

Article

Curved Surface Slider Design Procedure Aimed at Device Performance

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Abstract

The design of curved surface sliders hides some pitfalls that can affect the effectiveness of the isolation system, as pointed out by past theoretical and experimental studies. In this paper, the basic relationships of curved surface sliders are rewritten, defining a characteristic parameter. This relates the design parameters, i.e., the friction coefficient, the equivalent radius, and the seismic displacement, with each other but depends on the damping ratio only. As is well known, a high value of friction could prevent the onset of motion. The self-centering capacity depends on the equivalent radius. Finally, the seismic displacement affects the dimensions and, therefore, the material consumption and the required gap. The design procedure proposed here is organized in two main phases. In the first one, the feasibility of a base isolation system, consistent with the fixed building seismic capacity and maximum displacement, is analyzed. An admissible area, i.e., the couples of values of the effective period and damping ratio, is individualized on the acceleration–displacement (capacity) spectrum plane. To do that, the outcomes of a previous study are used. In the second phase, the iso- R and iso- μ curves are plotted in this area. These allow a suitable choice of the design parameters and, therefore, a performance-oriented design. A flowchart summarizes the method. Finally, some examples show practical applications and allow the verification of the effectiveness of the proposed procedure.

Keywords: seismic isolation; isolation devices; curved surface sliders; preliminary design; friction

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1. Introduction

Curved surface sliders (CSSs) played an important role in the history of seismic isolation [1–5]. In fact, the very first isolation device, the so-called aseismic joint, had the same operating principle as the modern curved surface sliders. It was designed by Stevenson in 1868 to realize a system with spherical rollers in niches to protect lighting systems in Japan [6]. The system proposed by Touaillon in 1870 [7] was also composed of spherical rollers in niches between the superstructure and foundations [8,9]. After other proposals [10], Viscardini proposed a new isolation system also made of spherical rollers in niches in 1909 [11].

Modern CSSs first appeared in 1985 when Victor Zayas submitted a patent application for a friction pendulum [12–14]. A schematic view of the device (single pendulum) is represented in Figure 1a. Then, more sophisticated devices were developed to optimize the material quantity and structural behavior. Therefore, the double (Figure 1b) and triple pendulums were proposed [15–17] and, subsequently, the quintuple pendulum [18]. CSSs have been extensively investigated over the last few decades and are currently regarded as a mature seismic isolation technology, with applications spanning bridges, buildings, and critical infrastructures [19–26].

CSSs have achieved ongoing success as a result of two very interesting characteristics [27]:

- The independence of the isolation period from the superstructure mass—this occurrence allows the isolation system to be designed almost independently of the structure that will be built above it.
- The automatic coincidence of the projection of the center of mass with the center of stiffness.

As will be discussed later, these characteristics are valid only from a purely theoretical perspective. In practice, the isolation period and the stiffness both depend on friction, which, in turn, depends on the vertical load on the device. Furthermore, CSSs can offer recentering capabilities, depending on the characteristics of the devices, their state of preservation, the acting load, and the characteristics of the seismic event [28–30].

Finally, the cost of the CSSs is lower than that of the corresponding high damping rubber bearings (HDRB).

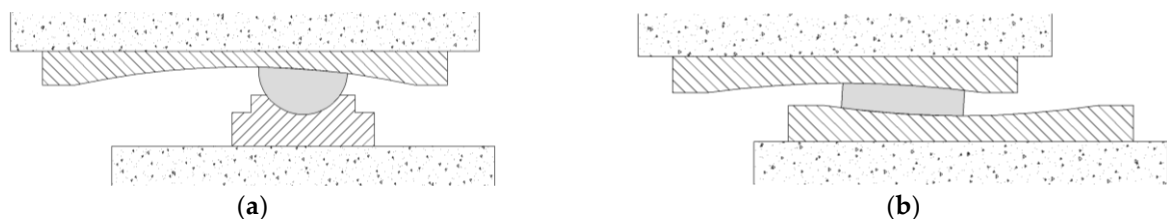


Figure 1. Schemes of (a) a single CSS and (b) a double CSS.

Although conceptually simple, at least, in a linear approach, the design of CSS isolation systems hides some pitfalls that can affect their effectiveness [31,32]. In particular, the influence of pressure, temperature, and sliding velocity must be accurately evaluated [33,34]. Variations in frictional behavior and hysteretic degradation may significantly influence their long-term response and, therefore, require appropriate monitoring and modelling strategies [35].

The effectiveness of seismic isolation systems under strong earthquakes has been widely confirmed [36–40]. Conversely, their behavior under low-intensity ground motions requires careful assessment. Field observation showed the satisfactory performance of structures isolated with HDRBs, albeit with significant changes in the resonance frequencies [41,42]. Instead, the influence of friction poses serious problems for the onset of motion and the effectiveness of isolation systems made of HDRBs and sliding devices (SDs) [43], and especially for CSS isolation systems [44]. The behavior of CSS systems observed during low-energy earthquakes underlined the importance of selecting a suitable friction value to enable the onset of motion of the devices also during low-energy earthquakes [45,46]. The behavior of CSSs under severe input motion was analyzed experimentally, demonstrating that, in general, devices can withstand displacements exceeding the design values without any evident loss of functionality. However, construction details significantly influence their behavior beyond the design limits [47].

These issues must be considered both in the application of seismic isolation in new constructions [48,49] and in the retrofit of existing ones [50]. Therefore, a simple, reliable, easily understandable, and verifiable design procedure is essential to facilitate a proper seismic isolation design. Previous studies addressed this issue with reference to HDRBs proposing a graphic approach to define the optimum values of device mechanical and geometrical parameters (such as rubber shear modulus, diameter, and thickness, and the number of rubber and steel layers) starting from the design requirements (such as device stiffness, maximum displacement, and vertical load) [51]. With the aim of achieving similar results, but with obvious differences in terms of the design parameters and relationships, this paper formulates a performance-oriented design procedure for CSSs. The aim is to determine the mechanical and geometric parameters of the device (i.e., the friction coefficient and equivalent radius) starting from the design requirements (i.e., the threshold limits for acceleration and displacement).

For this purpose, the basic relationships, which describe the CSS dynamics, are rewritten, introducing a characteristic parameter. This relates the governing parameters, i.e., the friction coefficient, the equivalent radius, and the seismic displacement, but depends only on the damping ratio [52,53].

The design process is organized in two main phases. The first analyzes the feasibility of a base isolation system. An admissible area, consistent with the fixed seismic capacity of the building and maximum displacement, is identified on the acceleration–displacement (capacity) spectrum plane. In the second phase, the iso- R and iso- μ curves are plotted in this area. These curves enable a performance-oriented design by selecting the design parameters μ and R and controlling the actual seismic displacement.

A flowchart clarifies the main steps of the methodology. Finally, some examples show practical applications and allow the effectiveness of the proposed procedure to be verified.

2. CSS Behavior and Modelling

In the experimental behavior of a single CSS, three phases can be identified, each characterized by a different value of the friction coefficient. The onset of motion is influenced by the static friction coefficient μ_{st} . The oscillations depend on the dynamic friction coefficient $\mu_d = \mu$. Finally, the change in the velocity sign is governed by the friction coefficient μ_1 . It is $\mu < \mu_1 < \mu_{st}$. Figure 2 shows the forces acting on a concave sliding surface during the oscillations. Given N is the vertical load, F_f the friction force, and P the normal contact force, the following law applies between the inertial force F and the displacement d :

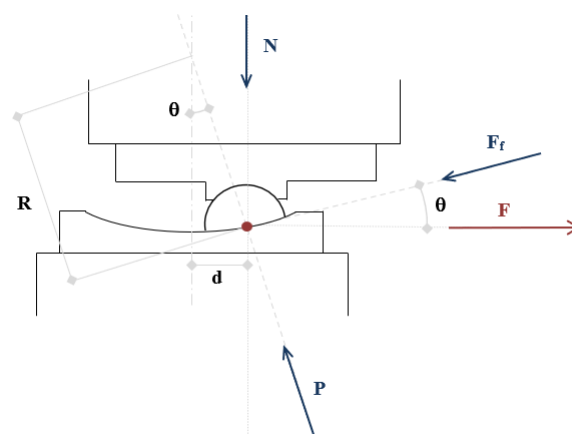


Figure 2. Forces acting on a concave sliding surface (the direction of the forces are for $\dot{d} > 0$).

$$F = \text{sign}(\dot{d}) \cdot \mu N + \frac{d}{R} N \quad (1)$$

This holds when approximating $\tan\theta \cong \sin\theta$ with a trigonometric error $\Gamma = (\tan\theta - \sin\theta)/\tan\theta$, that can be bounded under the following condition:

$$\theta < \arcsin \varepsilon \quad \rightarrow \quad d/R < \varepsilon \quad (2)$$

Based on the above, the simplified bilinear model shown in Figure 3 is usually adopted. An initial rigid phase, with a friction coefficient μ , is followed by a linear phase with stiffness $k = N/R = mg/R$ where m is the seismic mass on the isolator, and R is the sliding surface radius of the single CSS and twice the radius of the sliding surfaces in the case of a double CSS. The equivalent stiffness k_e depends on the maximum displacement of the cycle.

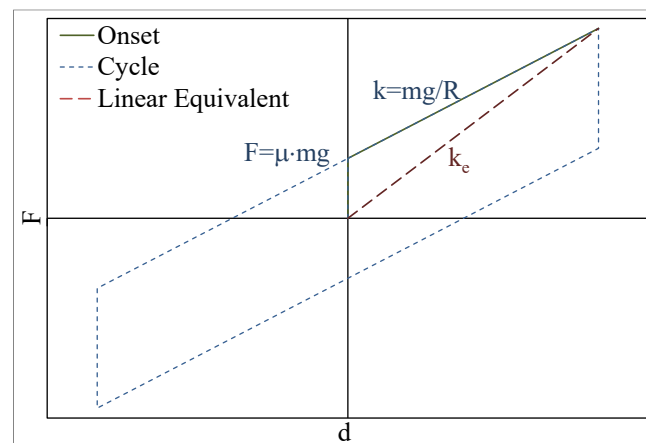


Figure 3. Typical simplified F-d law of a CSS. The equivalent stiffness k_e obviously depends on the maximum displacement d of the cycle.

It is worth noting that the friction coefficient μ mainly depends on three factors: the contact pressure σ (and, therefore, for a fixed contact area, the vertical load N), the sliding velocity, and the temperature [54,55]. If only the dependence on σ is considered, its variation can be written as follows (where $-1 < \alpha < 0$):

$$\mu = \mu_{\min} \left(\sigma / \sigma_{\max} \right)^{-\alpha} \quad (3)$$

where the minimum value of friction $\mu_{\min}$ corresponds to the maximum contact pressure $\sigma_{\max}$. Usually, $\sigma_{\max} = f_d$, i.e., the design value at the ultimate limit state, which is much higher than that under seismic conditions. This is calculated by considering the permanent loads with their (not amplified) characteristic values and a fraction of the characteristic value of the variable loads. If the displacement is very large and/or the radius R is quite small, the pressure under seismic conditions could be much higher than the previous one. It must be remembered that the design stress in seismic conditions should be reduced to account for the heat generated during the oscillations. This heat increases with friction, speed, duration, and the pressure itself [56]. In Figure 4, both μ and $\mu\sigma/\sigma_{\max}$ are plotted versus $\sigma/\sigma_{\max}$. It is evident that, when σ decreases, μ increases up to two to three times its minimum value. Nowadays, materials with a very low variation in μ with σ are available.

Equations relating the design variables of a device (friction coefficient μ and equivalent radius R) to the dynamic properties of the isolated system (effective vibration period T_{is} and damping ratio ξ_{is}) are given below. The non-dimensional characteristic parameter ρ for a CSS subject to a seismic displacement d_E is first defined:

$$\rho = \frac{\mu R}{d_E} \quad (4)$$

Dividing the horizontal recentering force (Equation (1)) by the displacement d_E and using the characteristic parameter ρ , the equivalent stiffness is given by the following:

$$k_e = \frac{N}{R}(1 + \rho) \quad (5)$$

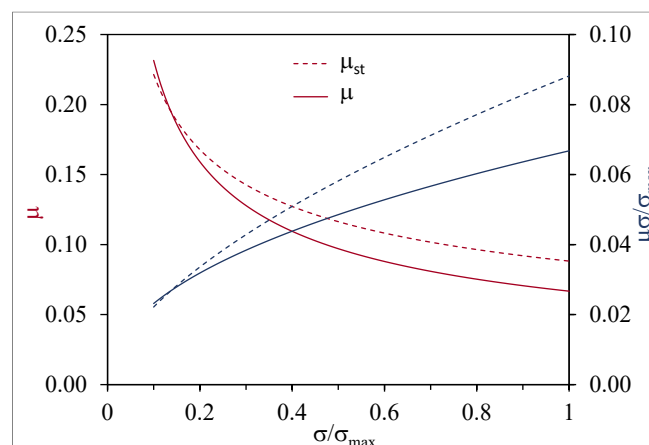


Figure 4. Static (μ_{st}) and dynamic (μ) friction coefficients (red lines, main vertical axis), and corresponding friction forces (blue lines, secondary vertical axis) versus the non-dimensional vertical load σ/σ_{max} (the same line styles apply to both the red and blue curves).

The corresponding effective period T_{is} , to be used in a linear model, and the corresponding equivalent radius R are related by the following:

$$\frac{T_{is}^2}{R} = \frac{(2\pi)^2}{g(1 + \rho)} \quad (6)$$

The damping ratio ξ_{is} is derived from the energy dissipated within a hysteresis cycle and the maximum elastic energy stored in the system. It is apparent that it depends on the characteristic parameter ρ only and vice versa, as it is the following:

$$\xi_{is} = \frac{2}{\pi \left(\frac{1}{\rho} + 1 \right)} \quad (7)$$

If ξ_{is} is fixed, the characteristic design parameter ρ is defined. Additionally, if T_{is} is also fixed, the equivalent radius R can be deduced from Equation (6). Finally, the friction coefficient μ can be deduced from Equation (4) for the seismic displacement d_E corresponding to T_{is} .

The curves T_{is} - R are plotted in Figure 5 for different values of ξ_{is} (blue lines, secondary axis). The curve relative to the maximum value $\xi_{is} = 0.28$ represents a limit relation between R and T_{is} : for a fixed R , it gives the minimum value of T_{is} , and, for a fixed T_{is} , it gives the maximum value of R . In the same figure, the diagrams μ/d_E are also plotted versus T_{is} for the same values of ξ_{is} (red lines, main axis).

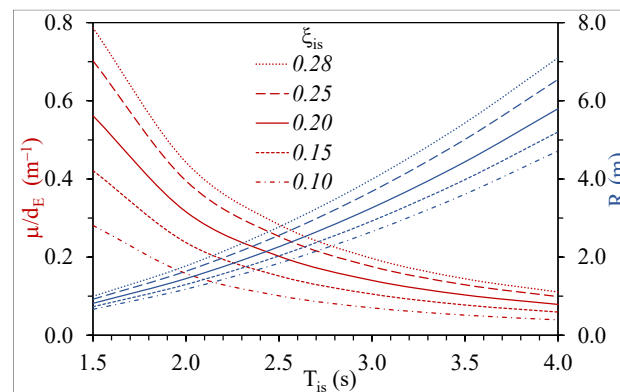


Figure 5. Ratio μ/d_E (red lines, main vertical axis) and radius R (blue lines, secondary vertical axis) versus T_{is} for different values of ξ_{is} (the same line styles apply to both the red and blue curves).

3. Note on the Preliminary Design of an Isolation System

When designing a seismic isolation system, the first step is to define the allowed acceleration in the superstructure and the allowed displacement of the isolation devices. From these, the threshold values of the spectral acceleration S_e^* and of the spectral displacement S_{De}^* can be deduced by applying the rules for the composition of the effects of seismic actions. The spectral displacement S_{De}^* is related to the horizontal allowed seismic displacement d_E^* through a relation of the form $S_{De}^* = d_E^*/\alpha$. In the absence of torsional rotation, following the usual seismic component composition rules of Eurocode 8 [57], it is $\alpha = 1.05$. The Type 1 acceleration elastic spectrum is considered here (Figure 6, main vertical axis), as suggested by the same code. It is defined by the following:

- The period values T_B and T_C , both depending on the soil type, and $T_D = 2.0$ s;
- The maximum value $S_{e,max}$, for a damping ratio $\xi = 0.05$, which is constant in the range $[T_B, T_C]$ of the period.

The elastic displacement spectrum is derived by dividing the acceleration elastic spectrum by the square of pulsation and amplifying it by the factor $\gamma_x = 1.2$, as required for seismic isolation devices (Figure 6, secondary vertical axis).

For damping factors other than 0.05, the elastic spectrum is modified by the coefficient $\eta = \sqrt{10/(5 + \xi \cdot 100)}$. It is $\eta = 1.0$ for $\xi = 0.05$ and can assume a value of $1.0 \geq \eta \geq \eta_{min}$, with $\eta_{min} = 0.55$ ($\xi_{max} = 0.28$) according to Eurocode 8 [58,59].

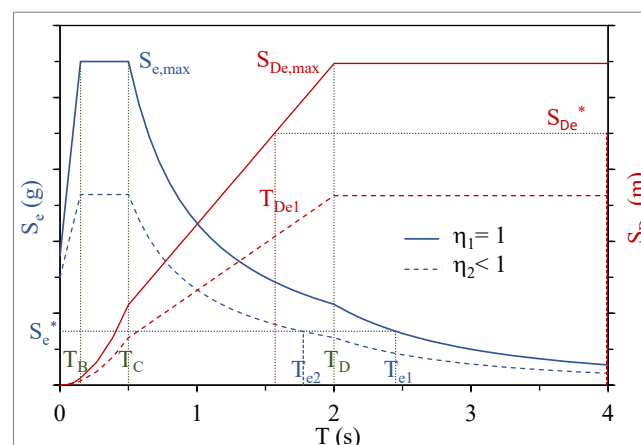


Figure 6. Elastic acceleration (blue lines) and displacement (red lines, amplified by γ_x) response spectra, for the two values of η (the same line styles apply to both the red and blue curves).

A procedure for a feasibility analysis of the seismic isolation strategy and the preliminary definition of admissible values of the damping ratio ξ_{is} and vibration period T_{is} has been previously proposed [60]. Two characteristic values for η have been defined. The first one corresponds to the condition $S_{De}(T_D) = S_{De}^*$ (i.e., the maximum spectral displacement is equal to the maximum threshold value):

$$\eta' = \frac{S_{De}^*}{S_{De,max}} = \frac{(2\pi)^2}{S_{e,max} T_C T_D} \frac{S_{De}^*}{\gamma_x} \quad (8)$$

If $\eta < \eta'$, then $S_{De}(T_D) < S_{De}^*$.

Suppose that T_e and T_{De} are the periods corresponding to S_e^* and S_{De}^* in the two spectra, respectively. The second characteristic value has been obtained from the condition $T_e = T_{De}$, both calculated in the range $[T_C, T_D]$:

$$\eta'' = \sqrt{\frac{S_e^*}{S_{e,max}} \frac{S_{De}^*}{S_{De,max}} \frac{T_D}{T_C}} = \frac{(2\pi)}{S_{e,max} T_C} \sqrt{S_e^* \frac{S_{De}^*}{\gamma_x}} \quad (9)$$

If $\eta < \eta''$, then $T_e < T_{De}$.

The meanings of the two characteristic values for η and their influence on the choice of the damping ratio and isolation period can be effectively illustrated using the capacity spectrum $S_e - S_{De}$ shown in Figure 7. Two spectra are first considered: $\eta = 1$ ($\xi = 0.05$, blue line), which sets the values $S_{e,max}$ and $S_{De,max}$, and $\eta = \eta_{min}$ ($\xi = \xi_{max}$, red line).

For any fixed value of S_e^* , three situations can occur, relative to different values of S_{De}^* , denoted by subscripts 1, 2, and 3, respectively:

- If $\eta' > \eta'' > \eta_{min}$, as in the case of $S_{De}^* = S_{De,1}^*$ (green line), the admissible area is limited by the lines $S_e = S_e^*$, $S_{De} = S_{De}^*$ and $T = 4.0$ s, and the spectrum η_{min} (red line). The spectrum η'' (dotted green line) does not influence this area.
- If $\eta'' > \eta' > \eta_{min}$, as in the case of $S_{De}^* = S_{De,2}^*$ (gray line), the admissible area is limited by the lines $S_e = S_e^*$, $S_{De} = S_{De,2}^*$ and $T = 4.0$ s, the spectrum η' , and the spectrum η_{min} . The area between the lines $S_e = S_e^*$ and $S_{De} = S_{De,2}^*$, and the spectrum η' , which is determined by the spectrum η'' (dotted gray line), gives further admissible points, with values of η between η' and η'' , $T_e < T_D$ and $S_{De} < \eta S_{De,max}$.
- If $\eta'' > \eta_{min} > \eta'$, as in the case of $S_{De}^* = S_{De,3}^*$ (yellow dotted line), the admissible area is limited by the lines $S_e = S_e^*$, $S_{De} = S_{De,3}^*$ and the spectrum η_{min} . For the points in this area, it is $T_e < T_D$.

Once η has been fixed, a value $T_e \leq T_{is} \leq 4$ s for the isolation period can be chosen. Only in the third case is the maximum value for T_{is} lower than 4.0 s.

The point at which the spectrum relative to $\eta = \eta_{min}$ assumes the value S_e^* defines the minimum values for $T_e (=T_{e,min})$ and $S_{De}^* (=S_{De,min})$. If $S_{De}^* < S_{De,min}$, there is no solution. If both η' and η'' are lower than the minimum value, one or both the threshold values S_e^* and S_{De}^* must be modified. As a last resort, the seismic protection strategy must be changed.

It is worth reminding the reader that the isolation period T_{is} should be at least three times the vibration period T_{fb} of the superstructure considered fixed at its base, in order to have a suitable dynamic decoupling between the superstructure and the substructure.

Once T_{is} has been fixed, the total mass M being known with a good approximation, the total stiffness of the isolation system can be deduced as follows:

$$k_{esi} = \left(\frac{2\pi}{T_{is}} \right)^2 \cdot M \quad (10)$$

It is equal to the sum of the stiffness of all devices. In a CSS system, the stiffness varies across the isolator, even when they are identical in geometry and materials. In fact, it depends on the mass m , i.e., on the vertical load N acting on each device.

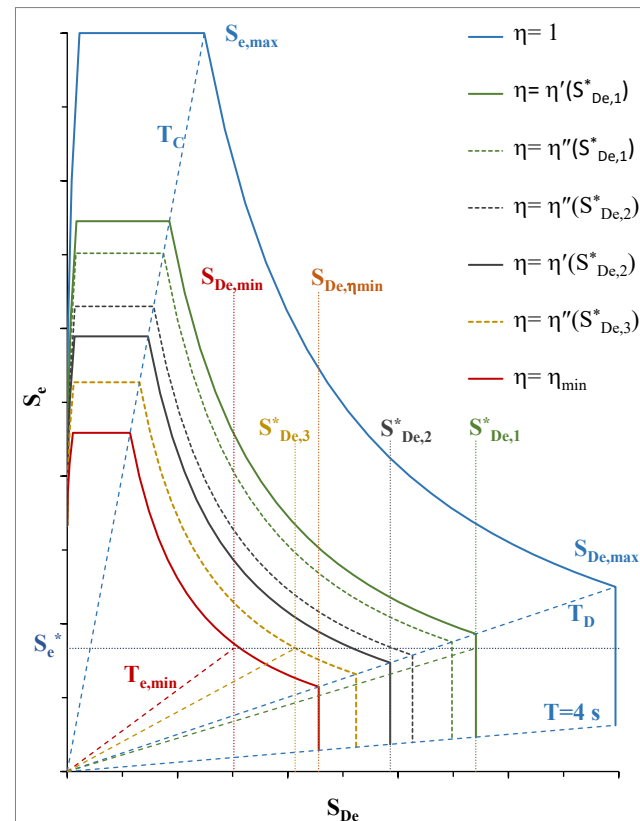


Figure 7. Possible cases in the capacity spectrum. The spectrum with $\eta = 1$ (blue line, relative to the minimum value of ξ) and that with $\eta = \eta_{\min}$ (red line, relative to $\xi_{\max}$) are first plotted. Then, three cases are considered for the displacement, namely, $S_{De,1}^*$ (green lines), $S_{De,2}^*$ (gray lines), and $S_{De,3}^*$ (yellow line). For each of them, the spectra relative to η' and η'' are plotted (only η'' for the last one, in which $\eta' < \eta_{\min}$).

4. Design Procedure Aimed at the Device Performance

Suppose that the spectrum parameters at the site are known and the threshold values S_e^* and S_{De}^* have been fixed. Starting from previous findings [60], the admissible values for the isolation parameters (ξ_{is} and T_{is}) must be searched within a restricted region of the normalized capacity spectra plane. The restrictions, which apply regardless of the type of seismic isolator intended to be used, ensure that the building capacity and boundary conditions are met while remaining within the applicability of the code spectra. In theory, any admissible pair of damping and period values is a possible solution, but this may lead to unsatisfactory friction and radius values. Therefore, a methodological framework is needed to converge on the most appropriate solution in terms of device-targeted performance.

Aiming for a CSS capable of activating under low seismic actions and featuring an adequate self-centering capacity, the design solution should aim for low values of both the friction coefficient and sliding surface radius. Furthermore, due to a combination of

environmental and economic reasons aimed at limiting material consumption, the device dimensions should not exceed what is strictly necessary.

To address the problem, the capacity spectra have been superimposed by the curves characterized by the same value of friction (iso-friction or iso- μ) and the curves characterized by the same value of the radius (iso-radius or iso-R). Figures 8a and 8b show two exemplary cases, with $\eta' > \eta_{\min}$, and $\eta' < \eta_{\min}$ but $\eta'' > \eta_{\min}$, respectively. Points taken under the black curve $d_E/R = \varepsilon$ ensure that the trigonometric error in Equation (1) is kept within preset bounds.

The iso-R curves were obtained through a direct method. For each value of R in a specified range, the following is carried out:

- (1) A suitable set of values of η_{is} (and then ξ_{is}) within the admissible area is established;
- (2) The corresponding values of ρ are calculated by Equation (7), which can be rewritten as follows:

$$\rho = \frac{1}{\frac{2}{\pi \xi_{is}} - 1} \quad (11)$$

- (3) The set of values of T_{is} is computed by Equation (6);
- (4) Finally, the corresponding couples of S_{De} and S_e are evaluated.

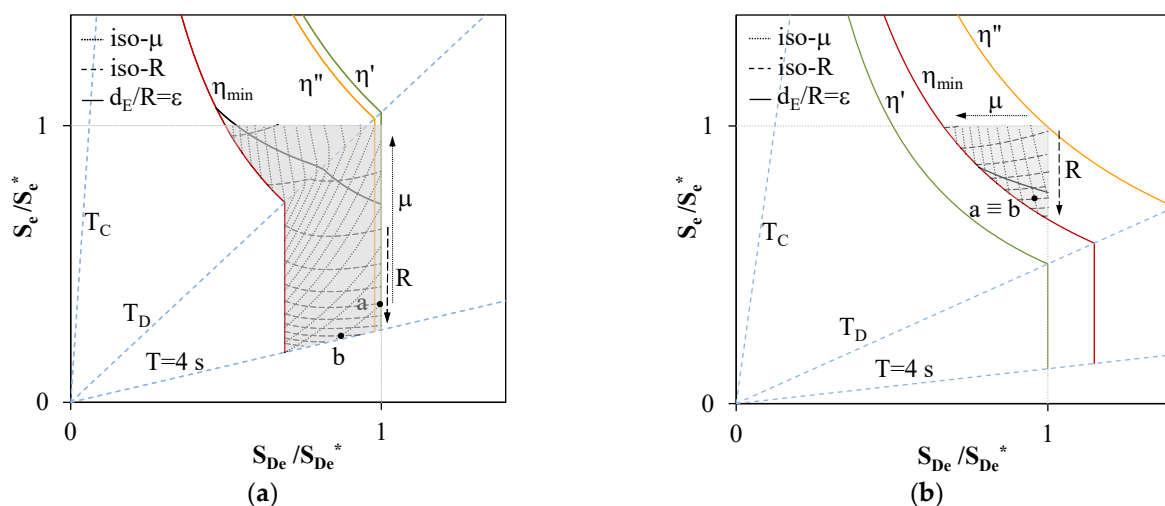


Figure 8. Admissible area superimposed by iso- μ and iso-R curves: (a) $\eta' > \eta_{\min}$; and (b) $\eta' < \eta_{\min}$ but $\eta'' > \eta_{\min}$. Arrows indicate increasing values of μ and R. Points under the black curve hold Γ within preset bounds. Points a and b indicate examples of targeted solutions.

The iso- μ curves were obtained through an iterative procedure. For each value of μ in a specified range, the following is carried out:

- (1) A suitable set of values of η_{is} (and then ξ_{is}) within the admissible area is established;
- (2) The corresponding values of ρ are calculated by Equation (7);
- (3) The iteration procedure is started by giving a value of $S_{De,0} = S_{De}^*$ (step 0):
 - Then, the corresponding values of R at the i.th step is calculated from Equation (4):

$$R_i = \frac{\rho \alpha S_{De,i-1}}{\mu} \quad (12)$$

- $T_{is,i}$ at the i-th step can be deduced from Equation (6);
- Finally, a new value for the displacement is obtained;

- The procedure is stopped when $S_{De,i} \cong S_{De,i-1}$. Otherwise, it continued to evaluate a new value for the radius from Equation (12).

(4) Finally, the corresponding couples of S_e can be deduced.

It is worth noting that, in Figure 8, the increment in the friction (which determines the spacing within the family of iso- μ curves) has been set to be the same in both charts. Instead, to provide a clearer representation, the increment in the sliding surface radius (which determines the spacing within the iso-R curves family) has been set differently between them. The arrows indicate the direction of increasing values. The iso- μ and the iso-R curves intersect, creating a grid. The intersection points that fall in the gray area represent the admissible solutions, for default values of μ and R. Those under the black curve fall within the preset trigonometric error.

Suppose we want to consider the activation of the device motion as a priority. In this case, the minimum iso- μ curve must be followed, moving toward solution a, if one wants to reduce the radius R and, thus, increase the self-centering capacity, or toward solution b, if one wants to reduce the displacement and, thus, the dimensions of the device. In both cases, the period and damping will change in the admissible ranges.

Once μ and R have been established, T_{is} and ξ_{is} can be easily deduced on the grid as the intersection point between the iso- μ and iso-R curves. If the grid is not available or the couple of values chosen do not belong to the grid, the point can be completely characterized through the following iteration procedure:

(1) The iteration procedure is started by giving a value of $S_{De,0} = S_{De}^*$ (step 0):

- The value of ρ_i at the i-th step is updated by Equation (4), which can be rewritten as follows:

$$\rho_i = \frac{\mu R}{\alpha S_{De,i-1}} \quad (13)$$

- The corresponding values of $\xi_{is,i}$ and $\eta_{is,i}$ are obtained by Equation (7);
- The period $T_{is,i}$ is computed by Equation (6);
- The spectral displacement $S_{De,i}$ is determined;
- The procedure is stopped when $S_{De,i} \cong S_{De,i-1}$; otherwise, it is continues to update a new value for ρ_i from Equation (13).

(2) Finally, the corresponding couples of S_{De} and S_e are determined.

The procedure described above is summarized in the flowchart in Figure 9.

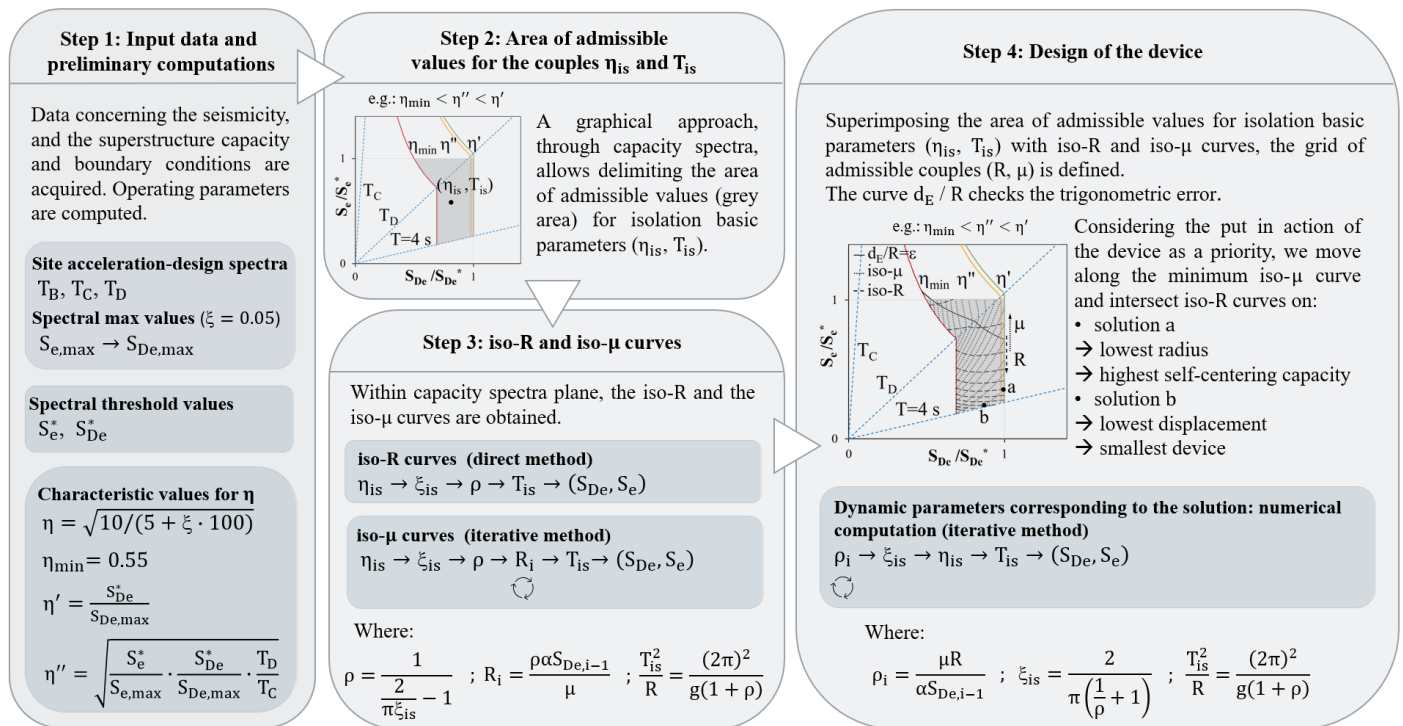


Figure 9. Flowchart of the CSS design procedure.

5. Examples

In this section, some numerical examples are given, organized according to the step-by-step design procedure summarized in Figure 9.

5.1. Step 1. Input data and preliminary computations

Consider a site with soil type B and suppose that the maximum spectral acceleration, i.e., its value between $T_C = 0.5$ s and $T_D = 2.0$ s, for the damping factor $\xi = 0.05$, is as follows:

$$S_{e,max} = 1.05 \text{ g} \quad (14)$$

The maximum spectral displacement, which occurs for $T > T_D$, can be deduced as follows:

$$S_{De,max} = 313 \text{ mm} \quad (15)$$

Assume a threshold value for the spectrum acceleration $S_e^* = 0.20$ g, which is a suitable value for newly built buildings, and consider four threshold values for S_{De}^* , equal to 150, 200, 250, and 300 mm, respectively. The characteristic values η' and η'' are computed.

5.2. Step 2. Space of admissible values for the couples η_{is} and T_{is}

For each S_{De}^* , the spectra corresponding to η_{min} , η' , η'' , and η_{max} are computed. They are plotted in Figure 10, where the gray admissible area is shown. The values of η' and η'' allow us to investigate all circumstances described in the previous paragraphs under the additional (optional) conditions $\eta_{max} = 0.816$ ($\xi_{min} = 0.10$) usual for CSS isolation systems.

5.3. Step 3. Iso-R and iso-μ curves

For values of η_{is} within the admissible area, the iso-μ and iso-R curves are obtained. To address a suitable technical behavior within typical ranges, the friction coefficient has been varied in the interval [0.025, 0.065] with a step of 0.005 and the radius in the interval [2.5, 6.0 m] with a step of 0.5 m.

5.4. Step 4. Design of the device

Superimposing the gray admissible area with the iso-R and the iso- μ curves, all the admissible couples (R, μ) are defined. The black curve for $\varepsilon = d_E/R = 0.15$ is also drawn to check the trigonometric error ($\Gamma < 0.01$) in Equation (1). Points under it correspond to $d_E/R = 0.15$.

Except for Case 02.150, for which the gray area is not intersected by the family of iso- μ and the iso-R curves above, in all other cases, they intersect, creating a grid of admissible solutions in the range $T > T_D$. As stated in the previous paragraph, assuming that activating the device is a priority, we move along the minimum iso- μ curve and converge on the following:

- Solution a, which corresponds to the lowest radius and, therefore, to the highest self-centering capacity;
- Solution b, which corresponds to the lowest displacement and, therefore, to the smallest device.

Searching for a tailored device that meets Case 02.150, albeit outside the preset suitable technical ranges of μ and R , solutions c and d have been explored.

In Table 1, the results are summarized and grouped in terms of the main parameters:

- The capacity spectra parameters, which define the admissible area;
- The sliding interface parameters, chosen between the joints of the grid generated by iso- μ and the iso-R curves within the admissible area;
- The dynamic behavior, parameters that determine the seismic response of the device.

The trigonometric check allows evaluating how acceptable the approximation introduced in Equation (1) is, when the solutions in Table 1 are adopted.

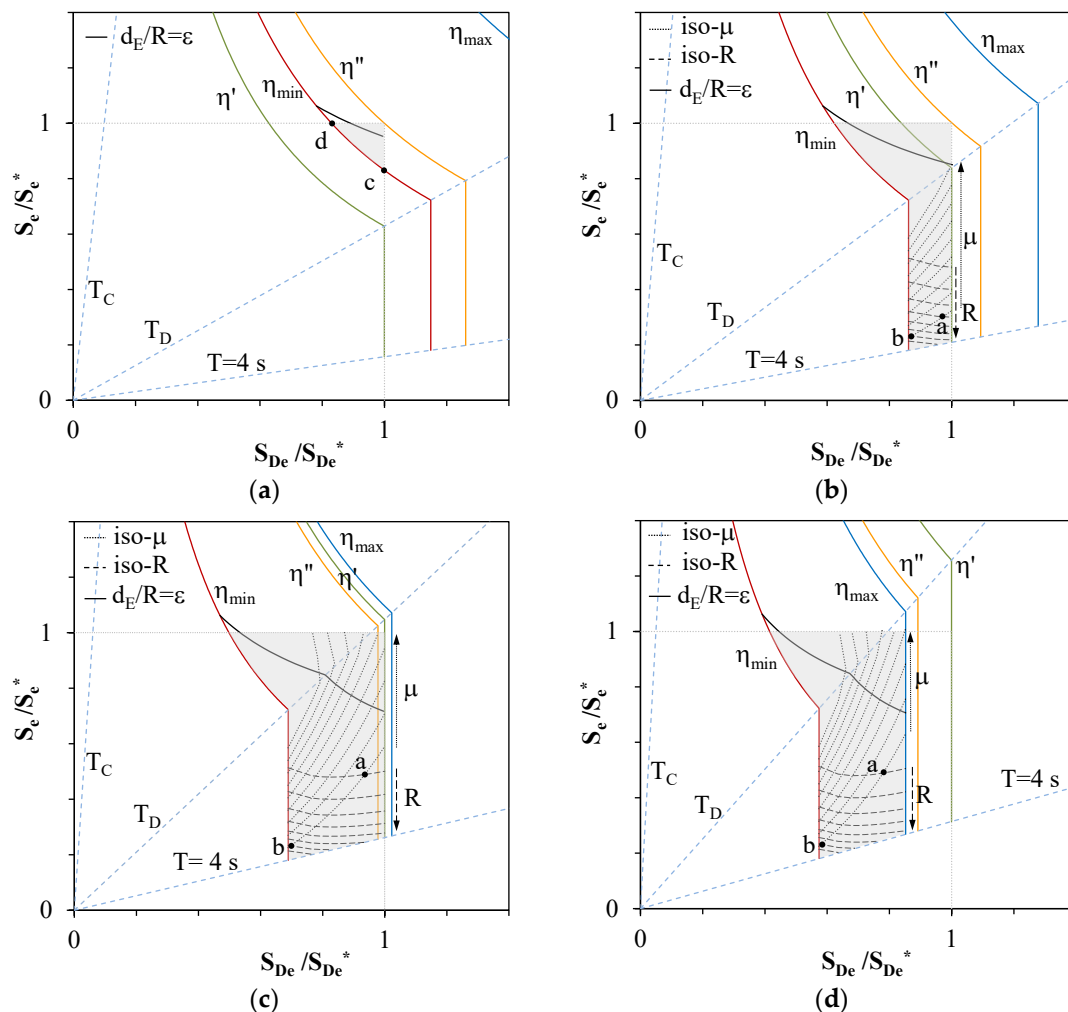


Figure 10. Admissible area superimposed by iso- μ and iso- R curves for: (a) Case 02.150; (b) Case 02.200; (c) Case 02.250; (d) Case 02.300. Arrows indicate increasing values of μ and R . Points under the black curve hold Γ within preset bounds. Points a and b indicate targeted solutions. Points c and d indicate admissible but unsuitable solutions.

For the seismicity considered here, some interesting conclusions can be drawn. When $S_{De}^* = 150$ mm, solutions for CSS are theoretically admissible. However, these correspond to values of the sliding surface radius and friction coefficient outside their suitable technical ranges. Increasing S_{De}^* up to 200 mm, a radius of 4.0 m or greater is needed to maintain the lowest friction coefficient.

From S_{De}^* up to and beyond 250 mm, a solution exists that employs the lowest friction coefficient and radius, thus ensuring device motion activation and a high self-centering capacity.

Under no circumstances can the lowest friction coefficient be combined with $R = 6.0$ m, as the maximum intercepted value is 5.5 m. However, this circumstance has no appreciable impact on the displacement, which comes to reach 174 mm, almost corresponding to the minimum value of the admissible area and, therefore, to the smallest admissible device.

Table 1. Example cases for $S_e^* = 0.20$ g and different values of S_{De}^* .

Case		02.150		02.200		02.250		02.300	
Capacity spectra	S_e^* (g)	0.20							
	S_{De}^* (mm)	150		200		250		300	
	$\eta_{\max}$	0.816							
	$\eta_{\min}$	0.550							
	η'	0.479		0.639		0.798		0.958	
	η''	0.604		0.698		0.780		0.854	
Solution		c	d	a	b	a	b	a	b
Sliding interface	μ	0.092	0.111	0.025	0.025	0.025	0.025	0.025	0.025
	R (m)	1.35	0.92	4.0	5.5	2.5	5.5	2.5	5.5
Dynamic behavior	ρ	0.78	0.78	0.49	0.75	0.25	0.75	0.25	0.75
	ξ_{is} (%)	28.0	28.0	20.9	27.3	12.9	27.3	12.9	27.3
	η_{is}	0.550	0.550	0.621	0.556	0.747	0.556	0.747	0.556
	T_{is} (s)	1.75	1.44	3.29	3.55	2.83	3.55	2.83	3.55
	S_e (g)	0.17	0.20	0.06	0.05	0.10	0.05	0.10	0.05
	S_{De} (mm)	150	124	194	174	234	174	234	174
Trigonometric check	d_E/R	0.12	0.14	0.05	0.03	0.10	0.03	0.10	0.03
	θ (°)	6.7	8.2	2.9	1.9	5.6	1.9	5.6	1.9
	Γ	0.007	0.01	0.001	0.001	0.005	0.001	0.005	0.001

6. CSS Isolation Systems

The procedure described brings us to the definition of the friction coefficient and the radius. Therefore, a plastic material that can guarantee the obtained value of μ can be chosen. If μ is independent of the contact pressure, all isolators will be equal, with the same size and the same value of μ .

If μ depends on the contact pressure, then one of the following paths can be followed:

- All devices will be manufactured identically. Under this hypothesis, the friction coefficient will differ for each isolator, and so will the maximum friction force. The onset of motion should be analyzed in detail.
- All devices will be manufactured to achieve the same friction coefficient μ . Under this assumption, since the vertical load N will differ from one device to another, the contact surface will also have to vary to maintain the same contact pressure. As a result, the maximum friction force on each device will be proportional to the vertical load. One could consider an additional element that defines the contact area, while keeping the rest of the device unchanged. One could define ranges for N to which the same μ could be assigned, to make the proposal more feasible/realistic.

7. Conclusions

Previous CSS design procedures typically start with arbitrarily chosen radius and friction values. This could lead to unsuitable effects and, thus, negatively impact the performance of the isolation system.

In this paper, a characteristic parameter is first identified that encompasses all the design parameters but depends only on the damping ratio. Then, a design approach is proposed that starts from defining, through the capacity spectra, the field of admissible values for the basic parameters η_{is} and T_{is} . These admissible values meet the isolated system requirements in terms of the maximum allowable spectral acceleration S_e^* , compati-

ble with the superstructure capacity, and maximum allowable spectral S_{De}^* displacement in the devices, compatible with the clearance around the building.

Within this admissible area, the iso-R and iso- μ curves are superimposed, thus obtaining a grid of couples of device parameters that meet the isolation system requirements. From this point onward, the design procedure directly focuses on the isolation system performance, by simultaneously managing the device easy activation, self-centering capacity, and dimensions. No matter which parameters are selected, the spectral threshold values in terms of acceleration and displacement will certainly be satisfied. A suitable flowchart synthesizes the method.

One of the strengths of this procedure is the graphical approach. This integrates the search for the target response of the isolated system with the target performance of the isolation system, allowing for a rational and careful choice of design parameters.

To illustrate practical applications, examples have been presented for representative acceleration and displacement thresholds, and for typical technical ranges of the friction and radius. Aiming for a CSS capable of activating rapidly and with an adequate self-centering capacity, the design solutions sought a low friction coefficient and a small sliding surface radius, ensuring that the device dimensions did not exceed what was strictly necessary. The results highlighted the validity of the approach and emphasized the need for adequate clearance around the building to optimize the effectiveness of CSS devices.

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