A Parametric Study Involving
Passive and Semi-active Control Schemes for Earthquake Protection of Buildings

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SUMMARY:
Semi-active devices are receiving increasing interest in the field of seismic protection of Civil Engineering structures. So far, several semi-active control devices have been developed and their efficiency demonstrated in numerical simulations and full scale implementations. In this context, this paper describes a parametric study that compares the performance of such devices with traditional passive control systems, in order to analyse the interest of moving from robust passive solutions to relatively more complex semi-active control systems.
For this purpose, a dynamic model was developed in Matlab software aiming to analyse single-degree-of-freedom structures with different fundamental periods of vibration, employing several passive and semi-active protection systems. The seismic events were simulated based on generated artificial accelerograms defined for each soil and seismic type indicated in the European regulation (EC8). The calculated response of these structures allowed to conclude that an ideal control scheme depends both on the structural properties and the seismic input.

Keywords: Earthquake engineering, Semi-active devices, Vibration Control

1. INTRODUCTION

In the recent past, several passive, active and semi-active control systems have been developed for the protection of structures against hazards such as earthquakes and strong wind storms. Although active control schemes provide upper class protection, they demand a high investment cost and require powerful external sources of energy, making these systems not attractive in the context of Earthquake Engineering problems. On the other hand, semi-active systems offer the reliability of passive solutions with increased performance due to the added adaptability and versatility (Kurino *et al.* 2009).

One of the most generalized and well accepted control systems is the HiDAX developed by Kurino *et al.* (2003 and 2009). More than 15 buildings have systems of this type or are currently being implemented. HiDAX system is designed to achieve maximum hysteretic dissipation of the mechanical energy present in structures induced by intense external loads. Other authors have developed different devices, namely the ‘Resettable semi-active stiffness damper’ (RSASD) by Yang *et al.* (2000 and 2007), which uses the same control concept and algorithm. In this control scheme the device remains locked, absorbing elastic energy in a compressed fluid. When it reaches maximum pressure, the controller opens a bypass valve that allows the fluid to flow between two chambers and dissipate the restored elastic energy.

In order to justify adequately the use of such systems, their efficiency needs to be compared with other traditional solutions like passive linear or non-linear dampers. In many papers, semi-active control is compared with the situation of uncontrolled structure, which is not sufficient to prove the merit of these systems. Therefore, in this paper the authors investigate the efficiency of a semi-active system in structural frames by comparing it with several passive protection designs. One hundred artificial accelerograms (10 for each earthquake type described in the European regulation, soil A to E, type 1 and 2) and a full array of structural properties were used in order to understand the control performance in its full scope.

2. CONTROL SCHEMES

One of the most well-known ways to control structural frames consists in adding a bracing system like the one represented in Figure 2.1.

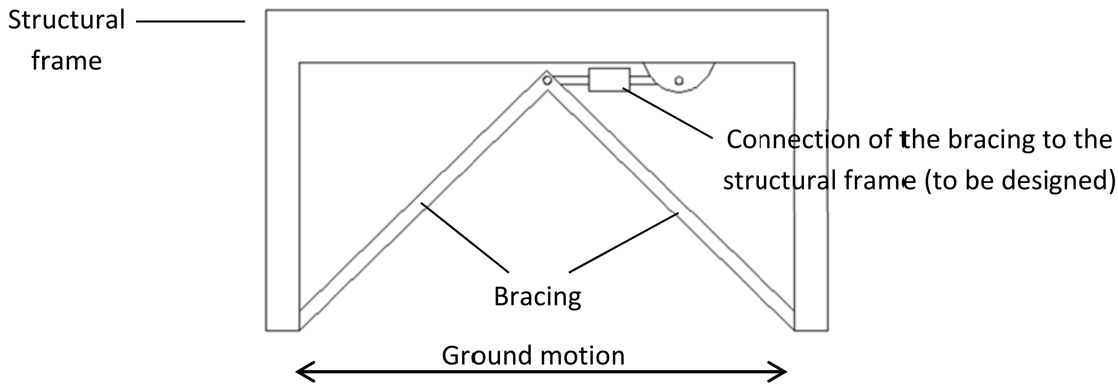

Figure 2.1. One bay frame and control implementation scheme

In this case the connection of the bracing to the structural frame is a key issue which affects the dynamic response. This is why it is necessary to consider the relative stiffness of this element when compared to the stiffness of the structure. In order to dissipate energy, several types of passive devices can be used by connecting the inverted V frame with the structure, namely rigid and rigid/plastic connections, friction and viscous dampers (Soong and Spencer 2002). The results presented in the literature show that viscous dampers are, comparatively to others, a more promising solution in terms of energy dissipation capacity (Agrawal *et al.* 2003). In this paper, the authors use viscous dampers and complete rigid connections (without damping devices) for comparison purposes.

Alternatively to passive solutions, several semi-active devices and algorithms have been proposed for earthquake design commanded by clipped LQR control (Kurata *et al.* 1999 and 2000), resettable semi-active stiffness dampers such as the HiDAX and the RSASD (Kurino *et al.* 2003 and 2009 and Yang *et al.* 2000 and 2007), semi-active friction devices (Nishitani *et al.* 2003) and non-resonant control (Nasu *et al.* 2001).

The resettable semi-active stiffness system is one of the most well accepted semi-active solutions because its energy dissipation capacity is designed to be higher than any other system (Kurino *et al.* 2003 and Agrawal *et al.* 2003). So, in this paper, the authors choose this semi-active system for comparison purposes.

2.1. Passive system design

2.1.1. Passive linear viscous dampers

It is well established that, in order to work properly, viscous dampers have to be designed aiming at achieving optimum (maximum) energy dissipation. Low resistance will result in low energy dissipation and high resistance will lead to a rigid connection, meaning higher natural frequencies and rigidity, but also low energy dissipation. As a result, it can be concluded that the structural damping ξ has a convex evolution, meaning there exists one value of C_{optm} that maximizes ξ.

Considering a system of 1-degree-of-freedom (1-DOF) with natural angular frequency ω_0, structural stiffness K_0, bracing stiffness k, and a connection constituted by a passive linear damper with damping constant C, the analytical expressions that give the ideal damper parameters was presented by Kurino (Kurino *et al.* 2003). In this approach, the rigidity ratio α is defined as

$$\alpha = {}^{k}/_{K_0} \tag{2.1}$$

leading to the ideal damper coefficient (C_{optm}) given by

$$C_{optm} = \frac{k}{\omega_0}\sqrt{\frac{2+\alpha}{2(1+\alpha)^2}} \tag{2.2}$$

If a linear viscous damper with such coefficient is considered, the new structural frequency ω and the new structural damping ξ_{optm} are determined according to the following expressions:

$$\omega = \omega_0\sqrt{\frac{2(1+\alpha)}{2+\alpha}} \tag{2.3}$$

$$\xi_{optm} = \frac{\alpha}{4\sqrt{1+\alpha}} \tag{2.4}$$

2.1.2. Passive non-linear viscous dampers

In this work the non-linear viscous dampers were considered to have a force/velocity relationship dependent on the damper coefficient C_{NL} and velocity coefficient α_{NL}. Considering v the velocity of the structure, the force in the damper F_{damper} is given by

$$F_{damper} = C_{NL}|v|^{\alpha_{NL}}sign(v) \tag{2.5}$$

The velocity coefficient α_{NL} usually varies between 0.3 and 1 in seismic applications. In this study a coefficient α_{NL}=0.5 was considered. For the non-linear passive damper, there is not an analytical formula that gives the optimum damper coefficient. In this case, the design of the non-linear damper depends not only on the structural properties, but also on the expected response (meaning that it depends on the seismic input). When designing a structure, it is intended to have an expected structural response near to the design limit. This means that the non-linear damper should be designed to work in that range in order to maximize its efficiency.

Taking into account that the objective of this work is to compare the responses between several control strategies, there was a need to develop a process to adequately design the non-linear dampers. One process that provided good results can be described as follows:

1. First, simulate the linear passive control system and determine the peak response velocity;
2. This peak velocity is considered as the estimated velocity for the non-linear passive design (v_{estim});
3. The damper coefficient is found so that the non-linear damper has the same force as the linear damper at the estimated velocity (Eqn. 2.6).

A sensitivity analysis was done in order to understand whether a variation in Eqn. 2.6 would enhance the efficiency of the non-linear semi-active system. It was concluded that a raise of 10% in the damper coefficient (Eqn. 2.7) would provide better results. This is a consequence of the estimated velocity being different from the response velocity.

Another process was considered which consisted in an iterative process where the damper coefficient was determined using the simulated response velocity of the non-linear damper. Nonetheless, the process proved to be very time consuming and the improvement was small. So Eqn. 2.7 was employed to design non-linear passive dampers.

$$C_{NL} \cdot {v_{estim}}^{\alpha_{NL}} = C_{optm} \cdot v_{estim} \;=>\; C_{NL} = C_{optm} \cdot {v_{estim}}^{1-\alpha_{NL}} \tag{2.6}$$

$$C_{NL} = 1.1 \cdot C_{optm} \cdot {v_{estim}}^{1-\alpha_{NL}} \tag{2.7}$$

2.2. Semi-active system design

Instead of having one passive viscous damper, in the semi-active design the device was considered to be a variable viscous device, meaning that the damping coefficient C can be controlled during the seismic event. The resettable control algorithm was employed (Kurino *et al.* 2003, Yang *et al.* 2007). This control law causes the device to be rigid while storing elastic energy, and when the structure inverts the movement the device is released, thus dissipating the stored energy. This procedure is accomplished by the following control law:

$$\begin{cases} F\dot{x} \geq 0 \quad \cup |F| \leq F_0: & C = C_{max} \\ F\dot{x} < 0 \quad \cap |F| > F_0: & C = C_{min} \end{cases} \tag{2.8}$$

In Eqn. 2.7 $\dot{x}$ stands for the derivate of the structural displacement x, thus meaning structural velocity. This control scheme allows the device to always act in opposition to the motion of the structure. The damping achieved by such a semi-active system ($\xi_{optm,sa}$) can be determined by (Kurino *et al.* 2003)

$$\xi_{optm,sa} = \frac{2\alpha}{\pi(1+\alpha)} \tag{2.9}$$

Fig. 2.2 shows a comparison of the damping augmentation determined in Eqn. 2.4 and 2.9 for different rigidity ratios α. It can be seen that the semi-active can achieve significant improvement in relation to an equivalent passive linear viscous device.

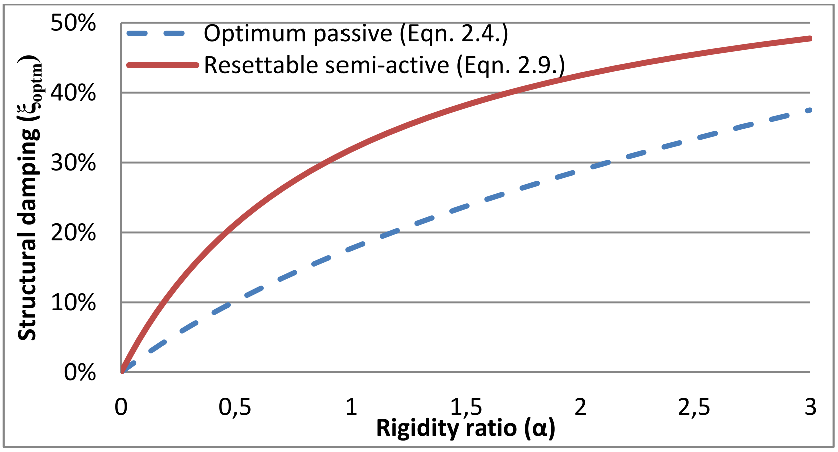

Figure 2.2. Damping with different control strategies

Fig. 2.3 shows an example of the hysteretic response of the linear passive viscous and semi-active device for the same response amplitudeδ. It can be seen that the semi-active dissipates much more energy than the passive device. However, the peak force is much higher for the semi-active device.

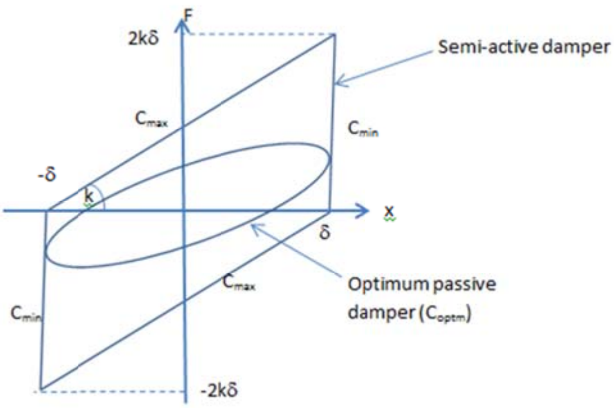

Figure 2.3. Hysteresis loop of semi-active and passive dampers under harmonic response $x = \delta e^{i\omega t}$(Kurino *et al.* 2003)

3. ARTIFICIAL ACELEROGRAMS

To compare the efficiency of the control systems the current European seismic design code (EN1998-1) was considered. In Fig. 3.1 it is possible to see the Eurocode 8 spectra for the various seismic events (eg. A-1 means soil A type 1). Also, the average (between the 10 generated acelerograms for each seismic event) artificial spectra are represented (eg. Art.A-1 means average artificial acelerograms spectra for soil A type 1). The design acceleration on type A ground was considered to be 3m/s^2.

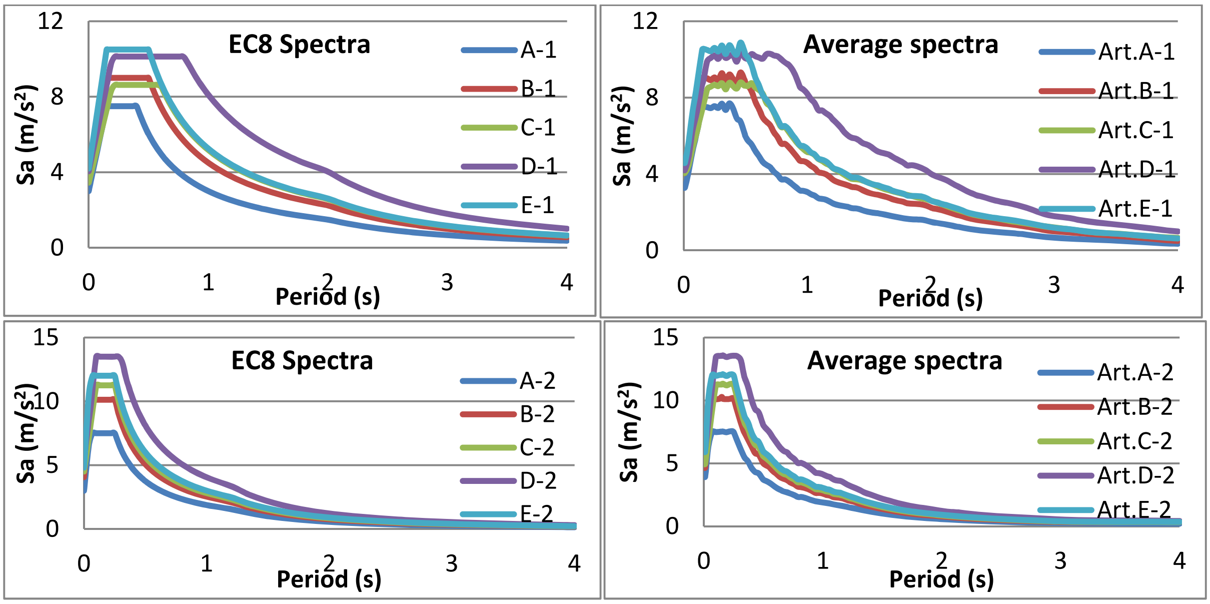

Figure 3.1. Eurocode 8 spectra and average artificial generated spectra

4. NUMERICAL SIMULATIONS

The developed numerical simulations involved a 1-DOF structure with different rigidity ratios and fundamental periods. Each pair of values of rigidity ratio and fundamental period characterizes one single structure. Each of these structures was subjected to 10 artificial acelerograms for each type of seismic event (the averaged value was considered for the results analysis). The structural inherent damping was considered to be 3%. In this problem a bracing system is added, meaning that the structural response depends not only on the fundamental period but also on the bracing ratio of rigidity.

In this study, the objective is to evaluate the effect of several control strategies in reducing the seismic response for every structure and every seismic input. For this purpose, 4 different types of structural protection (different bracing connection) were considered:

1. Optimum passive linear damper;
2. Passive non-linear damper (α_{NL}=0.5). To design this damper Eqn. 2.7 was employed. The estimated velocity was taken as equal to the average peak velocity simulated with the optimum passive linear damper;
3. Semi-active damper with the control law described in Eqn. 2.8;
4. Infinitely rigid connection between bracing system and structure.

For every structure and every artificial acelerogram, the peak displacement (d_{max}^{i}) and the peak control force (F_{max}) were determined. It's worth mentioning that, since the peak displacement is independent of the structural mass, only the peak control force needs to be normalized to the respective structural gravity force (i.e., divide the calculated control force by *mg*).

5. RESULTS

In Fig. 5.1 it is possible to see an example of the detailed results for the seismic input type 1 for soil A. It can be observed that the semi-active damper has, generally, a lower peak displacement than the passive linear damper, which is a consistent result with those available in the literature (Kurino *et al.* 2003). It can also be observed that the maximum displacements decrease with the increasing of the ratio of rigidity, and the rigid connection scheme exhibits the lowest reduction of displacements for the same rigidity ratio augmentation. As regard to the magnitude of the control force, it can be concluded that both passive viscous dampers exhibit similar behavior and the semi-active scheme reaches twice the force of the viscous dampers. Rigid connection responds with very high control force response.

In order to compare the performance of the different structural schemes, the semi-active system was selected as the reference method to control seismic vibrations. The rigid connection scheme was not considered because clearly is not an interesting solution. Figures 5.2 to 5.4 show the ratio between the semi-active and linear/non-linear passive control responses for the different seismic input. In these graphs, blue regions are those where the semi-active response is lower (ratio below 1). From these results it is possible to observe the full scope sensitivity of the parameters involved. Namely it can be seen that:

1. The semi-active system exhibits lower structural displacements in the region of the constant spectral acceleration branch (maximum amplification). For this reason, in type 2 seismic input the blue region (typically where the semi-active responds with lower displacements than the non-linear passive system) the peak displacement quotient is narrower than in the type 1 seismic input;
2. The semi-active system most efficient region corresponds typically to situations where the displacement quotient is close to 0.9 and the force quotient is close to 2. This means that, comparing the semi-active scheme with the passive non-linear damper, when the semi-active system is more efficient the needed control force doubles for the achievement of 10% reduction in displacements;
3. The non-linear viscous damper is more efficient in the regions of lower amplification and rigidity ratio;
4. When the rigidity ratio increases the semi-active most efficient region enlarges. This mean that semi-active system relative efficiency increases with the ratio of rigidity.

6. CONCLUSIONS

This study simulated the response of a well-known semi-active system and compared it with passive control strategies for structural frames. The choice of the structural protection scheme depends on several parameters, namely:

1. Structural fundamental period;
2. Bracing rigidity ratio;
3. Soil and seismic input type;
4. Design criteria (displacement, force and others if necessary).

The semi-active system exhibited a maximum improvement of about 10% in some cases. However, this improvement was achieved by doubling the peak amplitude of control force. Therefore, it can be concluded that semi-active systems should be properly reasoned to mitigate seismic vibrations. In particular, the results demonstrated that, taking this studied example, the semi-active strategy is adequate for controlling buildings when the following criteria are met:

1. Structural properties are within the regions with displacement quotient marked at blue:
    a. Typically structures with fundamental periods in the constant spectral acceleration branch (maximum amplification). This is most probable when seismic event type 1 is the most critical for the design;
    b. Bracings constructed have high rigidity ratio;
2. The control force does not condition the design, so only the structural response is critical.

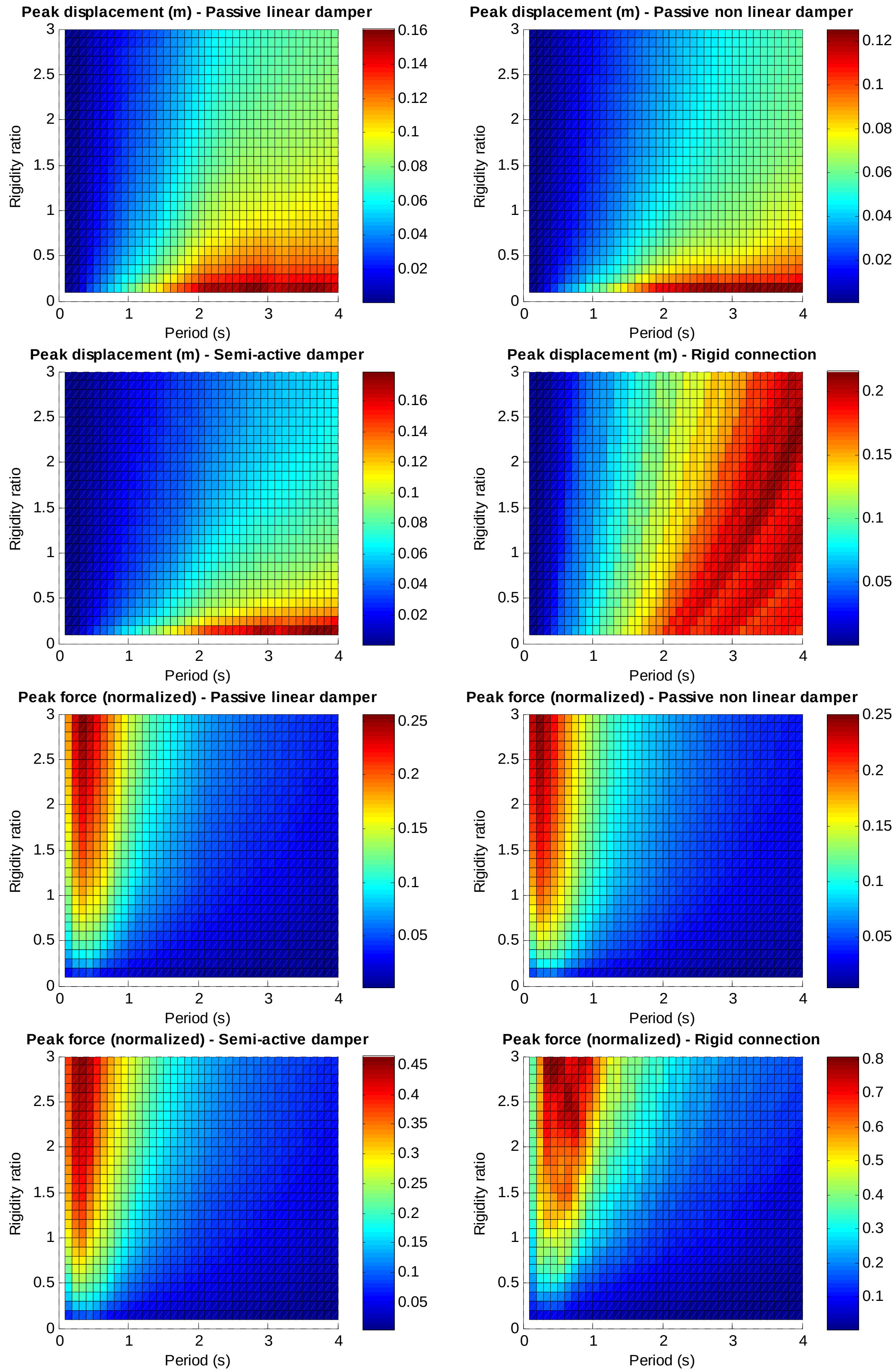

Figure 5.1. Detailed results for soil A type 1

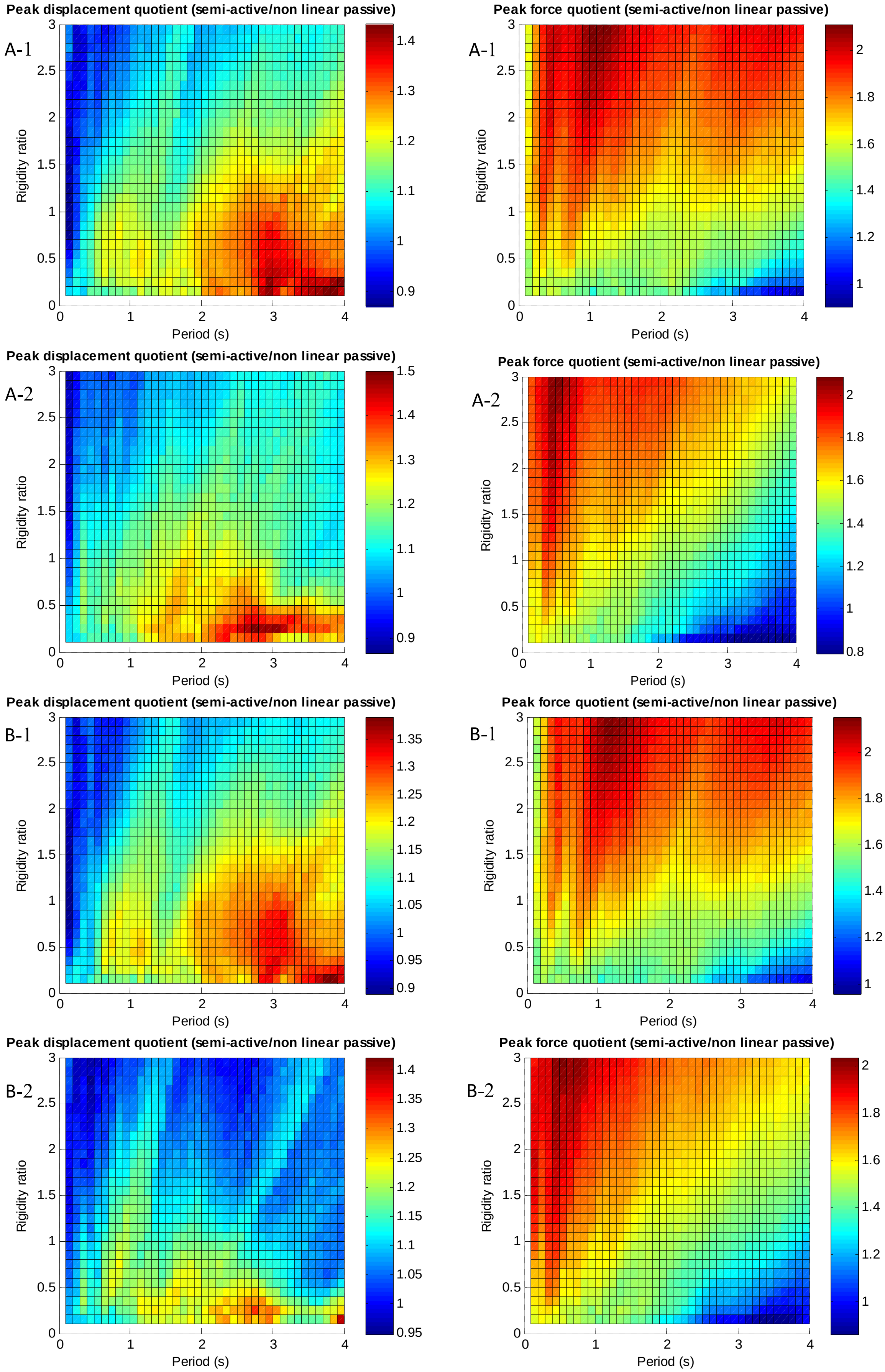

Figure 5.2. Comparison between non-linear passive and semi-active strategies - Soil A and B type 1 and 2

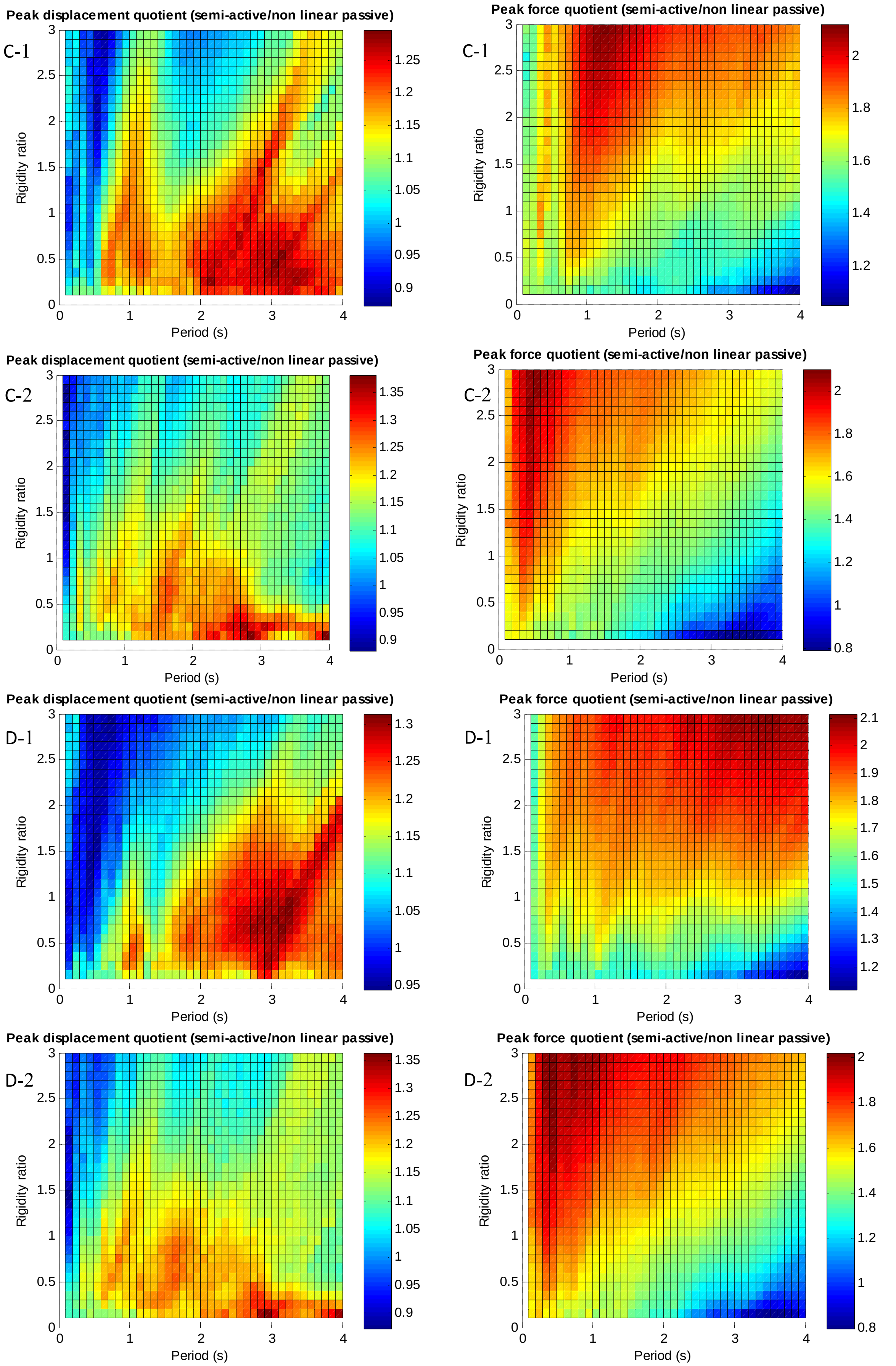

Figure 5.3. Comparison between non-linear passive and semi-active strategies - Soil C and D type 1 and 2

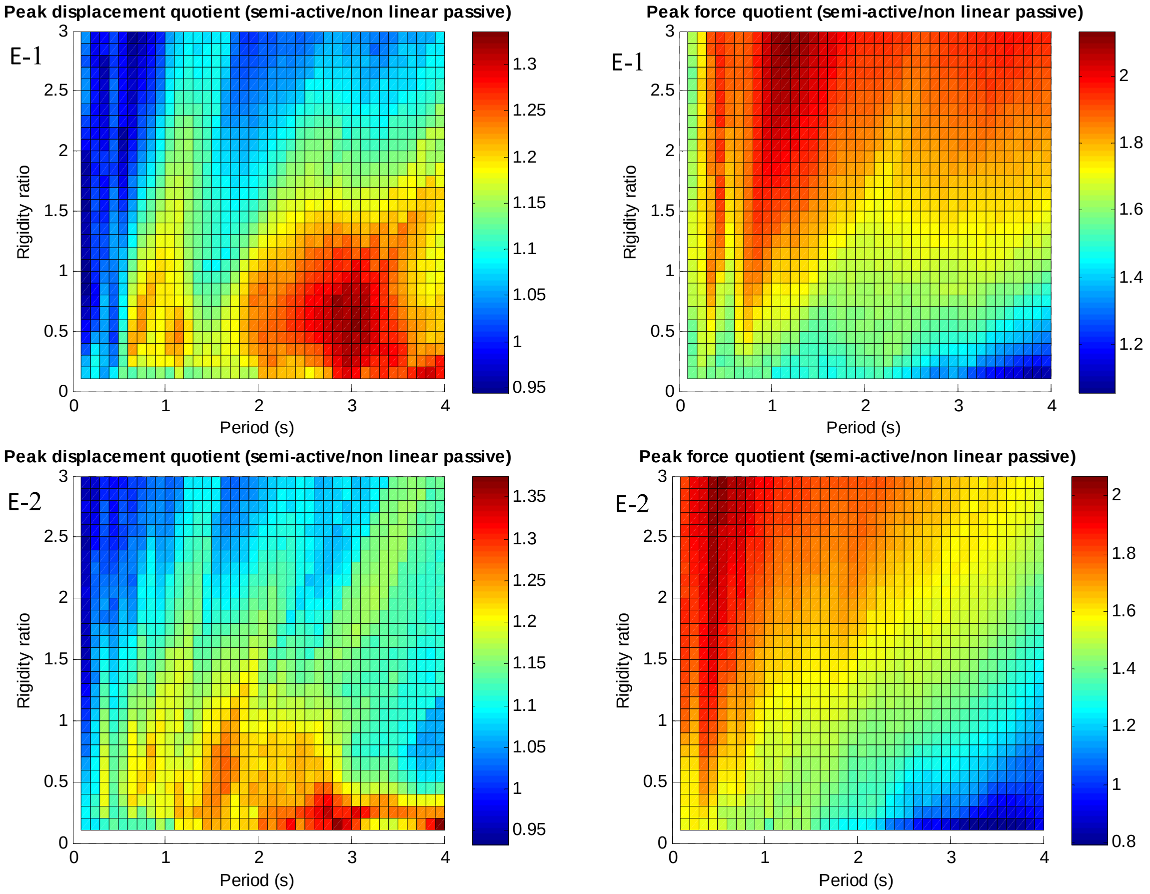

Figure 5.4. Comparison between non-linear passive and semi-active strategies - Soil E type 1 and 2

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