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Analysis and Comparison of Fourier and Wavelet Transforms: Application for the Study of Seismic Source Parameters, Case of the 2001 Arequipa Earthquake

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Abstract

Objective: The purpose of this study is to apply the spectral analysis technique to the aftershocks of the 2001 Arequipa earthquake (Mw=8.4), based on the Fourier and Wavelet transforms.The data corresponds to the world network (IRIS), which has a station called NNA that is located in Peru. Together, 10 records corresponding to replicas registered during a period of 10 days after the main event have been analyzed. The methodology used in this study was based on the SAC software that stands for "Seismic Analysis Code".As a result of the Fourier transform, the fracture radius values obtained are in the range of 0.21 to 1.15km, the stress drop values for the analyzed aftershocks are between 0.60 to 38.08Mpa, the Energy Magnitude is from 3.36 to 4.42Me; for Wavelet: the frequency content which presents the values between 0.18 to 0.30 Hz, The maximum radiated energy between 25.70 to 40.80, the values obtained are in the range of 92.18 to 146.12s.The analysis and comparison of the transforms showed that with the Fourier transform different parameters can be determined by applying spectral analysis, however, with the wavelet transform the maximum radiated energy was determined. This study contributes to the literature by finding these parameters of both transforms as it is of vital importance to determine the zones of energy accumulation that would cause earthquakes of great magnitude in the future.

Keywords: *Aftershocks, Spectral Analysis, Seismic Source Parameters, Fourier and Wavelet Transforms.*

INTRODUCTION

The western edge of South America is characterized as one of the most seismically active regions in the world. Peru is part of one of the seismic regions since it is located within the Pacific Ring of Fire, where more than 80% of the world's seismic energy is released. In Peru, earthquakes are produced from two sources. The most important considers the seismicity associated with the friction of the Nazca and South American plates within the process known as subduction. This seismicity is distributed from North to South, between the trench and the coastline, being responsible for the largest and most destructive earthquakes that have ever occurred in Peru. The second source considers the earthquakes that occur in the interior of the continent, these being associated with the presence of tectonically active faults. In Peru, seismic activity is directly associated with the subduction process of the Nazca plate under the South American plate, which develops at an average relative speed of between 7 and 8 cm/year. (Audemard M. et al., 2005) (Cristobal Condori & Hernando Tavera, 2012) (Norabuena et al., 1999) (Bernal et al., 2002) (DeMets et al., 1990; Norabuena et al., 1999)

An earthquake shook the southern region of Peru, on Saturday, June 23, 2001 at about 15:33:14 (local time), generating intense earth movements occurred along the coast of south-central Peru. about 110 miles (175 km) west of Arequipa, or about 370 miles (595 km) southeast of Arequipa of magnitude 8.4 Mw where the Nazca plate subducts beneath the South American plate, was calculated for this earthquake by the United States Geological Survey, NEIC. The epicenter of this earthquake was located by the Geophysical Institute of Peru (IGP) 82 km NW from the town of Ocoña, it was located in the sea, near the city of Ático (Arequipa). The tremor lasted about 30 seconds. Many aftershocks occurred since the earthquake, some of magnitude greater than 7 During the first 30 days of the earthquake, around 5000 aftershocks were recorded. To determine the size of the Arequipa earthquake, the scalar seismic moment is calculated from the amplitude spectra of the P wave recorded in seismic stations. In addition to the seismic moment, the fracture radius (r) and the mean

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displacement (Δu) of each of the aftershocks are estimated, the Fourier and Wavelet transforms will be applied. (Audemard M. et al., 2005) (Rodriguez -Marek et al., 2010) (Le Pigeon et al., 2002) (Borrero, n.d .) (Audemard M. et al., 2005; Kuroiwa, n.d .; Him Pigeon et al., 2002) (J. C. Ruegg , 2001) (Yanet Antayhua & Hernando Tavera, 2002) (Jiménez et al., 2021) (Stirling et al., 2001) (Yanet Antayhua & Hernando Tavera, 2002) (Yanet Antayhua & Hernando Tavera, 2002)

Background

V. Lina's research in 2020 determines the frequency content for the earthquake of August 27, 2013 in Colombia, through the process of deconvolution and the Fourier transform. (Girón-Lozano et al., 2020a)

In the work of G. Longchampse in 2015, the spectral parameters of the seismic source were determined, such as the corner frequency and the fall of stresses, in order to calculate the moment magnitude and radius of the seismic source in order to establish scale laws between these parameters, 9 earthquakes of great magnitude were studied from 1999 to 2006 whose magnitudes exceed 2.5 degrees. in a sector southeast of the province of Santiago de Cuba. On the other hand, in the research of A. Cichowicz in 2012 he estimated the parameters of a seismic source: moment magnitude, radiated seismic energy, corner frequency, radius of the source and static voltage drop, seismic signals recorded in a distance range ranging from 1 km to 80 km were analyzed. In the research of C. Florez in 2007, the frequency content of a set of signals from seismogenic sources near the city of San José de Cúcuta was determined. The techniques used for spectral analysis are the Fourier Transform and the Wavelet Transform, using their respective amplitude spectra. (Longchamp et al., 2015) (Florez & Lozano, n.d .)

Studies carried out by H. Kanamori and L. Anderson in 1975, allowed the formulation of empirical relationships to define the parameters of the earthquake source, concluding that the stress drop, which is between 3 and 10Mpa, is constant for intraplate and interplate earthquakes. Similarly, R. Archuleta in 1982, applying the technique of spectral analysis and using Brune's model, determined the parameters of the source of earthquakes that occurred in Lake Mammoth (California), and in this case the stress drop is constant at 50bars. (Kanamori & Anderson, 1975) (Archuleta et al., 1982)

In the case of Peru, in J. Mardini's research in 2022, the spectral parameters of the seismic source of the aftershocks of the Lomas earthquake of January 14, 2018 (7.1Mw), the corner frequency, stress drop, moment magnitude and rupture radius were determined. Instrumental correction was applied to the seismic signals to be taken to displacement, apply the fast Fourier transform and obtain the spectra. Similarly, in M. Ñahui's research in 2018, the parameters of the seismic source of the aftershocks of the 2001 Arequipa earthquake were determined. In the study by H. Tavera in 2001, the scalar seismic moment (Mo), the fracture radius (r) and the mean displacement (Δu) of the Arequipa earthquake of June 23, 2001 were estimated. The study carried out by H. Tavera in 2003 analyzed the fall of stresses of large earthquakes with a superficial focus, Intermediate and deep earthquakes occurred in Peru during the period from 1980 to 1995, determining that all earthquakes with a focus at shallow depth present a stress drop between 0.7 and 10Mpa. (Mardini , 2022) (María Delgado, 2018) (Yanet Antayhua & Hernando Tavera, 2002) (Hernando Tavera, 2003)

Area Of Study

In the southern region of Peru, on Saturday, June 23, 2001, an earthquake occurred that caused death and destruction in the departments of Arequipa, Ayacucho, Moquegua and Tacna, as well as the cities of Arica and Iquique in Chile. The maximum intensity of the earthquake was evaluated in VII-VIII on the Mercalli scale. This earthquake is one of the largest and most destructive to occur in this region in the last 100 years (Legrand et al., 2007)

The study area is located in the southern region of Peru, between coordinates -15. 6th and -18. 2º South latitude, -68. 7th and – 76. 2nd West longitude. The 2001 earthquake and series of aftershocks occurred in this area (Figure 1). The Arequipa earthquake was followed by a large number of aftershocks, which are distributed in a

SE direction suggesting that the rupture area possibly propagated in that direction. During the first 15 days of the earthquake, there were around 280 aftershocks with magnitudes greater than 4.0 (Ocola , 2008)

The study of the aftershocks obtained by a local seismic network has initially allowed us to observe a rupture area of 370x150 km2, in addition to a possible propagation of the rupture in a SE direction. (Malasavage et al., 2008).

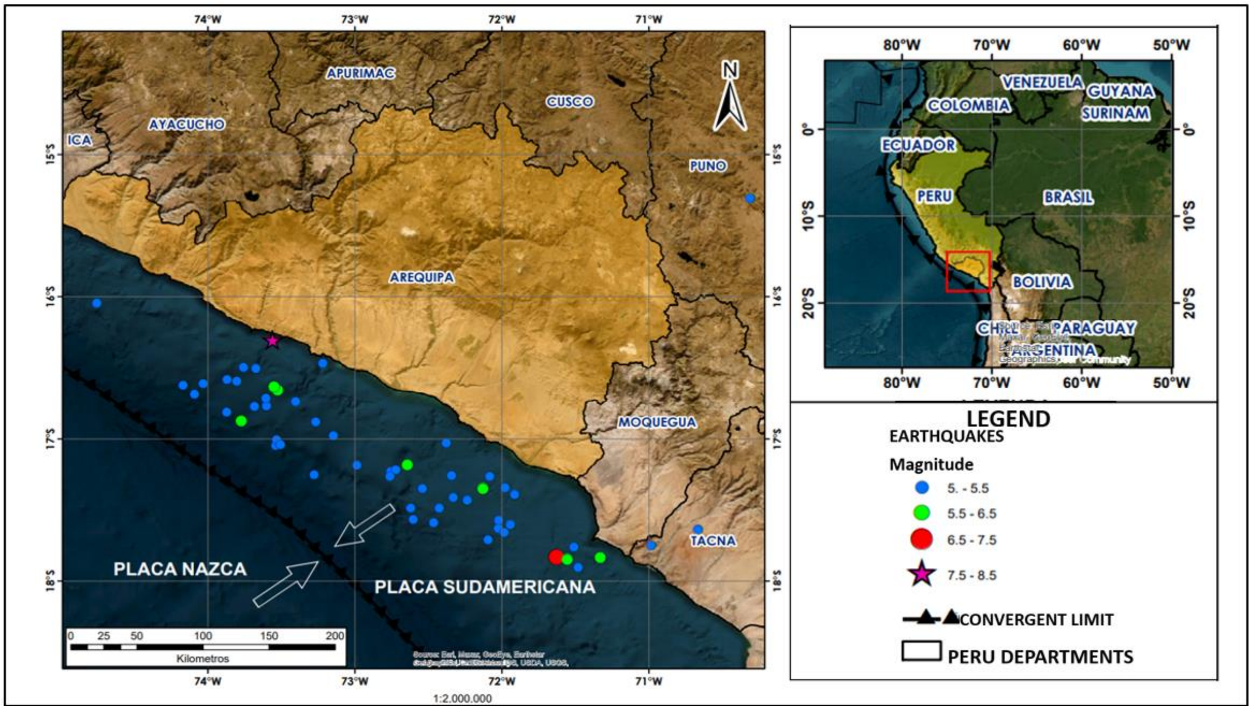

Figure 1. Location of the study area, the 2001 earthquake and its series of aftershocks. The circles correspond to the 42 aftershocks and the color depends on the depth as shown in the legend, they filtered from 5 degrees of magnitude, the pink star represents the main earthquake and the red box is the study area

METHODOLOGY

SAC and Matlab Software

The methodology used in this study was based on SAC software which stands for "Seismic Analysis Code". It was originally developed at Lawrence Livermore National Laboratory to analyze data in time series, especially seismic data. It is one of the most widely used data formats and programs in the seismological research community. The SAC software is a library based on (Seismic Analysis Code) to create and manage output files, which allows reading seismic files that have this type of format. FFT (Fast Fourier Transform), an algorithm that allows the fast Fourier transform to be performed to obtain the spectrum of the seismic signal and calculate the period, based on the spectrum it is possible to determine what type of signal. Filtering, allows you to remove background noise from the seismic signal, the system uses three types of filtering, BandPass, LowPass and HigPass. By applying any of these filters, it will be possible to observe the event very clearly. In the MATLAB software, the Wavelet transform was applied to the signals of the earthquakes. (Helffrich et al., 2013) (Zargar et al., 2013) (Boudouridis & Zesta , 2007)

Matlab (Matrix Laboratory) is a technical-scientific programming language that basically works with vector and matrix variables. It is easy to use because it contains several toolboxes with built-in functions (signal processing toolbox, control theory, wavelets, symbolic mathematics, etc.). Apply digital signal processing and the Matlab programming language to automatically read seismic signal parameters: P phase, S phase, polarity, duration, period, and amplitude. (Hu et al., 2006a) (Omar & Tintaya, 2007)

Fourier Transform

FFT is of great importance in a wide variety of applications, from digital signal processing and digital filtering; in general, the solution of partial differential equations or fast multiplication algorithms of large integers. When talking about digital signal processing, the FFT algorithm imposes some limitations on the signal and the resulting spectrum since the sampled signal to be transformed must consist of a number of samples equal to a power of two. (Prajapati & Singh, 2020a) (10. Characterization of Signals Seismic Using Analysis Spectra and Fourier Short Time Transform , n.d .) (Pezzo et al., 1987)

Because of its simplicity and clear physical meaning, the Fourier transform (FT) is the most popular method used for signal processing in multiple fields. It can be applied to any geophysical problem, especially for stationary signals, the spectrum of which does not vary over time. It represents the decomposition of a wave register into series of sinusoidal signals, i.e., it is able to distinguish the different frequency components of the signal and their respective amplitudes. It has been very useful for implementing analytical and numerical solutions of differential equations and for the analysis and processing of signals (Flórez Góngora & Lozano Lush , n.d .) (Baumbach & Bormann, 1999) (Girón-Lozano et al., 2020b) (Wang et al., 2017)

Fourier analysis allows the signal to be broken down into sinusoidal components of different frequencies, it can also be defined as a mathematical technique that can transform the point of view of a signal from the time domain to the frequency domain, as can be seen in Figure 2. A Fourier decomposition can describe a periodic signal as a Fourier series, i.e., as a sum of sinusoidal and cosinusoidal oscillations. By reversing this procedure, a periodic signal can be generated by superimposing sine and cosynusoidal waves. The general function is : (Chlieh et al., 2011) (Pritchard et al., 2007) (Boroschek & Comte, 2006) (Chik , Islam , et al., 2009)

$$x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} \left(a_k cos(k\omega_0 t) + b_k sen(k\omega_0 t)\right)$$

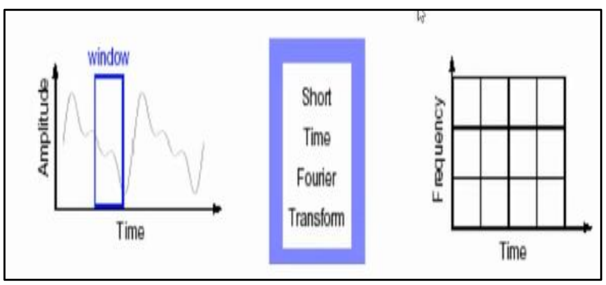

Figure 2. Fourier analysis, taken from (Sulla & Tavera, 2016)

The Fourier transform is used in the processing and analysis of signals giving satisfactory results in cases where these signals are periodic and regular enough, but the same does not happen for the analysis of signals whose spectrum varied over time, for the cases of these signals the Fourier transform with window is used.

Figure 3 shows when and at what frequency a certain event occurs in the signal, but with limited precision due to the fixed window, so new techniques suitable for processing non-stationary signals, such as the wavelet signal, emerge.

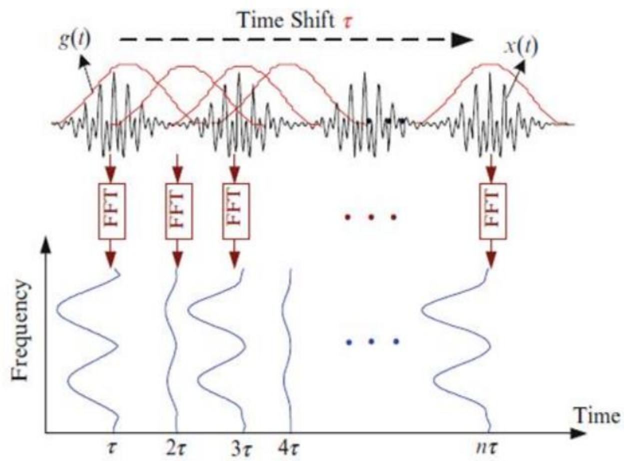

Figure 3. Illustration of Fourier transform into signal x(t), taken from (Sulla & Tavera, 2016)

Windowed Fourier decompositions have emerged in recent years as tools of great importance for signal analysis. The scalar seismic moment and fracture radius for an earthquake are calculated from the two most important characteristics of the amplitude spectra of the volume wave displacement; that is, the flat part of the spectrum at low frequencies ((Ω_0) and the corner frequency (fc) (Figure 4) (Unser , 1994) (Thorsten Bartosch & Dieter Sedl , 1999)

The corner frequency is inversely proportional to the dimensions of the source (r); while its flat part is proportional to the scalar seismic moment (Hanks & Wyss , 1972) (M_o) and fracture radius (r_0) of the aftershocks of the 2001 Arequipa earthquake, the amplitude spectrum of the P-wave displacement recorded at the NNA station has been used, as it is the station closest to the epicenter.

The seismic moment has been calculated using the relationship defined by Hanks & Wyss in 1972. (Hanks & Wyss , 1972) It is nothing more than a measure of the size of the seismic source and is defined as:

Where:

$$M_o = \frac{4\pi\rho v^3}{2\psi_0} R\Omega_0 \dots\dots(1)$$

Ω_0: Flat part, meets the spectrum

Mo: Seismic moment.

$\rho =$ density of the medium; 2.8 gr/cm^3

R=epicentral distance

v = velocity of the P wave; 5 Km/sec

ψ_0= radiation pattern. 0.4

The fracture radius was calculated from the corner frequency (fc) and the Brune ratio in 1970 (Brune, 1970)

$$r_0 = \frac{2.34\alpha}{2\pi f_c} \dots\dots(2)$$

Where:= velocity of the P wave and = corner frequency of the P wave.

The corner frequency (fc): can be shown theoretically as inversely proportional to the cube root of the seismic moment. (Sifuzzaman et al., 2009)

It can also be defined as the frequency below which the least amount of energy is located. In the spectrum it is the frequency value from which the spectrum shows a decay towards high frequencies and is proportional to the dimensions of the fracture. (Lu et al., 2019) (Chik , Taohidul Islam , et al., 2009)

Knowing the scalar seismic moment (M_o) and the fracture radius (r_0), the stress drop ($\Delta\sigma$), the mean displacement (ΔU) and the magnitude can be easily determined from the following Brune and Kanamori relationships (Brune, 1970; Kanamori & Anderson, 1975)

$$\Delta\sigma = 0.44(M_o/r^3) \quad \Delta U = M_0/4\pi r^2 \ldots\ldots(3)$$

$$M_w = (1/1.5)\log M_o - 10.7\ldots\ldots\ldots\ldots (4)$$

To determine the seismic source parameters for the aftershocks of the Arequipa earthquake of June 23, 2001, the following steps have been followed in the SAC software:

Baseline and instrumentation correction is applied to replica logs.

To eliminate the effect of noise, a low-pass filter is applied.

Application of the Fourier transform.

To calculate the Scalar Seismic Moment (Mo).

The magnitude Mw is estimated with the Kanamori ratio

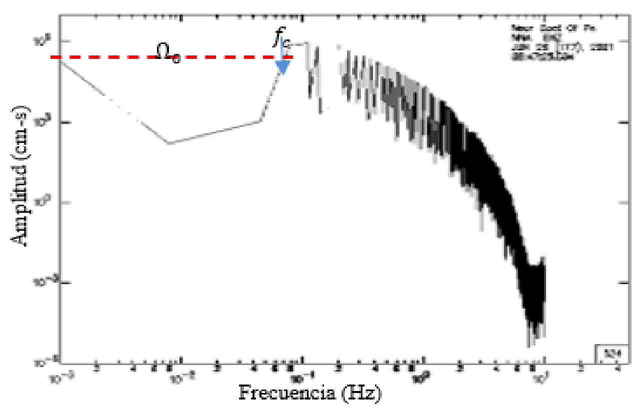

Figure 4. Fourier spectrum of the 2001

Wavelet Transform

Unlike a Fourier decomposition that always uses complex exponential basis functions (sine and cosine), wavelet decomposition uses a localized oscillatory function in time such as the parent or analytic wavelet. The mother wavelet is a function that is continuous in both time and frequency and serves as the source function from which the scaled and translated base functions are built. The mother wavelet can be complex or real, and usually includes an adjustable parameter that controls the properties of the localized oscillation. (Poggi et al., 2013) (Foufoula-Georgiou & Kumar, 1994) (Diallo et al., 2006)

TCW allows to improve the procedure of signal analysis in the time and frequency domain simultaneously. The frequency value is obtained from the inverse relationship with the ranges of levels called "scale"; therefore, the TCW analyzes signals in the time and scale domain. (Figure 5). To apply the TCW it is used as a base function, (wavelet mother) defined as: (Adhikari et al., 2020) (Prajapati & Singh, 2020a) (Prajapati & Singh, 2020b)

$$\Psi^{*}_{a,b}(t) = |a|^{-\frac{1}{2}}\Psi^{*}\left[\frac{t-b}{a}\right] a, b \in R \; ya \; \neq 0$$

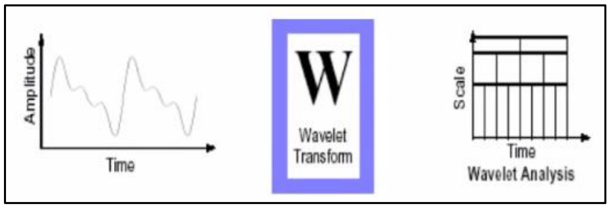

Figure 5. Wavelet analysis taken from (Sulla & Tavera, 2016)

Where the parameter "a" is the scale or expansion factor and the translation parameter "b" which actually provides the position of time. As the value of "a" increases, the effect of dilation in time "b" occurs and therefore, its contraction in the inverse case; that is, large-scale events usually last over time; while those on a low scale are short. The Wavelet Transform (TW) analyzes the signal in the time domain by applying low-pass and high-pass filters in order to eliminate certain high- or low-frequency ranges contained in the signal. Mathematically, a TW is a core function (parent wavelet), such that its integral converges to zero and that it can be moved, dilated, and compressed. (Strang, 1993) (Foster & David Lane, n.d .) (Bosman & Reiter, n.d .) (XIA Norman, 1999)

The term wavelet means small wave; where the term small refers to the fact that this function (window) is of finite length (compactly supported) and the term wave, refers to the function of an oscillatory nature. (Cabrera-Navarrete et al., 2020) (Ji et al., 2002) (Sinha et al., 2005)

The term mother indicates that the functions given for different regions of action used in the transformation process come from a main function or 'master wavelet'. That is, the mother wavelet is a prototype to generate the other window functions. (Grubb & Walden, 1997) (Li et al., 2009) (Chhatrapati & Ji, 2023)

Calculation of the breakout duration

The calculation of the breakout duration is made from the methodology proposed by Lomax in 2011, in the same way used by the author W. Sulla considers the following sequence: (Lomax & Michelini , 2011)

- The earthquake record in speed corresponding to a broadband station, with a vertical BHZ component, is selected.
- A bandpass filter with a frequency of 2 to 4 Hz is applied to the register.
- The amplitude values are squared so that it is proportional to the radiation of the seismic energy.
- The absolute value is applied and its subsequent smoothing of the amplitude values, to finally be normalized to the unit.
- Finally, the breakdown duration is considered from the time of initiation of P waves to the value that corresponds to the intercept of 20% of the amplitude with the decay of the amplification
- It is worth mentioning that it is not necessary to perform the correction by instrumental response to seismic signals, since the analysis is simply performed in the temporal component. (Figure 6).

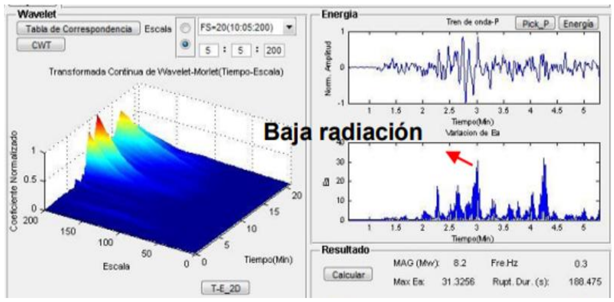

Figure 6. Calculation of breakout duration**.**

Data

In the present study, the method of J. Brune will be used to determine the parameters of the seismic source of the aftershocks of the 2001 Arequipa earthquake, obtained from the Nana station (NNA). The database used in this study corresponds to the IRIS global seismic network (Figure 7), of the Añaña station, as it is the closest to the epicenter of the earthquake. (Brune, 1970)

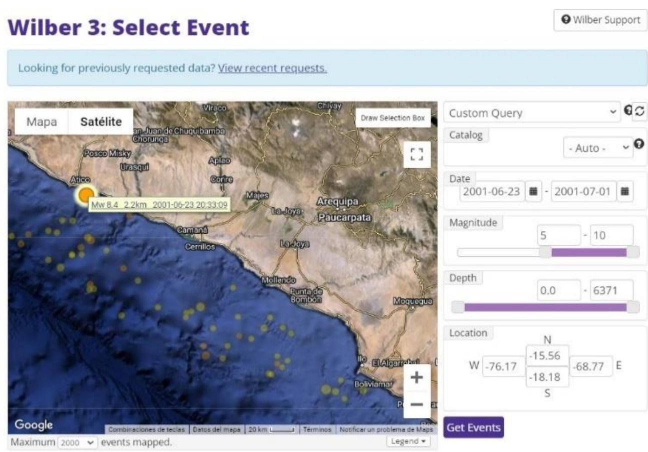

Figure 7. IRIS Window (period 23/06/2001 - 01/07/2001); a total of 55 replicas with a depth of less than 75 km were selected

It was filtered according to date and area, period 23/06/2001 - 01/07/2001 and a total of 10 aftershocks with a depth of less than 75 km were selected (Table 1), with epicenters distributed along the western edge of Peru.

The Ñaña station (NNA belongs to the global seismic network, IRIS). During the period of operation, it registered a significant number of aftershocks, its source parameters such as seismic moment and fracture radius, are obtained by applying the spectral analysis technique. The seismic source parameters are obtained using two characteristics of the amplitude spectra. (Hanks & Wyss , 1972)

Figure 8 presents the flowchart of the methodological processes followed in this research. The treatment stage comprises the processes of instrument correction and filtering of the seismic signal to eliminate unwanted frequency bands present in the signal. In signal processing, the first stage consists of the acquisition of the seismic signal,

The objective of this work is to reveal the comparison of the Fourier transform and wavelet in the analysis of seismic signals applied to the aftershocks of the 2001 Arequipa earthquake. The CWT method of continuous wavelet transformation does not require pre-selecting a window length and does not have a fixed time frequency resolution over the time frequency space compared to seismic signal analysis using the Short-Time Fourier Transform limits the time frequency resolution over a predefined window length. (Hu et al., 2006b) (Lockwood & Kanamori , 2006)

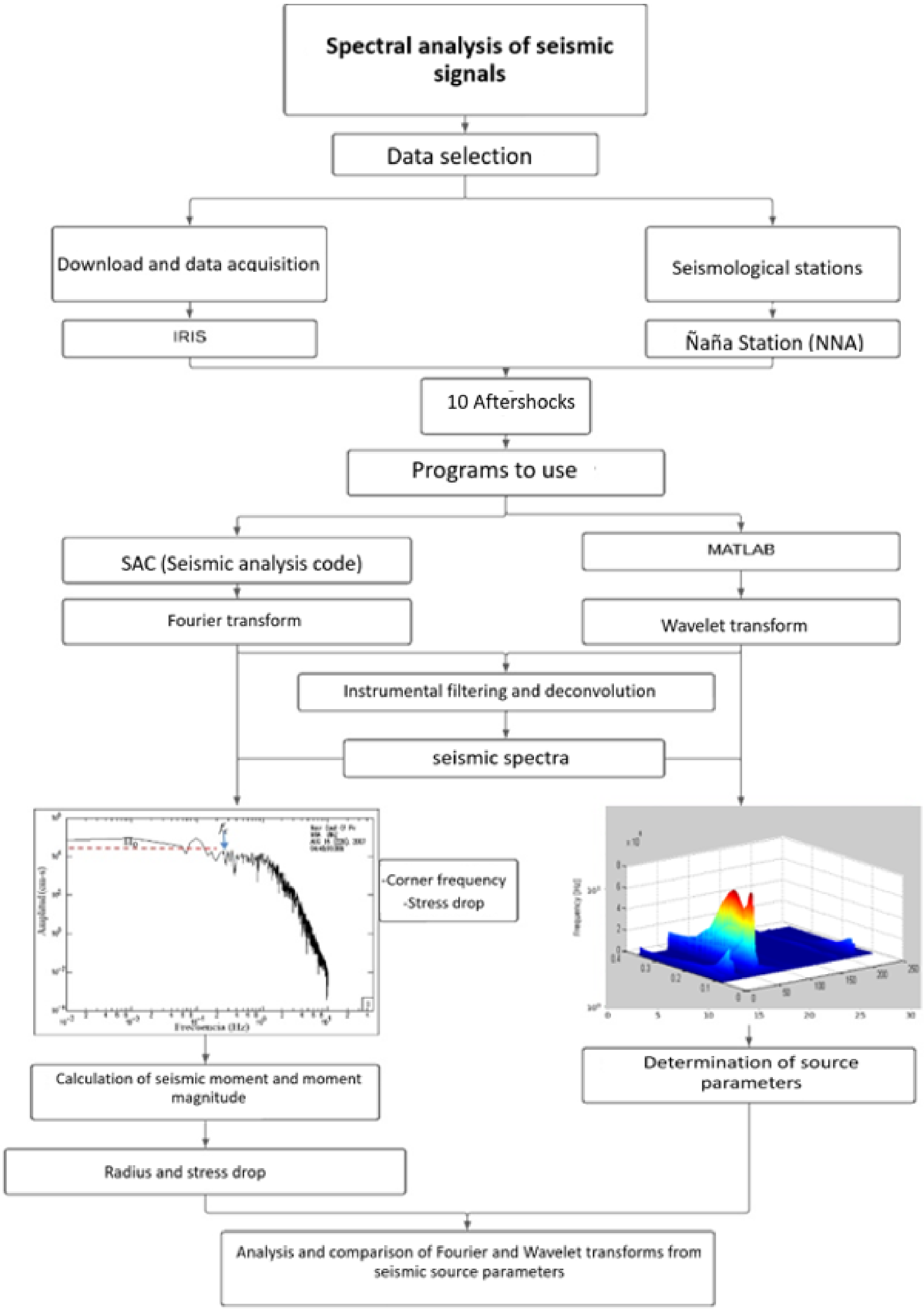

Figure 8. Flowchart of methodological processes.

Table 1 Database

Item	Fecha	Hora	Latitude	Longitude	Prof.	Mag.	MgType	LocationName
1	01/07/2001	11:06:30	-17.186	-72.984	33.0	5.4	Mw	NEAR COAST OF PERU
2	30/06/2001	8:57:19	-17.707	-72.093	33.0	5.3	Mw	NEAR COAST OF PERU
3	29/06/2001	22:33:19	-15.306	-70.311	33.0	5.4	Mw	SOUTHERN PERU
4	28/06/2001	21:35:24	-17.588	-72.463	33.0	5.3	Mw	NEAR COAST OF PERU
5	27/06/2001	0:21:06	-17.903	-71.48	33.0	5.4	Mw	NEAR COAST OF PERU
6	26/06/2001	8:47:09	-16.624	-74.168	33.0	5.4	Mw	NEAR COAST OF PERU
7	26/06/2001	4:18:32	-17.831	-71.63	33.0	6.7	Mw	NEAR COAST OF PERU
8	25/06/2001	22:14:09	-17.637	-70.667	73.7	5.4	Mw	NEAR COAST OF PERU
9	25/06/2001	6:38:48	-16.875	-73.772	38.0	5.7	Mw	NEAR COAST OF PERU
10	25/06/2001	3:48:58	-16.044	-74.755	33.0	5.3	Mw	NEAR COAST OF PERU
11	23/06/2001	20:33:09	-16.303	-73.561	29.6	8.4	Mw	NEAR COAST OF PERU

RESULTS

Fourier Transform Results

For the presentation and description of the results obtained in this research, for regional seismic events the records of the NNA seismic station of the Seismic Network of Peru are used, which registered more than 200 aftershocks of which six representative spectra are shown in Figure 9. After applying spectral analysis, the results are: The flat part of the spectrum (Ω) varies in a range between 2.35e-6 and 2.86e-2cm.s. The corner frequency (fc) varies between 0.33 and 7.78Hz.

The results shown in this study are based on the objective of determining the parameters of the seismic source of the aftershocks of the Arequipa earthquake of June 23, 2001, such as the seismic moment, the fall of stresses, the dimensions of the rupture and the average landslide. Following the procedure of the Brune model and the calculation of the seismic parameters defined by Kanamori. Digital records of 10 aftershocks in the range of magnitudes 5.3Mw to 6.7Mw have been analyzed, which occurred as a result of the Arequipa earthquake of June 23, 2001 in a distance range of approximately 0 to 75km during the months of June and July 2001. The analysis was carried out with records in their vertical components of the replicas that were recorded at the NNA station.

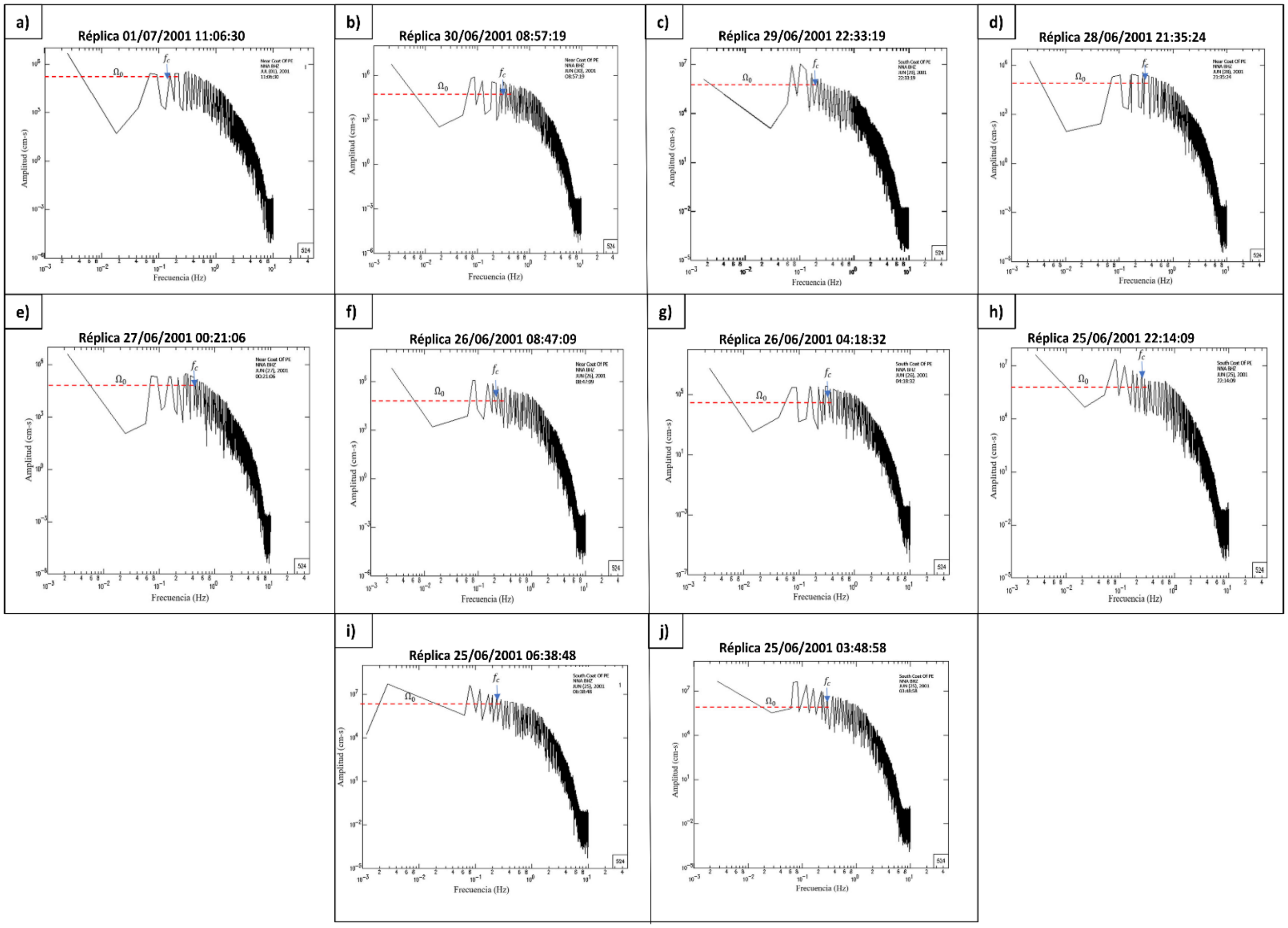

Figure 9. Application of the Fourier transform in aftershocks of the 2001 Arequipa earthquake:

Aftershock on July 1 at 11:06:30 near the coast of Peru with a magnitude of 5.4Mw, b) Aftershock on June 30 at 08:57:19 near the coast of Peru with a magnitude of 5.3Mw, c) Aftershock on June 29 at 22:33:19 in southern Peru with a magnitude of 5.4Mw, d) Aftershock on June 28 at 21:35:24 near the coast of Peru with a magnitude of 5.3Mw, e) Aftershock on June 27 at 00:21:06 near the coast of Peru with a magnitude of 5.4Mw, f) Aftershock on June 26 at 08:47:09 near the coast of Peru with a magnitude of 5.4Mw, g) Aftershock on June 26 at 04:18:32 near the coast of Peru with a magnitude of 6.7Mw, h) Aftershock on June 25 at 22:14:09 near the coast of Peru with a magnitude of 5.4Mw, i) Aftershock on June 25 at 06:38:48 near the coast of Peru with a magnitude of 5.7Mw, j) Aftershock on June 25 at 03:48:58 near the coast of Peru with a magnitude of 5.3Mw. In the 10 replicates the flat part of the spectrum (Ω) varies in a range between 2.35e-6 and 2.86e-2cm.s. and the corner frequency (FC) varies between 0.33 and 7.78Hz.

After analyzing the events, the following values of the spectral parameters of the seismic source have been obtained: Table 2 presents the list of the 10 representative aftershocks recorded at the NNA station, as well as their evaluated parameters such as seismic moment, radius, stress drop and Energy Magnitude (Me).

Table 2. TF Seismic Source Parameters

Item	Fecha dd/mm/aa	Hora (UTC)	Lat.	Lon.	Prof. (km)	Dist.	Mag.	Mo (N.m)	Radio (Km)	Δσ (Mpa)	Me
1	01/07/2001	11:06:30 a. m.	-17,186	-72,984	33.0	712,02	5.4 Mw	1.41E+19	0.56	1.15	3.38
2	30/06/2001	08:57:19 a. m.	-17,707	-72,093	33.0	815,87	5.3 Mw	1.95E+19	0.67	1.08	3.42
3	29/06/2001	10:33:19 p. m.	-15,306	-70,311	33.0	796,80	5.4 Mw	1.82E+19	0.51	1.87	3.61
4	28/06/2001	09:35:24 p. m.	-17,588	-72,463	33.0	781,06	5.3 Mw	1.31E+19	0.40	1.64	3.69
5	27/06/2001	12:21:06 a. m.	-17,903	-71,48	33.0	874,77	5.4 Mw	2.01E+19	0.58	1.72	3.55
6	26/06/2001	08:47:09 a. m.	-16,624	-74,168	33.0	590,86	5.4 Mw	1.33E+19	0.65	1.54	3.91
7	26/06/2001	04:18:32 a. m.	-17,831	-71,63	33.0	858,21	6.7 Mw	1.81E+18	0.50	1.03	3.90
8	25/06/2001	10:14:09 p. m.	-17,637	-70,667	73.7	914,35	5.4 Mw	6.45E+19	0.36	0.60	3.61
9	25/06/2001	06:38:48 a. m.	-16,875	-73,772	38.0	636,41	5.7 Mw	3.62E+18	0.21	1.22	3.54
10	25/06/2001	03:48:58 a. m.	-16,044	-74,755	33.0	504,33	5.3 Mw	1.71E+18	0.53	1.13	3.36
11	23/06/2001	08:33:09 p. m.	-16,303	-73,561	29.6	596,42	8.4 Mw	1.58E+21	1.15	38.08	4.42

Note. Author's elaboration (2024)

Wavelet Transform Results

To perform the spectral analysis of the TCW Wavelet transform for the 2001 Arequipa earthquake aftershocks, the records of the NNA station (Lima, Peru) were used, figures 10 show the graphs of the 3D Wavelet transform applied to the 2001 Arequipa earthquake aftershocks with which the frequency content and the maximum radiated energy could be calculated. Figure 10 shows graphs showing the breakout duration.

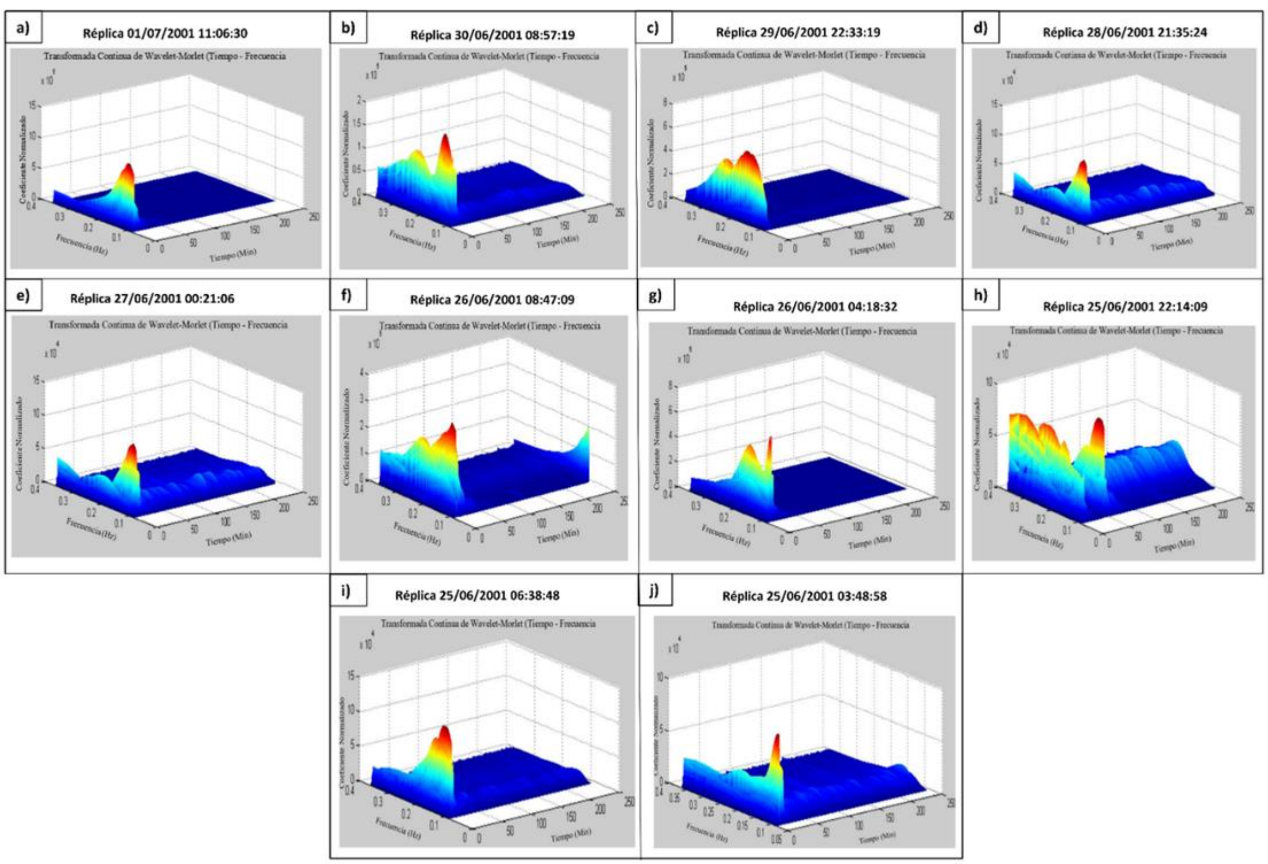

Figure 10. Application of the Wavelet transform in aftershocks of the 2001 Arequipa Earthquake:

Aftershock on July 1 at 11:06:30 near the coast of Peru with a magnitude of 5.4Mw, b) Aftershock on June 30 at 08:57:19 near the coast of Peru with a magnitude of 5.3Mw, c) Aftershock on June 29 at 22:33:19 in southern Peru with a magnitude of 5.4Mw, d) Aftershock on June 28 at 21:35:24 near the coast of Peru with a magnitude of 5.3Mw, e) Aftershock on June 27 at 00:21:06 near the coast of Peru with a magnitude of 5.4Mw, f) Aftershock on June 26 at 08:47:09 near the coast of Peru with a magnitude of 5.4Mw, g) Aftershock on June 26 at 04:18:32 near the coast of Peru with a magnitude of 6.7Mw, h) Aftershock on June 25 at 22:14:09 near the coast of Peru with a magnitude of 5.4Mw, i) Aftershock on June 25 at 06:38:48 near the coast of Peru with a magnitude of 5.7Mw, j) Aftershock on June 25 at 03:48:58 near the coast of Peru with a magnitude of 5.3Mw. In the 10 replicates, the frequency content has the follwing values, ranging from 0.18 to 0.30 Hz

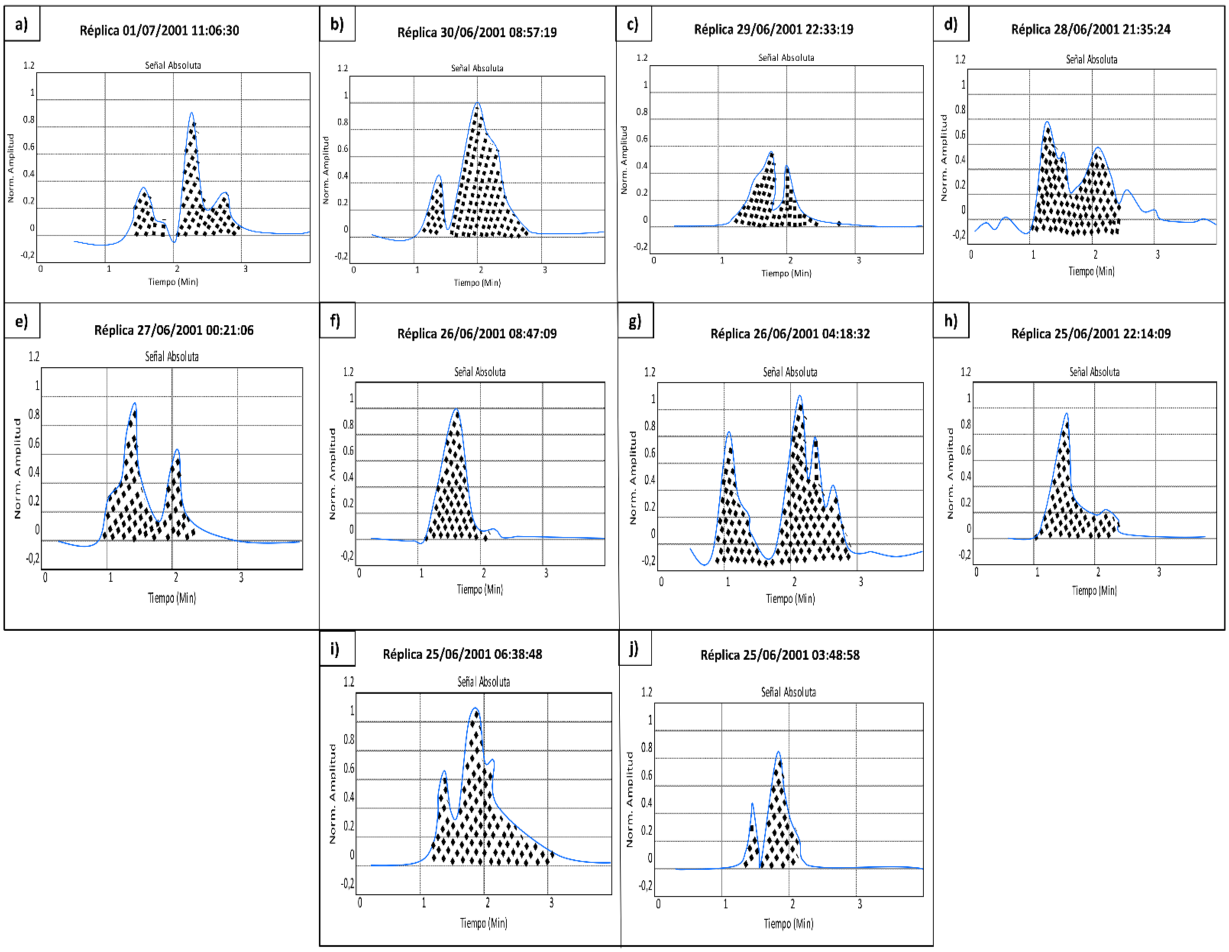

Figure 11. Application of the Wavelet transform in aftershocks of the 2001 Arequipa Earthquake:

Aftershock of 0l/07/2001 at 11:06:30 has an approximate rupture duration of 93.89s, b) Aftershock of 06/30/2001 at 08:57:19 has an approximate rupture duration of 92.18s, c) Aftershock of 06/29/2001 at 22:33:19 has an approximate rupture duration of 93.93s, d) Aftershock of 28/06/2001 at 21:35:24 has an approximate breakup duration of 92.20s, e) Aftershock of 27/06/2001 at 00:21:06 has an approximate breakup duration of 92.91s, f) Aftershock of 26/06/2001 at 08:47:09 has an approximate breakup duration of 93.90s, g) Aftershock of 26/06/2001 at 04:18:32 has an approximate breakup duration of 116.51s, h) Aftershock of 25/06/2001 at 22:14:09 has an approximate breakup duration of 93.92s, i) Aftershock of 25/06/2001 at 06:38:48 has an approximate breakup duration of 99.14s, j) Aftershock of 25/06/2001 at 03:48:58 has an approximate breakup duration of 92.18s. In the 10 replicates, the frequency content has the following values, ranging from 0.18 to 0.30 Hz

The spectral analysis from the TCW was studied by Chamoli, Lockwood and Kanamori, based on the evaluation of large earthquakes that generate tsunamis, most of which occurred in the Indonesian region. All these authors propose the TCW Wavelet transform as a suitable tool to identify events that can generate Tsunami. (Chamoli et al., 2010)

Table 3 presents the list of the 10 representative replicates recorded in the NNA station, for which the displacement spectra have been developed, as well as their parameters: frequency content, maximum radiated energy (maxEa) and breakdown duration obtained are in the range of 92.18 to 146.12s

Table 3. TCW Seismic Source Parameters

Item	Fecha dd/mm/aa	Hora (UTC)	Lat.	Lon.	Prof. (km)	Mag.	Frecuencia (Hz)	MaxEa	Duracion Rupt. (s)
1	01/07/2001	11:06:30 a. m.	-17,186	-72,984	33.0	5.4 Mw	0.19	26.22	93.89
2	30/06/2001	08:57:19 a. m.	-17,707	-72,093	33.0	5.3 Mw	0.18	25.78	92.18
3	29/06/2001	10:33:19 p. m.	-15,306	-70,311	33.0	5.4 Mw	0.19	26.29	93.93
4	28/06/2001	09:35:24 p. m.	-17,588	-72,463	33.0	5.3 Mw	0.18	25.70	92.20
5	27/06/2001	12:21:06 a. m.	-17,903	-71,48	33.0	5.4 Mw	0.19	26.21	92.91
6	26/06/2001	08:47:09 a. m.	-16,624	-74,168	33.0	5.4 Mw	0.19	26.20	93.90
7	26/06/2001	04:18:32 a. m.	-17,831	-71,63	33.0	6.7 Mw	0.24	32.54	116.51
8	25/06/2001	10:14:09 p. m.	-17,637	-70,667	73.7	5.4 Mw	0.19	26.23	93.92
9	25/06/2001	06:38:48 a. m.	-16,875	-73,772	38.0	5.7 Mw	0.20	27.67	99.14
10	25/06/2001	03:48:58 a. m.	-16,044	-74,755	33.0	5.3 Mw	0.18	25.74	92.18
11	23/06/2001	08:33:09 p. m.	-16,303	-73,561	29.6	8.4 Mw	0.30	40.80	146.12

Note. Author's elaboration (2024)

DISCUSSION

The main objective of this study is to analyze and compare the Fourier and Wavelet transforms from the seismic source parameters of the 2001 Arequipa earthquake aftershocks. The most complex step in the application of the spectral analysis technique from the Fourier Transform is the correct determination of the characteristics of the seismic spectrum; that is, the flat part (Ω) and the corner frequency (FC).

The scalar seismic moment is one of the most important parameters of the seismic source (Aki, 1967), because it determines the size of the earthquake. The amount of stresses released during an earthquake is a fundamental feature of the rupture process.

Comparison of Fourier and Wavelet Transforms

The performance of Fourier-based decomposition is evaluated and compared to that of wavelet decomposition. The performance of Fourier decomposition and wave decomposition in the analysis of seismic signals using Matlab programming was compared and its applicability was revealed. Fourier decomposition techniques have shown promise for significantly improving the accuracy and reliability of approximate signals by minimizing the built-in square error. Wavelet decomposition improves the signal-to-noise ratio, but its computational complexity is high and limited in advanced wavelet noise removal. The importance of this work lies in understanding the convenience and limitations of Fourier and wavelet decomposition in seismic signals.

Fourier transforms have been traditionally used in the past for time-frequency analysis. of numerous physical problems. Recently, a new time-frequency analysis technique. The use of temporally confined base functions, called wavelets, has been applied to many problems. The advantage of wavelets over conventional sinusoidal functions is their property of temporal location, providing information not only about the frequency or scale size of the features present but also about their location in the time series.

Table 2 presents the values of the determination of the seismic source parameters of the 2001 Arequipa earthquake, which were calculated from the spectral analysis using the flat part and its corner frequency as parameters. They allowed us to calculate: The seismic moment, the radius of the source and the fall of stresses.

The seismic moment is the product of the area of the fault plane. The radius of the source gives information about the extent of the break. The stress drop is the difference between the stresses before and after the earthquake occurred. The data obtained for the seismic moment and rupture area have been analyzed by comparing them with the data obtained for the aftershocks of the Arequipa Earthquake of 2001 on June 25, July 5 and 7, the seismic moment values for this study vary between 1.80E+19 ≤ M0 ≤ 1.20E+21 Nm. It is observed in Table 2 that the seismic moment obtained for the Arequipa earthquake is within the range of values reported in other studies

Table 4 presents the analysis and comparison of the Fourier and Wavelet transforms that were applied in the aftershocks of the 2001 Arequipa earthquake, which shows that with the Fourier transform different parameters can be determined by applying spectral analysis, however with the wavelet transform it was possible to determine the maximum radiated energy and the rupture time. since this transformation is more applied in cases of earthquakes with large magnitude that generate Tsunamis.

Table 4. TCW Seismic Source Parameters

Comparison	Fourier transform	Wavelet transform
Definition	Fourier decomposition decomposes a time-domain signal (which can be a function of time, spatial coordinates, or any time-series abscissa into complex exponentials (sines and cosines).	Wavelet decomposition is used to decompose a signal into wavelets, a localized oscillatory function in time such as the analyzer or parent wavelet.
Yield	The Fourier transform is most often used in digital signal processing for faster and easier performance. However, in the low frequency range, the Fourier transform is susceptible to background noise and body waves for seismic signal analysis.	Signals can be denoised based on wavelet decomposition by the following steps: decomposition, thresholding detail coefficients and reconstruction. Wavelet denoising increases the signal-to-noise ratio of noisy signals.
Limitations	Fourier decomposition is a constraint that accounts for both time and corresponding frequency information.	The approximate signal may be more distorted than the original signal when noise is removed by high-level wavelet decomposition; this compromises information gathering.
Seismic parameters	The determined scalar seismic moment is in the range of 1.71E+18 to 2.01E+19N.m. The fracture radius values obtained are in the range of 0.21 to	

Note. Author's elaboration (2024)

In the 2018 research presented by J. Mardini, he made the comparison with the study carried out by Abercrombie and Leary in which the authors compiled 800 seismic events 164 (mine earthquakes, volcanic and induced seismicity, aftershocks of large earthquakes and hydrofractures) with epicenters in California and the world, with small magnitudes, moderate and large (this compilation considers earthquakes from several studies). The fall of stresses in relation to the seismic moment with the rupture radius has been graphed, the values obtained in this study correlate with those obtained for the aftershocks of the Arequipa earthquake of 2001, as well as those obtained by other studies, so we see that the values of seismic moment for this study vary between 1.71E+18 to 2.01E+19N.m. (Rachel Abercrombie & Leary Peter, 1993)

In the 2016 research presented by Wilfredo Sulla in which the Continuous Wavelet Transform (TCW) methodology was proposed, based on the frequency content and energy released in seismic signals, he applied it to large earthquakes that occurred in Peru, among which is the 2001 Arequipa earthquake, which presented frequency content that varies between 0.3 and 05 Hz. The maximum radiated energy varies between 31.3 to 72.8 and the rupture duration between 95.2 to 188.5, these values are similar to the results of this study, but are within a lower range since in this study it was applied for aftershocks, however comparing it with the seismic signal of the same earthquake if it is within the range. (Sulla & Tavera, 2016)

CONCLUSIONS

The yields of Fourier decomposition and Wavelet decomposition for seismic signal analysis are clearly distinguished. Fourier decomposition is supported for easier and faster seismic signal analysis where wavelet decomposition is considered for underlying and stable noise reduction criteria. Wavelet analysis is robust to remove noise instead of Fourier analysis. Noise removal in low-level wavelet decomposition shows better performance. But at a high-level decomposition for a complex seismic signal, the signal information is lost a lot and is not suitable for use. It has been proven that the Wavalet transform is optimal for the analysis of tsunamis.

The following parameters were determined with the Fourier transform:

The determined scalar seismic moment is in the range of 1.71E+18 to 2.01E+19N.m.

The fracture radius values obtained are in the range of 0.21 to 1.15km.

The stress drop values for the aftershocks analyzed are between 0.60 and 38.08Mpa, which shows that this parameter is constant without taking into account the magnitude of the earthquake; that is, earthquakes of lesser or greater magnitude always develop similar values of stress drop.

The Energy Magnitude is from 3.36 to 4.42Me.

And with the Wavelet transform you can determine the following parameters:

The frequency content has the following values between 0.18 and 0.30 Hz

The maximum radiated energy (maxEa) ranges from 25.70 to 40.80.

The breakout duration values obtained are in the range of 92.18 to 146.12s.

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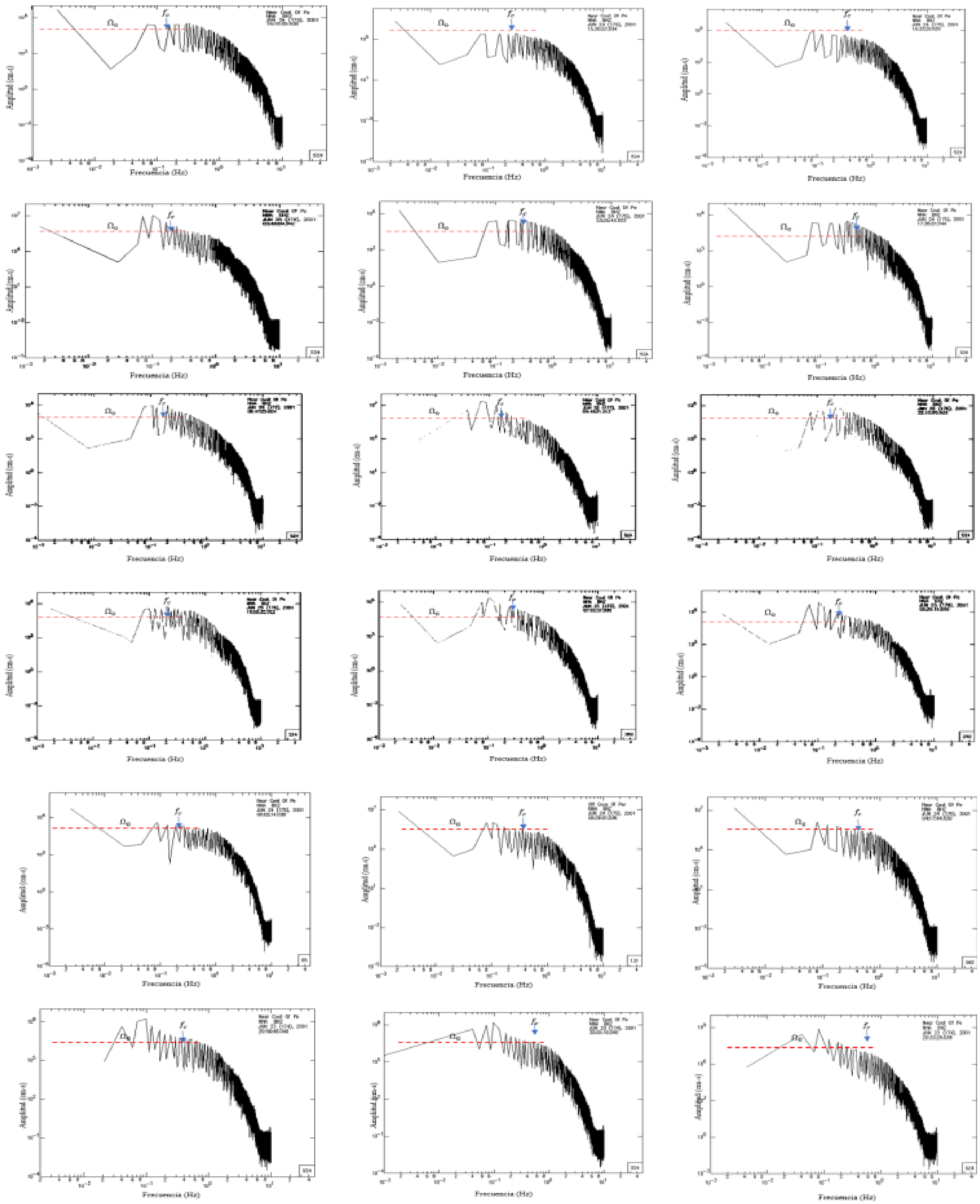
ANNEX 1: SEISMIC SOURCE PARAMETERS OF THE 2001 AREQUIPA EARTHQUAKE AFTERSHOCKS

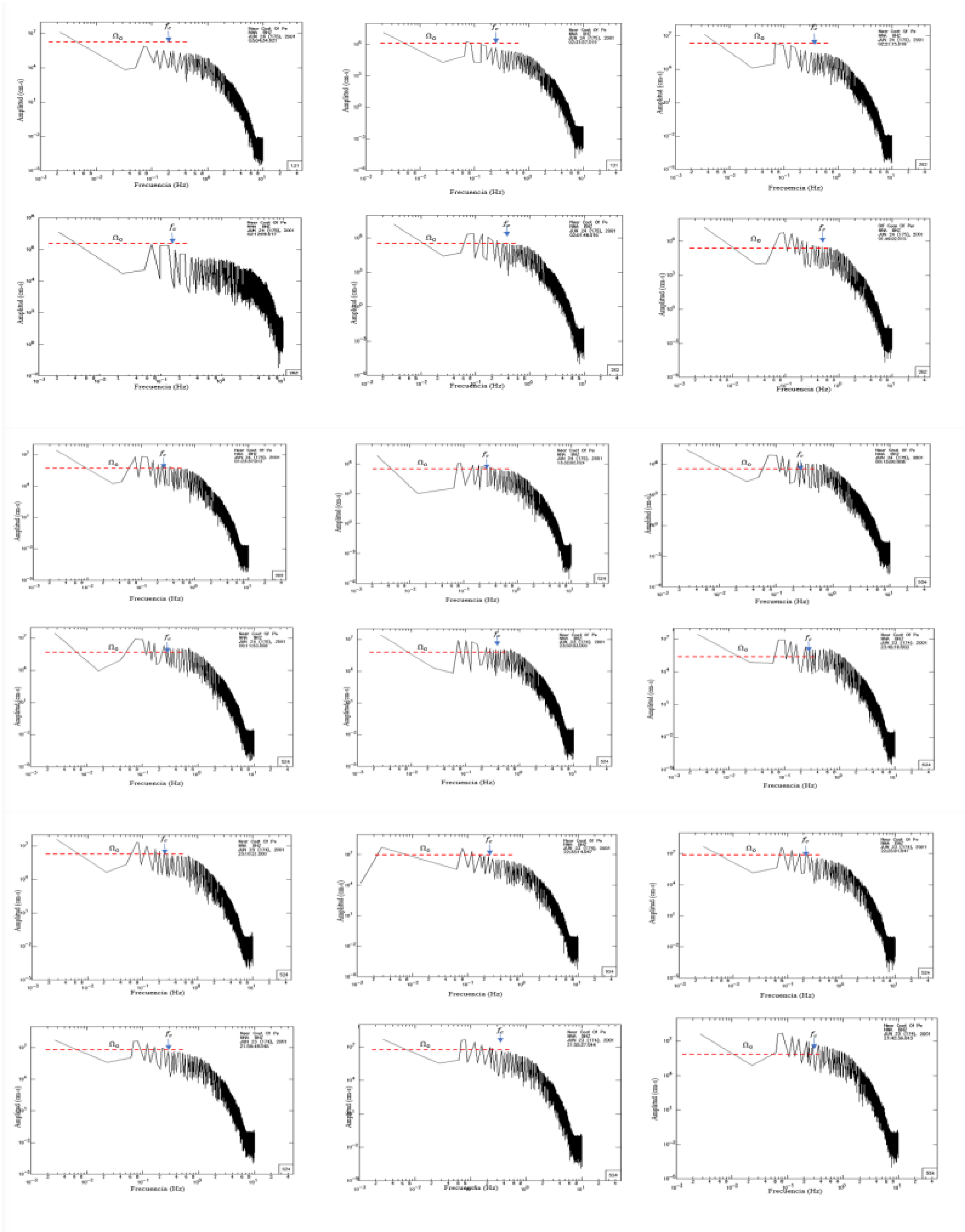
Table 5. Seismic source parameters of the 2001 Arequipa earthquake aftershocks

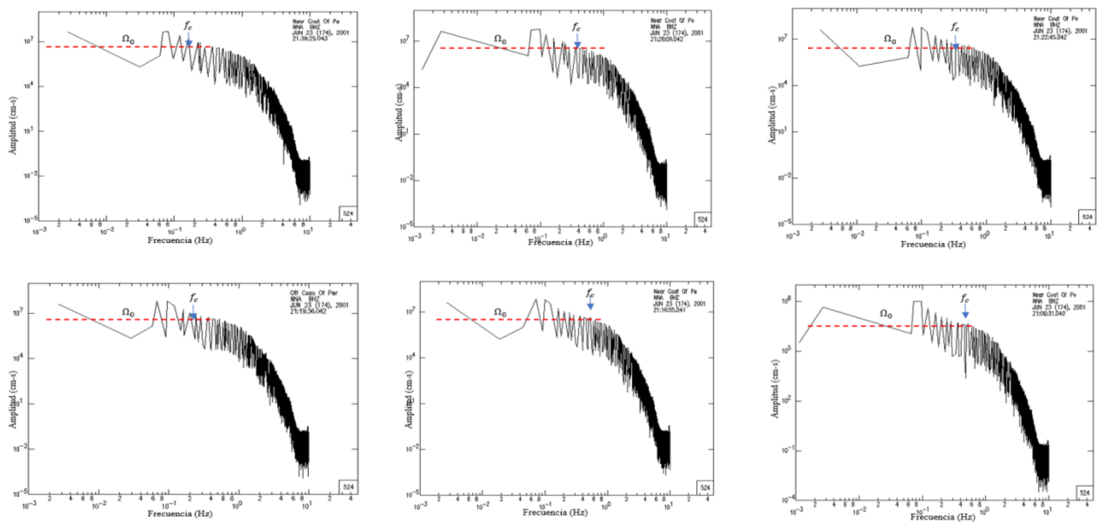
Item	Fecha dd/mm/aa	Hora (UTC)	Lat.	Lon.	Prof. (km)	Mag	Mo (N.m)	Radio (Km)	Δσ (Mpa)	Me
1	01/07/2001	11:06:30 a. m.	-17,19	-72,98	33.0	5.4	1.41E+19	0.56	1.15	3.38
2	30/06/2001	08:57:19 a. m.	-17,71	-72,09	33.0	5.3	1.95E+19	0.67	1.08	3.42
3	29/06/2001	10:33:19 p. m.	-15,31	-70,31	33.0	5.4	1.82E+19	0.51	1.87	3.61
4	28/06/2001	09:35:24 p. m.	-17,59	-72,46	33.0	5.3	1.23E+19	0.40	1.22	3.69
5	28/06/2001	04:24:46 a. m.	-16,77	-73.6	33.4	5.1	1.13E+19	0.26	1.24	3.54
6	28/06/2001	03:39:27 a. m.	-16,77	-73,68	33.0	5.0	1.11E+19	0.31	1.33	3.12
7	27/06/2001	12:21:06 a. m.	-17,90	-71,48	33.0	5.4	2.01E+19	0.58	1.72	3.55
8	26/06/2001	03:12:40 p. m.	-16,69	-74,09	29.2	5.0	2.13E+19	0.12	1.12	3.22
9	26/06/2001	12:51:14 p. m.	-16,71	-73,60	21.3	5.3	1.17E+19	0.51	1.31	3.44
10	26/06/2001	08:47:09 a. m.	-16,62	-74,17	33.0	5.4	1.33E+19	0.65	1.54	3.91
11	26/06/2001	04:18:32 a. m.	-17,83	-71,63	33.0	6.7	1.81E+18	0.50	1.03	3.90
12	25/06/2001	10:14:09 p. m.	-17,64	-70,67	73.7	5.4	1.81E+18	0.36	0.60	3.61
13	25/06/2001	07:58:13 p. m.	-16,51	-73,67	33.0	5.0	2.14E+19	0.44	1.10	3.24
14	25/06/2001	07:03:18 a. m.	-16,60	-73,80	33.0	5.2	3.17E+19	0.57	1.11	3.55
15	25/06/2001	06:38:48 a. m.	-16,88	-73,77	38.0	5.7	3.62e+18	0.21	1.22	3.54
16	25/06/2001	03:48:58 a. m.	-16,04	-74,76	33.0	5.3	1.71E+18	1.53	1.13	3.36
17	24/06/2001	11:26:17 p. m.	-16,88	-73,27	27.7	5.0	2.33E+19	2.40	2.22	1.84
18	24/06/2001	05:37:51 p. m.	-17,43	-72,23	37.8	5.1	6.13E+19	1.26	1.74	2.54
19	24/06/2001	04:15:06 p. m.	-16,74	-73,40	62.7	5.0	4.11E+19	0.33	1.88	5.12
20	24/06/2001	03:30:15 p. m.	-17,39	-71,91	33.6	5.0	2.12E+19	0.68	1.92	3.45

21	24/06/2001	02:32:43 p. m.	-17,35	-72,54	35.3	5.4	3.14E+19	0.22	2.12	3.21
22	24/06/2001	01:33:23 p. m.	-16,61	-74,03	19.4	5.1	1.27E+19	0.61	2.31	3.82
23	24/06/2001	01:31:22 p. m.	-17,26	-72,08	34.3	5.1	1.37E+19	0.55	1.14	3.81
24	24/06/2001	12:28:54 p. m.	-17,63	-72,02	3.7	5.0	1.82E+18	0.87	1.34	3.87
25	24/06/2001	08:11:38 a. m.	-17,05	-73,54	33.0	5.1	2.81E+18	0.43	1.82	3.64
26	24/06/2001	08:10:56 a. m.	-17,66	-71,98	33.0	5.0	1.12E+19	0.64	1.25	3.27
27	24/06/2001	06:08:23 a. m.	-16,47	-73,22	19.2	5.0	2.17E+19	1.57	2.11	3.57
28	24/06/2001	06:01:35 a. m.	-17,49	-72,62	21.3	5.0	2.62e+18	1.21	1.02	3.59
29	24/06/2001	05:29:23 a. m.	-17,01	-73,53	10.0	5.1	1.72E+18	0.66	2.10	3.30
30	24/06/2001	04:02:59 a. m.	-17,49	-72,42	33.0	5.1	1.24E+19	1.44	1.42	3.75
31	24/06/2001	03:04:06 a. m.	-16,98	-73,14	33.0	5.0	1.15E+19	0.27	1.94	3.04
32	24/06/2001	02:31:07 a. m.	-17.76	-71,51	41.2	5.4	2.18E+19	0.73	1.63	3.11
33	24/06/2001	02:20:32 a. m.	-17.57	-72,02	33.0	5.0	2.51E+19	1.68	2.72	3.46
34	24/06/2001	02:11:35 a. m.	-17,23	-72,75	33.0	5.2	2.13E+18	1.12	6.12	3.20
35	24/06/2001	02:01:14 a. m.	-17,22	-72,72	33.0	5.0	3.18E+19	2.51	3.31	3.74
36	24/06/2001	01:48:32 a. m.	-17,25	-73,28	36.8	5.3	4.33E+19	4.65	1.55	3.31
37	24/06/2001	01:22:53 a. m.	-17,60	-71.94	33.0	5.4	1.83E+19	1.50	1.23	3.33
38	24/06/2001	12:14:42 a. m.	-16,58	-73,87	33.0	5.2	1.51E+18	0.86	0.61	3.66
39	24/06/2001	12:11:13 a. m.	-17,41	-72,33	28.2	5.1	2.34E+19	0.94	1.19	3.03
40	23/06/2001	11:49:13 p. m.	-17,85	-71,56	33.0	5.6	3.77E+19	0.17	3.11	3.15
41	23/06/2001	11:44:57 p. m.	-16,77	-73,68	41.5	5.4	3.92e+18	0.11	1.45	3.34
42	23/06/2001	11:09:57 p. m.	-16,66	-73,53	10.0	5.9	1.61E+18	0.53	2.13	3.07

ANNEX 2: SPECTRA OF THE 2001 EARTHQUAKE AFTERSHOCKS




Frecuencia (Hz)



ANNEX 3: CALCULATION OF STRESS TRANSFER FROM SEISMIC SOURCE PARAMETERS

In the last 25 years there have been four earthquakes of great magnitude in Peru, therefore there is the presence of energy relaxed by these earthquakes, to know the characteristics of the rupture and the transfer of stresses it is necessary to study the distribution of slippage of the source and study the transfer of stresses using the Coulomb methodology. The stresses can be released or accumulated by aftershocks, so it is necessary to identify where the stresses released by these earthquakes have been transferred. Peru, as part of the Pacific Ring of Fire, is subject to high seismicity due to the interaction of the South American plate and the Nazca plate where the stresses accumulated over hundreds of years are released and/or transferred around the same fault or several nearby faults, so analysis of the seismic source and the analysis of the transfer of seismic stresses is very important. It is necessary to know those seismic rupture zones at the time the earthquake of greater magnitude occurred, since the energy that is released is transferred to other sectors of the fault to be relaxed by aftershocks or remains accumulated to generate a future earthquake.

For the calculation of the Coulomb Stress Transfer of each seismic event, the Coulomb 3.4 software developed by Toda in 2011 has been used. The rupture of a seismic fault permanently deforms the surrounding crust, changing the stress on nearby faults based on their location, geometry, and sense of slip. (Coulomb, n.d)

Table 6 of the seismic parameters is shown to determine the accumulation of energy of the Arequipa 2001 Earthquake, which according to the return period, presents an accumulation of stresses and energy that can be released in the coming years, since more than 20 years have passed since this earthquake occurred, in figure 12 you can see the graph of accumulation of stresses made in the Coulomb Software, which coincides with the rupture areas caused by the Arequipa earthquake. In the same way, the areas with the highest risk in Arequipa are shown for presenting a diverse geology. The new earthquake will start in one of these areas or in a chain. Explaining the behavior of the stresses, almost the entire fault has already released energy and the stresses are in the resistant areas. During subsequent earthquakes, the energy will be fully released and the final situation will be one of almost uniform stresses.

Table 6. Parameters of the seismic source of the 2001 Arequipa Earthquake

Item	Fuente	Lat.	Lon.	Prof. (km)	Mo (N.m)	Az	Buz	Mag. (Mw)
1	Estudio Actual	16.30 S	73.56 W	27.98	1.58E+21	309º	21º	8.4
2	CMT	17.21 S	73.02 W	25.7	4.9E+21	318º	14º	8.4
3	USGS	16.14 S	73.31 W	8	3.7E+21	263º	6º	8.3
4	NEIC	16.22 S	73.61 W	33	2.2E+21	309º	14º	8.4
5	IGP	16.20 S	73.75 W	38				5.4
6	EIC	16.15 S	73.40 W	30				5.4

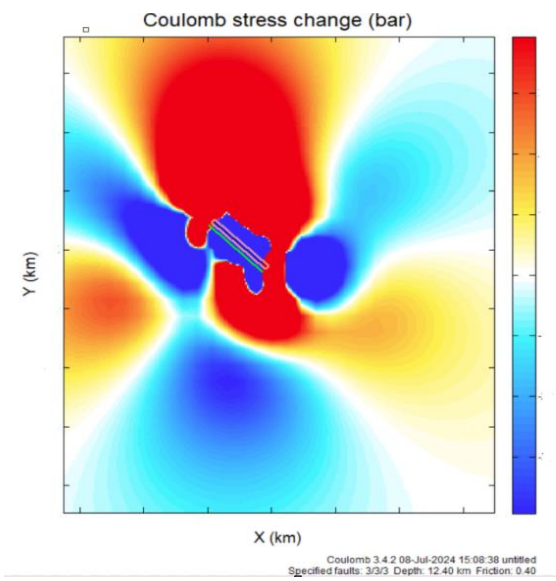


Figure 12. Transfer of Efforts in Coulomb

Earthquakes occur more frequently due to the interaction of tectonic plates that when they accumulate a large amount of effort and energy slide abruptly generating an earthquake. The most important seismic zones in the world are located around the Pacific tectonic plates. The longer that elapses without the occurrence of earthquakes, the greater the accumulation of energy that when released produces an earthquake of great magnitude involving large areas over which the displacements occur.