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Optimal Reduction of Seismic Floor Acceleration Response using Viscous Dampers connecting Non-Consecutive Floor Levels

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ABSTRACT

Several studies have explored the optimization of the seismic response of structures with viscous dampers. Most of these studies define the optimal performance of the system in terms of the inter-story drift response, either exclusively or in combination with other quantities such as floor acceleration, energy dissipation, or cost-related quantities. However, the optimal reduction of floor accelerations exclusively (i.e., without considering any other response quantity) has not been exhaustively analyzed. The location of dampers connecting non-consecutive floor levels in buildings is a popular technique used in Chile for improving the efficiency of the supplemental dampers in stiff structures. The objective of the study presented in this paper is to analyze the height-wise distributions of viscous dampers that minimize the seismic floor accelerations in multistory buildings, with emphasis on damper bracings that connect non-consecutive floor levels. Uniform and non-uniform solutions were explored, and suboptimal solutions that minimize the damping constants c were defined. The seismic demand was modelled as a non-stationary Gaussian process. The structures were modeled as shear-type, linear elastic models (1 DOF per story). Optimization algorithms were applied to find the optimal solutions. The objective function was defined in terms of the stochastic response of the structures. The second moment of the floor acceleration response was obtained using the Explicit Time Domain Method. It was found that configurations with dampers spanning 2 or 3 floor levels achieve the same damping ratio as configurations with dampers at every story, but with smaller values of c. In some cases, the optimal response reduction was achieved with less damping than the maximum possible damping level that is feasible in practice. It was also found that when dampers connect non-consecutive floor levels the optimal response reductions and the damping ratios are similar to those achieved when dampers connect consecutive floor levels.

Keywords: viscous dampers, optimization, floor accelerations

INTRODUCTION

Viscous dampers (VDs) are a popular option to improve the seismic performance of buildings. Since their early applications in the 1990's these devices have been broadly studied, and a great amount of research has focused on the optimization of both the properties and location of the devices within a structure that lead to an optimum response. This optimum response has usually been defined as a reduction of the deformation response of the structure. Other studies have also considered the floor acceleration response, cost-related criteria, and energy dissipation capabilities using different performance indexes. However, the optimal reduction of floor accelerations exclusively remains scarcely explored in the literature.

Seismic floor accelerations are responsible for the damage to building contents and acceleration-sensitive nonstructural components. These elements are an important fraction of the total cost of a structure [1]. The 2010 Maule, Chile earthquake left most structures with no visible structural damage [2], but nonstructural damage was nevertheless widespread [3], which led to long disruptions in economic activities. A recent study [4] used an optimization algorithm to find the optimal damping constants of each damper that produce the optimal reduction of peak floor accelerations (PFAs) in multi-story buildings.

A popular technique among structural designers in Chile is to place dampers in buildings connecting non-consecutive floor levels. This study explores the effects of this type of scheme on the optimal reduction of PFAs.

METHODOLOGY

Numerical modelling of structures

Structures were modelled as 2D linear systems with 1 lateral degree of freedom (DOF) per story as shown in Figure 1, where n is the number of stories. The mass was considered the same at every story and lumped to each DOF. Story stiffnesses were set in such a way that decrease along the height of the building, with a recursive factor of 95% (i.e., $k_i = 0.95\ k_{i-1}$).

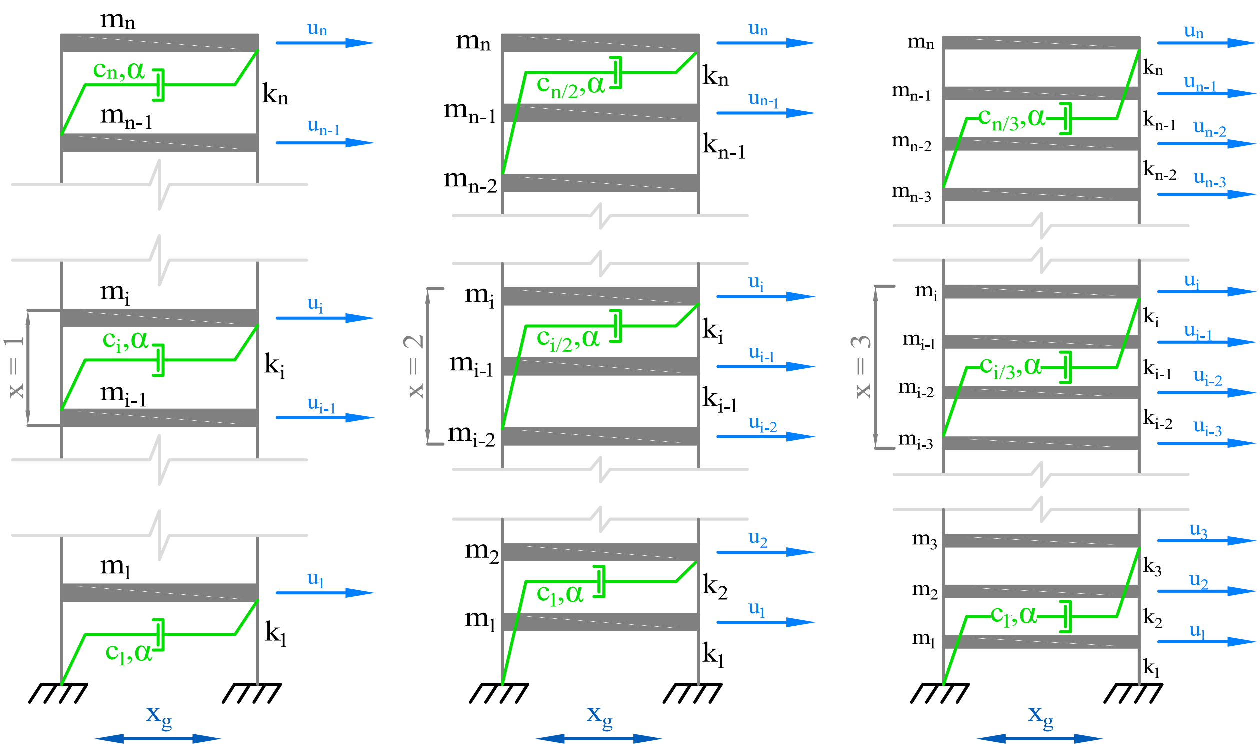

Figure 1. Schematics of simplified models considered.

Different number of stories and periods were considered as displayed in Table 1. For every number of stories 3 different first mode periods were considered: one rigid (T_{min}), one flexible (T_{max}) and one intermediate (T_{avg}).

Table 1. Considered periods for the different number of stories buildings.

N° stories	2	3	4	6	8	10	12	15	18	21	24	30
T_{min}	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.75	0.90	1.05	1.20	1.50
T_{avg}	0.45	0.60	0.70	0.95	1.15	1.40	1.55	1.85	2.10	2.30	2.50	2.75
T_{max}	0.80	1.00	1.20	1.55	1.90	2.25	2.50	2.90	3.25	3.55	3.75	4.00

Dampers were modelled as purely viscous dashpot elements, the effect of the stiffness in series will be discussed later. The maximum first mode supplemental (i.e., not including the intrinsic damping) damping ratio (ξ_1) considered is 30%, which is generally accepted as an upper limit for practical seismic applications [5]. This limit was defined by finding the damping constant that when located uniformly at every x stories achieves $\xi_1 = 0.3$. This damping constant is denoted as $c_{ref,x}$. Two different values of the velocity exponent (α) were considered: 1.0 (linear viscous dampers, LVDs) and 0.3 (non-linear viscous dampers, NLVDs). To reduce the computing time, NLVDs were linearized using two different criteria: harmonic linearization (energy equivalent) [6], [7], and statistical linearization [8].

Seismic Demand Modeling

The seismic excitation is modeled as a Gaussian non-stationary random process. The frequency content of the excitation is defined by the Kanai-Tajimi modified function [9]. Two different types of excitations corresponding to different soil conditions are considered (firm soil and soft soil).

Optimization Procedure

The stochastic response of the systems to the non-stationary seismic excitations was obtained by the Explicit Time Domain Method (ETDM) [10], [11]. The optimization function was then defined in terms of statistical moments of the response as shown in Eq. 1, where $\boldsymbol{c}$ is the vector of damping constants, $\ddot{\boldsymbol{u}}_{\boldsymbol{d}}^{\boldsymbol{abs}}$ is the vector of floor acceleration responses of the structure with supplemental VDs and $\ddot{\boldsymbol{u}}_{\boldsymbol{0}}^{\boldsymbol{abs}}$ is the vector of floor acceleration responses of the structure without supplemental VDs. $\sigma(\,)$ denotes standard deviation (i.e., RMS) and max[ ] extracts the maximum value over all stories and the entire response history.

$$f(\boldsymbol{c}) = \frac{\max\left[\sigma\left(\ddot{\boldsymbol{u}}_{\boldsymbol{d}}^{\boldsymbol{abs}}\right)\right]}{\max\left[\sigma\left(\ddot{\boldsymbol{u}}_{\boldsymbol{0}}^{\boldsymbol{abs}}\right)\right]} \tag{1}$$

Four different optimal solutions were found: optimal uniform (Opt UD), suboptimal uniform (Sub-Opt UD), optimal (Opt) and suboptimal (SubOpt). Uniform solutions refer to distributions where the value of c of all dampers is the same. Suboptimal solutions refer to a solution constrained to achieve 90% of the optimal response reduction. Out of the several solutions that comply with this condition, the one selected is the one that minimize the amount of added damping (defined as Σc_i). Single variable optimization problems were solved using the active-set optimization algorithm [12], and multiple variable cases were solved using the pattern search algorithm [13], [14], both available in MATLAB optimization toolboxes.

RESULTS

First the effect of connecting non-consecutive floor levels ($x > 1$) on ξ_1 is assessed. Figure 2 displays the ratio of the damping constant $c_{ref,x}$ (i.e., dampers spanning x floor levels), to the damping constant $c_{ref,1}$ (i.e., dampers connecting consecutive floor levels). The blue markers correspond to LVDs and are independent of the excitation since they are obtained by complex eigen value analysis. The orange markers, correspondent to NLVDs, are found using harmonic linearization and hence are dependent on the excitation. It can be observed that this ratio is independent of the number of stories, first mode period and frequency content of the excitation. The ratio is approximately constant at $c_{ref,x}/c_{ref,1} = (1/x)^{\alpha}$, as shown in dashed lines, meaning that, as expected, connecting non-consecutive floor levels has a geometric amplification effect.

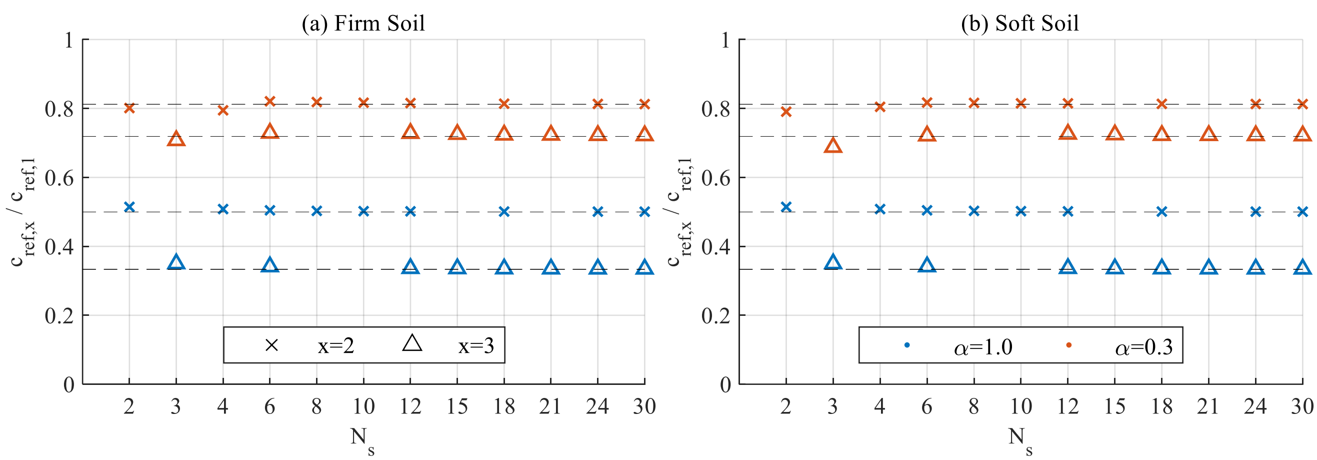

Figure 2. Ratio of $c_{ref,x}$ ($x = 2, 3$) to $c_{ref,1}$.

An exhaustive search procedure was performed to find the optimal uniform and suboptimal uniform solutions. The damping constant was increased from 0 to $c_{ref,x}$, and the response reduction (i.e., $RR = 1 - f(\boldsymbol{c})$, where $f(\boldsymbol{c})$ is given by Eq. (1) was obtained for each value of the damping constant. Results are displayed in Figure 3. It can be noticed that in systems with period T_{max} equipped with LVDs spanning 2 and 3 stories (i.e., $x = 2$ and $x = 3$) and subjected to the firm soil excitation the acceleration response is actually greater than that of the structure without LVDs (i.e., $\max\left[\sigma\left(\ddot{\boldsymbol{u}}_{\boldsymbol{d}}^{\boldsymbol{abs}}\right)\right] > \max\left[\sigma\left(\ddot{\boldsymbol{u}}_{\boldsymbol{0}}^{\boldsymbol{abs}}\right)\right]$). Further, in systems with period T_{avg} subjected to the firm soil excitation the optimal response reduction is significantly smaller than that in systems with period T_{min}. For this reason, this work focuses only on structures with period (T_{min}) as highlighted in Table 1.

Results of the optimization process are shown in Figure 4 and Figure 5. Figure 4 shows the optimal RR that can be achieved with the addition of VDs. It is noted that x does not have an effect on the optimal RR. As previously defined, the SubOpt UD and SubOpt RRs are constrained to 90% of the Opt UD and Opt RRs, respectively.

Figure 5 shows the value of the average damping constant (c) over all stories that produces the optimal RR shown in Figure 4. Observing the results for the Opt and Opt UD solutions it is noted that in structures subjected to the soft soil excitation the optimal c is equal to c_{ref}, whereas in structures subjected to the firm soil excitation the optimal c for the taller structures (i.e., larger values of n) is smaller than c_{ref}.

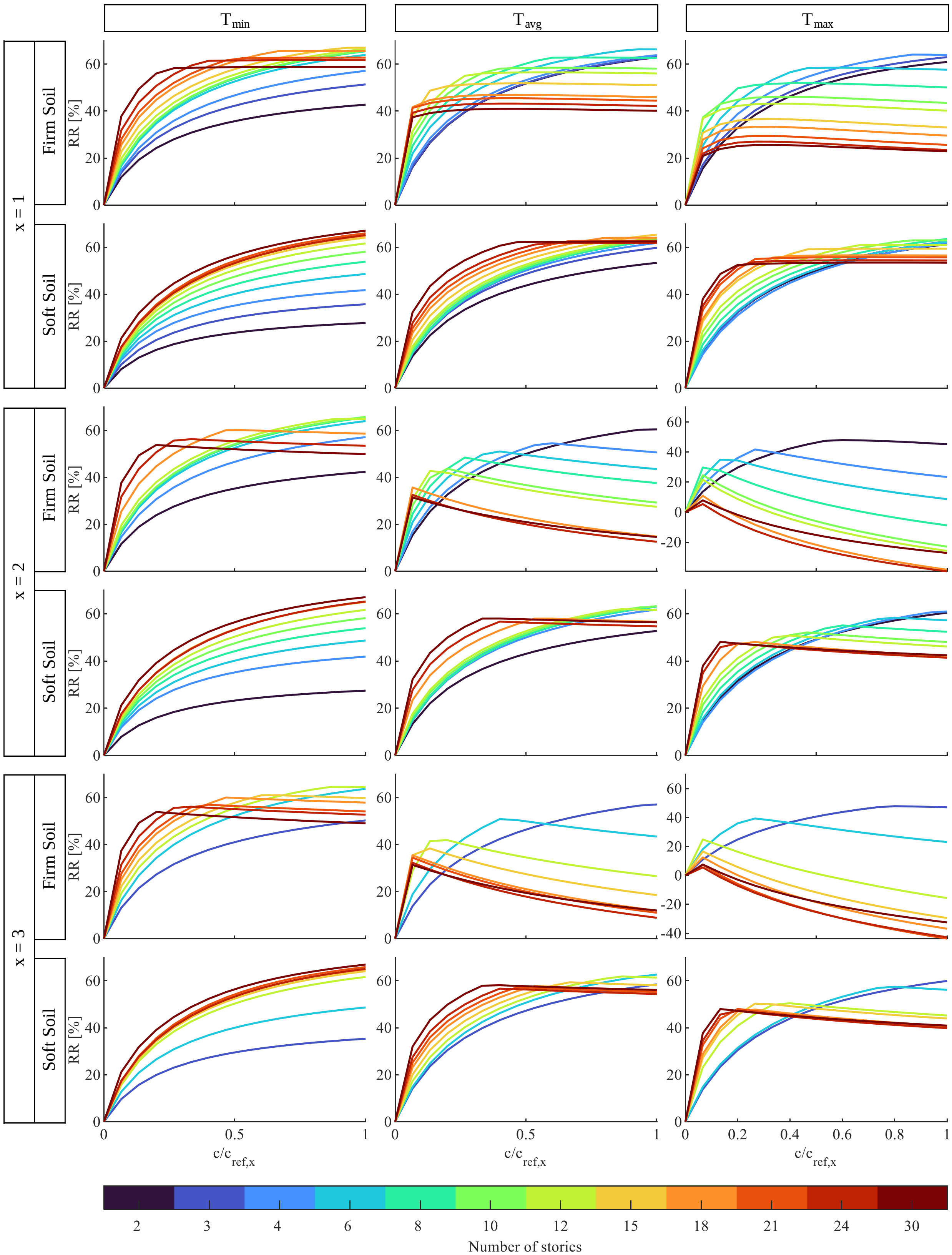

Figure 3. Evolution of RR vs. c with LVDs spanning x stories.

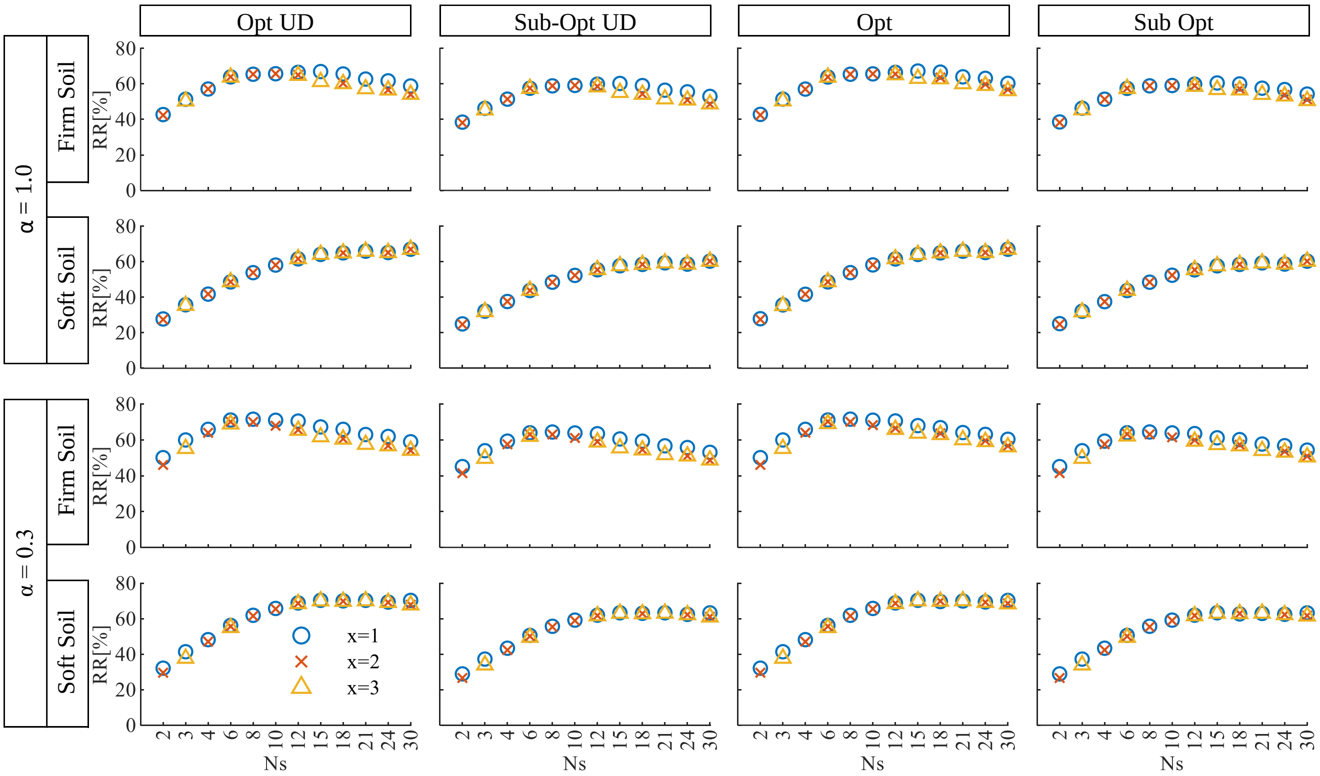

Figure 4. Optimal Response Reduction.

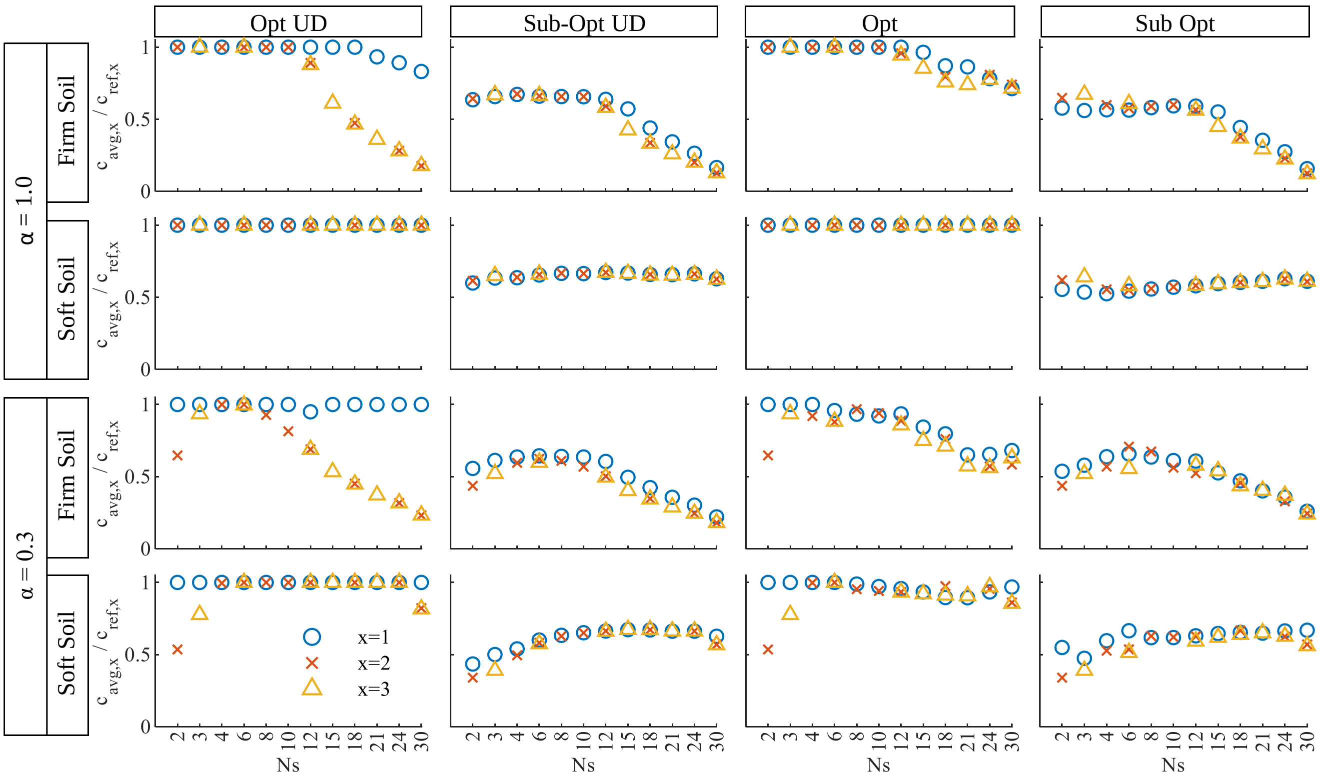

Figure 5. Optimal damping constants (average over all stories).

Results shown in Figure 5 also indicate that the effect of placing VDs spanning multiple stories on the average value of the optimal damping constant (c) is negligible in most cases.

Next, the effect of the optimal solutions on the reduction of inter-story drifts (ID) was evaluated. For this purpose, Monte Carlo (MC) simulation was used, and the ID response was set equal to the mean response to 400 realizations of the excitation. Results are shown in Figure 6. It is noted that although ID reductions were not considered as the optimization objective, important ID reductions are achieved in most cases. In soft soil cases, the effect of x is negligible. In firm soil cases, values of x greater than 1 seem to achieve smaller reductions in high-rise buildings. This is specifically observed in the Opt UD solution, where the smaller optimal values of c produce much smaller reductions of IDs in buildings subjected to the firm soil excitation.

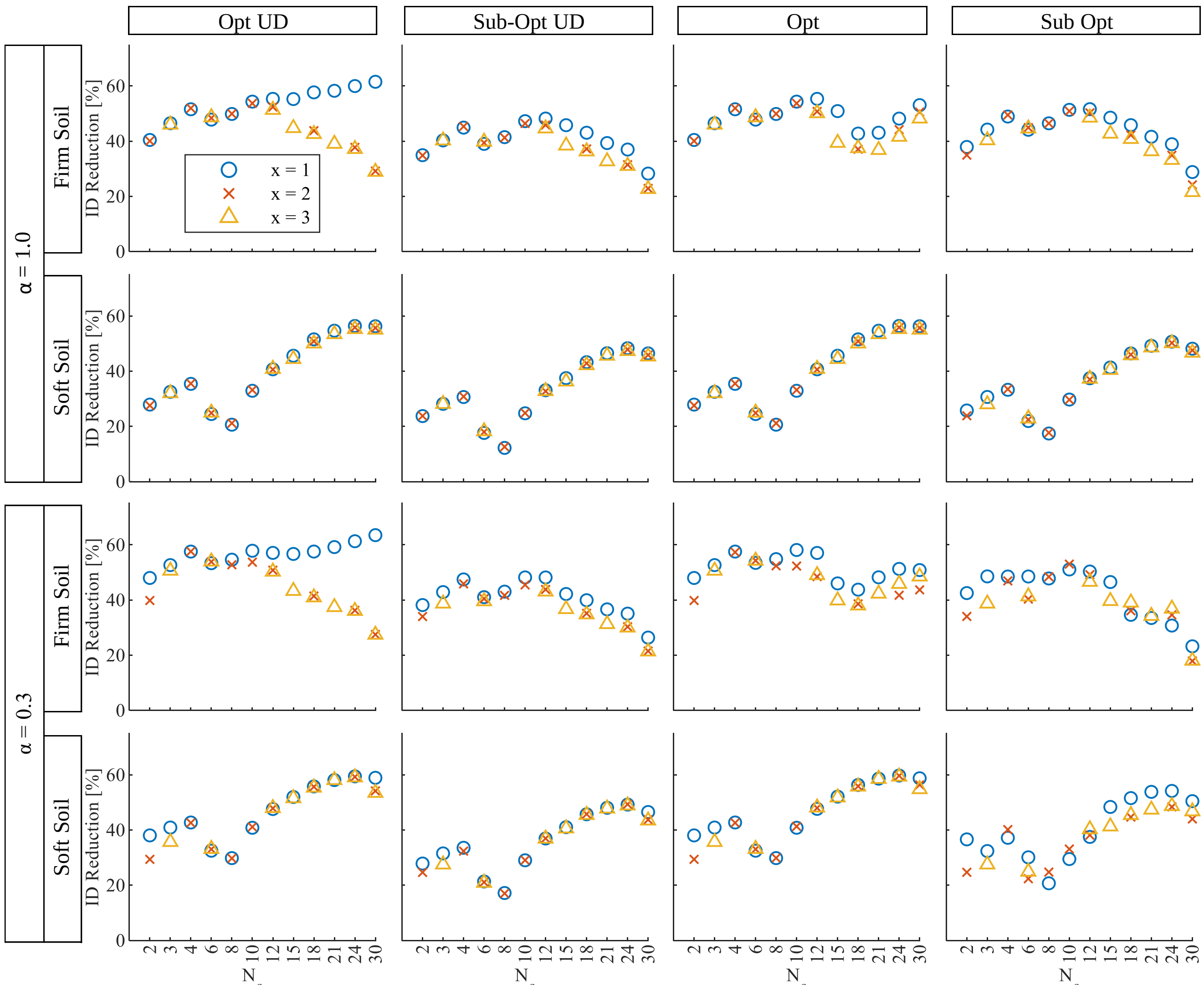

Figure 6. Inter story drift reductions achieved by the optimal solutions.

CASE STUDY

A real 16-story office building was modeled as a 2D, 16 DOF linear elastic model (1 horizontal DOF per story). The condensed model has a first mode period $T_1 = 0.83\ s$. Two configurations of VDs were considered: VDs spanning 1 and 2 stories. The same 4 optimal solutions described in the previous section were determined using optimization algorithms. The seismic excitation was given by a set of 44 representative Chilean ground motions, and the objective function was defined in terms of median response values. Due to computing time limitations, and in order to explicitly consider the nonlinear behavior of the NLVDs, the optimal non-uniform distributions of NLVDs were found using only one ground motion. As defined before, the maximum value of c considered for each type of VD is the value that produces $\xi_1 = 30\%$ (supplemental damping only). The maximum c for LVD ($c_{ref,L}$) was found iteratively through complex eigenvalue analysis, and the maximum c for NLVD ($c_{ref,NL}$) was found iteratively through harmonic linearization. The values obtained are shown in Table 2.

Table 2. c_{ref} values used in the case study.

x	$\boldsymbol{c_{ref,L}}$ $[\boldsymbol{kN(s/m)}]$	$\boldsymbol{c_{ref,NL}}$ $[\boldsymbol{kN(s/m)^{0.3}}]$
1	4099	7109
2	2048	5775

The obtained optimal distributions for $x = 1$ and $x = 2$ are shown in Figures 7 and 8, respectively. It can be noted that for both values of x and α the Opt UD distribution matches the maximum considered values of c (Max UD distribution). For both values of x, the NLVDs SubOpt UD solutions require higher values of c than LVDs SubOpt UD solutions. The optimal non-uniform solution (Opt) is similar to the Opt UD solution except for a small number of dampers. For all the observed cases suboptimal solutions require much smaller damping constants than the optimal solution, even though the level of response reduction is very close to the optimal (i.e., by definition, 90% of the optimal).

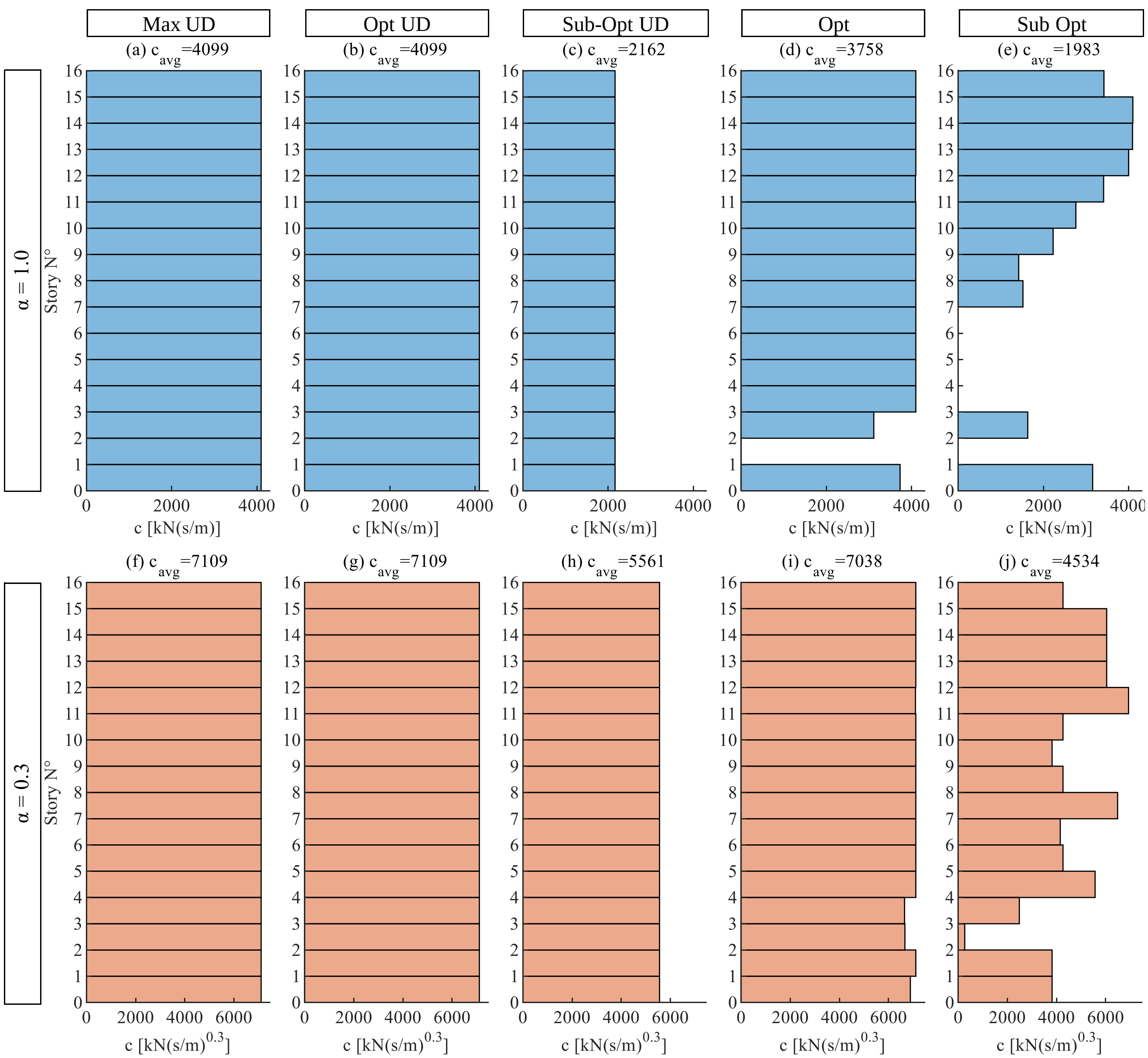

Figure 7. Optimal height-wise distributions of dampers spanning 1 story (x=1).

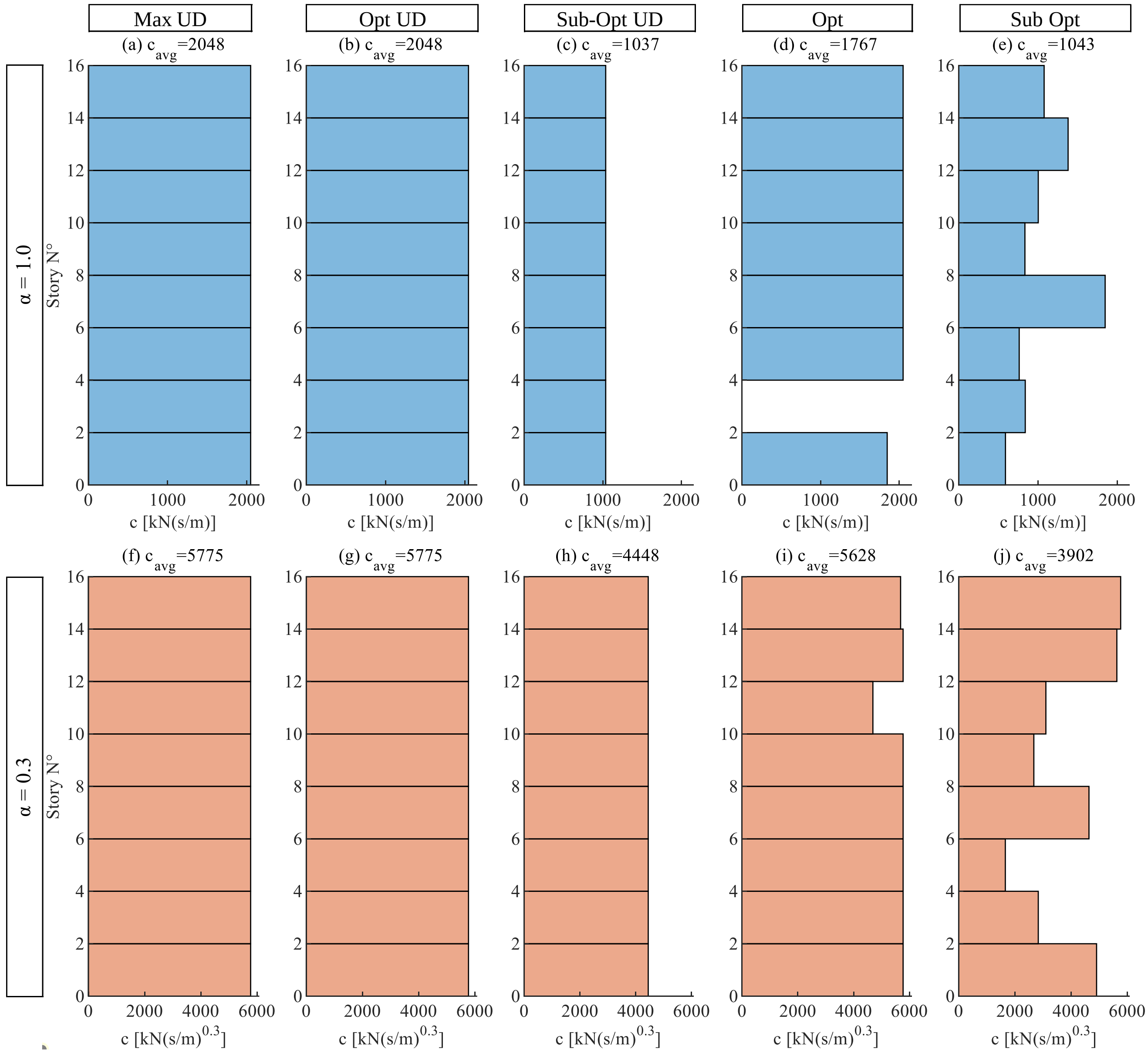

Figure 8. Optimal height-wise distribution of dampers spanning 2 stories (x=2).

The effect of the optimal solutions on the dynamic response of the structure is shown in Figure 9. Part (a) shows the optimal PFA_{max} reduction found by the optimization algorithm. It is noted that for all the distributions considered, LVDs achieved larger reductions than NLVDs. The effect of the number of stories spanned (i.e., the effect of x) on the reductions is negligible.

Part (b) of the same figure shows the ID reductions produced by the optimal solutions. It is noted that although the ID reduction was not an optimization objective, important reductions are nevertheless achieved. Both values of α led to similar ID reductions and the number of stories spanned by the devices (x) does not have a significant impact. A trend similar to that of the ID reductions is observed in the elastic base shear reductions (part (c)).

Parts (d) and (e) of the figure show the maximum VD force and the dissipated energy ratio, respectively. In both cases, NLVDs seem to perform better than LVDs in the sense that forces are smaller, but the dissipated energy is larger. This is an advantage of NLVDs over LVDs that is frequently mentioned in the literature.

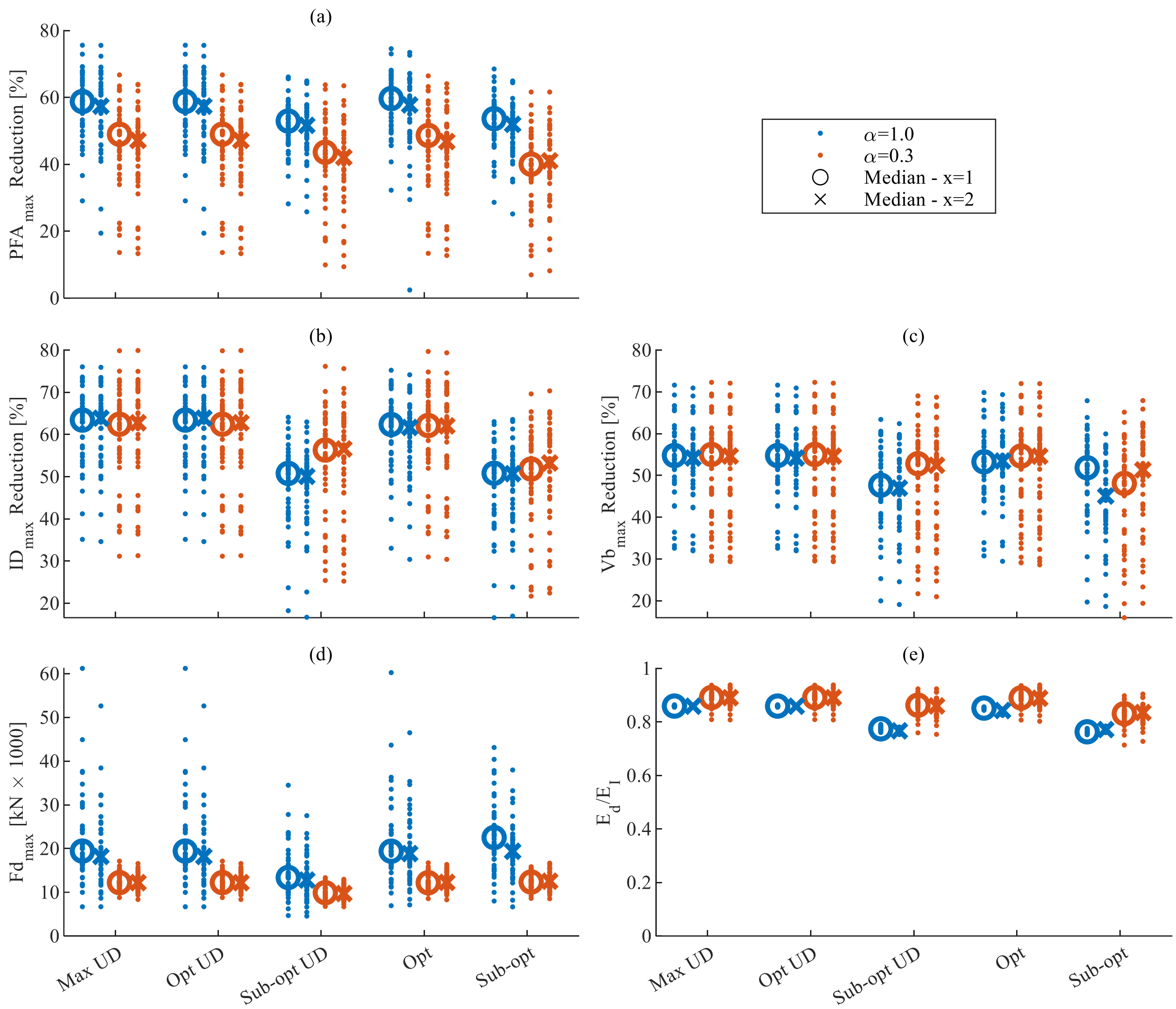

Figure 9. Effects of damper distributions on dynamic responses.

The PFA profiles produced by the optimal solutions can be observed in Figure 11, which also show PGA values at the zero ordinate. It can be noted that all the distributions led to notable reductions of PFAs. As mentioned before, better reductions are achieved with LVDs. The floor level at which the PFA reaches its maximum value changes from the roof level when there is no supplemental damping to the first floor level when the supplemental damping is optimal.

All the optimization procedures performed in this study were carried out assuming that the supplemental dampers are purely viscous dashpot elements. The stiffness of the braces and the intrinsic axial stiffness of the devices were ignored. In the following section of this case study supplemental dampers are modeled by a Maxwell element. When $x = 1$ the axial stiffness of each device was set equal to the lateral stiffness of the story at which the device is located ($k_{Mxw} = 1\ k_{sto}$). When $x = 2$ the axial stiffness of each device was set equal to the series combination of the lateral stiffnesses of the stories spanned by the device.

Figure 10 shows floor spectra at the roof level when the height-wise distribution of supplemental dampers are the optimal distributions shown in Figures 7 and 8. When the axial stiffness of the dampers is considered, the corresponding spectra are displayed in dashed lines. It is noted that when VDs are modeled as pure dashpot elements the reductions in floor spectra ordinates are greater than when the axial stiffness is included. This effect is more notable in the range of periods around the second mode period. These observations are valid regardless of the value of x and the value of α.

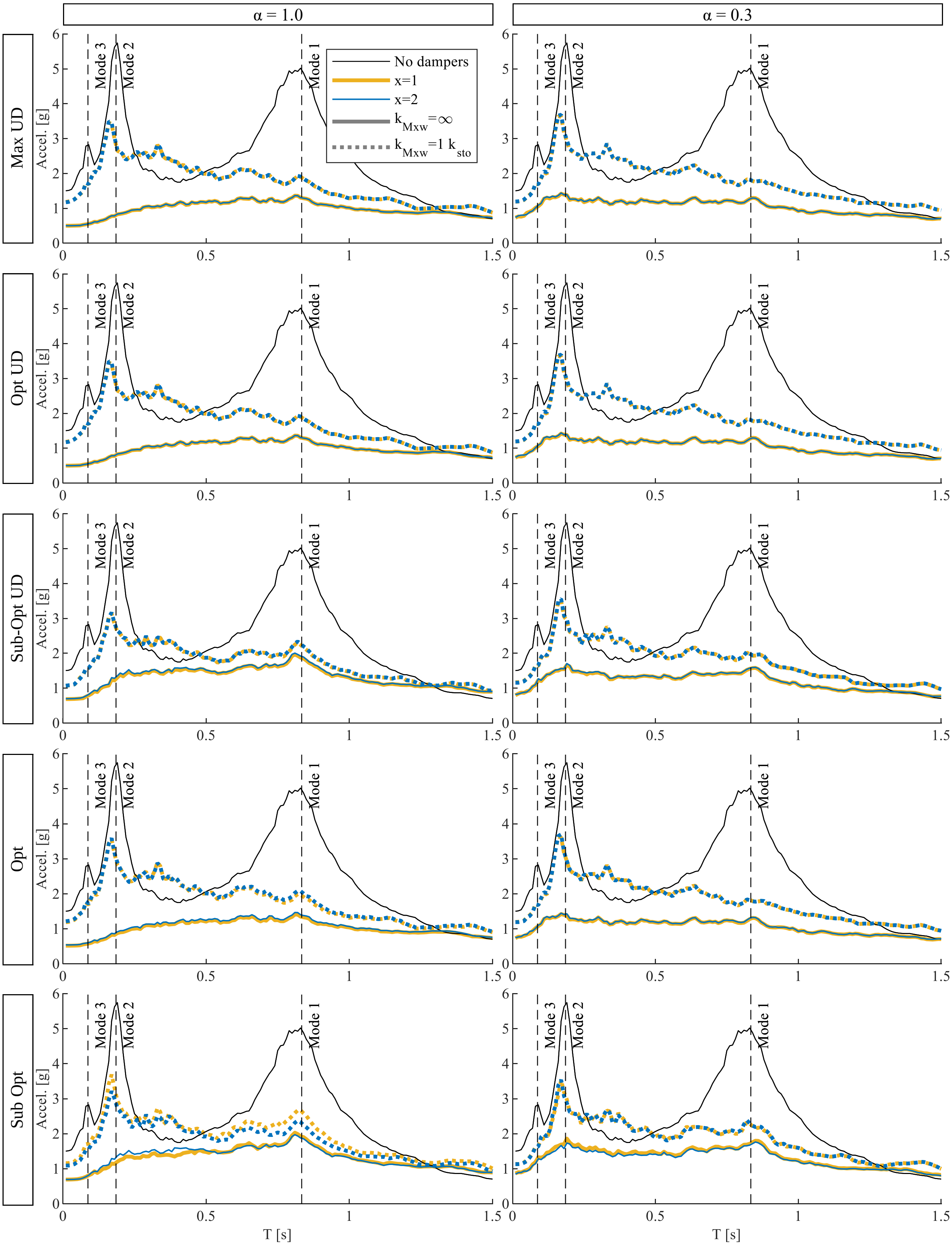

Figure 10. Roof level floor spectra.

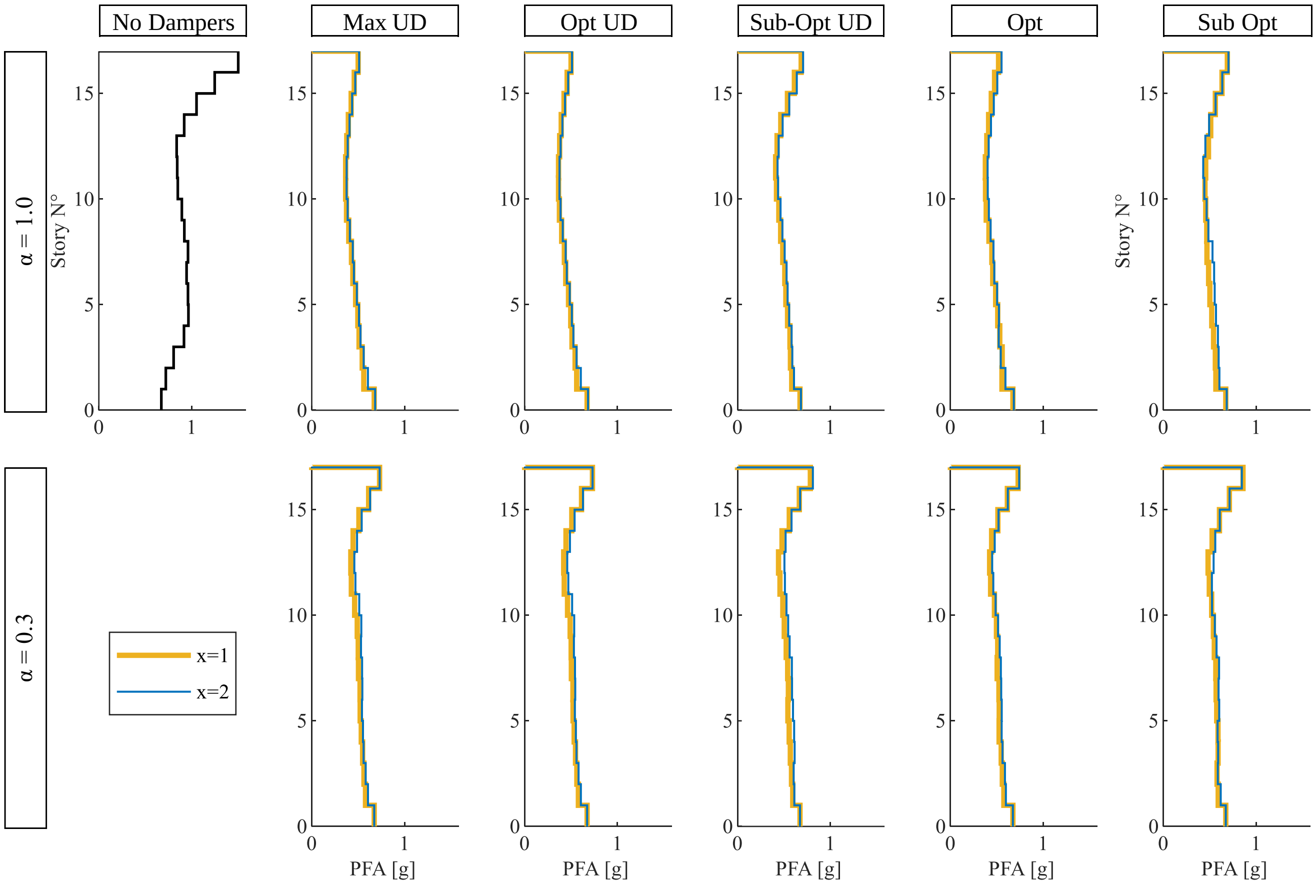

Figure 11. PFAs with optimal VD distributions.

CONCLUSIONS

Height-wise distributions of viscous dampers were found for the optimal reduction of peak floor accelerations, and the effect of dampers connecting non-consecutive floor levels was explored. It was found that, in relatively rigid structures, damper configurations spanning multiple stories can achieve the same level of reductions as configurations with one device per story.

Suboptimal solutions that minimize the amount of added damping but are constrained to a fixed level of reduction were also obtained. These solutions achieve 90% of the optimal response reductions but with significantly less damping than the optimal solutions.

Although the optimization objective was the reduction of peak floor accelerations, important reductions of inter-story drifts were also achieved. The case study also showed that optimal solutions dissipate large amounts of energy.

The effect of the series stiffness of the dampers was considered in the case study. It was shown that when the value of the series stiffness is set equal to the stiffness of the story at which the damper is located the acceleration response (i.e., floor spectra) is greatly affected. Hence, whenever possible (the actual value of the series stiffness is usually unknown) the series stiffness should be explicitly considered in order to properly estimate floor accelerations in buildings equipped with supplemental viscous dampers.

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