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Underdamped elastic response spectra of microtremors using Newmark's β-method

Espectros de respuesta elástico sub-amortiguados de microtremores usando el método β de Newmark

Kléber Augusto Jaramillo Galarza*
Andrea Natalí Zárate Villacrés*
Diego Hernán Hidalgo Robalino*
Marcelo David Guerra Valladares*

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ABSTRACT
In the absence of seismic records, this study focuses on using microtremors as surrogates to analyze ground signals during earthquakes. Earthquake engineering uses response spectra to evaluate the structural reaction to vibrations, condensing the complex dynamics required for design. The central objective is to generate response spectra in underdamped systems using Newmark's β method, considering displacement, velocity and acceleration with operations research methodology. The sample consists of 171 points of the Riobamba seismic zonation study. Using environmental microtrepidation results, accelerogram matrices were obtained for each component. Maximum values of displacement, velocity and acceleration were extracted for a natural period of 3 seconds with a damping of 5% and plotted to obtain response spectra. This methodological approach provides a robust analysis of the underdamped response of the system, offering crucial insights for seismic design and engineering.

* Máster en Ingeniería Matemática y Computación., Universidad Nacional de Chimborazo, kjaramillo@unach.edu.ec, https://orcid.org/0000-0003-1488-5412
Master of Engineering in Engineering Civil. Universidad Nacional de Chimborazo, andrea.zarate@unach.edu.ec, https://orcid.org/0000-0002-7183-2862
Magíster en Ingeniería Estructural / Ingeniero Civil. Arquitecto. Universidad Nacional de Chimborazo, dhhidalgo@unach.edu.ec, https://orcid.org/0000-0003-1341-8206
Ingeniero Civil. Magíster en Ingeniería Civil con mención en Estructuras Sismorresistentes, Universidad Nacional de Chimborazo, mguerra@unach.edu.ec, https://orcid.org/0000-0003-4119-4959

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Keywords: microtremors, seismicity, sub-damped response spectra.

RESUMEN

En ausencia de registros sísmicos, este estudio se enfoca en utilizar microtremores como sustitutos para analizar las señales del suelo durante sismos. La ingeniería sísmica emplea espectros de respuesta para evaluar la reacción estructural ante vibraciones, condensando la compleja dinámica requerida para el diseño. El objetivo central es generar espectros de respuesta en sistemas sub-amortiguados mediante el método β de Newmark, considerando desplazamiento, velocidad y aceleración con la metodología de investigación de operaciones. La muestra consiste en 171 puntos del estudio de zonificación sísmica de Riobamba. Utilizando resultados de microtrepidación ambiental, se obtuvieron matrices de acelerogramas para cada componente. Se extrajeron valores máximos de desplazamiento, velocidad y aceleración para un período natural de 3 segundos con un amortiguamiento del 5%, graficándolos para obtener los espectros de respuesta. Este enfoque metodológico proporciona un análisis robusto de la respuesta sub-amortiguada del sistema, ofreciendo perspectivas cruciales para el diseño sísmico y la ingeniería.

Palabras clave: espectros de respuesta sub-amortiguados, microtrepidación ambiental, sismicidad

INTRODUCTION

Ecuador is characterized by great seismic vulnerability and danger due to its location in the Pacific Ring of Fire, for this reason the seismic resistant design of structures takes special interest within this environment, especially in the development of innovative technological conceptualizations whose purpose is to protect the structures, their occupants and contents, from the harmful effects of the forces generated during a seismic event. (Pardo, 2017). When an earthquake is generated, energy release is generated in the Earth's crust, at the moment a sudden slip occurs along an active fault, this energy takes the form of seismic waves through geological strata (Hidalgo, 2011)The source produces waves that cover a wide range of frequencies, and before reaching the surface they are altered by the characteristics of the medium in which they propagate, acting as a filter that amplifies or attenuates a specific type of frequency (Hurtado, Barbat, 2011). (Hurtado, Barbat, & Canas, 2016).In addition, when the system is forced to vibrate

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at excitation frequencies that coincide with the natural frequencies of the system, a state of resonance is produced and therefore, dangerous and high impact oscillations occur, the maximum values of resonant frequencies lead to response spectra, subsequently generating the design spectra that must be integrated to the seismic regulations for public safety and for the generation of seismic resistant structural designs. (Paz, 2014).

At present, research related to the generation of seismic response spectra is scarce, these studies are of great importance especially for those areas that are prone to natural phenomena such as earthquakes, as they contribute to the analysis of seismic waves generated during earthquakes both in the soil location and in its structures, This type of studies requires seismic resistant designs with quite accurate modeling and supported by specific software that are used as a black box because its only function is the entry of input data to obtain results, which does not allow to know the previous steps and even the uncertainties associated with the methods used by the program, this modeling is done through specific mathematical processes that allow the application of dynamic parameters of systems subjected to seismic loads.

The obtaining of spectra contributes to the evaluation of the capacities of the types of soils and the conditions in which they are found to withstand a given earthquake. In this research, programming skills are developed in relation to programming for the creation of routines that are limited to obtain design and seismic response spectra for a given structure and design values are obtained for the realization of safe constructions that have the conditions to withstand seismic displacements. (Hernández & Mercado, 2015).

In the research carried out by Mora (2012), related to local design spectra for the city of Riobamba from environmental vibration measurements, the city of Riobamba is located in zone V, which represents a high seismic hazard, for this study parameters were used that allow obtaining design spectra, through the approximate determination of true values of seismic force to which structures are subjected during their useful life, through this study, the need to use environmental vibration measurements was considered, through processes based on statistical methods, with which elastic acceleration response spectra were generated with a damping fraction equal to 5% in correspondence with the seismic zoning map of the city, which contributed to find an applicable local design spectrum.

Another study is the one conducted by Galarza (2016), in which a methodology is proposed for obtaining seismic floor spectra, for this procedures are proposed that allow obtaining spectra in which the seismic action is defined on the basis of the structure, this is done with power spectra that characterize the movement of the soil in the frequency domain, the methodology used was supported by the theory of random vibrations in which the characterization of the movement is proposed from Fourier amplitude spectra compatible with a soil response spectrum, with this it is not necessary to use ground motion records or accelerogram. (Galarza, 2016).

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Another research is the one carried out by Paz (2014), focused on the calculation procedure for the elaboration of seismic spectra for the seismic-resistant design of structures, in which seismic spectra are considered important as a tool for analysis and design of structures, minimum properties are described for dynamic analysis such as: mass, damping, stiffness; from this, the vibration theory of a particle is determined through the generation of spectra; where, starting from seismic readings , it considers free motion as the simplest for the analysis of a moving particle. In addition, linear systems are analyzed which obey Hooke's Law, therefore, only small deformations are considered and the response of the particle or a single system with a single degree of freedom to a seismic record (accelerogram) is obtained, the graphs obtained represent maximum responses for different systems, this response spectrum uses a design spectrum suitable for elastic design, inelastic aspects of the systems are also analyzed, where nonlinear effects are considered to obtain a more realistic design. (Paz, 2014).

The seismic hazard study in Ecuador is still under development, new seismogenic zones have not been defined and active faults have not been modeled, nor has an attenuation study of accelerations, velocities, displacements and seismic intensities been performed, considering the existing anisotropy and heterogeneities, in addition to the determination of seismic recurrence with the new seismogenic sources defined and the updated hypocenter catalogs (Hidalgo, 2011). (Hidalgo, 2011)..

Under this context and considering that many times small earthquakes are forgotten due to the little information available and often there are only testimonies from populated areas, causing the epicenters to be poorly located, this information has not been well received by researchers and often discarded to take as valid only that based on instrumentation, the lack of information over time makes it important to study the microtremors and the need to instrument them more often and compare these data over time is born.

During the history of the city of Riobamba, it has been affected by some earthquakes of great intensity, thus in the year 1645 the city was known as a Villa that according to data from 1605 was defined as "four streets both lengthwise and widthwise with a central square..., whose buildings were made of adobe and thatched roofs and about three or four tile roofs...."According to testimonies, reference is made to the fact that the buildings were built on bad soil, which led to an amplification of seismic waves, according to the data provided by the Geophysical Institute of the National Polytechnic School, the epicenter was located at coordinates -1.68S and -78.55W very close to the village, being felt in Quito with countless aftershocks produced several deaths. According to historical archives and considering the type of houses built at the time, this earthquake can be classified as grade VI on the modified Mercalli scale (Barahona and Mora, 2013). In 1968, an earthquake qualified by history as a "dreadful cataclysm" in the central zone of the Ecuadorian highlands, according to reports of the date, the terrible soil on which the city was built and the poor quality of materials with which the houses of the time

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were built, places this earthquake as a grade VII on the modified Mercalli scale. In 1797, the total destruction of the town of Riobamba was recorded, being catalogued as the most destructive earthquake and of greater magnitude in its entire history, grade IX on the modified Mercalli scale (Alvarado, García, Mojácar, and Alvarado). (Alvarado, García, Mothes, & Segovia, 2004)..

The objective of this research is to generate seismic response spectra using Newmark's Methodβ for the case of underdamped systems, based on displacement, velocity and acceleration by means of a function developed in MATLAB.

MATERIALS AND METHODS

The maximum rock acceleration expected for the design earthquake expressed as a fraction of the acceleration of gravity is considered by the Z zone factor; According to the site where the building is to be constructed, six seismic zones must be considered in Ecuador. Table 1 of the Ecuadorian Construction Standard 2015 - Seismic Hazard Seismic Resistant Design shows the Z values according to these zones; it is necessary to know the maximum ground acceleration in the area where the building will be constructed during its useful life to be taken into account in the seismic design (Aguiar, 2008).

Table 1 . *Seismic zoning of Riobamba soils .*

Type of soil	V_s (m/s)	N(SPT)	T_s (s)	Effect
S1	>750	>50	<0.2	Healthy or partially altered rock, dense and dry sandy, silty or clayey gravels, dense sands, soils and deposits of volcanic origin, firmly cemented, tuffs and conglomerates.
S2	$200<V_s<750$ <200	10<N<30 4<N<10	$0.2<T_s<0.6$	Intermediates Semi-dense Loose
S3	<200		>0.6	Soft
S4				Special, with high liquefaction potential, collapsible and sensitive, peats, muds, organic soils, fillers, clays and silts of high plasticity (IP>75).

Source: (Ministry of Urban Development and Housing, 2000)..

The seismic zoning map is the result of the seismic hazard study for a 10% exceedance in 50 years (return period 475 years) which includes 0.50 g saturation of seismic acceleration values in rock in the Ecuadorian coastline characterizing zone VI (NEC, 2015).

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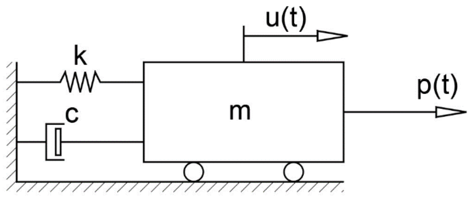
Traditionally, seismic-resistant design in engineering has been based on the acceleration, velocity and displacement response spectra defined by

$$S_r \rightarrow r(T_n, \zeta) \equiv máx_t |r(t, T_n, \zeta)| \tag{1}$$

where $S_r \rightarrow r(T_n, \zeta)$ represents the strain, velocity or acceleration response spectrum of the one degree of freedom (1GDL) structure, t the response time, T_n the natural period and ζ the critical damping fraction. Soil characterization and its effect on buildings are one of the uses of response spectra, a graph representing the maximum response of a set of 1GDL oscillators with the same damping as a function of their natural period of vibration subjected to a history of given accelerations or accelerograms. A representation used for a 1GDL system is the "Mass-Spring-Damper" system, consisting of a rigid block of mass $m$which can move only in one direction, the displacement defines its position, the elastic resistance $u(t)$ defines its position, the elastic resistance of this displacement is given by the stiffening spring. $k$the energy loss mechanism is symbolized by a shock absorber, (see figure 1). c(see figure 1).

Figure 1. Typical representation of a 1 GDL system.



Where:
$m =$ Inertial characteristic of the structure, it is the weight divided by gravity.
$k =$ Elastic restoring force and the potential energy capacity of the structure is the spring constant.
$c =$ Frictional characteristic and energy loss of the structure, it is the damping element.
$p(t) =$ External forces acting on the structural system, it is the excitation force of the system which is a function of time.

The motion of any body tends to decrease with time, this decrease is associated with the energy loss that occurs in each system produced by friction or damping forces (Chopra, 2014). Conventional structures have critical damping fractions less than 0.10, this damping fraction is usually expressed as a percentage, systems with $\zeta < 0.10$ are known as under-damped, the decay rate in free vibration is the most important effect of damping.

Figure 2 represents the motion $u(t)$ due to the initial displacement $u(0)$ for three different values of critical damping fraction, the system oscillates around its

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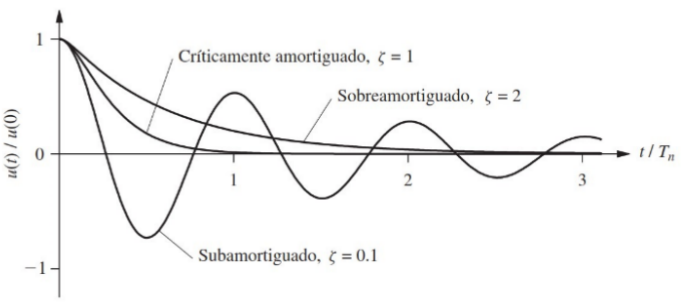
equilibrium position with an amplitude that decreases progressively if $c < c_{cr}$ o $\zeta < 1$ the system returns to its equilibrium position without oscillation when $c = c_{cr}$ o $\zeta = 1$ and similarly the system oscillates slower when $c > c_{cr}$ or for $\zeta > 1$ (Chopra, 2014).

Figure 2. Free vibration of underdamped, critically damped and overdamped systems.



Source: (Chopra, 2014)

When the excitation force $p(t)$ or ground acceleration $\ddot{u}_g(t)$ in a 1GDL system vary with time or if the system is nonlinear, the analytical solution of the equation of motion is not possible, Newmark's methodβ can be approached as a step-by-step numerical resolution in time for the integration of the second order differential equation, the method is stable since for 1GDL systems it uses time intervals smaller than $0.551T_n$ to obtain an accurate representation of the excitation and response.

The method is based on the assumed variation of the acceleration, the numerical solution to the response $u_{i+1}, \dot{u}_{i+1}\ y\ \ddot{u}_{i+1}$ at the instant $i + 1$ and satisfy equation (2)

$$m\ddot{u}_{i+1} + c\dot{u}_{i+1} + (f_s)_{i+1} = -m\ddot{u}_{g\ i+1} \quad (2)$$

$(f_s)_{i+1}$ is the external restoring force in time i for an elastic system $(f_s)_i = ku_{i+1}$

The numerical method starts with initial conditions $u_0 = u(0)$ y $\dot{u}_0 = \dot{u}(0)$ to start the iterative calculation, for linear systems the equation (2) becomes

$$m\ddot{u}_{i+1} + c\dot{u}_{i+1} + ku_{i+1} = -m\ddot{u}_{g\ i+1} \quad (3)$$

Where:

$m, c\ y\ k =$ They are the mass, damping and stiffness of the system.

$u, \dot{u}\ y\ \ddot{u} =$ Displacement, velocity and acceleration respectively.

$-m\ddot{u}_{g\ i+1} =$ Ground acceleration

The algorithm of Newmark'sβ method for linear systems is as follows:

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1. Enter mass $m$damping fraction ζ and natural period of vibration T_n.
2. Calculate $k = \frac{4m\pi^2}{{T_n}^2}$ y $c = 2\zeta\sqrt{km}$
3. Enter $\gamma = \frac{1}{2},\ \beta = \frac{1}{6}$ for the linear acceleration method.
4. Select ΔtThe accelerograms work with intervals equal to 0.02 s.
5. The iteration starts with $u_0 = u(0),\ \dot{u}_0 = \dot{u}(0)\ y\ \ddot{u}_0 = \ddot{u}(0)$
6. Calculate factors $F_1, F_2\ y\ F_3$

$$F_1 = \frac{1}{\beta(\Delta t)^2}m + \frac{\gamma}{\beta\Delta t}c$$

$$F_2 = \frac{1}{\beta\Delta t}m + \left(\frac{\gamma}{\beta} - 1\right)c$$

$$F_3 = \left(\frac{1}{2\beta} - 1\right)m + \Delta t\left(\frac{\gamma}{2\beta} - 1\right)c$$

7. Calculate effective stiffness matrix $\hat{k}$

$\hat{k} = k + F_1$

8. Calculate iteratively over time for $i = 0,1,2,...$ of displacement, velocity and acceleration.

$$\hat{p}_{i+1} = -m\ddot{u}_{g\,i+1} + F_1 u_i + F_2 \dot{u}_i + F_3 \ddot{u}_i$$

$$u_{i+1} = \frac{\hat{p}_{i+1}}{\hat{k}}$$

$$\dot{u}_{i+1} = \frac{\gamma}{\beta\Delta t}(u_{i+1} - u_i) + \left(1 - \frac{\gamma}{\beta}\right)\dot{u}_i + \Delta t\left(1 - \frac{\gamma}{2\beta}\right)\ddot{u}_i$$

$$\ddot{u}_{i+1} = \frac{1}{\beta(\Delta t)^2}(u_{i+1} - u_i) - \frac{1}{\beta\Delta t}\dot{u}_i - \left(\frac{1}{2\beta} - 1\right)\ddot{u}_i$$

9. Update the values of displacements, velocities, accelerations and move to the next point from step 8, and so on until completing the loop from instant zero to instant $t$where t represents the total time of recording values of ground accelerations.
   $u_i = u_{i+1}$
   $\dot{u}_i = \dot{u}_{i+1}$
   $\ddot{u}_i = \ddot{u}_{i+1}$

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RESULTS

The study by Mora and Barahona (2013) obtained local design spectra from environmental vibration measurements supported by accelerogram data from the city of Riobamba. Despite the fact that the NEC 2015 places the city of Riobamba in zone V of high hazard, there are no updated studies that allow the exact quantification of the city's exposure to seismic hazards, hence the importance of obtaining local design spectra, but to achieve this, seismic response spectra must first be obtained; due to the absence of accelerograms recorded over time, the need to use environmental microtrepidation as a tool to obtain response spectra is born since these are good predictors of soil behavior.

Once the phases imposed in the methodology have been fulfilled in correspondence with the collection, identification, analysis, documentation, verification and change management, we proceed to the design of the software, which is built under the MATLAB (MAtrix LABoratory) software tool, which has an integrated development environment (IDE) and its own programming language, the implementation of algorithms is very simple compared to other programming languages, it can be executed in interactive environments, as well as through scripts (extension *.m files), among the major advantages of this program is the simple handling of matrices and operations with vectors.

The application of mathematics in the solution of real problems is undoubtedly one of the main achievements, mathematical models can be solved analytically and numerically as in this case, in this work a dynamic model is presented due to its evolution over time, the main purpose of the mathematical model to be developed is to predict the response of the system under given conditions. Several flowcharts were made, one of the main ones is the one in which the function for the generation of the response spectrum of all the instrumented points is determined, where the importance of the code is to visualize the dispersion of the values obtained and to see if there is a relationship between instrumented points, it is the basis for the next step in the research since it is intended to continue the study from these results to normalize these response spectra and obtain a local design spectrum.

Once the required programming is established, we have the graphical function of the respective curves of all the points instrumented simultaneously, one graph for displacement, one for velocity and one for acceleration as shown in figure 4, 5 and 6 respectively.

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Figure 3 Flow chart for the generation of Response Spectra for all instrumented points.

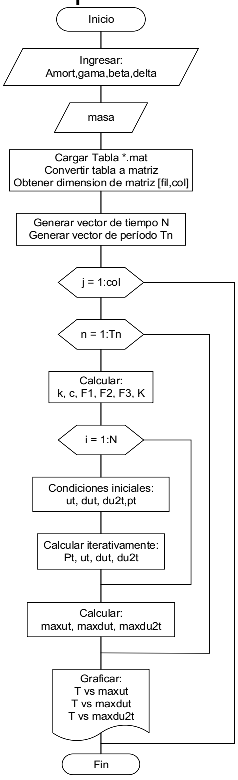

Figure 8 represents the set of all the displacement response spectra of the 171 instrumented points with a damping factor of 5% for the horizontal North-South component.

Figure 4 Plot of the displacement response spectra of the 171 points instrumented withζ = 5% horizontal North-South component.

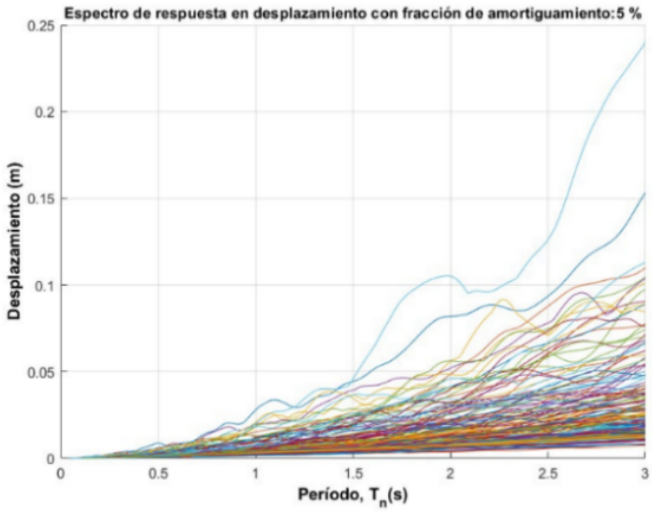

Figure 5 represents the set of all the velocity response spectra of the 171 instrumented points with a damping factor of 5% for the horizontal North-South component.

Figure 5 Graph of the velocity response spectra of the 171 points instrumented withζ = 5% horizontal North-South component.

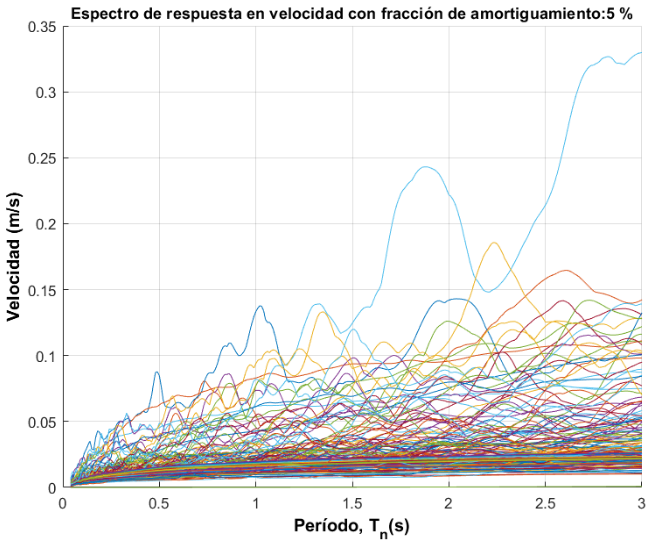

Figure 6 shows the acceleration response spectrum of the 171 points with a damping factor of 5% for the horizontal north-south component.

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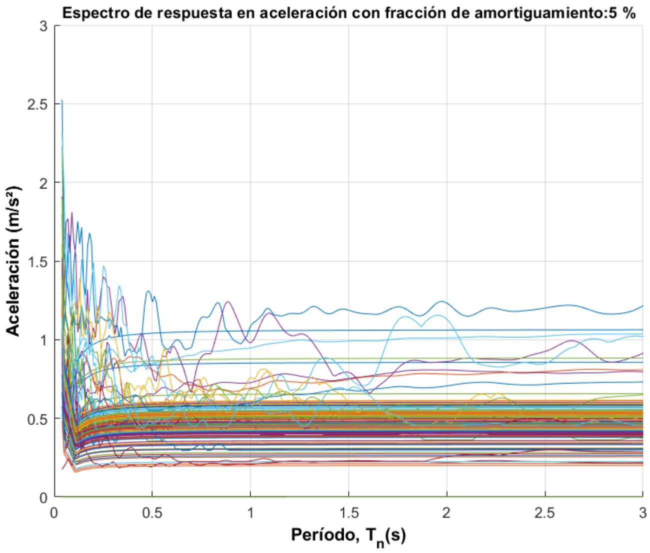
Figure 6 Graph of the acceleration response spectra of the 171 points instrumented withζ = 5% horizontal North-South component.



Finally, the evaluation of the program is performed with point P130 North-South component located between Lizarzaburo and Miguel de Santiago streets with UTM coordinates (759043.6,9817754.1), geographic coordinates Latitude: -1.647462 and Longitude: -78.671729, in addition, the response spectra in displacement, velocities and accelerations of this instrumented point with different values of damping factor are presented, obtaining the following results.

Displacement response of point P130 EO component.

On the abscissa axis the time in seconds and on the ordinate axis the displacement in meters of the maximum absolute response of the ground motion of point #130 obtained by environmental microtrepidation, horizontal east-west component for period values 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 seconds, from these graphs the absolute maxima are obtained for each time instant and are represented in a single graph presented in Figure 7.

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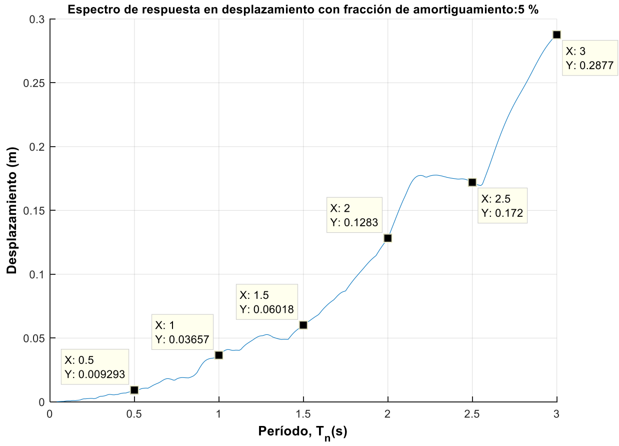
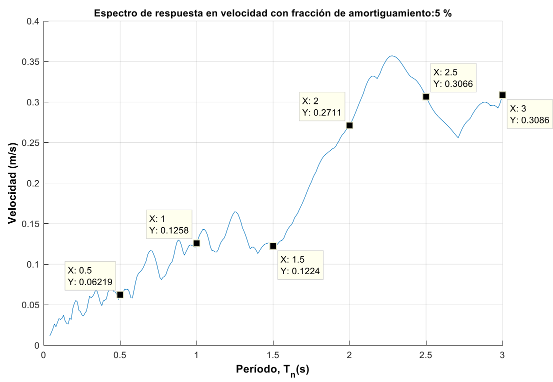
Figure 7 Displacement response spectrum of point P130 east-west horizontal component.



Velocity response of the P130 point EO component.

On the abscissa axis the time in seconds and on the ordinate axis the velocity in meters per second of the maximum absolute response of the ground motion of point #130 obtained by environmental microtrepidation, horizontal east-west component for period values 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 seconds, from these graphs the absolute maximums are obtained for each instant of time and are represented in a single graph presented in Figure 8.

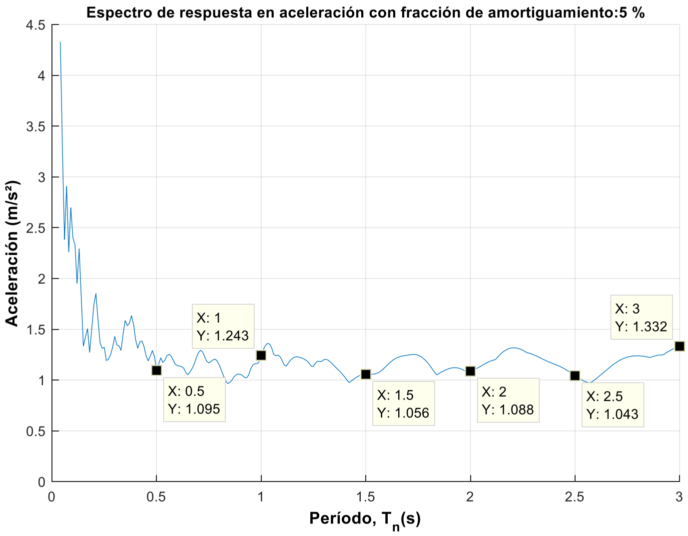
Figure 8. Velocity response spectrum of point P130 east-west horizontal component.



Acceleration response of the P130 point EO component.

On the abscissa axis the time in seconds and on the ordinate axis the acceleration in meters per second squared of the maximum absolute response of the ground motion of point #130 obtained by environmental microtrepidation, horizontal east-west component for period values 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 seconds, from these graphs the absolute maxima are obtained for each time instant and are represented in a single graph presented in Figure 9.

Figure 9. Acceleration response spectrum of point P130 east-west horizontal component.



Displacement, velocity and acceleration response spectrum of the P130 point EO component for various damping factors.

The spectra in figures 10 and 11 represent the effect of the value of the damping fraction, it can be seen that the higher the value of critical damping, the lower the values of displacement and velocity at an instant of time.

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Figure 10. Displacement response spectrum of point P130 east-west horizontal component, for various damping factors.

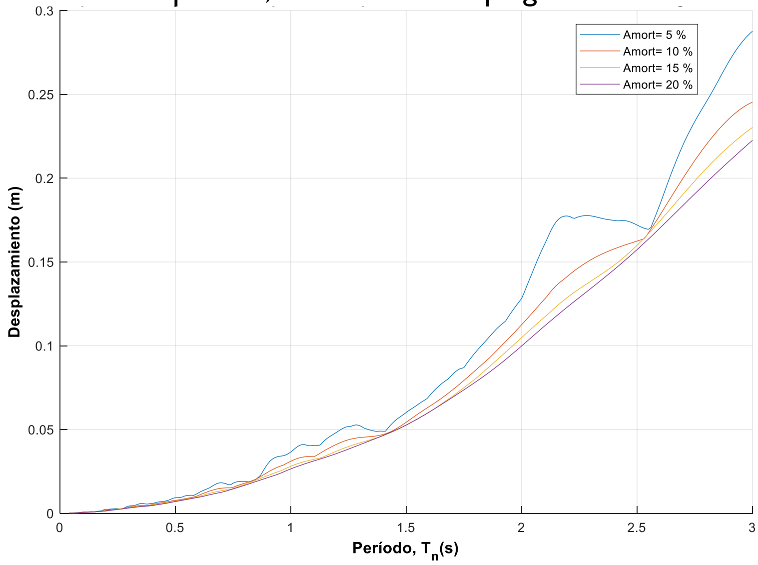
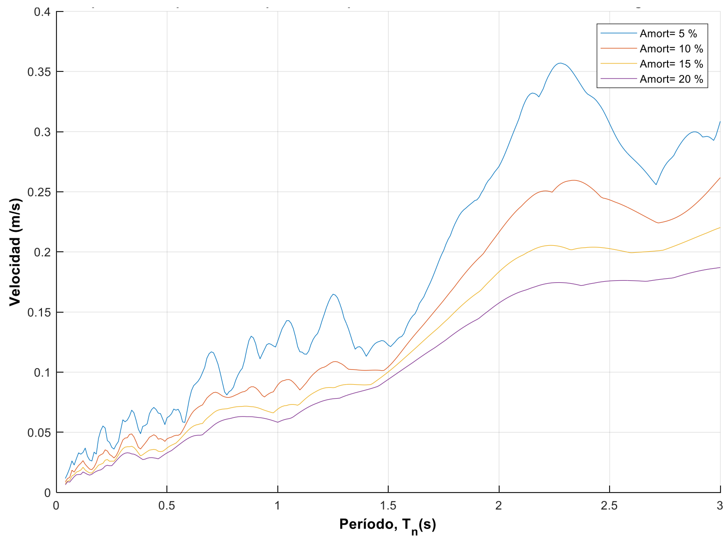


Figure 11. Velocity response spectrum of point P130 east-west horizontal component, for various damping factors.



The acceleration spectrum in Figure 12 represents a building subjected to an artificial earthquake with different damping factors. The effect of damping on the dynamic response of a building can be seen, since the higher the damping value, the lower the spectral acceleration at a given instant of time. Figure 16 shows the damping effect as a function of the spectral acceleration values, these acceleration values are in

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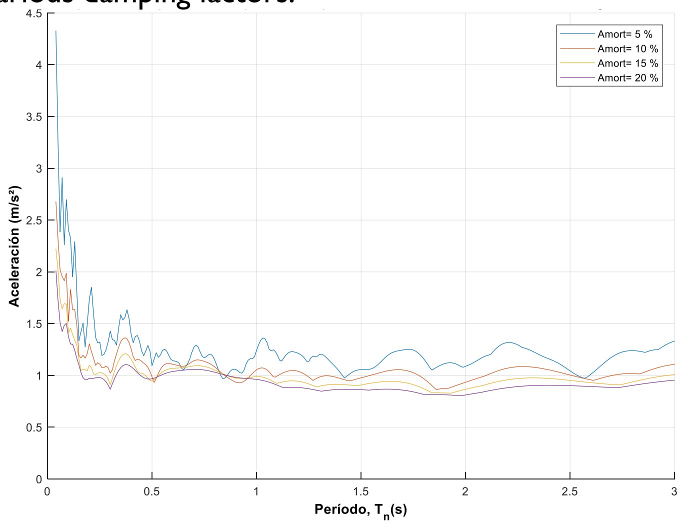
correspondence with the norms and have allowed the standardization of the design spectrum, according to the classification of seismic zones of the country, taking as a base a damping factor of 5%, which allows the use of seismic dissipators to increase the damping of the structure.

Figure 12. Acceleration response spectrum of point P130 east-west horizontal component for various damping factors.



DISCUSSION

The reduction of seismic risk has been the fundamental premise in seismic engineering, an analysis option in the absence of seismic records or accelerograms is the study of environmental microtrepidations, with local seismic zoning based on these microtremors the fundamental periods of the ground are obtained, The analysis of these results by means of programmed functions for the generation of seismic response spectra using numerical methods allows the study of the effect of ground acceleration on buildings, the generation of these graphs or spectra transmits to the structural engineer information for the design of buildings.

Campaña (2016), proposes a tool that he calls PUCEstruct, as a support for civil engineers, before seismic hazards and that is supported by the Ecuadorian Construction Standard 2015, this has an easy interpretation with results that are estimated reliable, this program is developed under the computational tool MATLAB and determined deformation spectra, pseudo velocity and pseudo acceleration for a seismic event (p.7-62), this research is of importance because of the use of the same tool and the use of standardized norms that allow professionals to rely on viable conditions for the realization of their work and especially for decision making.

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Erazo and Vargas (2020), propose a Software for Processing and Correction of Records, and Generation of Seismic Response Spectra, developed under the MATLAB tool, for this began with the correction of line records by means of the Berg and Housner method, which is a classical method. Subsequently, the acceleration, velocity and displacement response spectra were obtained based on methods in the time and frequency domain, whose methods were the Newmark, Duhamel Integral and Fourier Transform. Once the results of both the corrections and the response spectra of a record were obtained, the verifications were carried out with the Prism program of INHA University. Through this research it is demonstrated that the MATLAB computational tool allows the correction of seismic records and the generation of response spectra, and corroborates the benefit provided by the Newmark method, which is based on the assumption of the response acceleration variation and when performing the evaluation, the result is similar to the one obtained in the research proposed in this article.

The vibration period of the building improves the seismic response, the seismic isolators decrease the stiffness of the building resulting in the fundamental period of an isolated structure being greater than that of a structure with a stationary base, the spectral acceleration decreases with a greater vibration period.

The higher the damping, the lower the spectral acceleration in an instant of time, simulates the effect of a structure with seismic dissipators, their main function is to dissipate the accumulation of energy, in other words, they increase the damping of the structure.

The results obtained by environmental microtrepidations allow evaluating the dynamic response of the soil, serving as substitutes for signals obtained by real earthquakes.

The study of seismic behavior is undoubtedly an exciting topic for researchers and the results obtained are of great importance for structural engineers, the lack of local studies motivates the study of these phenomena, the movement of any body tends to decrease with time, in the seismic resistant design the complicated dynamic response of the seismic responses necessary in the structural calculation are addressed in the investigation of these spectra, therefore the generation and study of these spectra take importance.

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