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Influence of the Ground Acceleration Variation Mode on the Linear Elastic Response Spectrum

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Abstract

This work focuses on comparing the seismic response spectrum of El Centro obtained under two different assumptions about the nature (linear variation and constant mean) of the ground acceleration over a time increment. This research proposes a quasi-analytical approach to solving the differential equation of motion of a simple oscillator forced by an earthquake, combining trigonometric relationships and integration by parts theories. The generated differential equation is solved using the Duhamel integral, making two assumptions about the ground acceleration. An iterative calculation allows us to obtain the different points of the time displacement and then construct the oscillation curves (displacements) as a function of time. The response spectrum is constructed using the maxima of the oscillation curves and their corresponding periods for the same damping ratio. The other spectral curves are obtained by repeating the same scenario as many times as there are damping ratios, and for each assumption. Comparison of the results shows that the maxima of the oscillator responses correspond to the same periods, and that apart from the difference between the responses of the spectral curves at zero damping ratio, the other spectral responses are similar for non-zero damping ratios. Furthermore, the difference between the spectral responses is so small for the first curves and so negligible for the others that both approaches lead to similar results.

Keywords

Damping Ratio, Simple Oscillator, Ground Acceleration, Response Spectrum, Linear Behavior

1. Introduction

The study of the response of structures subjected to earthquakes is essential for their design. The fundamental problem of seismic design lies in determining the response of a structure to seismic movements. Several approaches are used for this purpose, among which the response spectrum is the most widely used tool for determining responses. Despite this, some earthquakes remain destructive or leave significant damage to structures after they have occurred. This has led scientists to continue research on constructing the response spectrum in order to guarantee the stability of structures against seismic forces. Thanks to the development of numerical tools, characterizing the seismic signal is no longer a problem today, but its mathematical modeling remains a concern [1]. Constructing the response spectrum requires first modeling this seismic signal during the solution of the forced differential equation generated by the simple oscillator. In [2] and [3], Newmark proposed two assumptions about ground acceleration for the numerical solution of this differential equation. The first assumption is that ground acceleration varies linearly over a time increment, and the second is that the mean is constant over the same time increment. For structures with linear elastic behavior, Nkibeu *et al.* [4] proposed an algorithm for transforming the seismic signal into a linear elastic response spectrum by solving the differential equation using the Duhamel integral, taking the first assumption. This article focuses on constructing seismic response spectra with two assumptions about ground acceleration behavior for different damping rates on one part, and comparing the maximum responses obtained on the other part to examine the discrepancies arising from the assumptions.

This manuscript demonstrates the influence of assumptions made about seismic acceleration on spectral displacements. In engineering, the search for less complex methods that do not significantly impact the result is always desirable. Solving the differential equation of earthquake-forced oscillations under the assumption of a constant mean seismic acceleration is less tedious than when it varies linearly.

2. Methods

When designing a structure that will be subjected to an earthquake, it is necessary to predict its dynamic response. Before evaluating this response, the structure must be modeled using a realistic model that accurately reflects it. Among the models, the simplest is called the "skewer" model, which combines mass and lifting elements. Newton's equation of motion is then applied to the mass, generating a heterogeneous second-order differential equation with constant coefficients and a second term [5]. Several numerical approaches are used to solve this differential equation. Chopra *et al.* suggest using the convolution integral or Duhamel integral approach because it is quasi-analytical once the assumption is made about the ground acceleration [6]. Constructing the linear elastic response spectrum requires, in addition to modeling and formulating the equations, defining the mode of variation of the ground acceleration over a time increment, solving the equation, and developing a program for plotting the response spectra [7].

2.1. Modeling and Equation Formulation

The structure is modeled using a skewer model, combining mass and stiffness elements, with a single translational degree of freedom and attached to the ground by means of a vertical rod of negligible mass. This model is called a simple oscillator and is illustrated in **Figure 1**.

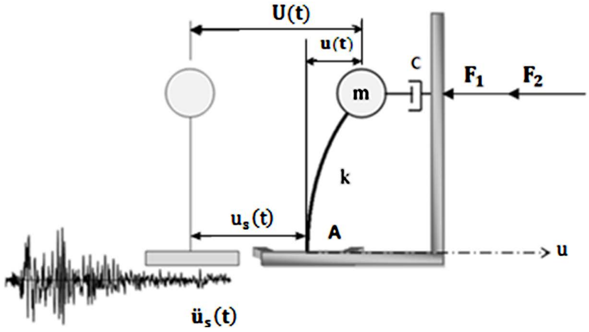

Figure 1. Simple oscillator subjected to a seismic signal $\ddot{u}_s(t)$.

When a seismic signal is applied to the base of the oscillator, it begins to oscillate and generates two forces in the same direction, and opposite to the direction of movement:

- An elastic restoring force expressed by $F_1 = k \cdot u(t)$;
- A damping force expressed by $F_2 = c \cdot \dot{u}(t)$.

Applying the fundamental principle of dynamics to mass, we obtain the following equation of motion for damped forced oscillations [6].

$$m \cdot \ddot{U}(t) + c \cdot \dot{u}(t) + k \cdot u(t) = 0 \tag{2.1}$$

with $\ddot{U}(t) = \ddot{u}_s(t) + \ddot{u}(t)$, it gives:

$$m \cdot \ddot{u}(t) + c \cdot \dot{u}(t) + k \cdot u(t) = -m\ddot{u}_s(t) \tag{2.2}$$

where m, c, k respectively designates the mass, the damping constant, and the stiffness of the rod.

$\ddot{U}(t), \ddot{u}(t), \dot{u}(t), u(t)$ respectively denotes the total acceleration, the acceleration, the velocity, and the relative displacement of the mass of the oscillator.

2.2. Solving the Equation of Motion

To solve this equation, divide expression (2.2) by *m*, and set $\xi = \frac{c}{2m\omega}$, $\omega^2 = \frac{k}{m}$, we obtain the refined expression (2.3):

$$\ddot{u}(t) + 2\xi\omega\dot{u}(t) + \omega^2 u(t) = -\ddot{u}_s(t) \tag{2.3}$$

where ξ is the damping ratio and ω the natural frequency of the oscillator.

In [6] and [8], Anil K. Chopra and Alain Pecker propose expression (2.4) as the ideal method for solving the linear differential Equation (2.3). Its general solution, for the underdamped oscillator, is of the form:

$$u(t) = A\cos(\omega_D t - \varphi)e^{-\xi\omega t} - \frac{1}{\omega_D}\int_0^t \ddot{u}_s(t)e^{-\xi\omega(t-\tau)}\sin\omega_D(t-\tau)d\tau \quad (2.4)$$

where ω_D is the angular frequency of the damped oscillations and is expressed by $\omega_D = \omega\sqrt{1-\xi^2}$.

The right-hand side of Equation (2.4) describes free oscillations with damping, while the right-hand side describes forced oscillations with damping. In the general case, the free oscillations disappear in a fraction of a second, giving way to established forced oscillations. The general solution (2.4), therefore, takes the form of expression (2.5):

$$u(t) = -\frac{1}{\omega_D}\int_0^t \ddot{u}_s(t)e^{-\xi\omega(t-\tau)}\sin\omega_D(t-\tau)d\tau \quad (2.5)$$

Equation (2.5) is called the convolution integral or Duhamel integral, which we solved by a quasi-analytical method by considering two hypotheses on the behavior of the ground acceleration during a time increment [2]:

- The ground acceleration $\ddot{u}_s(t)$ varies linearly within each time increment Δt;
- The ground acceleration $\ddot{u}_s(t)$ is an average constant within each time increment Δt.

The two assumptions and approximations of the seismic signal are represented in **Figure 2** and **Figure 3**.

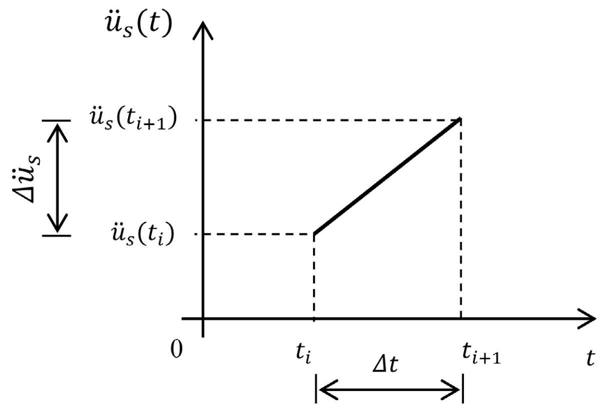

Figure 2. Approximation of the linear seismic acceleration $\ddot{u}_s(t)$ during a time increment Δt.

Figure 2 represents the assumption of linear variation of the seismic acceleration. Using Thales' relation, I obtain the approximation of this acceleration by expression (2.6).

$$\ddot{u}_s(t) = \frac{\Delta\ddot{u}_s}{\Delta t}t + \ddot{u}_s(t_i) \quad (2.6)$$

with $\Delta t = t_{i+1} - t_i$ and $\Delta\ddot{u}_s = \ddot{u}_s(t_{i+1}) - \ddot{u}_s(t_i)$.

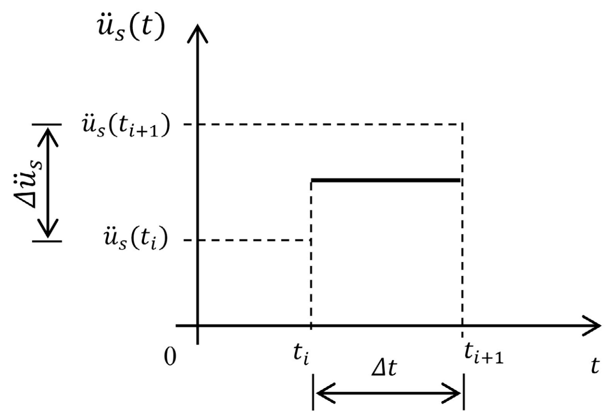

Figure 3. Approximation of the seismic acceleration $\ddot{u}_s(t)$ average constant during a time increment Δt.

Figure 3 represents the assumption of a constant mean seismic acceleration. Approximation (2.7) is obtained by averaging the largest and smallest seismic accelerations that bracket the time increment.

$$\ddot{u}_s(t) = \frac{1}{2}\left(\ddot{u}_s(t_i) + \ddot{u}_s(t_{i+1})\right) \tag{2.7}$$

2.2.1. Solving the Equation of Motion by Considering That the Ground Acceleration Varies Linearly over a Time Increment Δt

Solving Equation (2.5) requires changes of variables, then the use of trigonometric relations, and finally several part-wise integrations.

By posing $h(t-\tau) = \frac{1}{\omega_D} e^{-\xi\omega(t-\tau)} \sin\omega_D(t-\tau)$, the integral (2.5) becomes

$$u(t) = -\int_0^t \ddot{u}_s(\tau) h(t-\tau) d\tau \tag{2.8}$$

Moreover: $\sin\omega_D(t-\tau) = \sin\omega_D t \cos\omega_D\tau - \cos\omega_D t \sin\omega_D\tau$ and $e^{-\xi\omega(t-\tau)} = e^{-\xi\omega t} \cdot e^{\xi\omega\tau} = \frac{e^{\xi\omega\tau}}{e^{\xi\omega t}}$.

And expression (8) becomes:

$$h(t-\tau) = \frac{1}{\omega_D}\frac{\sin\omega_D t}{e^{\xi\omega t}} e^{\xi\omega\tau} \cos\omega_D\tau - \frac{1}{\omega_D}\frac{\cos\omega_D t}{e^{\xi\omega t}} e^{\xi\omega\tau} \sin\omega_D\tau \tag{2.9}$$

Substituting expression (2.9) into (2.8), we obtain:

$$u(t) = -\left[\frac{1}{\omega_D}\frac{\sin\omega_D t}{e^{\xi\omega t}}\int_0^t \ddot{u}_s(t) e^{\xi\omega\tau} \cos\omega_D\tau d\tau - \frac{1}{\omega_D}\frac{\cos\omega_D t}{e^{\xi\omega t}}\int_0^t \ddot{u}_s(t) e^{\xi\omega\tau} \sin\omega_D\tau d\tau\right] \tag{2.10}$$

By posing $A(t) = \int_0^t \ddot{u}_s(t) e^{\xi\omega\tau} \cos\omega_D\tau d\tau$ and $B(t) = \int_0^t \ddot{u}_s(t) e^{\xi\omega\tau} \sin\omega_D\tau d\tau$, Expression (10) can also be written in the form.

$$u(t) = -\left[\frac{1}{\omega_D}\frac{\sin\omega_D t}{e^{\xi\omega t}} A(t) - \frac{1}{\omega_D}\frac{\cos\omega_D t}{e^{\xi\omega t}} B(t)\right] \tag{2.11}$$

Let's study the functions $A(t)$ and $B(t)$ in the interval $[0,t]$. To do this, subdivide this interval into small time intervals $\left[t_i, t_{i+1}\right]$.

At time $t = t_i$; $A(t_i) = \int_0^{t_i} \ddot{u}_s(t) \mathrm{e}^{\xi\omega\tau} \cos\omega_D \tau \mathrm{d}\tau$ and $B(t_i) = \int_0^{t_i} \ddot{u}_s(t) \mathrm{e}^{\xi\omega\tau} \sin\omega_D \tau \mathrm{d}\tau$.

At time $t = t_{i+1}$; $A(t_{i+1}) = \int_0^{t_{i+1}} \ddot{u}_s(t) \mathrm{e}^{\xi\omega\tau} \cos\omega_D \tau \mathrm{d}\tau$ and $B(t_{i+1}) = \int_0^{t_{i+1}} \ddot{u}_s(t) \mathrm{e}^{\xi\omega\tau} \sin\omega_D \tau \mathrm{d}\tau$.

The relationship between $A(t_i)$ and $A(t_{i+1})$ and is given by expression (2.12).

$$A(t_{i+1}) = A(t_i) + \int_{t_i}^{t_{i+1}} \ddot{u}_s(t) \mathrm{e}^{\xi\omega\tau} \cos\omega_D \tau \mathrm{d}\tau \tag{2.12}$$

Proceeding in the same way as before, the relationship between $B(t_i)$ and $B(t_{i+1})$ is given by expression (2.13).

$$B(t_{i+1}) = B(t_i) + \int_{t_i}^{t_{i+1}} \ddot{u}_s(t) \mathrm{e}^{\xi\omega\tau} \sin\omega_D \tau \mathrm{d}\tau \tag{2.13}$$

Introducing the analytical expression for ground acceleration (2.6) into the established expressions (2.12) and (2.13), and after several integrations by parts, we obtain the discretized partial solutions given by the expressions (2.14) and (2.15).

$$\begin{aligned} A(t_{i+1}) = A(t_i) &+ \frac{\Delta\ddot{u}_s}{\Delta t}\Bigg[\frac{\omega_D}{\left[\omega_D^2 + (\xi\omega)^2\right]^2}\mathrm{e}^{\xi\omega\tau}\Bigg[\left(\tau\left(\omega_D^2 + (\xi\omega)^2\right) - 2\xi\omega\right)\sin\omega_D\tau \\ &+ \frac{\cos\omega_D\tau}{\omega_D}\left(\xi\omega\tau\left((\omega_D)^2 + (\xi\omega)^2\right) - (\xi\omega)^2 + (\omega_D)^2\right)\Bigg]\Bigg]_{t_i}^{t_{i+1}} \\ &+ \left(\ddot{u}_s(t_i) - \frac{\Delta\ddot{u}_s}{\Delta t}t_i\right)\left[\frac{\omega_D}{\omega_D^2 + (\xi\omega)^2}\mathrm{e}^{\xi\omega\tau}\left(\sin\omega_D\tau + \frac{\xi\omega}{\omega_D}\cos\omega_D\tau\right)\right]_{t_i}^{t_{i+1}} \end{aligned} \tag{2.14}$$

$$\begin{aligned} B(t_{i+1}) = B(t_i) &+ \frac{\Delta\ddot{u}_s}{\Delta t}\Bigg[\mathrm{e}^{\xi\omega\tau}\Bigg[\frac{\cos\omega_D\tau}{\omega_D}\left(-\tau + \frac{\xi\omega}{\omega_D^2 + (\xi\omega)^2}\left(1 + \xi\omega\tau\left(\omega_D^2 + (\xi\omega)^2\right) - (\xi\omega)^2\right) + \omega_D^2\right) \\ &+ \frac{\sin\omega_D\tau}{\omega_D^2 + (\xi\omega)^2}\left(1 + \xi\omega\tau\left(\omega_D^2 + (\xi\omega)^2\right) - 2(\xi\omega)^2\right)\Bigg]\Bigg]_{t_i}^{t_{i+1}} \\ &+ \left(\ddot{u}_s(t_i) - \frac{\Delta\ddot{u}_s}{\Delta t}t_i\right)\left[\frac{\mathrm{e}^{\xi\omega\tau}}{\omega_D^2 + (\xi\omega)^2}\left[-\omega_D\cos\omega_D\tau + \xi\omega\sin\omega_D\tau\right]\right]_{t_i}^{t_{i+1}} \end{aligned} \tag{2.15}$$

Introducing expressions (2.14) and (2.15) into expression (2.11), we obtain the general discretized solution given by expression (2.16).

$$\begin{cases} u(t_i) = -\left[\dfrac{1}{\omega_D}\dfrac{\sin\omega_D t}{\mathrm{e}^{\xi\omega t_i}}A(t_i) - \dfrac{1}{\omega_D}\dfrac{\cos\omega_D t}{\mathrm{e}^{\xi\omega t_i}}B(t_i)\right] \\ u(t_{i+1}) = -\left[\dfrac{1}{\omega_D}\dfrac{\sin\omega_D t_{i+1}}{\mathrm{e}^{\xi\omega t_{i+1}}}A(t_{i+1}) - \dfrac{1}{\omega_D}\dfrac{\cos\omega_D t_{i+1}}{\mathrm{e}^{\xi\omega t_{i+1}}}B(t_{i+1})\right] \end{cases} \tag{2.16}$$

2.2.2. Solving the Equation of Motion by Considering That the Ground Acceleration Is Constant on Average over a Time Increment Δ*t*

For this second hypothesis, the solution of Equation (2.5) follows the same procedure as before, with the sole difference that the ground acceleration no longer varies linearly over a time increment but rather remains constant over the same time increment. By introducing the analytical expression for ground acceleration (2.7) into the established expressions (2.12) and (2.13), and after several part-integrations of Equation (2.5), we obtain the discretized partial solutions given by expressions (2.17) and (2.18).

$$A(t_{i+1}) = A(t_i) + \frac{1}{2}(\alpha_i + \alpha_{i+1})\left[\frac{\omega_D}{\omega_D^2 + (\xi\omega)^2} e^{\xi\omega\tau}\left(\sin\omega_D\tau + \frac{\xi\omega}{\omega_D}\cos\omega_D\tau\right)\right]_{ti}^{ti+1} \quad (2.17)$$

$$B(t_{i+1}) = B(t_i) + \frac{1}{2}(\alpha_i + \alpha_{i+1})\left[\frac{e^{\xi\omega\tau}}{\omega_D^2 + (\xi\omega)^2}\left[-\omega_D\cos\omega_D\tau + \xi\omega\sin\omega_D\tau\right]\right]_{t_i}^{t_{i+1}} \quad (2.18)$$

Introducing expressions (2.17) and (2.18) into expression (2.11), we obtain the general discretized solution given by expression (2.19).

$$\begin{cases} u(t_i) = -\left[\frac{1}{\omega_D}\frac{\sin\omega_D t_i}{e^{\xi\omega t_i}}A(t_i) - \frac{1}{\omega_D}\frac{\cos\omega_D t_i}{e^{\xi\omega t_i}}B(t_i)\right] \\ u(t_{i+1}) = -\left[\frac{1}{\omega_D}\frac{\sin\omega_D t_{i+1}}{e^{\xi\omega t_{i+1}}}A(t_{i+1}) - \frac{1}{\omega_D}\frac{\cos\omega_D t_{i+1}}{e^{\xi\omega t_{i+1}}}B(t_{i+1})\right] \end{cases} \quad (2.19)$$

2.3. Construction of the Linear Elastic Response Spectrum

To implement functions (2.16) and (2.19), we consider the data of the North-South component from the accelerogram of the EL CENTRO earthquake of May 18, 1940 [9]. Its duration is 31.18 sec, and the ground accelerations are recorded every 0.02 sec. These accelerations have for unit the acceleration of gravity and are worth 9.81 m/s^2 for this case. The seismic accelerations were used in their raw state without correction or filtering. The displacements obtained in meters were converted to centimeters. Oscillators have periods ranging from 0.2 sec to 20 secs with a pitch of 0.2 sec. For the damping ratio, they vary from 0% to 10% with a pitch of 1%.

The initial conditions are: When the oscillators are in equilibrium, that is to say, with no displacement, velocity, and acceleration are zero. At time $t = 0$, $u(0) = \dot{u}(0) = \ddot{u}(0) = 0$. This also implies that $A(0) = B(0) = 0$.

For each plotted curve, we find the maximum amplitude of the response and the period T of that oscillator. This pair constitutes a coordinate of the linear elastic response spectrum for the fixed relative damping ratio ξ. The next step involves finding the coordinate pairs of the series of oscillators with natural periods varying from 0 to 20 seconds, for the same damping ratio. The curve connecting all the points of the pairs constitutes the linear elastic response spectrum. The other spectral curves are thus obtained by repeating the same process, for the relative damping ratio varying from 0% to 10%.

3. Results and Discussion

3.1. Results

Figure 4 and Figure 5 show the different linear elastic response spectra for damping rates ranging from 0% to 10% in 1% increments. Figure 4 is obtained under the assumption that the ground acceleration varies linearly over a time increment, and Figure 5 is obtained under the assumption that the ground acceleration is constant over the same time increment.

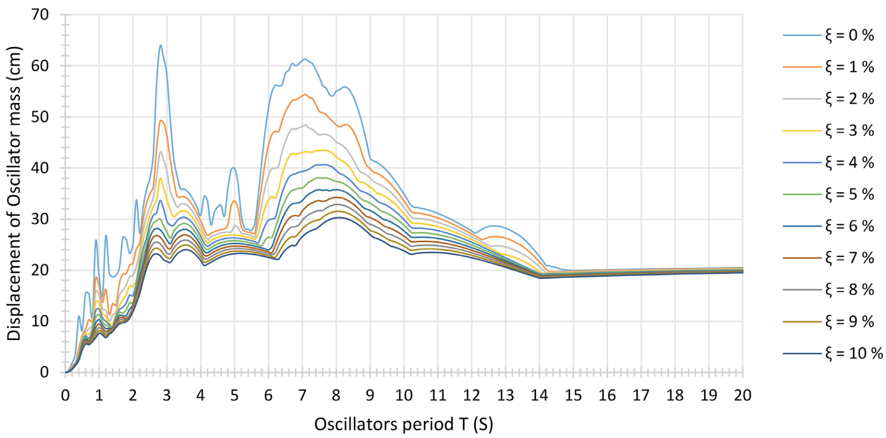

Figure 4. Elastic response spectrum assuming linear variation of ground acceleration over a time increment.

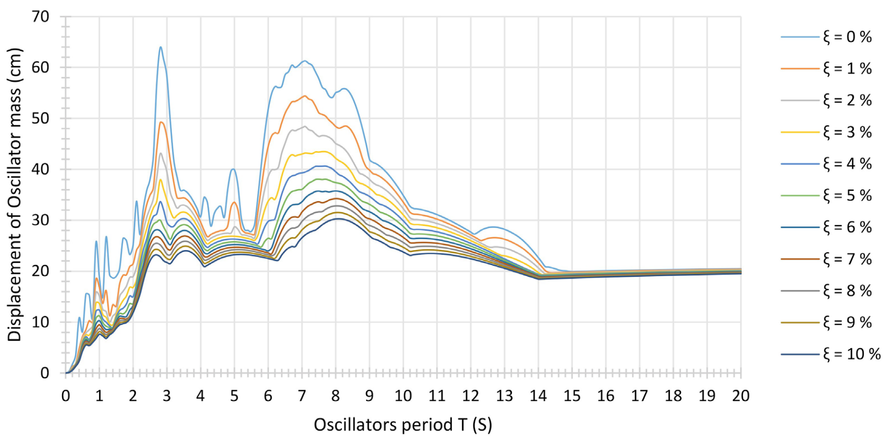

Figure 5. Elastic response spectrum assuming constant average ground acceleration over a time increment.

3.2. Discussion

Analysis of the obtained response spectra allowed us to determine the oscillation periods corresponding to the maximum responses as a function of the damping rate. This analysis is summarized in Table 1 and Table 2. The first column presents the damping rate, the second column the periods corresponding to the maximum response values, and the third column the values of these maximum responses. The maximum response values (63.86 cm and 63.84 cm) were obtained for a damping rate of 0%.

Table 1. Periods of simple oscillators giving maximum responses according to the assumption of linear variation of ground acceleration during a time increment.

Damping Ratio ξ in %	Oscillators Periods T in (s)	Maximum Responses in (cm)
0	2.80	63.86
1	7.10	54.37
2	7.10	48.39
3	7.60	43.47
4	7.70	40.63
5	7.70	38.05
6	8.00	35.75
7	8.00	34.24
8	8.00	32.83
9	8.10	31.51
10	8.10	30.29

Table 2. Periods of simple oscillators giving maximum responses according to the assumption of a constant average of ground acceleration over a time increment.

Damping Ratio ξ in %	Oscillators Periods T in (s)	Maximum Responses in (cm)
0	2.80	63.84
1	7.10	54.37
2	7.10	48.39
3	7.60	43.47
4	7.70	40.63
5	7.70	38.05
6	8.00	35.75
7	8.00	34.24
8	8.00	32.83
9	8.10	31.51
10	8.10	30.29

3.3. Comparison of the Results Obtained

The aim of this analysis is not to conduct a detailed study, but to compare the maximum responses obtained by the different approaches for each damping ratio and spectrum. Analysis of these results allowed us to determine the differences between the spectral responses measured in the same configurations, for the same period, and the same damping ratio. This comparison is presented in **Table 3**.

Table 3. Analysis of the responses of simple oscillators based on the two hypotheses put forward regarding ground acceleration.

Damping Ratio ξ in %	Oscillators Periods T in (s)	Responses of Simple Oscillators in (cm)		Difference in %
		Linear Variation of Ground Acceleration	Constant Average Ground Acceleration	
0	2.80	63.86	63.84	0.03
1	7.10	54.37	54.37	0.00
2	7.10	48.39	48.39	0.00
3	7.60	43.47	43.47	0.00
4	7.70	40.63	40.63	0.00
5	7.70	38.05	38.05	0.00
6	8.00	35.75	35.75	0.00
7	8.00	34.24	34.24	0.00
8	8.00	32.83	32.83	0.00
9	8.10	31.51	31.51	0.00
10	8.10	30.29	30.29	0.00

4. Conclusion

This manuscript presents the construction of the linear elastic response spectra of simple oscillators subjected to earthquakes. This is achieved by making two assumptions about the behavior of ground acceleration over a time increment. The differential equation generated by the model is solved using the Duhamel integral for each assumption made about the seismic signal. An algorithm was then developed to calculate the solutions of the differential equation and automatically construct the response spectra. The results show that the oscillator periods yielding the maximum responses are the same, except for the first case, for a damping ratio $\xi = 0\%$, which shows a slight variation of 0.03% in the responses. In the other cases, with higher damping ratios, the maximum responses are the same regardless of the nature of the seismic acceleration behavior over a time increment. The difference between the maximum responses.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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