 \leq 1 \]
where the over-bar notation ‘‘’ denotes the mean value over different ground motion records in a suite.

The genetic algorithm (GA) toolbox in MATLAB was adopted to solve the multi-objective optimization problem, in which both the population size and the number of generations were set to 100. The PID and the LQR controllers are optimized on the Big suite. The resultant optimal co-

size and the number of generations were set to 100. The PID and the LQR the multi-objective optimization problem, in which both the population

ground motion records in a suite.

controller and

variable. The fuzzy controller directly outputs the command voltage

in Fig. 9. Fig. 8(b), and the block diagram of the fuzzy control scheme is depicted

resultant input-output relationship of the fuzzy controller is shown in

thus eliminating the need of using the clipped-optimal algorithm. The

4.4. Fuzzy control

The fuzzy controller is classified as an intelligent controller because it simulates the logical reasoning of the human brain (Djedoui et al., 2018) by mapping the input space to an output space based on a set of pre-

scribed fuzzy rules in the “if-then” format. Since the rules usually rely on expert knowledge, a ready-made fuzzy controller by Lu et al. (2010) was adopted in this study for its simple form and easy implementation. They showed both theoretically and experimentally that this controller was very effective in controlling the seismic responses of a semi-active base-isolated system. It includes a fuzzification interface that converts the input variables to the degrees of membership, an inference engine that defines the relationship between the memberships and specific voltages, and a defuzzification interface that converts the weighted membership to the command voltage $V$ (Fig. 8(a)). In the present application, the absolute value of the relative velocity of the isolation layer $|\dot{x}|$, after being normalized by a factor of 0.3, is taken as the input variable. The fuzzy controller directly outputs the command voltage $V$, thus eliminating the need of using the clipped-optimal algorithm. The resultant input-output relationship of the fuzzy controller is shown in

Fig. 8(b), and the block diagram of the fuzzy control scheme is depicted in Fig. 9.

5. Results and discussions

Consistent with the optimization objective in Equa. (17) for the PID and LQR controllers, the response reduction ratios of $R_D$, $R_V$ and $R_A$ defined in Equa. (16) are used as metrics to evaluate the control performance of not only the PID and LQR controllers, but also the fuzzy controller. As aforementioned, the goal is to minimize $R_D$ and $R_A$, while $R_V$ remains less than unity. Fig. 10 shows the mean reduction ratios $R$ and

the range of plus/minus one standard deviation of the ratios $\sigma_R$ when the performance of the three controllers is tested on the 3986 ground motion records in the Big suite.

When all the 3 986 records are considered, it is evident that the control objective is successfully achieved by the fact that the $R_D$ is very close to unity (1.00 for the PID and 0.99 for the LQR cases) while the $R_V$ and $R_A$ are as low as approximately 0.7 and 0.5, respectively, for both the PID and LQR controllers. In addition, the ready-made fuzzy controller exhibits similar performance as the other two controllers do, although it was not explicitly optimized.

However, $R$ and $\sigma_R$ vary significantly with the increasing numbers of ground motion records involved in the evaluation. This is true for all the response reduction ratios in all the cases of different controllers. As mentioned in the Introduction, most existing research on semi-active control adopted no more than 16 records in the optimization and/or performance evaluation (see Fig. 1). Such a small number of input records is apparently inadequate in light of the significant variation of $R$ and $\sigma_R$ as observed in Fig. 10. Indeed, their values do not stabilize until the number of records exceeds 50. Therefore, it is deemed necessary to use no less than 50 ground motion inputs to appropriately assess the uncertainty in the control performance of semi-active base-isolated systems.

More importantly, it is vital to test the controller on earthquake ground motions that are not part of the suite used to optimize it, because the ground motion in a future earthquake event is essentially unknown. To this end, Fig. 11 and Table 3 summarize the response reduction ratios by the three controllers for not only the Big suite but also the other three suites, which are much smaller but much more popular in the semi-active control community. It is unfortunate to observe that the satisfying performance of the semi-active controllers on the Big suite fails to generalize to other ground motion suites. Specifically, all three controllers still perform well on the Johnson suite. This is simply because two of the four records of the suites, namely the Sylmar and the KJMA records, are also from the PEER database and are present in the Big suite. In contrast, for the NN-1 and NN-2 suites, whose records are completely new to the controllers, the mean drift response ratios $R_D$ exceed unity by 1.44–1.72 times, and the dispersions $\sigma_D$ are 1.72–2.95 times as large as those for the Big suite. Meanwhile, all the controllers exhibit much poorer performance in terms of the reduction in the floor velocity and acceleration responses. For example, $R_V$’s for all the three controllers on the NN-1 suite are greater than unity, suggesting a high probability that the maximum $PFV$ responses of the semi-active isolation system will inversely exceed those of the passive counterparts.

The expected response reduction ratios $R$ of the controllers on the Big suite approximately follow a lognormal distribution. Fig. 12 depicts the regressed distributions of $R_D$, $R_V$ and $R_A$ for the PID controller for example, where the shadow bands represent 90% confidence intervals.
The confidence intervals are determined by the naïve method suggested by Zhou and Gao (1997). The corresponding $R$ factors on the individual ground motions in the other smaller but popular suites are overlapped in the graphs. The $R_D$ factors for four of seven records in the NN-1 suite and one in the NN-2 suite fall outside the 90% confidence interval. The $R_V$ and $R_A$ factors for three records in the NN-1 suite and one in the NN-2 suite fall outside the 90% confidence interval. It is worth noting that neither of the ground motion suites are specifically selected to be extremely critical for semi-active control, but they are adopted simply because of their popularity. The high chance of the ground motions in these suites to make the controller perform unexpectedly poorly underscores the lack of adaptability of the controller, even if it has been optimized for nearly 4000 ground motion records. The other two controllers suffer from the same problem.

Fig. 10. Variation of control performance of (a) PID, (b) LQR, and (c) Fuzzy controller with the increasing number of input records in Big suite.

Fig. 11. Control performance of (A) PID, (B) LQR, and (C) Fuzzy controllers for four suites of ground motions.
It is worth noting that the uncertainties in the structural properties and input signals are neglected in this study because they are usually much less significant than the uncertainty in the earthquake excitations. Many advanced control algorithms have been proposed to deal with such uncertainties, among which is a variety of output-only strategies (Wang et al., 2020, 2022b). However, these algorithms are also expected to suffer from a lack of adaptability as illustrated in this study for the three basic algorithms. The framework of assessing the performance uncertainty presented in this paper, i.e., to test the performance by a separate set of ground motion that is new to the controller, also apply to other more advanced controllers.

6. Conclusions

The seismic performance of a base-isolated system with MR dampers semi-actively controlled by three types of most popular controllers, namely PID, LQR and fuzzy controllers, was assessed through nonlinear response history analyses. An exhaustive suite of 3 986 ground motion records was adopted to optimize and/or validate the controllers, which were then tested by the other three suites of ground motions to gain insight into the adaptability of the controllers in the significant uncertainty of earthquake ground motions. The following conclusions can be drawn from the results:

(1) In contrast to the common practice to use only a very small number of ground motions in developing semi-active control systems, it is necessary to use at least 50 ground motion records to appropriately assess the performance uncertainty of semi-active base-isolated systems.

(2) The popular controllers involved in this study, i.e., the PID, LQR, and fuzzy controllers, are very likely to perform unexpectedly poorly under new ground motions other than those they are optimized for. This suggests a common lack of adaptability for uncertain ground motion inputs in future earthquake events and a necessity of developing highly adaptive control strategies for real-world applications.

In this study, we only tested three basic controllers. More advanced control strategies out there are expected to suffer from the same lack of adaptability. Interested readers are encouraged to assess the performance uncertainty of their controllers by the same framework proposed in this paper. In addition, this study only focuses on the uncertainty caused by earthquake excitations. The uncertainties in the structural properties and input signals should also be considered in developing highly adaptive control strategies.

Conflict of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled “Performance uncertainties of semi-active base isolation systems”.

Author agreement

All the authors contributed to the study have approved the final version. This is the first time submission to this journal and also do not consider to submit to other Journals. And we'd like to give the permission to the publisher to reproduce this paper in all media.

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