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SPECTRAL-TEMPORAL FEATURES OF SEISMIC LOADINGS ON THE BASIS OF STRONG MOTION WAVELET DATABASE

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ABSTRACT: There are many different techniques for seismic impact simulation for engineering purposes. Some of them are very detailed and while practice needs quite simple and effective one. All of the techniques widely used determine envelop of seismic process in the time domain. Currently, it is possible to build a model based on a detailed study of the spectral and temporal energy content of seismic process. Wavelet analysis is an effective tool for spectral-temporal analysis. New type of database was developed for new seismic loadings model research. The main features are: wavelet transformation of initial seismic data (accelerograms), taking into account relative orientation of fault plane and station site. New algorithms of polarization and wavelet analysis were developed. The second one is based on fast Fourier transform and more efficient for big data processing. Spectral-temporal envelope matrix was introduced as new parameter for development of new impact models. Polarization analysis results show a good accordance of p-wave ellipsoid azimuth correlation with calculated one, while s-wave (group of SH-waves) plane is strongly influenced by relative fault plane location. Obtained results may be used for new empirical-analytical model of seismic impacts development for usage in seismic design.

Keywords: Seismic Impact, Wavelet Analysis, FFT, Strong Motion Database, Polarization

INTRODUCTION

Adequate account of seismic impacts on designing and existing building is one of the main goals of Engineering Seismology, Earthquake Engineering as a basis, as it allows to significantly reduce both economic and social damage.

At the present time to determine the seismic effects to justify the seismic resistance is allowed to use any of the following methods (in particular, nuclear facilities safety manual RB-06-98):

1. Methods of using records of strong earthquakes.
2. Methods based on the fault model.
3. Methods of using the standard spectra.

In areas with moderate seismic activity it is difficult to obtain strong earthquakes accelerograms in a short time. In this regard, recording of weak earthquakes is generally used. Weak earthquakes records scaling, of course, allow taking into account the impact of regional and local features of the site, but differing from the possible real strong earthquakes impacts. Real impacts may be accounted by means of strong motion databases. The development of this approach is a method of instrumental analogies - a way of selecting the most appropriate database records to generate an ensemble of seismic impacts.

Building models of active faults is quite labor problem, which complicates the use of this approach in mass construction, which tend to use more simple procedures based on empirical data linking exposure parameters (amplitude, duration, the predominant period) with parameters such as the epicentral distance, focal depth and magnitude.

A number of methods are developed in recent years, on the basis of this approach with different parameters used. This is the work of D. Boor [1]-[2], I. Beresnev, G. Atkinson [3]-[4], A.A. Gusev [5], and others. This approach (based on I. Beresnev FINSIM program) taking into account the peculiarities of the Caucasus was also used for the modeling of synthetic accelerograms for Vladikavkaz fault (close to Vladikavkaz city – capital of the North Ossetia-Alania Republic) [6].

All of the techniques used determine envelop of seismic process in the time domain. Currently, it is possible to build a model based on a detailed study of the spectral and temporal energy content of seismic impacts based on advanced mathematical methods such as wavelet analysis finding different applications in engineering seismology [7]-[10]. For example Iyama and Kuwamura (1999) [7] derived an energy principle for wavelet transform, which states that the wavelet coefficients represent the contribution from the local time-frequency cell to the total energy of the signal and based on the energy principle derived in Iyama and Kuwamura (1999) [7], Spanos and Failla (2002) [8] derived a relationship between wavelet coefficients and evolutionary power spectral density.

First stage included strong motion data selection. Data on source parameters and spatial location of the fault was one of the required criteria. Polarization analysis was used for seismological and record parameters comparison to filter local specific site effects and data projection on source-site direction A_R and its perpendicular A_τ. Wavelet analysis was used for time-frequency decomposition of signals and special database was formed.

On the next stage strong motion wavelet data were approximated by spectral-temporal envelope function. So seismic loadings are described by such impact parameters as amplitude and duration estimated for each frequency. Third parameter – time shift were added for data consistency. Reconstructed signal based on introduced parameters (three spectral curves) is in a good accordance with initial time-frequency matrix.

STRONG MOTION DATA

Data of Strong Motion Virtual Data Center (VDC) (http://www.strongmotioncenter.org) was selected for analysis. The base contains data about source mechanics, fault type, etc. Three component records of seismic stations located on bedrock and dense soils ('Hard Rock', 'Rock', 'Very dense soil and soft rock') were selected. Three component records with known orientation of seismometers are needed for polarization analysis. Soft soils data will be used in next stage of investigation. Finally 95 records of 26 earthquakes were selected from VDC database. MS Access database were created for data management and analysis. The main form of the database is shown in Fig. 1in example, the Loma Prieta earthquake (Loma Prieta, Santa Cruz Mountains 1989-10-18 00:04:15 UTC). The form contains earthquake data area: magnitude, location, depth, source parameters and linked records data table: station, ground conditions and a link to the directory containing the appropriate accelerogram and results of data processing. The position and the epicenter of seismic stations is displayed on the scheme, based on The Google Static Maps API.

EqName	Loma Prieta
EqDate	18.10.1989 0:04:15
Region	California
Latitude	37.0407
Longitude	-121.8829
Depth	17.5
Mechanism	Reverse-Oblique
Strike	128
Dip	70
Rake	140
ML	7
Mw	7
Ms	7.1

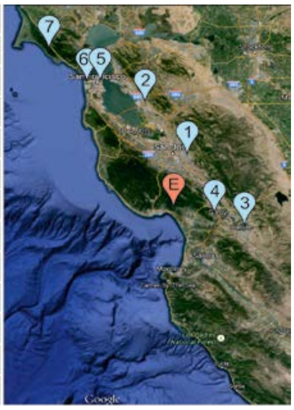

Fig. 1. Main form of strong motion database: E – epicenter; numbers – seismic stations

POLARIZATION ANALYSIS

Capabilities of seismic waves identification based on polarization analysis was developed by V.G. Alkaz [11]. Proposed technique was practically used for situational processing of Kirov 2008 earthquake in North Ossetia and currently used for rapid information based on one station solution [12].

Epicenter azimuth and seismic angle of emergence ray are defined on eigenvectors e^j_n and eigen values λ_n of a^i_j matrix:

$$\left(a^i_j - \lambda_n \cdot \delta^i_j\right) e^j_n = 0, \qquad (1)$$

$$a^i_j = \sum_t u_i(t) \cdot u_j(t),$$

where i,j= x, y, z, and summing is performed in selected time interval.

Polarization parameters of first p-waves arrivals and SH and L waves group was calculated for collected strong motion records (Table 1). Example of Loma Prieta earthquake record analysis is given in Fig. 2.

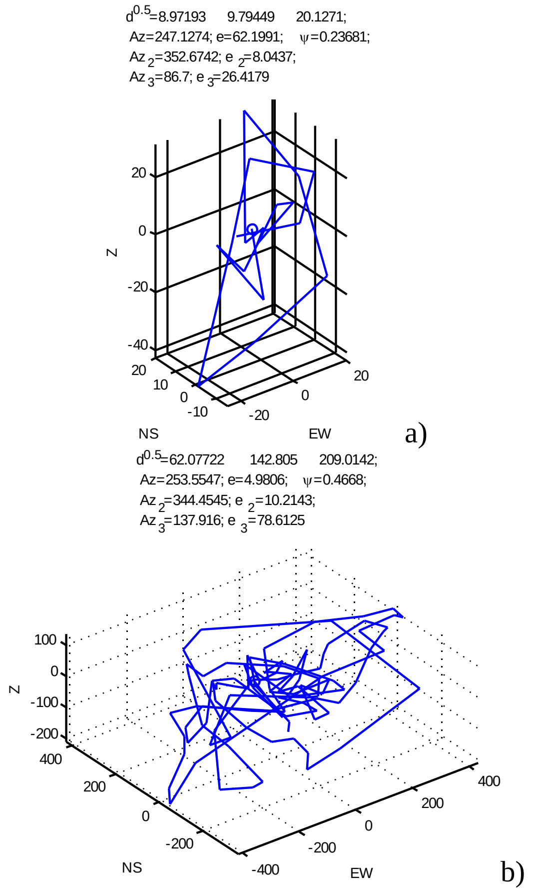

Fig. 2 Polarization analysis of strong motion data: a) first p-wave arrivals; b) group of SH and L waves (Accelerogram of strong Loma Prieta earthquake (1989), station Gilroy Array, site-fault distance 2.8 km)

D, km	$Az_{calc.}$	P wave polarization			S wave polarization			
		e_P	ψ_P	Az_P	E_S	ψ_S	S wave orien-tation	Az_S
28.6	285.4	62.2	0.34	247.1	5.0	0.47	253.6	163.6
36.3	204.4	62.9	0.48	203.5	10.7	0.91	312.7	222.7
48.2	296.5	85.5	0.04	285.8	2.1	0.26	359.1	269.1
70.4	167.0	54.3	0.31	164.7	5.4	0.84	104.1	194.1
94.7	151.6	51.0	0.38	150.2	2.9	0.44	239.9	149.9
97.8	148.6	65.2	0.38	140.3	13.5	0.42	265.8	175.8

Table 1 – Seismic waves polarization parameters (Loma Prieta earthquake, 1989)

For epicentral distances D more than 50 km azimuths calculated on seismological data Az_{calc} are in good accordance with defined by polarization analysis of first p-wave arrivals Az_p. While in near-source zone fault orientation causes complex polarization, especially of s-waves. Depending on relative fault-station orientation s-wave polarization may reach 0.9.

TIME DOMAIN ENVELOPE (IN STANDARD RESPONSE SPECTRA TECHNIQUE)

Methods based on standard response spectrum, have been widely used due to the possibility of modelling accelerograms for given parameters of seismic impact on the basis of stochastic models. Basis of the method developed by K.S. Zavriev, A.G. Nazarov, I.L. Korchinski, Y.M. Eisenberg et al. Empirical relationships between the main earthquake parameters and seismic records were obtained by F.F. Aptikaev and others.

There are three main independent parameters describing the seismic ground motion: amplitude, which characterizes the signal intensity, duration of vibrations and the predominant period of the spectrum.

Another important value for the practice of designing buildings and structures - logarithmic spectral width S, is stable and has a value of S = 0.60 ± 0.24 [13]. Relation to the areas of real and normalized vibrational spectra with absorption and nonlinearity parameters was obtained in V.B. Zaalishvili [14]. On the basis on the parameters of the expected seismic event: magnitude, focal depth, and epicentral distance parameters of seismic impact are calculated and accelerogram is synthesized on the basis of corresponding response spectrum and signal envelope. The envelope is defined only in the time domain.

The envelope of the vibrations is given by empirical formula [15]:

$$A(t) = \frac{A_{\max} 3td}{9t^2 - 9td + 4d^2}, \qquad (2)$$

where t – time value, d – duration. Vibrations duration d is defined as time interval between the first and the last sample where $A \geq 0.5A_{MAX}$. Time envelope curve example for Vladikavkaz fault conditions at distance to the territory of Vladikavkaz city (T = 0.25 s, d = 1.5 s, A = 280 cm/s^2) is shown in Fig.3.

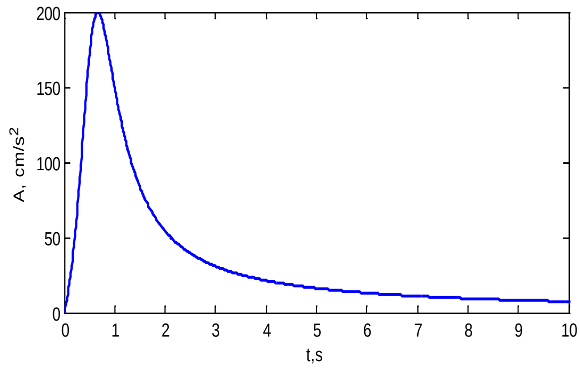

Fig. 3. Time envelope curve for Vladikavkaz fault

TIME-FREQUENCY ENVELOPE OF SEISMIC PROCESS

Form of the envelope is determined in the time domain. Currently, it is possible to build a model based on a detailed study of the spectral and temporal parameters of seismic records based on advanced mathematical methods of analysis (wavelet analysis, polarization analysis, etc.), we had applied the analysis of glacier Kolka fall seismic records on September 20, 2002 and records of earthquakes in North Ossetia, records of powerful vibration sources, meteorological data [16]. In addition, the full account of the seismic impact is only possible in three-dimensional form, so often used in the calculation of the components identical procedure for all the components and the condition of statistical independence. Accounting for the direction of arrival of seismic waves also will improve the reliability and validity of the results.

Development of a new model requires a representative set of data and the development of efficient algorithms for spectral-temporal decomposition of seismic signals. In addition, the database should include information on the parameters of the earthquake.

The continuous wavelet transformation (CWT) is the inner product of f(t) and the basis functions

$$\psi_{a,b}(t) = a^{-\frac{1}{2}} \psi\left(\frac{t-b}{a}\right), \ a \in R^+, \ b \in R, \qquad (3)$$

so that

$$CWT_f(a,b) = a^{-\frac{1}{2}} \int_{-\infty}^{+\infty} \psi^*\left(\frac{t-b}{a}\right) f(t)dt \qquad (4)$$

Functions $\psi_{a,b}$ are called wavelets («short waves»). They can be considered as scaled and shifted versions of the prototype function $\psi_{a,b}(t)$. Parameter b shows the location in the time, a – scale parameter.

In some mathematics books only real functions are considered as wavelets. Indeed, in many problems (image compression, etc.) there is no need to consider a complex space, however signal processing will be performed naturally analogous to Fourier transformation used as a complex wavelet function. An example would be a Morlet wavelet (Fig. 4) that consists of a plane wave modulated by a Gaussian function:

$$\psi_0(\eta) = \pi^{-\frac{1}{4}} e^{i\omega_0\eta} e^{-\frac{\eta^2}{2}}, \qquad (5)$$

where ω_0 is dimensionless frequency, usually taken to be 6.

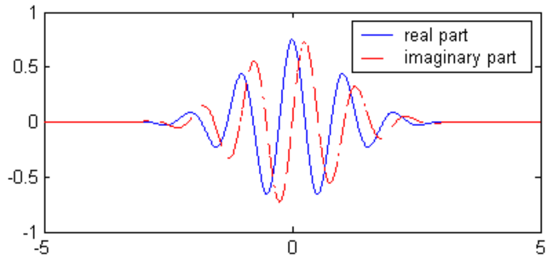

Fig. 4 Morlet wavelet, ω_0=6

The term "wavelet" is used generally to refer to orthogonal and non-orthogonal wavelets. The term "basis" refers only to a set of orthogonal functions. Application of orthogonal basis involves the use of a discrete wavelet transform, while the non-orthogonal wavelet functions can be used in both discrete and continuous wavelet transformation (Farge 1992).

The continuous wavelet transformation of a discrete sequence x_n is defined as the convolution x_n of the scaled and shifted function $\psi_0(\eta)$:

$$W_i(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^*\left[\frac{(n'-n)\Delta t}{s}\right], \qquad (6)$$

$$\psi\left[\frac{(n'-n)\Delta t}{s}\right] = \left(\frac{\Delta t}{s}\right)^{\frac{1}{2}} \psi_0\left[\frac{(n'-n)\Delta t}{s}\right] \qquad (7)$$

where the function $\psi_0(\eta)$ is normalized to have unit energy.

By zooming scale s and moving along the time index n, one can construct dependence of amplitude on the scale and time.

For an orthogonal system of wavelets the scales choice s is limited by discrete set (Farge 1992). For non-orthogonal wavelet analysis, the random set of scales can be used to build a more complete picture. The most convenient way is to record the scales as the fractional power of two [17]:

$$s_j = s_0 2^{j\cdot\delta j}, \quad j = 0,1,\dots,J \qquad (8)$$

$$J = \delta j^{-1} \log_2\left(\frac{N\Delta t}{s_0}\right) \qquad (9)$$

where s_0 – is the smallest scale, J defines the maximum scale.

Scale s_0 has to be selected so that the equivalent Fourier period is approximately equal to Δt. Selection of small value δj depends on the wavelet width in the spectral space. For Morlet wavelet δj =0.5 is the greatest value, that gives sufficient sampling scale, while for the other wavelet functions can be used greater value. Smaller values δj give better resolution.

An important aspect of wavelet analysis is to determine the relationship between the scale s and the vibration frequency. The ratio between the equivalent Fourier period and scale can be obtained analytically for Morlet wavelet as well [17]

$$\lambda = \frac{4\pi s}{\omega_0 + \sqrt{2+\omega_0^2}}, \qquad (10)$$

where λ is Fourier period.

If ω_0=6, then λ=1.03s.

Since function $\psi(\eta)$ is generally complex wavelet transform then $W_n(s)$ is also complex. The transform can be divided into a real part $\Re\{W_n(s)\}$ and an imaginary $\Im\{W_n(s)\}$, or the amplitude $|W_n(s)|$ and a phase $\tan^{-1}[\Im\{W_n(s)\}/\Re\{W_n(s)\}]$.

Spectral-temporal decomposition of signals was performed using a wavelet transform algorithm which was developed based on the fast Fourier transform (FFT) [17]. Entries were previously projected onto the components related to the mutual arrangement of fault and station. The azimuth of the seismic wave was calculated using the coordinates of the station and the epicenter and compared with the results of determining the direction of oscillation according to the polarization analysis. An example of the original recording (accelerograms) strong earthquake and its wavelet decomposition is shown in Fig. 5.

For each of the frequency components A_τ envelope approximation was performed by the formula (2), which was introduced in addition to the time coordinate offset. The result was obtained for the frequency dependence of these parameters (Fig. 6).

On the basis of the curves shown in Fig. 5, wavelet spectrum was recovered – Fig. 7. Deviation of the reconstructed wavelet amplitude spectrum from the real in main part of the signal does not exceed 20%.

CONCLUSIONS

Wavelet transform is a modern tool for detailed seismic data analysis. For effective data processing Fast Discrete Wavelet Transform (FDWT) algorithm was realized on the basis of Fast Fourier Transform (FFT).

Approximation was applied to each frequency content of wavelet decomposition of accelerograms and sets of time envelopes were obtained. Amplitude, duration and time shift spectral parameters were introduced to describe frequency-time content of seismic impacts.

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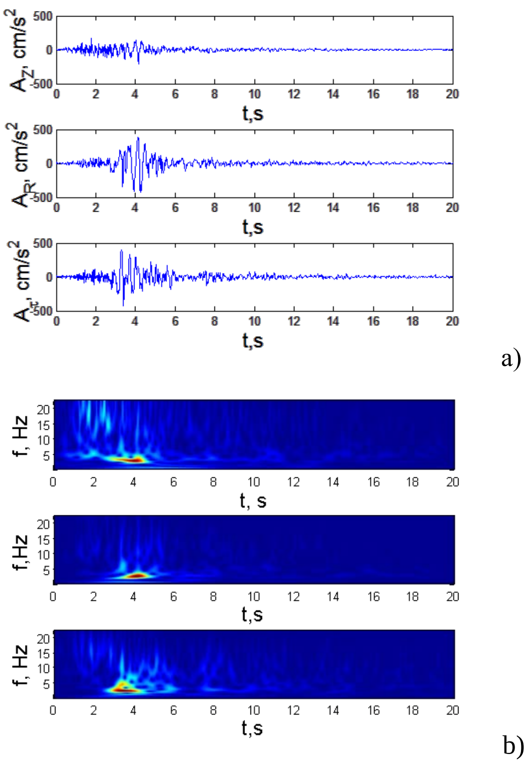

Fig.5. Accelerogram of strong Loma Prieta earthquake (1989), station Gilroy Array, site-fault distance 2.8 km: a) vertical component A_Z and projections on source direction A_R and its perpendicular A_τ; b) corresponding wavelet record decomposition

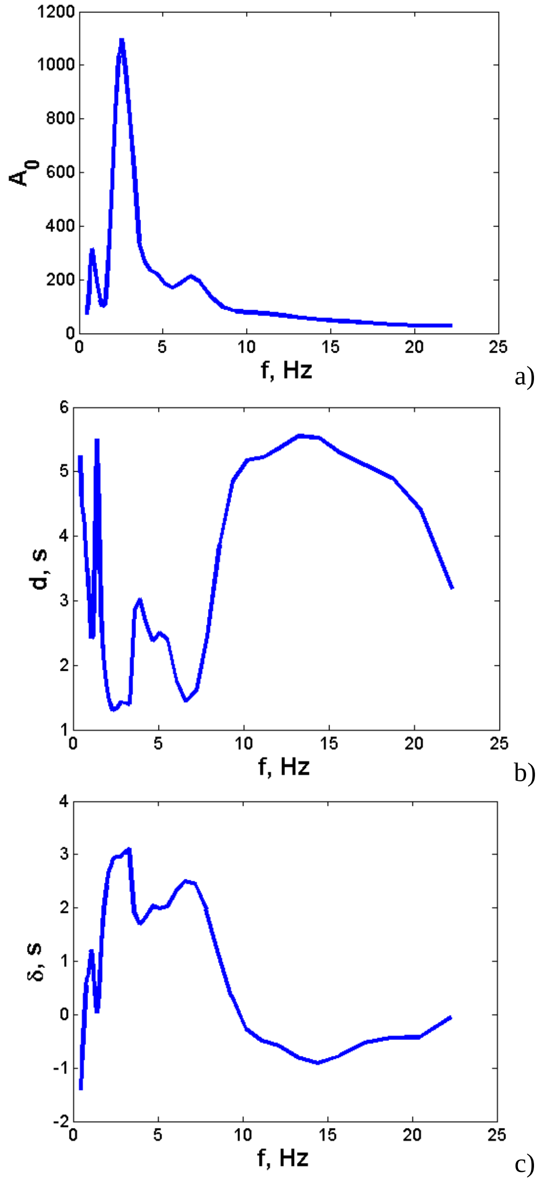

Fig.6. Parameters of spectral-time domain decomposition: amplitudes (a); duration (b), time shift (c)

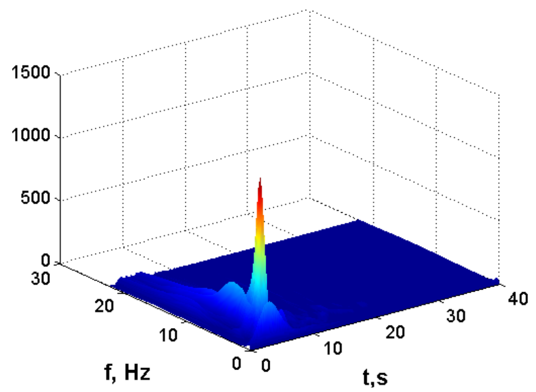

Fig.7 Recovery of parametrized wavelet decomposition of earthquake record

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