SH-waveform modeling of small local seismic events in Ladoga lake

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Abstract

A lot of seismic phenomena with small magnitude has been taking place in the Ladoga lake region (northwestern Russia). One of them is the earthquake which was recorded on the 31st of July, 2010 followed by the swarm of microearthquakes near Nikonovsky cape. There is only one station in the region that is why it is difficult to process the data. In this work, we propose a new approach to construct synthetic seismograms of the main event with minimum data. Also this approach applies us to calculate parameters of the source. The approximate magnitude of the main event is $M_L = -0.8$. For swarm events, we have magnitude values from -1.0 to -2.6 . The data of swarm events (microearthquakes) is used to test the technique of constructing synthetic seismograms. The approach we propose is based on Green's function method with using two temporal δ -sequences (the Lorentzian function and the continuous Dirichlet kernel). A comparison of synthetic and real seismograms shows that the Lorentzian function is better to describe small local events, and the continuous Dirichlet kernel is more appropriate for earthquakes. This approach can be generalized to various problems of different nature.

Keywords Earthquake swarm · Microearthquake · Green's function · Synthetic seismogram · SH-wave · Seiche

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1 Introduction

One of the most informative source in geophysics is the analysis of the wave propagation in elastic medium. The solution of the wave equation allows us to obtain various medium parameters or source parameters. One of the generally accepted methods for solving such problems is Green's function method [10, 12, 14, 17, 20, 22, 23]. It is widely used to solve inhomogeneous differential equations with boundary conditions in various fields of science. The main aim of this article is to develop an approach for solving similar problems like modeling waveform of events with small magnitude (such as microearthquake,

technogenic noise, the noise from the drilling rig, etc. [7, 12, 18, 22, 26]).

On the basis of Green's function method, we will construct synthetic seismograms for microearthquakes from Ladoga lake. Such microearthquakes are usually generated by natural rock masses or by induced seismic events [8, 26]. The seismic network on Ladoga lake is limited by one station [9] only, and the magnitudes of the earthquakes are small. Thus the distant stations register no waves at all, and we will use the data from one station only. We are interested in the earthquake from the swarm events on the 31st of July, 2010, in Ladoga Lake [3]. The swarm events are related to the seiche (according to the authors of the article [3]). Seiches in bodies of water are associated with

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a number of earthquakes [4, 13, 15]. Before the main event happened on the 29th of July, 2010, there was a strong atmosphere pressure variation in the area of Ladoga lake and then the seiche began. These microearthquakes were detected until the 31st of July, 2010. This phenomenon is accompanied by appearance of a standing wave with a large period in the pond. In other words, the enclosed body of water resonances as a whole part. When the wind failed and atmosphere pressure turns to be normal, the water returns to its equilibrium state of damped oscillations. The height of the seiche on large lakes is usually about 20–30 cm. This event (according to the authors of the article [3]) served as a trigger for a whole earthquake swarm of seismic events near Valaam island. Considering this, noise level increases on seismograms along the vertical axis (z axis), as claimed by the authors of this article [2] (see in Fig. 1). It is known that seiche provides SH-wave in elastic media [4, 15], so z-component could be excluded from consideration.

Valaam's station is located on the bedrock in the underground bunker far from technogenic noise [2]. So background noise is much lower than global level on the average. This position provides us to record local events in the frequency range from 1 to 17 Hz. During storms in

Ladoga lake, the noise is quite low at frequencies above 2–3 Hz. Noted that during storms increasing noise level of seismogram vertical component in comparison with horizontal components on interval 0.4–5 Hz is unusual [9]. It is associated with the location of seismic station. Such a low noise level is a reason why this station is so sensitive to microearthquakes and local events.

Valaam's Island is the largest island in the archipelago of the same name, which is situated in the northern, deepest part of Ladoga lake (with maximum depths more than 200 m). The island belongs to the Valaam-Salma island string stretched in the submeridional direction, the geomorphological features of which have not been adequately studied. All islands of the Valaam-Salma island string have the same origin and united geological base, which was tectonically split into different-sized blocks. By the way, it is considered that the rocks consists of quite dense medium mainly crushed or monolith gabbro-diorite [16, 19].

Seismic events near Valaam's island are divided into two parts. The first of them happened due to reaction of crumbling rocks to water pressure near cape with $M_w = -2$ [2]. They probably mark one of the underwater fracture zones of the rock mass of the cape (Fig. 2). The second part are related to the seiche from Ladoga lake.

Fig. 1 The seismogram of the earthquake, occurred at 18:44 GMT on 31 July 2010 near Valaam island [3]. The vertical lines mark the *P*-wave arrival (*Pg*) and the *S*-wave arrival (*Sg*)

Fig. 2 A map of the part of Ladoga lake [2, 3] where the location of the seismic station (black square), small local events (small black dots) and several main swarm events (big black dots) are marked. The main earthquake is marked with the arrow

For example, we work with two cases of events: occurred in 2006 [2] and in 2010 [3]. In Fig. 2, we mark the position of the station and locations of several main local events occurred previously. The first part is marked with black small circles (small black dots) on the insert in Fig. 2. These events take place immediately close to the Nikonovsky cape at a depth of up to 50 m with latitude 61.36 ± 0.01 and longitude -329.12 ± 0.01 (Fig. 2). The second part of events presents the earthquake swarm (big black dots). They are located at a depth from 300 up to 700 m with latitude 61.34 ± 0.01 and longitude -329.17 ± 0.01 . In this work, we will describe one of the small local events from the Fig. 2. It is marked with a star (★). At the same time, we consider the main event with magnitude $M_L = -0.8$ (marked with the arrow) with latitude 61.37 and longitude -329.03 . All these events are known to occur near Valaam's island. Thus we can use the nearest events to check our technique of constructing synthetic seismograms.

The main aim of this article is to develop a approach for solving problems like modeling waveform of events with small magnitude. The work consist of three parts. In the first part Green's function method and features of the proposed technique for constructing a synthetic seismograms are described. In the second part, a synthetic seismogram for an event of the earthquake swarm is constructed. In part 3, the main event is considered. Therewith the parameters of the earthquake source will be found, by comparing the synthetic seismograms with the real ones. In conclusion, we discuss the developed model and the possible applications.

2 Green's function method for constructing a synthetic seismograms

The displacements in the elastic medium is described by the equation of motion. It can be written as [11]:

$$\rho \frac{\partial^2 u_\alpha}{\partial t^2} = \frac{\partial \sigma_{\alpha\beta}}{\partial r_\beta} + F_\alpha, \quad (1)$$

where $u_\alpha(\mathbf{r}, t)$ is components of the vector of displacement at point $\mathbf{r}$ in the time t ($\alpha = 1, 2, 3$), $\mathbf{F}$ is the body force per unit volume, ρ —density and $\hat{\sigma}$ —stress tensor.

We use the Green's function method to find the displacement [1]. The Green's function $\hat{G}(\mathbf{r}, \mathbf{r}'; t, t')$ is the displacement field generated by a point instant source located at the point $\mathbf{r}'$ and acted at time t' . For a stationary homogeneous medium, it can be rewritten as $\hat{G}(\mathbf{r} - \mathbf{r}'; t - t')$ and the Green's function satisfies the differential tensor equation [1]:

$$\left[\rho \delta_{\alpha\gamma} \frac{\partial^2}{\partial t^2} - C_{\alpha\beta\gamma\zeta} \frac{\partial^2}{\partial r_\beta \partial r_\zeta} \right] G_{\gamma\eta}(\mathbf{r} - \mathbf{r}'; t - t') = \delta_{\alpha\eta} \delta(\mathbf{r} - \mathbf{r}') \delta(t - t'), \quad (2)$$

where $\delta(t)$ or $\delta(\mathbf{r})$ is the delta-function, $\delta_{\alpha\eta}$ is the Kronecker delta: $\delta_{\alpha\eta} = \begin{cases} 1, & \alpha = \eta, \\ 0, & \alpha \neq \eta, \end{cases}$ $C_{\alpha\beta\gamma\zeta}$ is the fourth-order elasticity tensor. For an infinite isotropic media, we have:

$$\begin{aligned} \hat{G}(\mathbf{R}, t) = & \frac{t}{4\pi R^3} \left(3 \frac{\mathbf{R} \otimes \mathbf{R}}{R^2} - \hat{1} \right) 1_{[R/c_s, R/c_p]}(t) + \\ & + \frac{1}{4\pi R c_s^2} \left(\hat{1} - \frac{\mathbf{R} \otimes \mathbf{R}}{R^2} \right) \delta\left(t - \frac{R}{c_s}\right) + \\ & + \frac{1}{4\pi R c_p^2} \frac{\mathbf{R} \otimes \mathbf{R}}{R^2} \delta\left(t - \frac{R}{c_p}\right), \end{aligned} \quad (3)$$

where $\mathbf{R} = \mathbf{r} - \mathbf{r}'$, $\hat{1}$ is the unit 3×3 tensor, and $\otimes$ —the tensor product symbol ($\mathbf{R} \otimes \mathbf{R}$ is 3×3 matrix), c_s and c_p are S- and P-wave velocities, respectively, $1_{[a,b]}(t)$ is the indicator (characteristic) function of the interval $[a, b]$:

$$1_{[a,b]}(t) = \begin{cases} 1 & t \in [a, b], \\ 0 & t \notin [a, b]. \end{cases} \quad (4)$$

Formula (3) is an equivalent form of the classical Stokes solution (see, e.g., [1, Eq. (4.23)]).

In an attenuating medium, Green's function solution [6] can be obtained by adding dimensionless attenuation coefficients $\varepsilon_{s,p} \ll 1$ of S- and P-waves, respectively. For the far-field zone, we have the modification of the formula (3):

$$\begin{aligned} \hat{G}(\mathbf{R}, t) \sim & \frac{1}{4\pi R c_s^2} \left(\hat{1} - \frac{\mathbf{R} \otimes \mathbf{R}}{R^2} \right) \delta_s^{(R)}\left(t - \frac{R}{c_s}, \frac{\varepsilon_s R}{c_s}\right) \\ & + \frac{1}{4\pi R c_p^2} \frac{\mathbf{R} \otimes \mathbf{R}}{R^2} \delta_p^{(R)}\left(t - \frac{R}{c_p}, \frac{\varepsilon_p R}{c_p}\right). \end{aligned} \quad (5)$$

Here $\delta_{s,p}^{(R)}(t; \tau)$ are a delta sequences with the retarded time $\frac{R}{c_{s,p}}$ depended on material dispersion laws for these waves,

τ is the temporal width of the delta sequences equal to $\tau = \frac{\varepsilon_{s,p} R}{c_{s,p}}$ of S- and P-waves, respectively.

So we consider two cases of frequency dependent attenuation:

$$\begin{cases} \text{case 1, } \omega \rightarrow \omega(1 + i\varepsilon \operatorname{sgn}(\omega)) \\ \text{case 2, } \omega \rightarrow \omega(1 + i\varepsilon \omega / \omega_0). \end{cases} \quad (6)$$

The first case is more typical for solids and second for liquids accordingly to [1, Sec. 5.5.1]. Thus, the exponential contribution in (5) can be written in (R, ω) -representation:

$$\exp\left(i \frac{\omega R}{c}\right) \rightarrow \begin{cases} \exp\left(i \left(1 + i\varepsilon \operatorname{sgn}(\omega)\right) (\omega/c) R\right), & \text{case 1,} \\ \exp\left(i \left(1 + i\varepsilon \omega / \omega_0\right) (\omega/c) R\right), & \text{case 2,} \end{cases} \quad (7)$$

where ω is the angular frequency, ω_0 is a reference value of ω . For each case, we have

$$\delta_1^{(R)}\left(t - \frac{R}{c}, \frac{\varepsilon R}{c}\right) = \frac{2}{\pi} \cdot \frac{\theta(t - R/c) \varepsilon R/c}{(t - R/c)^2 + (\varepsilon R/c)^2}, \quad (8)$$

$$\delta_2^{(R)}\left(t - \frac{R}{c}, \frac{\varepsilon R}{c}\right) = \theta\left(t - \frac{R}{c}\right) \sqrt{\frac{\omega_0 c}{\pi \varepsilon R}} \exp\left(-\frac{\omega_0 c}{4 \varepsilon R} t^2\right). \quad (9)$$

The presence of the Heaviside step functions θ in $\delta^{(R)}$ provides the retarded (in particular, casual) character of the Green's function. In Eq. (7) we neglect ω -dependence of velocity c or, equivalently, omit small real corrections to c arisen from the dispersion relations (see [1, Box 5.8]).

The displacement $u_\gamma(\mathbf{r}, t)$ can then be described by using the source function $\mathbf{F}(\mathbf{r}, t)$ and Green's function $\hat{G}(\mathbf{r} - \mathbf{r}_1; t - t_1)$ as follows:

$$u_\gamma(\mathbf{r}, t) = u_0(\mathbf{r}, t) + \int d\mathbf{r}_1 \int_{-\infty}^t dt_1 G_{\gamma\eta}(\mathbf{r} - \mathbf{r}_1; t - t_1) F_\eta(\mathbf{r}_1, t_1), \quad (10)$$

where $u_0(\mathbf{r}, t)$ is a solution of homogeneous equation (1) with $\mathbf{F} = \mathbf{0}$. In our case $u_0(\mathbf{r}, t) = 0$ since the waves are generated only by localized forces and the field is to vanish at infinity. In this work, we use double-couple without a moment as function $\mathbf{F}(\mathbf{r}, t)$ [21].

It should be noted that the actual source has an impulse character extended in time, and time dependence of the function $\mathbf{F}(\mathbf{r}, t)$ differs from the ideal $\delta(t)$ -function. In the sources modeling, we will use two δ -sequences: the first one is based on the Lorentzian function (or "Poisson kernel"), and the second one—on a continuous version of the Dirichlet kernel:

$$\begin{aligned}\delta_L(t, \tau) &= \frac{1}{\pi} \cdot \frac{\tau}{t^2 + \tau^2}, \\ \delta_D(t, \tau) &= \frac{\sin(t/\tau)}{\pi t}\end{aligned}\quad (11)$$

with $\delta_{D,L}(t, \tau) \rightarrow \delta(t)$ for $\tau \rightarrow 0$. The differences between these functions are illustrated in Fig. 3.

The parameter τ is a characteristic temporal width of quasi- δ -functions $\delta_L(t - r/c, \tau)$ and $\delta_D(t - r/c, \tau)$. It is convenient to use the Lorentzian function if the resulting wave is a highly concentrated (in the time-domain) signal, while the Dirichlet kernel is more appropriate for a time-stretched and oscillated signal.

This approach allows us to model events of different types shown in Fig. 2 and to construct the relevant synthetic seismograms. The values of the model parameters are determined by minimizing the difference between real and synthetic seismograms using the least-squares fitting. The parameter set will be taken for the cases of small local event 2006 [2] and of earthquake 2010 [3] separately.

3 Synthetic seismogram of the small local event of the earthquake swarm

Firstly, we describe the small local event which was marked with ★ on the map in Fig. 2. It is known from the seismic data [9] that the source of the event is located at the distance of about 320 m from the station and at the depth of about 100 m. For convenience, we will use the coordinate system associated with the source. As the origin of the Cartesian system, we use the hypocenter and direct the x axis to the north (ns), and y axis to the east (ew).

For this event, we test the technique to construct synthetic seismograms with source [5] as double-couple without a moment. The double-couple without a moment is

usually used to describe earthquake's sources [5]. This type of source is equivalent to fault shift. It can be represented by two perpendicular dipoles. Each of them is formed by a pair of oppositely directed point forces of the same magnitude which are located at the same point.

Known data is limited with the seismogram from a single station, and there is no *P*-wave in seismogram (solid lines in Fig. 4). That is why we cannot obtain a focal mechanism. Nevertheless, we have localised source and can make some conclusions about nature of the source. Particularly, real signal is highly concentrated in time. Therefore, we can use the Lorentzian function δ_L for δ -function approximation, but for comparison we will also consider the continuous Dirichlet kernel δ_D . As we said earlier, small local events related to seiche contains only SH-wave, so z-component could be excluded from consideration. Thus, we use ns and ew components of the seismogram only. To sum up, we model the x and y components of SH-wave velocity vector.

Fig. 4 The seismograms of real small local event (solid lines) and synthetic seismograms (dotted lines) for the source model of a double-couple without a moment with two types of δ -sequences: **a** the Lorentzian function, **b** the continuous Dirichlet kernel

Fig. 3 An illustration of the difference between the δ -sequence δ_L and δ_D : **a** the Lorentzian function, **b** the continuous Dirichlet kernel, both with $\tau = 0.04$

However, taking into account the location of the station and the geological structure of the Nikonovsky cape, we should confine ourselves to considering a homogeneous unlimited medium (consisting of gabbro-diabases with $c_s = 3.3$ km/sec). To obtain the displacement, we use the Green's function in the far-zone form of Eq. (5):

$$\begin{aligned} \mathbf{v}_S(t) &= \mathbf{n}_{SH} \frac{A}{4\pi r c_s} \frac{d^2}{dt^2} [\delta_L(t - r/c_s; \tau)], \\ \mathbf{v}_S(t) &= \mathbf{n}_{SH} \frac{A}{4\pi r c_s} \frac{d^2}{dt^2} [\delta_D(t - r/c_s; \tau)] \end{aligned} \quad (12)$$

for δ -sequences δ_L and δ_D , respectively, where A is a constant, $\mathbf{n}_{SH}$ is a unit vector of SH-wave direction. With the least squares method, we will compare the obtained and the real seismograms. As a result, we get the synthetic seismograms for the Lorentzian function (dotted lines in Fig. 4a) and for the continuous Dirichlet kernel (dotted lines in Fig. 4b). Finally, synthetic seismogram for the Lorentzian function is close enough to real and well describes the source for our small local event, as seen from Fig. 4a.

4 The earthquake source model

The earthquake was recorded on the 31st of July, 2010 on Ladoga lake near Valaam island. According to the seismogram, the source is at a depth of 2 km and at a distance from the epicenter to the station of about 2.3 km. The approximate magnitude of the event is $M_L = -0.8$ [3]. We undermine features which make seismogram of the earthquake (Fig. 1) and the small local event (Fig. 4) qualitatively different.

One of the main differences between them is that the record of the earthquake spreads out in time longer than for the small local event. That is why it is described by the second presentation of δ -function δ_D . We can clearly identify P -wave on the ew axis despite its low amplitude. The arrival times of the P - and S -waves are marked with green vertical lines supplemented with the yellow boxes on them (Fig. 1). First line corresponds to the P -wave and second one to S -wave. By analogy with the small local events, we will use only ns and ew components to modeling SH-wave velocity vector.

It should be also taken into account that the depth of the earthquake is significantly different from the depth of the small local event, so one needs to take into account the seismic waves attenuation in the medium. To this aim, we multiply the formula for S -wave amplitude by the attenuation factor [1]

$$\mathcal{D}_s = \exp [-(\omega/2Q_s)t], \quad (13)$$

where ω is the linear frequency on which the earthquake was filtered, Q_s is quality-factor for the S -wave.

By analogy with small local events in this case, we consider homogeneous unlimited medium and use Green's function in the far-field form of Eq. (5) and two types of δ -sequences δ_L and δ_D . The SH-wave velocity can be written in the form:

$$\begin{aligned} \mathbf{v}_{SH}(t) &= \mathbf{n}_{SH} \frac{A_1}{4\pi r c_s} \frac{d}{dt} \left[\mathcal{D}_s \frac{d}{dt} \delta_L(t - r/c_s; \tau) \right], \\ \mathbf{v}_{SH}(t) &= \mathbf{n}_{SH} \frac{A_2}{4\pi r c_s} \frac{d}{dt} \left[\mathcal{D}_s \frac{d}{dt} \delta_D(t - r/c_s; \tau) \right], \end{aligned} \quad (14)$$

for δ -sequences δ_L and δ_D , respectively, where A_1, A_2 are constants and $c_s = 3.3$ km/sec.

We model the x and y components of SH-wave velocity vector (14) for various values τ . We use least squares fitting of time dependence of synthetic SH-wave velocity vector and experimental seismograms. As a result, we get $\tau = 0.012$ s⁻¹ for continuous Dirichlet kernel and $\tau = 0.038$ s⁻¹ for the Lorentzian function. Resulting synthetic seismograms for SH-wave are presented in the Fig. 5 together with the corresponding real seismograms. Of these two cases, the best coincidence with the actual seismogram is obtained for continuous Dirichlet kernel.

Figure 5 shows that the synthetic seismogram quite well coincides with the central peaks on both axes. But only synthetic seismograms for continuous Dirichlet kernel is close enough to real and well describes the source. It is worth noting that this approach can only determine the form of the time dependence by the data from one station.

5 Discussion

Ladoga lake is untypical region for monitoring earthquakes due to its low seismic activity. The seismic data processing is compounded by the unique station presented in the region (Fig 2). Valaam's station is located in quite dense medium from mainly crushed or monolith gabbro-diabase far from technogenic noise [2]. Thus we have considered the observed numerous seismic events of small magnitude in the Ladoga region.

The synthetic waveforms were modeled by Green's function method with two temporal quasi- δ -function approximations for it (the Lorentzian function in Fig. 3a and the continuous Dirichlet kernel in Fig. 3b). We tested method on closer events (on small local event and on the main microearthquake from the swarm events). The seismograms differ in the type of signal: For small local events, we have highly concentrated (in the time-domain) signal and for earthquake—time-stretched and oscillated signal. It can be seen in Figs. 4 and 5 correspondingly.

Fig. 5 The synthetic (dotted lines) and real (solid lines) seismograms of main event for two types of delta-sequences: **a** the Lorentzian function, **b** the continuous Dirichlet kernel

Two types of synthetic waveforms were built for each of the events. First type (the Lorentzian function) is presented in Figs. 4a and 5a. The continuous Dirichlet kernel is shown in Figs. 4b and 5b. The best coincidence with the actual seismograms of small local event and of microearthquake are obtained for the Lorentzian function and for the continuous Dirichlet kernel correspondingly. Based on this, we can determine the degree of applicability of each of the functions.

One of the main limitation of this study is the only one station. Thus this approach can only determine the form of the time dependence, but the orientation of the source could not be determined. Our approach turns to be very promising for solution of the similar and more complicated problems. In particular, we note that the Green's function of elastic waves in an infinite half-space [24, 25] allows to take into account together with the bulk *S*- and *P*-waves also the Rayleigh surface waves.

6 Conclusion

The seismic activity of the Ladoga region is lower than other Scandinavian regions. By the way, there are a lot of microearthquakes that occur in quite dense medium mainly crushed or monolith gabbro-diorite near Valaam's island. In this work, we are considering microearthquakes from the swarm events on the 31st of July, 2010 in Ladoga Lake [3].

The synthetic waveforms shown in Figs. 4 and 5 were calculated for a source type as double-couple without a moment. The displacements were calculated by Green's function method. In this method, we have used two temporal quasi- δ -function approximations (the Lorentzian function and the continuous Dirichlet kernel). The Lorentzian function is used to describe small local events with a highly concentrated (in the time-domain) signal (see in Fig. 4a). While the continuous Dirichlet kernel is

more appropriate for earthquakes with time-stretched oscillated signal (Fig. 5b). The parameters of the model are calculated with least squares fitting of synthetic SH-wave seismograms and seismic wave attenuation in the medium. Also we have tested the construct method on closer events. Using only SH-wave data, the orientation of the source could not be determined. Future studies building on these method will aim to calculate focal mechanism from the data of several seismostations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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