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Modeling of Strong Ground Motion Within the Baikal Rift Zone: The Irkutsk Case

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Abstract: The Baikal Rift Zone is seismically active and each well recorded strong earthquake (for example, as the Kultukskoe earthquake (South of Baikal), on August 27, 2008, with $M_w = 6.3$) is the reason to refine existing models for seismic hazard estimates. There are several approaches to study strong ground motion, and one of them is to model synthetic accelerograms to reconstruct the rupture process. In this paper we are mostly interested in calculating accelerograms for the city of Irkutsk, considering source spectra with two corner frequencies, primarily, to reconstruct impact from the Kultukskoe earthquake.

Keywords: earthquake, source spectra, strong ground motion, the Kultukskoe earthquake, synthetic accelerogram, seismic hazard

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Research Article

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Introduction

The Baikal Rift Zone is one of the most active seismic regions in Russia where currently such strong earthquakes occur as the Bystrinskoe earthquake with a magnitude $M_w^{GCMT} = 5.5$ (on September 21, 2020), Kultukskoe earthquake with a magnitude $M_w^{GCMT} = 6.3$ (on August 27, 2008), Khovsogol earthquake with a magnitude $M_w^{GCMT} = 6.8$ (on January 11, 2021) and other felt events. Seismic monitoring in the region is provided mostly by the Baikal Branch of Geophysical Survey RAS (GS RAS, https://seis-bykl.ru/). Its network consists of up to 23 accelerometers what is the most informative data when strong earthquakes occur nearby. Analyses of such data helps to clarify strong ground motion prediction equations what is of a great significance since there are big cities as Irkutsk, Ulan-Ude with about half of million population each, and diverse infrastructure. According to latest estimates [*Pisarenko et al.*, 2022] the maximum possible magnitude in Irkutsk is up to 7.9, so works on seismic hazard should be carried out regularly, especially after well recorded strong earthquakes [*Shebalin et al.*, 2022].

One of the traditional approaches to estimate seismic impacts is the use of regional empirical dependences of one or another parameter (for example, the maximum amplitude of accelerations) on distance and magnitude ([*Aptikaev*, 2012] and others). Note that in this case, most of these empirical dependencies are obtained from a set of information about earthquakes of moderate magnitudes from a limited range of distances (associated with the aperture of seismic networks), and then such dependencies are extrapolated to large magnitudes, with assumptions. Another problem faced by this traditional approach of empirical consideration of seismic effects is the complexity of the source process, which leads to obtaining several characteristic magnitudes/depths/distances for the same earthquake. Currently it is generally recognized [*Cesca et al.*, 2017; *Hayes et al.*, 2010; *Thio and Kanamori*, 1996] that the description of the source of a strong earthquake by the function of a point source makes it possible to obtain only "apparent" characteristics of the source, since the source itself has a complex structure and, accordingly, is characterized by a complex source function (for example, the function of the derivative of the seismic moment in time), which, first of all, manifests itself at close distances and should be taken into account when obtaining seismic hazard estimates. Modern databases on the source parameters of strong earthquakes (for example, SCARDEC [*Vallée et al.*, 2010], SRCMOD [*Mai and Thingbaijam*, 2014] also confirm the presence of a complex structure of the source process of strong earthquakes, and also, with some assumptions, make it possible to suggest earthquake scenarios under certain seismotectonic conditions.

At the same time, if earlier modeling of scenario earthquakes was limited to obtaining a finite number of synthetic accelerograms from a point or extended source (for example, in [*Gusev and Pavlenko*, 2009], nowadays there is an approach to calculate such synthetic accelerograms from a complex source process, and the number of such accelerograms is determined by the density of the grid (with a step from a few meters to the first tens of meters) specified in the modeling of the source process. Thus, the traditional fundamental seismological problem has moved into the category of obtaining and analyzing "big data". Modern algorithms and computing power make it possible to simulate such scenario earthquakes [*Mai*, 2005; *McKenna*, 2011].

Unfortunately, such high-density grids need also high-density observations to verify multiple models what is currently not provided by seismic networks, especially accelerometer networks of Baikal Branch GS RAS. So, modeling of strong ground motion for the Baikal region is still meaningful only within the stage of synthetic accelerograms from a point or extended source. However, considering accumulation of broadband seismic data, especially in the range of moderate earthquakes, one can consider using not only the standard Brune source model, which is usually set as a default parameter, but its modifications, for example, as the Aki-Brune-Gusev model [*Skorkina and Gusev*, 2017] what allows to get better fitting at high frequencies.

In this work, the Kultukskoye earthquake ($M_w^{GCMT} = 6.3$, 76 km from the "Irkutsk" station) was chosen for modeling synthetic accelerograms, considering the Aki-Brune-Gusev source spectrum model. It should be noted that the selected earthquake is one of the unique events for the Baikal region, since it allows verification of the obtained simulation results at close distances [*Melnikova et al.*, 2014].

Input data and method

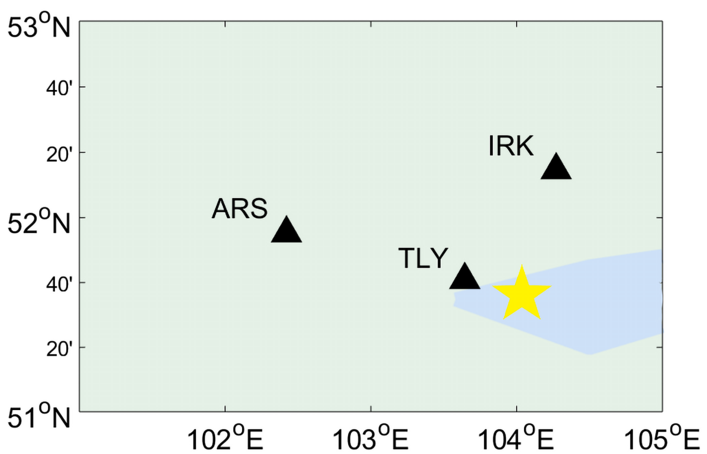


Figure 1. Map of the epicenter of the Kultukskoe earthquake and closest accelerometers.

A distinctive feature of the destructive seismotectonic processes in the Earth's crust of the Baikal subregion is the presence of a unique, by its huge size and great depth, water lens within the Baikal rift. Its walls are framed by the extensive seismically active normal faults, including the earthquake-prone Primorskii fault. Earthquake sources associated with normal faults mostly have the corresponding normal-fault, sometimes normal-fault strike-slip focal mechanisms, which naturally reflects the process of the present-day oblique rifting extension of the Earth's crust [*Gileva et al.*, 2021].

There are 22 accelerometers in Baikal Branch of GS RAS, however, we are interested primarily in three of them. It is the IRK accelerometer because of location directly in the city, with hypocentral distance of 76.2 km. Also, the TLY and ARS accelerometers is of big interest since it is the closest station to the source (28.8 km and 116.9 km, respectively) (Figure 1).

To calculate acceleration time histories, we used a stochastic method [*Boore*, 2003; *Pavlenko*, 2013], accounted for finite dimensions of a seismic source (with the possibility to prescribe the slip distribution over the fault plane). In the simulations, the earthquake sources were represented as a set of subsources with its locations as an elongated source.

When analyzing observed source spectra for the Baikal region (for example, Figure 3 in [*Dobrynina*, 2009], it was noted that the high-frequency part of such spectra is not always well described using the Aki-Brune (or "omega-square") source model, which suggests the contribution of the complex rupture process to the generated displacements.

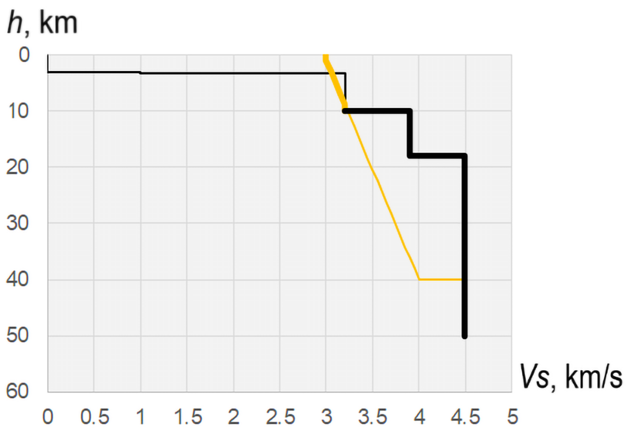


Figure 2. The velocity models are shown, where black line corresponds to the ak135 model and orange line corresponds to [*Zorin et al.*, 2002]. The bold line (orange from 0 to 10 km and black from 10 to 50) corresponds to assumed velocity model.

In modelling we used the Aki-Brune-Gusev [*Skorkina and Gusev*, 2017] spectral source model, what reflect the less amplitudes at high-frequency part of the spectra. To illustrate this approach in more detail, we introduce the following source spectrum model. We assume that the function of a source spectrum $m(f) = \dot{M}_0(f)/M_0$ has the form of

$$m(f) = K_1(f) \cdot K_2(f),$$

where each multiplier $K_k(f)$, $k = 1, 2$, describes the contribution of each corner frequency and contains the corresponding parameter f_{ck}. The $K_k(f)$ function has the form

$$K_k(f) = \left(1 + \left(\frac{f}{f_{ck}}\right)^{2\delta_k/\beta}\right)^{\beta\varphi_k/2}.$$

To obtain the spectrum of the Brune model [*Brune*, 1970], in Boatwright's modification [*Boatwright*, 1978], the following model parameters should be specified as: $K_3(f) = 1$; $f_{c1} = f_{c2}$; $\beta = 0.5$; $\delta_i = 1$; $\varphi_i = 1$. In the calculations below, we assumed that: $\beta = 0.5$; $\delta_k = \{1.25, 0.75\}$; $\varphi_k = \{1.0, 1.0\}$. This particular set of parameters was chosen empirically, taking into account a number of theoretical considerations.

The value of the parameter determines the sharpness of the spectral angle. Boatwright found in 1978 that the observed spectral angles are much sharper than the Brune model predicts with its β=1.0; Boatwright used β=0.50.

The values of the parameters δ_1 and δ_2 in any model with a flat acceleration spectrum should add up to 2.0, which is the case. Also, the parameter δ_1 specifies the slope of the first segment of the spectrum, from f_{c1} to f_{c2}. Both some recent publications and analysis of observed data have shown that δ_1 is somewhat higher than the traditional value $\delta_1 = 1.0$: the accepted value $\delta_1 = 1.25$ reflects this information.

The values of the parameters φ_k determine the asymptotic slope of the right branch of the spectrum component, and for $k = 1$ and 2, $\varphi_k = 1.0$ is taken in accordance with tradition.

To determine parameters describing the media structure one should assume a velocity and attenuation model and ground conditions. The velocity model used is the ak135 [*Kennett et al.*, 1995] with modification (Figure 2), available for Baikal region obtained earlier using receiver function method (Figure 9 in [*Zorin et al.*, 2002]).

The attenuation model was applied according to [*Pavlenko and Tubanov*, 2017]. Unfortunately, there are no detailed velocity model for upper layers up to bedrocks, and different kappa were considered in agreement with assumed ground conditions for IRK, ARS and TLY stations (Table 1).

Table 1. Information on seismic stations used

Seismic station	Latitude	Longitude	Ground condition	Assumed k_0
TLY	51.681	103.644	Blocks of rock, rubble, gravel up to 5 m, marbles, slatestone	0.012
IRK	52.243	104.271	Argil sand ground up to 13 m	0.02
ARS	51.920	102.421	Blocks of rock, gravel, rubble with fine sandy loam	0.012

Results

The calculated synthetic accelerograms for S-waves can be seen in the Table 2 where our results compared to registered acceleration time histories [*Melnikova et al.*, 2014] recorded by three closest stations (TLY, ARS, IRK).

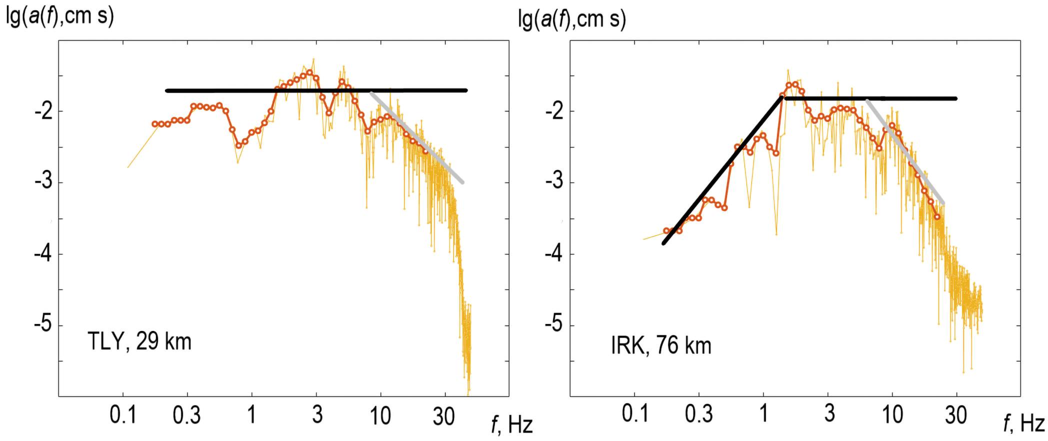


Figure 3. Fourier acceleration spectra (original and smoothed) for TLY and IRK stations. Black line corresponds to the Brune model, and grey line corresponds to high-frequency part in agreement with Aki-Brune-Gusev model.

The "intensity" column in the Table 2 consists of two values, where "observed" value is according to macroseismic data [*Melnikova et al.*, 2014], and "modelled" is calculated using the maximum acceleration from modelled acceleration time history using the equation [*Wald et al.*, 1999]:

$$I = 3.66\,\mathrm{lg}(\mathrm{PGA}, \mathrm{cm/s}^2) - 1.66, \quad 5 \leq I \leq 9.$$

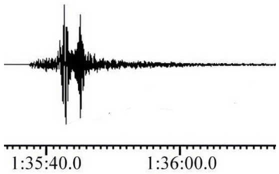
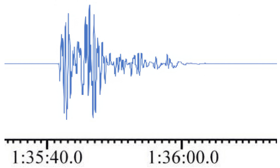
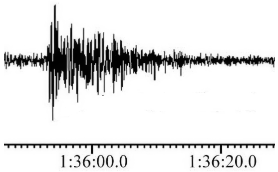
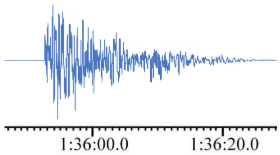
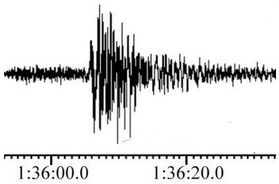
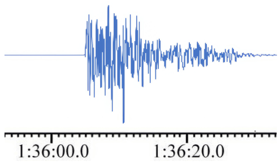
It can be seen that waveforms of modelled S-waves quite fit the shape of observed waveforms. For example, as for TLY, two different peaks can be seen in modeled acceleration time histories as it was observed. Such evidence indicates for a complex source where maximum slip did not happen simultaneously but distributed within an elongated source.

In Figure 3 there are spectra of S-waves for TLY and IRK stations. Since the TLY station is located in near-field (29 km from the source of $M_w = 6.3$), we can analyze only a high-frequency part where there is a high-frequency cutoff ($f_{\max}$) which corresponds to the Aki-Brune-Gusev model. In classical Brune model the plateau should continue up to the upper frequency limit of registration (in agreement with black line in the figure). Meanwhile for the IRK station (at 76 km), the spectrum can be analyzed in all frequency range, and it corresponds to the Brune model up to plateau, however, at high frequencies again we see the high-frequency cutoff. Note that nevertheless the site conditions differ significantly, high-frequency cutoff locates in the interval about 7–10 Hz what may be interpreted as source-controlled effect. The differences in high-frequency slopes of modelled spectra are due to kappa k_0 (near-surface attenuation) in Table 1.

On the one hand, the discrepancies in values of calculated intensities can be due to site conditions. Unfortunately, accelerometer stations are not provided with detailed velocity profiles up to bedrock as it is proposed, for example, by [*Haslinger et al.*, 2022] and they have not been estimated empirically as for Kamchatka accelerometers [*Gusev and Skorkina*, 2020].

On the other hand, we do not have updated dependencies between intensities and registered accelerations in the region, so, relations obtained using world data can be also applicable here only as a first approximation, and should not be considered for seismic hazard estimates in the region.

Table 2. Comparison of observed and modelled accelerograms for the Kultukskoe earthquake ($M_{\mathrm{w}}^{\mathrm{GCMT}} = 6.3$)

Station	Observation	Modeling	Intensity
TLY (Δ = 28.8 km)			I = 7.0 (observed) I = 6.9 (modelled)
IRK (Δ = 76.2 km)			I = 6.0 (observed) I = 5.8 (modelled)
ARS (Δ = 116.9 km)			I = 5.0 (observed) I = 5.2 (modelled)

Conclusions

For the first time, we have simulated accelerograms for the Baikal region using the Aki-Brune-Gusev spectral model that allowed us to fit observed waveforms for the Kultukskoe earthquake. It also means that used spectral models better fit to observed fault rupture time histories.

However, such simulation still is not enough to estimate strong ground motion prediction equations in the region, as one can see how deviate predicted and observed values of intensities (calculated using modelled accelerations). Also, ground conditions should be studied in more details, especially for accelerometers sites.

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