ABSTRACT

In regions with moderate seismic activity it is difficult to obtain strong ground motions for a short time interval so synthetic accelerograms are usually used for seismic design. Stochastic modeling can be used for seismic loadings modeling based on empirical data on variation of dominant period, maximum acceleration and duration with distance to possible earthquake source, its magnitude and depth. Duration governs the form of envelope function for dominant period signal then normalized by maximum acceleration. This technique was developed on the basis of wavelet analysis. 3D time-frequency envelope function for seismic loadings modeling was proposed and analyzed for strong motion records.

Keywords: Design; Acceleration; Spectral; Time-frequency; Wavelet

1. INTRODUCTION

The problem of an adequate assessment of seismic hazard is the most important task of engineering seismology. The urgency of the problem is growing rapidly with the steady development of urbanized territories. It is known that in the Caucasus, the greatest risk in terms of economic and social losses are related to seismic events. Suffice it to recall Dagestan (Dagestan, 1970), Chernogorskoye (Chechnya, 1976), Dmanisi (Georgia, 1978), Spitak (Armenia, 1988), Rachinskoye (Georgia, 1991), Barisakho (1992), Goubanskoe, Baku (2000), Tbilisi (2002), Kurchaloy (2008) earthquake. The city of Vladikavkaz is located within the seismic fault zone with the maximum potential magnitude $M = 7.1$ (6.5–7.1) (Zaalishvili, Rogozhin, 2011).

In the dynamic theory of seismic stability, from the simple considerations of physical expediency, the value of the acceleration of the movement of the base or the force of impact was introduced as an index of the effect on buildings and structures. It is generally accepted that the use of acceleration as an index of the level of seismic action allows to adequately characterize the intensity of earthquakes. This approach, being simple and convenient for practical use, is reflected in the Construction Norms for seismic design and construction in seismically hazardous areas of most countries of the world. In this case, as a rule, the horizontal values of the accelerations are used. Thus, design of buildings and structures for seismic impacts, the magnitude of the acceleration is used as the index of seismic action. In the case of earthquakes, a certain magnitude and acceleration distance are distributed according to the normal law (Zaalishvili, 2009). From the point of view of the engineer, the frequency features of the vibration of soil in the foundation of buildings (Zaalishvili, 2016) and, in fact, the vibration of buildings (Polyakov, 1978) are of particular interest.

Currently, the following methods are used to determine seismic impacts in the form of accelerograms
(acceleration time history) (RB-06-98):

1. Methods using records of strong earthquakes.

2. Methods based on fault models.


In areas with moderate seismic activity, it is difficult to obtain records of strong earthquakes in a short time. At the same time, scaling records of weak seismic events undoubtedly allows taking into account the influence of regional and local features of the site, but the records differ from the real strong impact. In this connection it is expedient to use databases of strong motions, the creation of which allowed creating a method of instrumental analogies or a method of selecting from the database the most suitable records and site conditions for forming an ensemble of seismic impacts (Zaalishvili, Kharebov, Mel'kov, 2014).

The construction of fault models is quite a labor-consuming task, which makes it difficult to use this approach in mass construction, where, as a rule, the simplest procedures based on empirical data characterizing the binding parameters (amplitude, duration, predominant period) with parameters such as epicentral distance, depth of the source and magnitude (Zaalishvili et al., 2010). The basis of the method was developed by D. Boor (1983) and was further developed in the works of I. Beresnev, D. Atkinson (Beresnev, Atkinson, 1998), Gusev (Gusev et al., 2005).

Methods based on standard reaction spectra have found wide application due to the ability to simulate accelerograms for given seismic parameters on the basis of stochastic models. Fundamentals of the method were developed by K.S. Zavriev, E. Mononobe, A.G. Nazarov (Zavriev et al., 1969), I.L. Korchinsky (Korshinsky et al., 1961), Ya. M. Eisenberg (Eisenberg, 1976). Empirical relationships between the main parameters of the seismogram and the earthquake were obtained by F.F. Aptikayev (1981), etc. There are three main independent parameters that describe the seismic motion of the soil: the amplitude characterizing the intensity of the signal, the duration of the vibrations and the predominant period. Another important for the practice of designing buildings and structures is the logarithmic width of the spectrum \( S \), which is stable and has the value \( S = 0.60 \pm 0.24 \) (Aptikayev, Erteleva, 2008). Based on the parameters of the expected seismic event: magnitudes, depth of focus, type of movement and epicentral distance, the indicated indices are calculated, on the basis of which the reaction spectrum and the envelope are calculated.

The shape of the envelope is determined only in the time domain. At present, it is possible to build a model based on a detailed study of the spectral-temporal parameters of seismic records based on modern mathematical methods of analysis (wavelet analysis, polarization analysis, etc.). Spectral methods of analysis of seismic records, in particular, were used in the study of the fall of the Kolka glacier (Zaalishvili, Mel'kov, 2014).

2. SPECTRAL-TEMPORAL REPRESENTATION OF SEISMIC IMPACT

The Strong Motion Virtual Data Center (VDC) Strong Motion Database (http://www.strongmotioncenter.org) was used to select ground motion records for the analysis. The database contains data on the source mechanism, estimation of the shortest distance to the rupture surface, and other data. Since the study of the influence of ground conditions at this stage was not included in the research task, seismic stations located on bedrock and dense ground (‘Hard Rock’, ‘Rock’, 'Very dense soil and soft rock’), only three- on which the exact orientation of geophones is known, which makes it possible to use polarization analysis for processing. These conditions in the VDC database are met by 95 records of 26 earthquakes. To manage data, the MS Access database was created (Zaalishvili et al., 2016). The main form of the database is shown in Figure 1. Seismic event data is stored in the Earthquakes table, corresponding to the record in the Records table. As an
example, the earthquake of Loma Prieta (Loma Prieta / Santa Cruz Mountains 1989-10-18 00:04:15 UTC) is considered. The form contains the area of the earthquake data: magnitude, coordinates, depth, parameters of the source, and the associated table of records with station coordinates, a brief description of the ground conditions, and a reference to the directory containing the corresponding accelerogram and the results of data processing - Figure 2. The locations of the epicenter and the seismic (recording) stations are displayed in the corresponding diagram, based on the Google Static Maps service.

Figure 1. The main form of the database

The spectral-temporal decomposition of the signals was performed using a wavelet transform, the algorithm of which was developed on the basis of a fast Fourier transform (FFT). The wavelet transform is the inverse Fourier transform of the product (Torrence, Compo, 1998):

$$W_m(s) = \sum_{m=0}^{N-1} \hat{x}_n \hat{\psi}^* (s\omega_n) e^{im\omega_n \Delta t},$$  \hspace{1cm} (1)

where $\hat{x}_n$ – Fourier transform of the signal; $\hat{\psi}$ – Fourier transform of wavelet function, the (*) indicates the complex conjugate; $s$ – wavelet scale; $N$ – number of samples; $\Delta t$ – time step; and the angular (cyclic) frequency is defined as:

$$\omega_n = \begin{cases} 2\pi k / N \Delta t, & k \leq N/2 \\ 2\pi k / N \Delta t, & k > N/2 \end{cases}.$$
The calculation algorithm was implemented in MATLAB on the basis of the invert fast Fourier transform function, which increased the calculation speed by more than 10,000 times compared to the use of direct calculation. It should be noted that, unlike standard functions, the coefficients of the wavelet expansion in this case were calculated with the same time step by the corresponding step of discretization of the original signal, i.e. the decomposition is initially “redundant”, which is necessary for a more convenient graphical representation of the results (the problem of signal compression is not put in this case) – Figure 2.

Figure 2. Loma Prieta (1989) earthquake record (1989), Gilroy Array Sta 1 station, CA-Gavilan College, Water Tank, distance to the fault of 2.8 km: a) vertical component AZ and two horizontal: projected toward AR and perpendicular to this direction Aτ; b) the corresponding wavelet decomposition of the records.
The obtained spectral-temporal decompositions of seismic records were approximated by the envelope, which for each frequency had a standard form used in the method of normal spectra (Aptikayev et al., 1979), except of frequency domain and introduced parameter $\delta$:

$$A(t, f) = \frac{A_0(f) \cdot 3(t - \delta(f)) \cdot d(f)}{9(t - \delta(f))^2 - 9(t - \delta(f))d(f) + 4d(f)^2},$$

(2)

where $d(f)$ – duration; $\delta(f)$ – time shift; $A_0(f)$ – maximum amplitude; $t$ – time domain.

The shape of the envelope is shown in Figure 3. The difference is in the approximation of each frequency component and an additional parameter – the time shift. As a result, each spectral-temporal image of the accelerogram is represented by an ensemble of envelopes, which can be specified by three spectral curves – $A_0(f)$, $d(f)$, $\delta(f)$ – Figure 4.

![Figure 3. Example of envelope function](image)

To simulate the spectral envelope for a given magnitude $M$ and the shortest distance to the rupture plane $R$, statistical processing of instrumental data was performed by the method of multiple regression analysis. Dependencies were searched in the form:

$$A(f) = a_0(f)M + a_1(f) \log(R) + a_2(f),$$
$$d(f) = d_0(f)M + d_1(f) \log(R) + d_2(f),$$
$$\delta(f) = \delta_0(f)M + \delta_1(f)R + \delta_2(f).$$

(3)

In this case, the coefficients are functions of frequency, the results are given in Table 1.
Figure 4. Parameters of the spectral-temporal expansion: amplitude (a), duration (b) and time shift \( \delta \) (c). Accelerogram of the earthquake Loma Prieta (1989), station Gilroy Array Sta 1, CA - Gavilan College, Water Tank
Table 1. Results of calculation of regression coefficients for spectral curves

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</table>
3. MODELING OF SEISMIC IMPACT ON THE BASIS OF THE REVERSE WAVELET TRANSFORMATION

Since the wavelet transform is a bandpass filter with a known frequency response (wavelet function), it is possible to reconstruct the original signal using inverse convolution in the case of orthogonal transformation, but for continuous wavelet transformation this is complicated by redundancy in time and frequency scale. However, redundancy makes it possible to use an excellent function for signal reconstruction, the simplest of which is the delta function (Farge, 1992):

$$x_n = \frac{\delta \sqrt{\Delta f}}{C_\delta \psi_\delta (0)} = \sum_{j=0}^{\infty} \frac{\text{Re}(W_j(s_j))}{\sqrt{s_j}}$$  \hspace{1cm} (4)

The multiplier $C_\delta$ is the reconstruction of the delta function from its wavelet transform and it is consistent for each base function and for the Morlet wavelet $C_\delta = 0.776$.

To reconstruct the accelerogram from the simulated amplitude spectrum, it is suggested to use the following formula:

$$A(t) = \sum_j A(f,t) \cos(\varphi(f)) \cos(2\pi f \cdot t), \text{ where } \varphi(f) = 2\pi f \cdot \delta(f)$$  \hspace{1cm} (5)

An important difference of this formula is the use of empirical data in phase modeling, in contrast to the method using standard spectra, in which "phase angles are random variables distributed in the interval from 0 to 2 \pi" (RB-06-98).

The algorithm for calculating the synthetic accelerogram is the following:

1) Calculation of the spectral curves $A(f)$, $d(f)$, $\delta(f)$ by formulas (3) for given magnitudes $M$ and the shortest distance to the fault plane $R$.

2) Simulation of the spectral-temporal envelope $A(f,t)$ by the formula (2) for each frequency. Use anti-aliasing if necessary.

3) Calculation of the synthetic accelerogram by inverse wavelet transform using formula (5).

As an example of the practical use of the proposed method, the Vladikavkaz fault with a seismic potential $M = 7.1$, close to the territory of Vladikavkaz city, is considered (Figures 5–6). Accelerograms were also modeled by the finite-fault model in the FINSIM (Beresnev, Atkinson, 1998) program (Zaalishvili et al., 2010), and also by standard spectra technique described in RB-06-98. A comparison of the Fourier spectra and dynamic response factor curves (normalized response spectra constructed for the periods) obtained by different methods is shown in Figures 6–7. The maximum in the spectrum at 2.4 Hz coincides with the finite fault simulation results for the position of the source in the eastern part of the fault and exceeds it in amplitude, and on the curve of the dynamic coefficient this manifests itself in a significant peak with a period of 0.41 s. And it might be important for practical construction and risk assessment especially taking into account that there are many 4-5 storey masonry and 5-9 storeys wireframe buildings in Vladikavkaz city. Differences in spectral content obtained by different methods may refer to different aspects of result accelerogram forming, including relative source orientation to the site. It should be also noted that in this paper the dependencies are obtained for the selection of accelerograms, most of which are obtained in North America, so for different regions the corresponding coefficients in further work will be specified.
Figure 5. The spectral-temporal envelope of the synthetic accelerogram for the Vladikavkaz fault (M = 7.1, R = 10 km) (a) and the accelerogram synthesized for this fault (b)
Figure 6. Spectra of accelerograms calculated by different methods: 1 - finite-fault model (source in the western part of the fault); 2 - finite-fault model (source in the central part of the fault); 3 - finite-fault model (source in the eastern part of the fault); 4 - method using standard spectra; 5 - method of the spectral-temporal envelope.

Figure 7. Dynamic response factor curves calculated from synthetic accelerograms obtained by different methods: 1 - finite-fault model (source in the western part of the fault); 2 - finite-fault model (source in the central part of the fault); 3 - finite-fault model (source in the eastern part of the fault); 4 - method using standard spectra; 5 - method of the spectral-temporal envelope; 6 - Dynamic factor curve according to SNIP II-7-81 *.
4. CONCLUSION

1. Based on fast Fourier transform (FFT), the algorithm of fast discrete wavelet transform (FDWT) is implemented and a database of spectral-temporal images of strong motions records is created.

2. The seismic impact can be approximated by a set of envelope functions, so that for each frequency a certain duration, amplitude and time shift are given.

3. A formula for the generation of a seismic signal based on the inverse wavelet transform is proposed, taking into account the phase characteristics of the signal for different frequencies.

4. The proposed method of generating synthetic accelerograms is based on the inverse transformation of the spectral-temporal image, obtained from empirical data and characterized by the approximation of the waveform to real effects, in each specific case characterized by a certain set of periods.

5. For the Vladikavkaz fault, the prevailing period 0.41 s (frequency of 2.4 Hz) of seismic impact that exceeds design values for mass construction, was obtained for the first time, this obviously needs to be taken into account in further studies. It should be noted that at this frequency, the predominant components are also allocated on the records obtained for the finite-fault model.

5. REFERENCES


RB-06-98 Determination of initial seismic ground motions for design bases. Moscow: Federal Supervision of Russia on Nuclear and Radiation Safety (Gosatominadzor of Russia), 2000. (in Russian)


