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ScienceDirect

Russian Geology and Geophysics 58 (2017) 844–854

RUSSIAN GEOLOGY AND GEOPHYSICS

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Determination of corner frequencies of source spectra for subduction earthquakes in Avacha Gulf (*Kamchatka*)

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Received 3 June 2016; accepted 20 October 2016

Abstract

The source spectra of $M = 4.0–6.5$ subduction earthquakes of 2011–2014 in Kamchatka are studied. The dataset comprises 1272 source spectra recovered from *S* waves of 372 earthquakes recorded by six digital rock-ground stations. The structure of the spectra is examined on the basis of a spectral model with three corner frequencies f_{c1}, f_{c2}, and f_{c3}. It was assumed that the spectra behave as f^{-2} between f_{c2} and f_{c3}, where f_{c3} denotes "source-controlled f_{max}" after Aki and Gusev. To determine the corner frequencies, we extracted the source spectra from *S*-wave spectra using a previously developed attenuation model for the study area. The spectra were first reduced to the reference hard-rock station, employing a specially determined set of spectral amplifications of stations. We approximated the recovered source spectrum by a piecewise power-law function, estimated f_{c1}, f_{c2}, and f_{c3}, and examined their dependence on the seismic moment M_0 (i.e., scaling). The dependence $f_{c1}(M_0)$ does not contradict the hypothesis of source similarity when one expects $f_{c1} \propto M_0^{-1/3}$. For f_{c2} and f_{c3}, the scaling is close to $f_{c2} \propto M_0^{-0.23}$ and $f_{c3} \propto M_0^{-0.13}$, respectively, indicating a clear violation of the similarity, especially prominent for f_{c3}. Systematic identification of the frequency f_{c3}, its determination, and analysis of its scaling are the main results of the study, important for understanding the physics of earthquake source processes. The use of f_{c3} as a source parameter in strong ground motion simulations will eliminate biases in estimating attenuation parameters, in particular, the spectral decay parameter "kappa".

Keywords: earthquake; source spectra; scaling law; third corner frequency; f_{max}; source-controlled f_{max}; kappa

Introduction

The study of earthquake source spectra is of interest to earthquake source physics and is important for the solution of engineering seismology problems. In theory, a source displacement spectrum (SDS) is described by the level of the flat part of the spectrum and position of its crossover points or corner frequencies. The standard model of the source displacement spectrum is the omega-square (ω^{-2}) model (Aki, 1967; Brune, 1970), which includes a flat ($\propto f^0$) segment at low frequencies (LF) and a falloff at high frequencies (HF). These two segments are separated by a crossover at the corner frequency f_c. As early as in (Brune, 1970), it was noted that this corner can be split into two; the corresponding corner frequencies will be denoted by f_{c1} and f_{c2}. The frequent occurrence of a crossover at f_{c2} is known (Gusev, 1983, 2012; Papageorgiou and Aki, 1983; and others), but the properties of f_{c2} are not well understood.

Source acceleration spectra (SAS), which increase as f^2 at LF and have two crossovers at f_{c1} and f_{c2} and a plateau ($\propto f$) at $f > f_{c2}$ are useful for many purposes. In acceleration spectra, this plateau is always followed on the right by an upper (HF) cutoff of the spectrum. In the ω^{-2} model, this cutoff is usually attributed to an increase in ray path loss with increasing frequency. If the loss is known, it can be taken into account, so that the source spectrum recovered from observations should be flat. In practice, after the described correction of HF, the cutoff typically persists; in (Hanks, 1982), the cutoff frequency of such a residual cutoff is denoted as f_{max}. In (Gusev, 1983; Papageorgiou and Aki, 1983), the formation of this cutoff is attributed to the source (see the discussion in (Gusev, 2012). Soon, however, it was shown (Anderson and Hough, 1984) that its probable cause is the intrinsic loss in the near-surface layers. This loss is characterized by the

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1068-7971/$ - see front matter © 2017, V.S. Sobolev IGM, Siberian Branch of the RAS. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.rgg.2017.06.007

quantity κ_0 ($\kappa_0 = \int_l dt/Q$, where l is the short segment of the ray directly beneath the station). However, it has been systematically found that $f_{\max}$ can be detected in acceleration spectra corrected for both types of loss: along most of the ray path and directly beneath the station. These facts indicate that $f_{\max}$ is partly of source origin. The contribution of the source to the generation of $f_{\max}$ is now generally recognized in principle (Purvance and Anderson, 2003), but the issue has been studied insufficiently.

The complex nature of the phenomenon has led to the emergence of awkward terms: 1) site (station)-controlled $f_{\max}$ and 2) source-controlled $f_{\max}$; hereinafter, they will be denoted as (1) f_κ and (2) f_{c3}, i.e., the third corner frequency. The latter parameter is an important subject of this study. There are still no approaches that would allow a reliable and systematic separation of the contributions of f_κ and f_{c3} to the observed f_{max} effect. It is believed that by determining and compensating for the wave propagation loss, it is possible to establish the reality of the upper cutoff of SAS and, in case of success, obtain numerical estimates for f_{c3}. For the Avacha Gulf region in East Kamchatka, the loss parameters of the medium ($Q(f)$ and κ_0) were reliably estimated in (Gusev and Guseva, 2016a).. These estimates of the loss can be used to correct station spectra in this region.

Mass estimates of f_{c2} and f_{c3} for Kamchatka were first obtained from the data of the single PET station for 1993–2005 (Gusev and Guseva, 2014) using a preliminary loss model. However, due to the limited reliability of these results and the overall low knowledge of the parameters f_{c2} and f_{c3}, this work should be performed at a new level. It employs refined estimates of the intrinsic loss in the medium and a network of stations instead of a single station. In 2008–2010, a network of stations was organized for the Avacha Gulf region, providing an opportunity to carry out such study, to be described below.

Initial data set

By 2011, a digital seismic network which uses CMG5T and CMG5TD accelerometers was deployed in Kamchatka (Chebrov et al., 2013). To study earthquake source spectra in the region, we processed records of such instruments located on rock or hard ground at the Dal'niy (DAL), Khodutka (KDT), Karymshina (KRM), Petropavlovsk (PET), Russkaya (RUS), and Shipunskii (SPN) stations in the Avacha Gulf region in 2011–2014 (Fig. 1*a*). The range of hypocentral distances r is 45–250 km, mainly over 75 km (Fig. 1*b*), the depths are up of 170 km, mainly up to 50 km, and the range of magnitudes M_L is 4.0–6.8. Records of 372 subduction earthquakes were processed. Records with high noise levels or multiple events were excluded.

The absence of records at distances less than 50–70 km from the stations (Fig. 1*b*) is a specific property of subduction earthquake records obtained in Kamchatka: their sources are beneath the ocean floor, and the stations are on the coast. Processing of such data does not always provide full information about the source and medium, and this has to be accepted.

Principles of conversion of observed spectra to the source

To validate the employed data analysis technique, it is necessary to consider the earthquake source, the source spectrum, and its relationship to the station record (signal).

The case of a homogeneous lossless medium (ideal case). In this paper, the internal structure of earthquake sources is not considered. An earthquake source is described using an equivalent point source—a double couple whose scalar seismic moment increases according to a law $M_0(t)$; the rate of its increase is $\dot{M}_0(t)$. The amplitude spectrum of $\dot{M}_0(t)$ will be denoted as $\dot{M}_0(f)$; it is called the source spectrum. The seismic moment as a numerical parameter of the source is $M_0 = M_0(t)\big|_{t=\infty} = \dot{M}_0(f)\big|_{f=0}$. Up to a factor, the functions $\dot{M}_0(t)$ and $\dot{M}_0(f)$ coincide, respectively, with the time history $D(t)$ and spectrum $D(f)$ of the body-wave displacement signal in the ideal case of a homogeneous unbounded elastic lossless medium. In this case,

$$D(t) = A_1 \dot{M}(t - r/c_S);\quad A_1 = \frac{R_S}{4\pi\rho c_S^3 r}, \tag{1}$$

where R_S is the radiation pattern for the S wave displacement (below, we use the value $R_S{}^2 = 0.4$ averaged over the source sphere) and ρ and c_S are the density and velocity of S waves. It is also useful to introduce the function $\ddot{M}_0(f)$ related to the spectrum $V(f)$ of the velocity signal $V(t)$, and the source acceleration spectrum $\dddot{M}_0(f) = (2\pi f)^2 \dot{M}_0(f)$ related to the spectrum $A(f)$ of the acceleration signal $A(t)$. In studies of real sources, the calculated signal spectra have to be smoothed (averaged over a limited frequency band), which is justified by the absence of distinct systematic peaks and troughs in the observed spectra. To recover source spectra from real records, the recorded spectra had to be reduced to the ideal conditions described above.

Approximate characteristics of real cases. In practice, in addition to (1), there are several effects more, which will be described by using additional factors on the right side of (1). These include:

1.1. The free surface effect, factor $C_{11} \approx 2.0$.

1.2. Projection of the S wave displacement vector onto the direction of the receiver component C_{12}. We worked with spectra of the horizontal components and set $C_{12}^2 = 0.5$.

1.3. Ray curvature. Its effect can be written as the factor $C_{13} = G(r)/r$. Under our conditions, this factor is difficult to estimate reliably as the form of records is hardly consistent with the principles of geometric seismics. We will set $C_{13} = 1$.

2.1. The influence of the ratio of the impedances (acoustic stiffnesses) of the medium near the source (0) and receiver (1), $C_{21}(f) = (c_S{}^{(0)}\rho^{(0)}/c_S{}^{(1)}\rho^{(1)})^{0.5}$. This factor depends on