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SEISMIC ANALYSIS OF BRIDGES WITH SEMI-ACTIVE DAMPERS

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SUMMARY

The semi-active devices are seismic protection systems whose characteristics can be modified during the earthquake action in order to improve the structural behavior. The main issue in the optimization of the seismic behavior of a structure with semi-active devices is the correct definition of the activation criterion. This criterion involves the definition of the time instant when the device should be turned on and the duration of the activation period. In this paper, the results of a semi-active algorithm to apply in a variable damping device are presented. It also presented a simplified method to estimate the optimal characteristics of variable damping semi-active devices.

INTRODUCTION

Within natural disasters, the earthquakes are the ones that have more impact on the populations, not only because of the human losses and material damages but also for its unpredictable character. This scenario has motivated the researchers to pursuit new solutions in the improvement of structural anti-seismic behavior. As result of this effort, techniques to diminish the earthquakes effects have been developed, construction techniques in general and more recently, protection techniques.

The use of seismic protection systems allows the improvement of structural global dynamic behavior. These systems have the ability to change the structure dynamic characteristics or to influence the seismic action transmission to the structure. The seismic protection systems can be divided in four groups, accordingly to its properties: passive, active, hybrid and semi-active. Passive protection systems do not need external energy to operate. The most common examples of this type of systems are the viscous dampers and the base isolation systems. The active protection systems are based on the on-line forecast of the structural dynamic response and in the instantaneous application of forces in the structure to improve its global behaviour. The reaction forces can be produced by hydraulic actuators which, accordingly to the displacements measured, input the necessary movement to eliminate or reduce the seismic effect. The hybrid control consists in a combination of passive and active systems, i.e. a hybrid system has an active control system actuating on a structure with passive protection devices.

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The semi-active systems can be designated, in a generic way, as controllable passive devices, i.e., passive protection systems whose properties can be modified during the seismic action, in order to optimize the structural behavior. The most important advantage, when compared to active systems, is that they have low energy requirements, what can be a major advantage during seismic events [1]. The variable stiffness device, variable damping device, controllable fluids device and variable friction device are examples of semi-active seismic protection devices. In this paper, the results of a study about the use of variable damping device for bridge protection are presented [2].

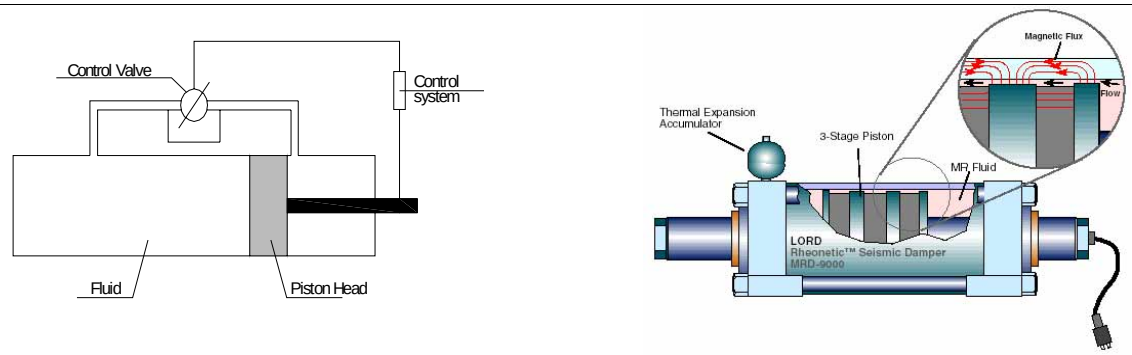
SEMI-ACTIVE VARIABLE DAMPING DEVICES

There is a strong similarity between the semi-active variable damping devices and the viscous passive dampers. The main difference is the capacity of the firsts to change theirs damping characteristics. The modification of the damping characteristics can be obtained actuating mechanically on the fluid flow channels or actuating directly on the fluid, changing its properties.

In the first case the aperture size of the valve that regulates the fluid flow is controlled, changing the damping. Systems of this type are called viscous semi-active devices (Figure 1a).

The second case refers to controllable fluids devices (Figure 1b), which consist in devices that allow the reversible modification of a viscous fluid free flow to a semi-solid flow with a controllable resistance. This modification happens in milliseconds when the fluid is exposed to an electric or magnetic field [1]. The fluid in the device interior has certain particular characteristics and it is called magneto-rehological fluid or electro-rehological fluid, whether it reacts to a magnetic or to an electric field, respectively. These fluids are constituted by non-colloidal, polarized particles that are dispersed in mineral or silicon oil. When a magnetic or electric field is applied, particle series are formed, causing a sudden change in the rehological behavior of the fluid, which becomes semi-solid, with a viscous behavior.

The practical result of these devices' behavior is the possibility of controlling the damping level in each instant, within the limits and capacities of the devices.



a) Semi-active viscous damper ***b) Semi-Active controllable fluid damper***

Figure 1: Semi-active control systems with variable damping

THE SEMI-ACTIVE VARIABLE DAMPING CONTROL

Semi-active control systems, as well as active control systems, use control algorithms through which an improvement of the structural behavior is obtained. Semi-active systems constitute a new and promising field of research within seismic protection systems. Various semi-active algorithms have been proposed all over the world. In this paper, a semi-active variable damping control algorithm is tested.

The main characteristic of the control algorithms is the control criterion. It is this characteristic that defines the behavior of the device and its influence in the structure. The definition of the control criteria includes the definition of the variables to be controlled. Usually, the control variables are variables that deal with the structure movement, as its displacement, velocity or/and acceleration.

The algorithm control

To evaluate the structure seismic response without any kind of seismic protection, it is necessary to solve the following equilibrium equation:

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_s \tag{1}$$

To consider variable damping, a new term must be included in the equation:

$$m\ddot{x} + c_{str}\dot{x} + c_{dev}\dot{x} + kx = -m\ddot{x}_s \tag{2}$$

$$m\ddot{x} + \left(c_{str} + c_{dev}\right)\dot{x} + kx = -m\ddot{x}_s \tag{3}$$

The term c_{str} represents the structural damping and the term c_{dev} the damping contribution of the device. The damping contribution of the device, c_{dev}, depends simultaneously on the type of device and on the used algorithm. When the device is off, c_{dev} reflects the natural damping correspondent to passive part of the device. When turned on, the modification of the damping values depends of the device characteristics, though it is possible to recognize two types of variation: continuous variation and discrete variation. Continuous variation devices allow the adjustment of the damping force in each time step. The discrete variation devices change the damping by steps or levels, each one of them corresponding to a certain amount of damping. In this paper, an “ON-OFF” semi-active variable damping system was considered, i.e. the device’s damping coefficient can only assume two values, one for the on mode (c_{MAX}) and other in the off mode (c_{MIN}).

In order to study the influence of the different variables, the analyzed algorithm uses only one control variable. To compare the results, three types of semi-active control were considered: displacement response control, velocity response control and acceleration response control.

Using an algorithm with only one variable the decision of activating or not the system depends on the control variable value. Therefore, if the control variable is the velocity it means that the device is turned on or off whenever the structural velocity response overpasses a certain predefined limit. In spite of the control being a velocity control, the goal to achieve with the semi-active device can be the limitation of another variable. Considering the bridge design as an example, even if the main goal is the maximum deck displacement limitation, it is not mandatory that the control variable would be also the displacement. The results of the study developed showed that the most effective way to limit the maximum displacement is using the velocity as a control variable.

Hence, whatever control variable is to be used it is necessary to define the limit value that controls the system activation. Basically, the problem is to choose the adequate limit value of the control variable (for instance, the velocity) in order to limit the maximum displacement to a certain value (goal to achieve). The solution is not easy, as it is very much conditioned by the seismic action characteristics. In order to gain sensibility for this problem, a parametric study was conducted, in which the definitions of the seismic action present in the Portuguese code were considered [3].

Portuguese seismic action

Portugal is located in the southwest extreme of Europe. The continent parcel sits in the Eurasian plate, Madeira archipelago is in the African plate and Azores archipelago is located in the convergence between the Eurasian, African and North American plates. This implies a distinct seismic behavior in different zones of the Portuguese territories. Therefore, two types of seismic actions and four seismic regions are considered. The characteristics of the two types of seismic actions that can occur in Portugal are: one with low focal distance (action type 1), 10s of duration and moderate magnitudes, and the other with long focal distance (action type 2), 30s of duration and high magnitude.

The Portuguese code defines three soil types: type I corresponds to rocks and very dense hard cohesive soils; in type II, very hard, compact cohesionless soils and medium consistency cohesive soils are considered; type III includes loose cohesionless soils, soft and very soft cohesive soils.

Parametric analysis

The limit values of the control variable were set as percentages of the spectral values (response spectra values) corresponding to the structural characteristics. Structures with frequencies between 0.25Hz and 1.25Hz were analyzed. To evaluate the efficiency of each damper solution, the deck maximum displacement value was calculated, for each one of the oscillators. Regarding the damping, it was considered that each oscillator had a 5% damping and that the device damping could change between 0% and 20%, which corresponds to consider a variation of the total damping between 5% and 25% (structure+device). The displacements results were presented in the form of the relation between the maximum obtained displacement and the spectral displacement for 5% damping.

In the parametric study several sets of artificial accelerograms were used. For each type of seismic action and soil definition, a set of 10 different time series was generated. The presented results correspond to the average of the maximum responses obtained with each time series.

The results of a system with displacement response control subjected to the Seismic Action type 1 and Soil Type I (according to the Portuguese code) are presented in Figure 2. In Figures 3 and 4, the velocity and acceleration results for the same seismic action are shown.

Analyzing the displacement response control, one concludes that the results are not very sensitive to the control value. For control values close to the spectral value (ratio “control value/spectral value” close to 1), the reduction that occurs in the maximum value is quite small. However, when lower control values are considered, the reduction on the maximum value becomes more significant. Hence, the displacement response control is only recommended for low control values, when compared with the spectral values. For large control values, the response reduction is non-significant.

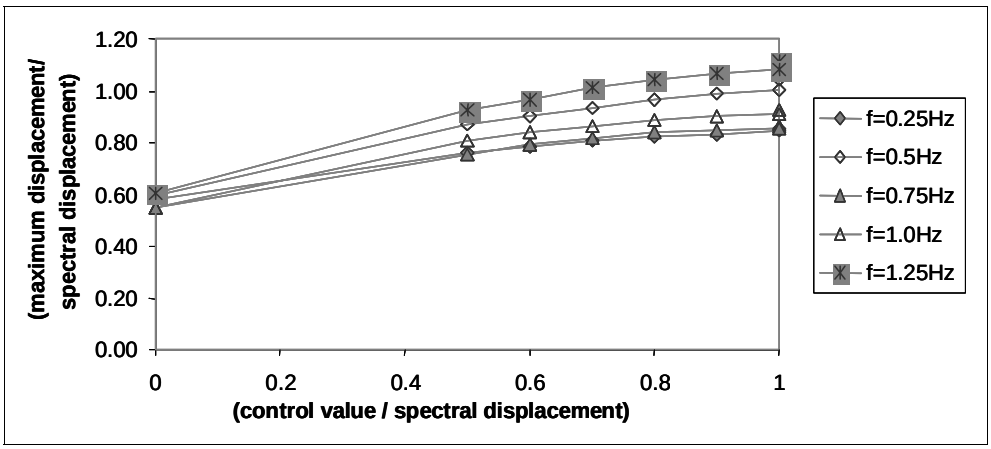


Figure 2: Displacement response control results

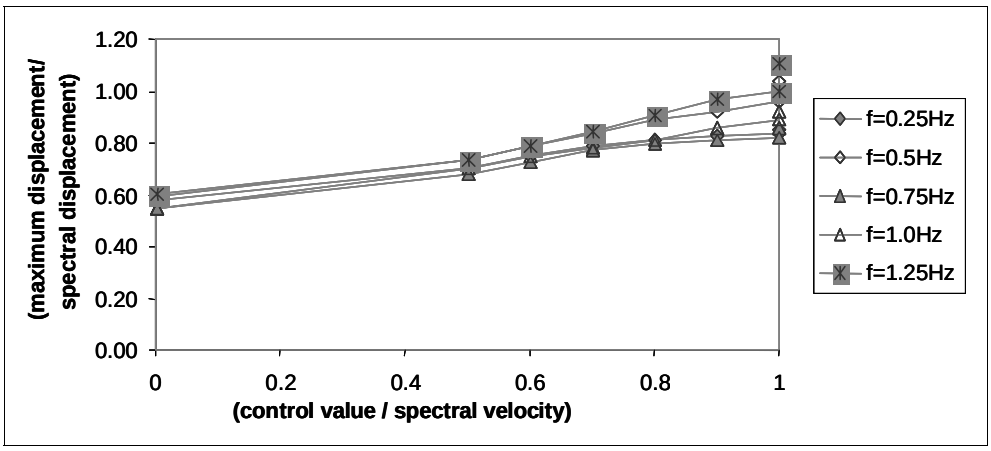


Figure 3: Velocity response control results

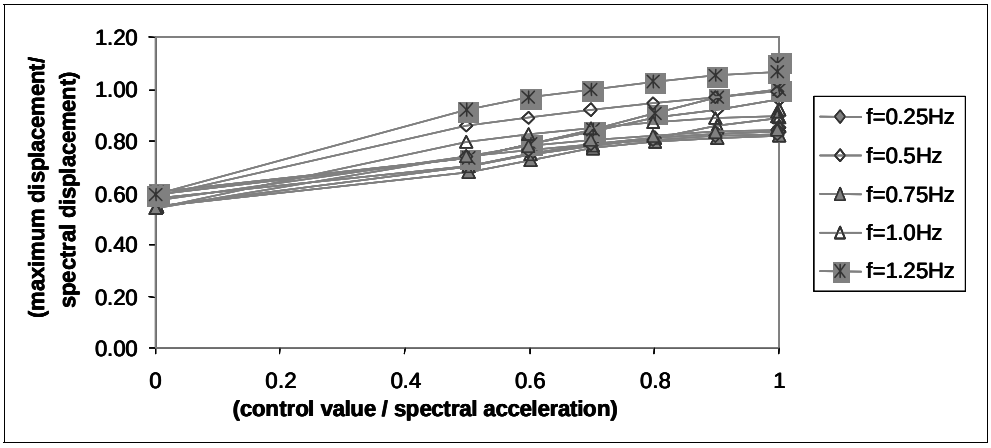


Figure 4: Acceleration response control results

Regarding the velocity response control and comparing it with the displacement response control, there is a more effective reduction on the maximum displacements with the decrease of the control value. Hence, the velocity response control is recommended for control values close to the spectral values, which reveals a high efficiency. For low control values, the improvement obtained is non-significant.

When the acceleration response control is adopted, there is some similarity between its results and the results of the displacement response control. However, it is suggested not to use the acceleration response control due to several reasons. In addition to its minor efficiency, there are others reasons that must be mentioned. The accelerations registered in an earthquake are constantly changing from positive values to negative values, from high amplitude values to low amplitude values. Due to this fact, the semi-active acceleration control causes a constant switch on and off of the device, which can be commanded by the algorithm to occur with a time interval of 0.01 seconds. This behavior is not recommended to assure the adequate control of the response. In addition, there is a very high amount of energy consumed by the device.

Influence of the seismic action type

While in seismic action 1, soil type I, the concentration of energy is in the high frequencies, seismic action 2, soil type III has the highest energy concentration in low frequencies. The comparison of these two extreme situations was done for the same type of control situation. In Figure 5 the spectrum response of the two types of seismic action are presented. Seismic action 1 provides higher values of acceleration for high frequencies as opposed to seismic action 2, as it was said before.

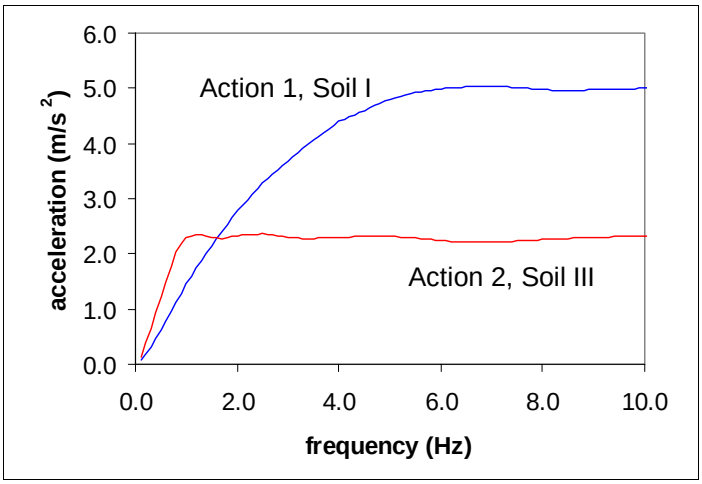


Figure 5: Response Spectra comparison

In Figure 6 and 7, the displacement results for each one of considered seismic actions are presented. At a first glance the results are similar, with a better uniformity with the frequency for the seismic action type 2.

Observing in detail one can conclude that the results for the higher frequencies considered (1.0Hz and 1.25Hz) are lower for the seismic action type 2. This result was expected since this seismic action has lower energy for this frequency range.

The presented results show that there is little influence of the seismic action type on the global results.

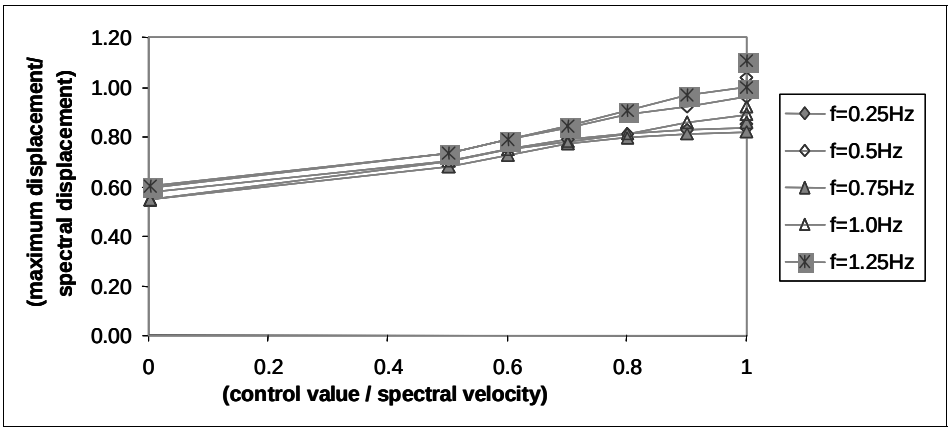


Figure 6: Maximum displacement with velocity control (Action type 1, Soil type I)

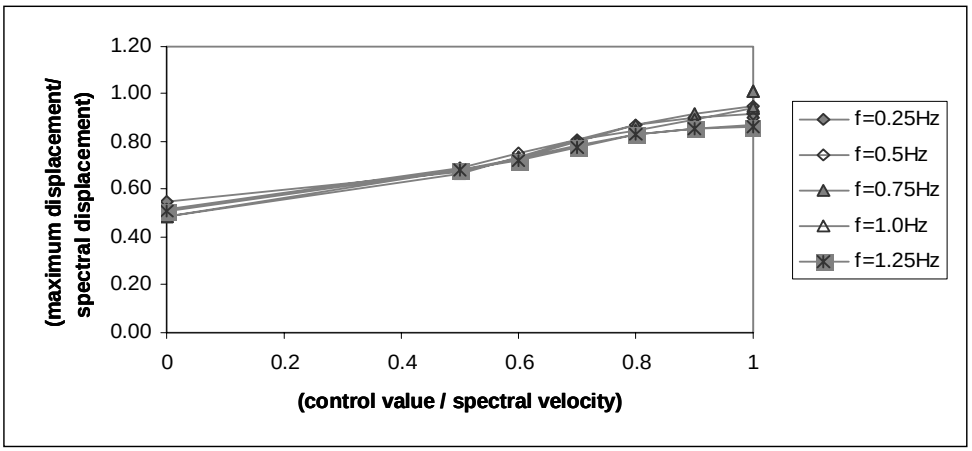


Figure 7: Maximum displacement with velocity control (Action type 2, Soil type III)

Energetic comparison

In order to characterize the relative energy efficiency, an energetic comparison between displacement response control and velocity response control has been conducted. For this study, the dissipated energy and the consumed energy by the device were evaluated.

An acceleration series with the characteristics of a seismic action type 1 and soil type III was used in the analysis of a structure with a frequency of 0.50Hz. The evolution of the dissipated energy is presented in Figure 8a. Here, one verifies that the device dissipates less energy in the case of displacements control. This result might increase the energy dissipation by the structure, which is exactly what should be prevented from happening.

Supposing that the system energy consume, while the device activated, is constant per unit time, the total energy consumed by the device can be estimated. In Figure 8b a qualitative graph of the accumulation of energy consumed by the device is presented, for the 2 situations in analysis.

According to the results present on Figure 8, the displacement response control strategy conducts to a higher energy consume, since the device stay more time activated.

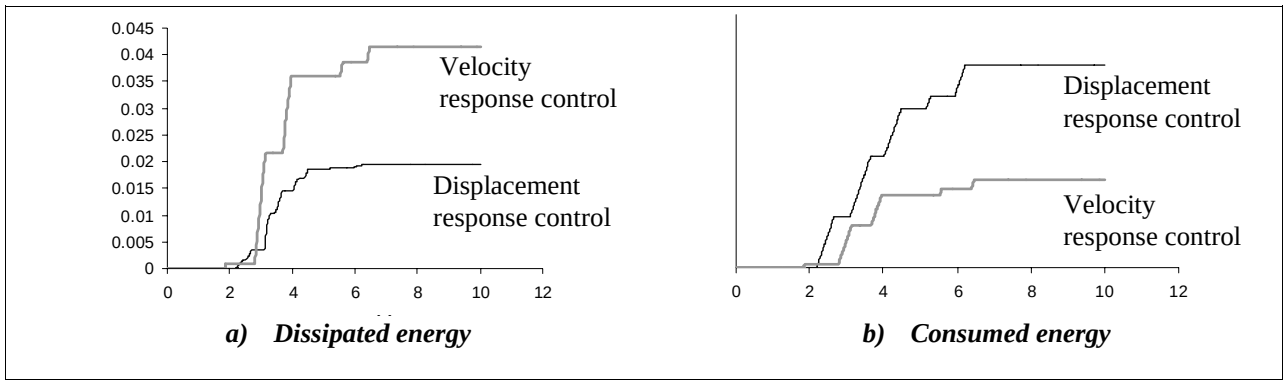


Figure 8: Energetic comparison

BRIDGE SEISMIC ANALYSIS WITH SEMI-ACTIVE DAMPERS

Analysis Methodology

Due to the complexity of the analysis of the seismic response of structures with semi-active devices, the choice of the optimal characteristics of these systems is not an easy task. A simple and easy method for the estimation of the device parameters is very important for its handling and broad implementation.

Considering the variable damping algorithm, a semi-active protection system design method was developed to estimate the device characteristics in order to obtain a certain value of the structure maximum displacement.

The method presented is applicable to the variable damping algorithm with velocity response control. The first operation of the method is the calculation of the seismic response with the natural properties of the structure, no semi-active device and no control. The maximum displacement obtained is then plotted in charts whose abscissas corresponds to the relation between the velocity control value and the velocity spectral value and in ordinates are the values of displacement. Because there was no control, the relation between the control value and the spectral value is the maximum, i.e. the calculated point corresponds to abscissa 1.0 (Point A in Figure 9).

The next step is the calculation of the structural response considering maximum damping of structure+device, through all the time-history analysis. The maximum displacement obtained is plotted in the same chart, with the abscissa 0, once it corresponds to the maximum control, i.e. for a null control value, which means that the device is always active (Point B in Figure 9). After these two points have been marked, a line connecting the two is drawn (see Figure 9). A line with positive inclination is obtained.

The objective of the method is to specify the control value to use in order to grant that the maximum displacement does not overpass a predetermined value. Then, a horizontal line is drawn at the level of the target maximum displacement allowed, as it can be seen in Figure 9.

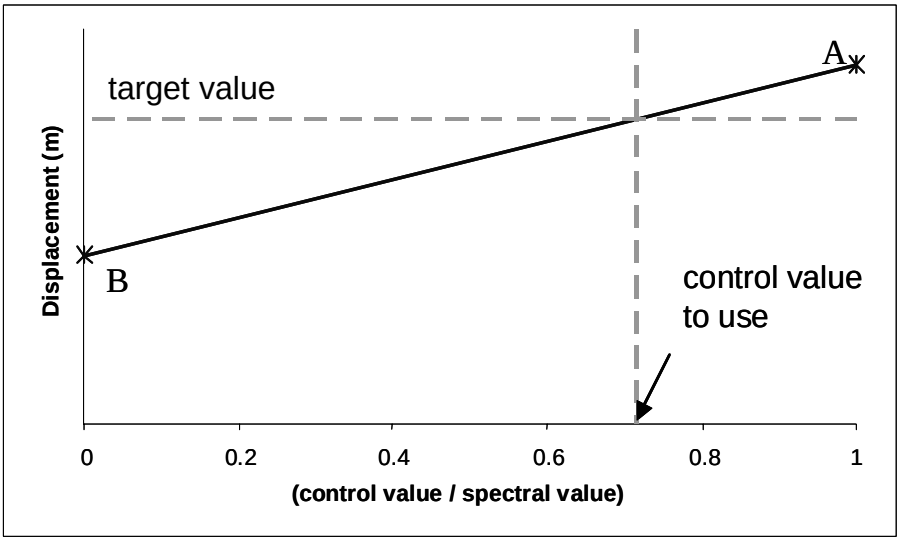


Figure 9: Design Method (scheme)

Where this line meets the line previously drawn, a vertical line is plotted. The abscissa value of the vertical line reveals the relation between the control value and the spectral velocity value for the structural frequency. The control value to use is determined by multiplying the obtained result by the spectral velocity. With this, the velocity beyond which the device should be turned on is determined. When the velocity is lower than the control value, the device is turned off.

Case Study

The design method was tested on a case study with successful results. The longitudinal view and transversal section of the viaduct analyzed are shown in Figure 10. The structure chosen for analysis is a reinforced concrete viaduct, rectilinear in the horizontal plane and with a non-significant inclination in the vertical plane. Its total length is 145.53m and its highest height relatively to the ground is 30m.

Two longitudinal pre-stressed beams support the deck. The piles support the beams through pot bearing devices, allowing rotations in the either perpendicular direction to the pile axis. The displacements are restrained in both longitudinal and transversal directions, establishing a hinge support on top of each pile. In the abutments, the pot-bearing devices restrained the transversal displacements but allow the longitudinal ones.

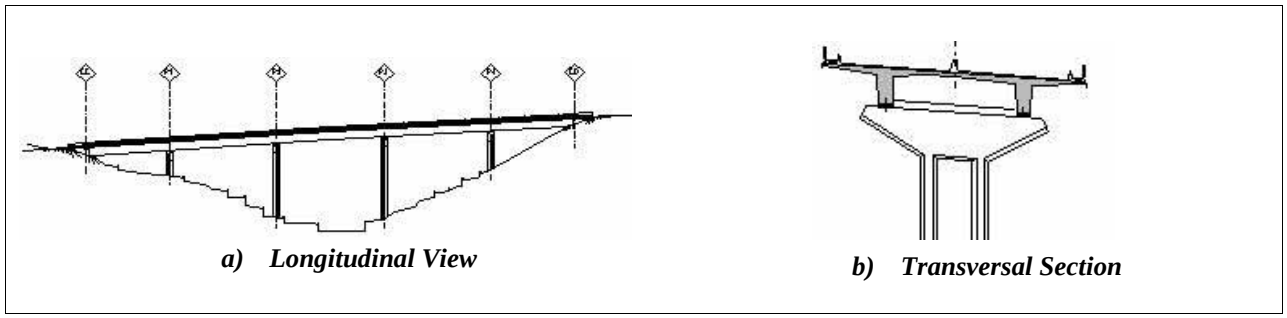


Figure 10: Case Study

The 3D model presented on Figure 11 was analyzed for the calibration of the SDOF model representative of the viaduct. The properties of the SDOF model are resumed in Table 1. After the calibration, the SDOF

viaduct model analysis was conducted for the application of the semi-active algorithm with velocity response control. The damping of the device was established as varying from 0% to 20%. The structural damping of the structure was assumed to be 5%. The structure was considered to be located in a hard soil (soil type I).

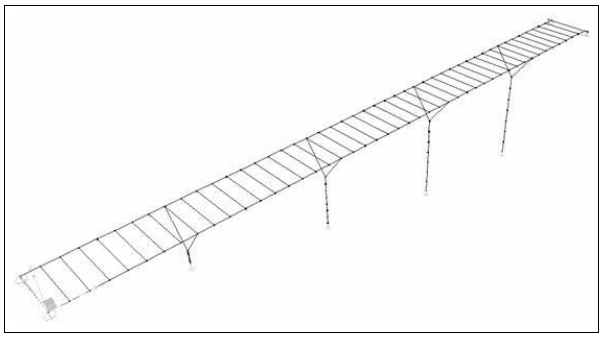


Figure 11: Case Study – 3D Model

The objective of the analysis was to establish the control value to guarantee that the maximum displacement would not overpass 0.045m. The steps of the design method were followed for each one the seismic actions. The spectral velocities for the structural frequency are 0.243m/s and 0.343m/s for seismic actions 1 and 2. To determine the maximum displacement responses for the structure with its damping (point A in Figure 9) and for the structure+device with total damping of 0.25 (point B in Figure 9), the displacements response spectrum can be used, as both of responses are determined with no control. Therefore, for seismic action 1 the maximum displacements obtained for 5% and 25% damping were 0.0505m and 0.0296m, respectively. For seismic action 2 and for the situation of 5% of damping, the maximum displacement obtained was 0.0763m, for 25% of damping was 0.0409m. Using the proposed method, the control values needed to grant that the maximum displacement allowed were determined. For seismic action 1, the velocity beyond which the device should be turned on is 0.179m/s and for seismic action 2, 0.037m/s. Because the latter is the lowest, is the one that should be used.

Table 1: Properties of SDOF Model

Total mass		(ton)	7179
First mode	Period	(s)	1.53
	Frequency	(Hz)	0.66
Participating Mass		(ton)	6646

The efficiency of the method is guaranteed by the semi-active variable damping control with velocity response control. Indeed, the velocity response control causes a concave curvature in the results when these are plotted in a chart whose ordinates are the maximum displacements obtained and the abscissas the relation between the control value and the spectral velocity value, as can be observed on Figures 3, 6 and 7. The design method consists in drawing a line that connects the extremes of the chart, which means that the method results will always be superior to the actual ones, granting the safety of the structure.

Since the seismic action type 2 is the most conditioning one, 10 accelerograms for this action and soil type I were generated. The semi-active algorithm with velocity response control was applied to each one of the accelerograms with the control value of 0.037m/s. The maximum displacements were determined for each one of the accelerograms and the average was performed. It was obtained average maximum result of 0.0407m, which is, as expected less than the maximum displacement allowed pre-established (0.045m).

From the exposed, one can realize the simplicity of this method. In fact, the control velocity value is promptly determined without difficult calculations.

CONCLUSIONS

The semi-active control systems represent a seismic protection solution with a very high potential of development, in particular its application in bridges.

In order to improve the efficiency of these systems it is necessary to establish an adequate control algorithm. In this paper the results of displacement, velocity and acceleration response control are presented, having concluded that the velocity response control allows a higher reduction of the maximum displacements.

The use the acceleration response control is not recommended mainly due to the great variation of acceleration values when an earthquake occurs, which causes an inadequate control and a high energy consumption by the device.

The displacement response control, in spite of allowing an acceptable reduction in the maximum displacement of the structure, it is not as efficient as the velocity response control system. Relatively to the velocity response control, the displacements control forces to longer periods of activation, which means superior energy consumption. For these reasons and for the algorithm here developed, velocities control is the one recommended as, globally, has the best performance.

The proposed method for the estimation of the characteristics of semi-active dampers with variable damping is easy to implement and is efficient.

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