PARAMETERS OF SMALL EARTHQUAKES AND THEIR CONNECTION WITH RADIATED SEISMIC SIGNAL FREQUENCY

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Abstract

The relationship between basic earthquake parameters (linear size of source, source volume, energy and magnitude) and the characteristics of radiated seismic signal for a great energy range (10^5 - 10^{22} erg) was analyzed from a theoretical perspective. For the first time earthquake energy was shown to be connected with the seismic signal period by a 6-degree relationship that may be explained within the framework of the theory of dimension. Previously registered observational data were firstly analyzed. Original results of small seismic events registered by ground seismic stations and hydroacoustic devices in the frequency range 20-1000 Hz were presented. The experiments were carried out at Kamchatka Peninsula and Sakhalin-Kuril region. Hydrophones were installed in an ocean shelf and lakes. The relationship between signal period (T) and earthquake energy (E) for a wide range of seismic events was obtained. Previously derived dependences established by Gutenberg, Richter and Kasahara agree with the relationship yielded in this piece of work. The dependence of seismic signal attenuation on signal frequency (f) and on receiver-source distance was studied in different media, including a combined medium. A signal with a frequency higher than 200 Hz (typical of micro-ruptures) decays completely at a distance substantially smaller than 1 km. Therefore, small seismic events (micro-earthquakes and micro-ruptures) are not registered by ground stations but may be recorded by hydroacoustic receivers located in the water layer.

Resumen

Las relaciones entre parámetros básicos de terremotos (dimensión lineal de la fuente, volumen de la fuente, energía, magnitud) y las características de las señales sísmicas irradiadas para un gran rango de energías, 10^5 - 10^{22} erg, se analizan desde un punto de vista teórico. Por primera vez se ha demostrado que la energía de los terremotos está conectada con el período de la señal sísmica por una relación de grado 6 que puede ser explicada en el marco de la teoría de la dimensión. Primero se analizaron los datos observacionales registrados previamente. Se presentaron los resultados originales de pequeños eventos sísmicos, registrados a través de estaciones sísmicas en tierra y dispositivos hidro-acústicos en el rango de frecuencias entre 20 y 1000Hz. Los experimentos se llevaron a cabo en la Península de Kamchatka y en la región de Sakhalin-Kuril. Los hidrófobos fueron instalados en una plataforma oceánica y en lagos. Se obtuvo la relación entre el período (T) de la señal y la energía de los terremotos para un gran rango de eventos sísmicos. Las relaciones establecidas previamente por Gutenberg, Richter y Kasahara coinciden con las relaciones obtenidas en este trabajo. Se estudió la dependencia de la atenuación de la señal sísmica con la frecuencia de la señal (f) y con la distancia entre receptor y fuente en diferentes medios (incluyendo un medio combinado). Dado que una señal con frecuencia mayor a 200Hz (típica en micro-rupturas) decae completamente a una distancia sustancialmente menor a 1 Km., los eventos sísmicos

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pequeños (micro-terremotos y micro-rupturas) no se registran en estaciones en tierra. Sin embargo, pueden registrarse a través de receptores hidro-acústicos ubicados en un medio líquido.

Introduction

According to modern concepts, the process of EQ's seismic wave generation and the process of an elastic wave radiation (from crack initiation or system of cracks) are similar from a physical point of view. These two processes differ in their scale. That is, the whole spectrum of seismic events (from micro-EQ up to catastrophic EQ) from an energy point of view differs in 18 orders and the period of radiated signals for these events differs only in 3 orders.

The relation $E(erg)=1000(erg/\ cm^3)*V(cm^3)$, where E- is an energy radiated by EQ and V is a source volume, was proposed by Tsuboi [1956]. The relation: $\lg E = \lg V + 3$ was obtained by data processing of aftershock area after underground nuclear explosion in Sadovsky et al, 1985.

The objective of this research work is to develop a procedure to estimate frequency and energy parameters of small EQs. This work is also dedicated to an analysis of small EQ parameters; of the high frequency signal attenuation in various media and of the possibility of such signal registration for the various source-receiver distances. Small EQs occur more often than large EQs but small EQ signals give us large integral information content. Signals from small sources are characterized by high frequencies, by rapid signal decay in solid media and especially in sediments (down to total attenuation in these media). These signals may be registered in a water layer because of weak attenuation of the acoustic signals in this medium.

Seismic signals originated in solid medium reach the sea floor and, after converting in the water/bottom boundary, propagate in the water layer. The transverse waves convert in the water/bottom boundary into longitudinal waves and then both waves propagate in the water layer with the same velocity. The difference in arrival times of these waves ($\Delta\tau$) to the receiver enables us to estimate the depth of the seismic event focus beneath the bottom (H).
These empirical relations between the source energy (where M is the EQ magnitude) and the period of radiated seismic signal (T) were proposed:

- by Gutenberg, Richter [1961]: $\lg T= -0.82+0.22M$; (1)
- by Kasahara [1961]: $\lg T= -0.78+0.28M$. (2)
- by [Sasorova, Levin, 2001] $L \approx B1\ T^2$, (where B1 = 2500 m/s2). (3)
  This relation was obtained as a result of data processing of signals radiated from EQs, rock bumps and geoacoustic emission.

Short analysis of observational data in small seismic events

Seismic signal parameters by hydro-acoustic (HA) records must be estimated. Magnitude (Ml) was determined from duration of a given HA record (t) according to the following relation:

- $Mb=2.30+\lg t$, for $t >=100$ s [Brocher, 1983];
- Or by calibration table proposed by Solovev and Kovachev [1996] for $t <100$ s. The regression function and unbiased estimate of determination factor (R^2) was here defined as follows: $Ml =3.213 \lg (t)-3.6328$ (4) and $R^2=0.9996$. Hence residual dispersion, determined by random component, is negligibly small.

The linear size (L) of small EQ source may be estimated by relation (3) according to the registered signal period (T). The depth of EQ source under sea bottom may be estimated by the $\Delta\tau$ value. A seismic event with signal duration from one to ten seconds is called micro-earthquake (MEQ), whereas an event with signal duration shorter than 100 milliseconds is called micro-rupture (MRP). The data obtained in several series of HA observations was later analyzed.

1. Micro-earthquakes (MEQ) picked up from HA records [Mogi, 1998], registered in ocean from shipboard just before the EQ. In the MEQs registered with signal duration from 1 to 7 s, Ml being from -3.6 to -0.9. Ml calculated by relation (4).
2. Micro-earthquakes (MEQ) picked up from HA records [Spindel et al, 1974], registered near ocean floor: with t between 5 and 90 s, Ml being from -1.4 to +2.6.
3. Signals registered in the water-filled boreholes in California [Teng et al, 1981] with t near 0.001 s, and M<= -7 (calculated by authors, the magnitude relation being little known).
4. Signals registered by ground-based high-output geophone [Udachin et al, 2005] with M ≈ -4, and T (signal period) between 0.05 and -0.30 s.
5. Data analysis of several series of HA observations made in water layer in seismic active zones of Far Eastern Russia was performed. The data series was obtained from the bottom self-contained system, which was deployed in the near bottom water layer in high-activity seismic areas (the Pacific coastline of Russia). One all-around looking hydrophone was used. HA records with frequency range (2 -1400 Hz) were registered. The EQs on these records were preceded by the series of MEQs. The t value varies from 0,8s to 103 s (Ml from -4.0 to +2.8.), but the t value for the overwhelming majority of MEQs (85%) is between 3s and 4 s (Ml from -1.8 to -2.8). The signal frequency (f) corresponding to the maximum signal amplitude varies from 20Hz to 120 Hz. [Sasorova et al, 2005]
6. The HA array was deployed in the near bottom water layer not far from the Pacific coastline of Kamchatka Peninsula [Lappo et al,2003]. The sampling rate was 300 per second; the instrumental band-pass filter isolated the frequency range 40Hz – 110 Hz, the observation period was – 276 days. Two types of seismic acoustic signals were detected in the HA records (Fig.1): the MEQs with duration 3 s-4 s and the MRP with duration from 0.01 to 0.06 s. The Ml value for MEQs was estimated from -2.1 to -1.8 and the estimation of Ml value for MRPs was from -10 to -8. MEQs occurred before EQ start as a packet of 5-15 events from various sources but situated alongside each other. The H value for these events was estimated from 200 m to 500 m under the ocean bottom. MRPs also occurred as several pulse packets, and their decay was very fast.
7. The next series of data was collected by Kamchatka research team [Kuptsov et al, 2005] from a water reservoir (lake) not far from the Pacific coast of Kamchatka. They used several HA receivers deployed in the water layer not far from the lake bottom. The frequency pass band was from 10 Hz to10 kHz. The sharp increase of the MRP signal density in time unit was noticed 20-30 hours before the EQs. The radiation of these signals continued several hours (10-15 h) and after that the density of the MRP signals vanished almost completely 10-17 hours before the main shock. The set of MRP signals may either be chaotically distributed in time or may form a train of signals of the same type. According to our estimations, acoustic signal sources were located not far from the receivers directly under the lake bottom (H = 3 - 20 m). The average t value was about 15 ms, average Ml =–8, frequency f – from 1 to 6 kHz.
8. A mobile station for simultaneous recording of seismic and hydro-acoustic signals was deployed in a water reservoir near Kholmsk [Sakhalin Is., August 2006]. Two all-around looking hydrophones were used. All channels (seismic and HA) were synchronized, sampling rate being - 200 Hz. The series of similar signals (trains) appeared in HA channels 21:22:40

before EQ start (total number of trains - 256). The radiation continued more than 10 hours, and then signals vanished completely 11:6: 03 before the main shock. The number of signals in the train varied significantly (from 7 to 130). No significant changes were observed at this time in the seismic channels. Every signal consists of two connected pulses with duration of 0.075 to 0.1 s (total duration – 0.2 s.). Magnitude of one pulse may be estimated as Ml =–6 - –7.

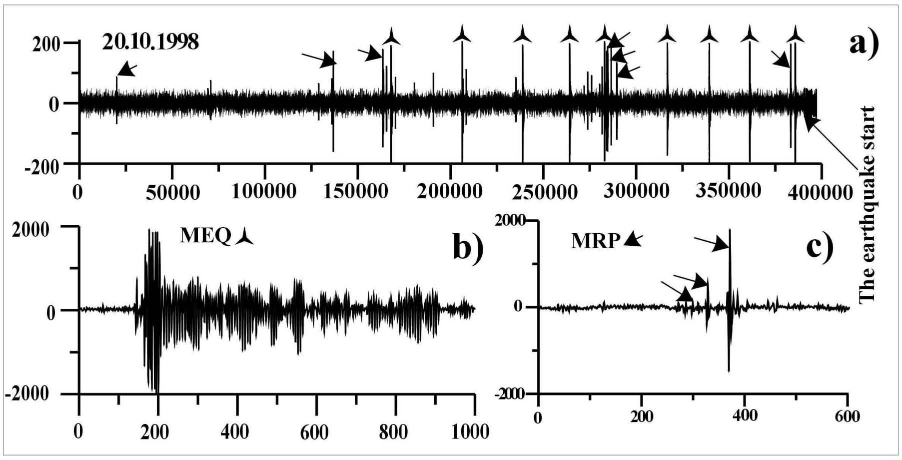

Figure 1. The typical HA record were EQ starts at the very end of the record (a). MEQs are labelled as triangle stars and MRPs are identified as arrows. One MEQ with duration of 3 sec is presented in Fig. 1b and the sequence of MRPs is shown in Fig. 1c. The horizontal axes for all fragments are time axes in samples (300 samples per sec); the vertical axes for all fragments are in mV.

9. The next series of HA observations were carried out on Kunashir Is. (Lagunnoe lake, in August - September 2007). The sampling rate was 250 Hz. EQs and MEQs were registered on HA records. The t value for MEQs varies from 0.6 to 4 s. The estimation of Ml values varies from -4.3 to –1.7. Registered frequency range f was from 20 to 80 Hz.

10. The series of HA observations on Sakhalin Is. (lake, area of active fracture near the mud volcano). A hydrophone with sensibility 200mkV/Pa was used. A lot of chaotic distributed pulses, from MRPs, were registered. Main component frequencies of the spectrum were near ~360 and ~160 Hz. MRP duration varied from 0.18 to 0.035 s. Ml estimation was from- -6 to -8. A powerful high frequency wave arrival and then a short-term attenuation of amplitude and frequency are typical for these signals.

Discussion and comparative analysis of observation data and results of calculations

Let us compare in Table 1 the Ml assessment defined by signal duration in relation (4) and by signal period (T) defined according to relation (3).

The relations obtained by Gutenberg and Richter (1) and Kasahara (2) and by other authors (3) were recalculated considering the radiated signal period dependence on energy. Three plots of the recalculated linear approximations shown in Fig.2. agree with each other. Let us note that this relationship is satisfied in a wide energy range (10^3 to 10^{22} erg).

Afterwards, a comparative analysis of the dependence of the radiated signal period on magnitude obtained from observational data was conducted. The observational and calculated periods determined for the same magnitude values indicated very close compliance.

Table 1. A comparison of two magnitude scales defined by signal duration (relation (4)) and by signal period

	A number of observation series	Type of detected	Magnitude (Ml) calculated by relation (4)	Magnitude (M) calculated by relation (3)
1	5 (BSCS)	MEQ	from +2.8 to -4.0	from -0,4 to -3.5
2	6 (HA array)	MEQ	from -1.8 to -2.1	from -1.6 to -2.7
3	6 (HA array)	MRP	from-7 to -8	from -9 to *
4	7 (Kamchatka)	MRP	from-8 to -11.0	from -9 to -11.0
5	8 (Kholmsk)	MRP	from -6 to -7.0	**
6	9 (Kunashir Is.)	MEQ	from -1.7 to -4.3	from -2.5 to -2.8
7	10 (mud volcano)	MRP	from -7.0 to -8.0	from -5.5

Remarks: *The frequencies f>150 Hz were inaccessible in these observations (because of the use of an input filter). ** Only waveform envelope is accessible in this case (high frequencies were inaccessible).

If radiated signal period dependence on EQ energy is known, then it is possible to obtain an attenuation signal assessment in various media and for various source energy levels (in different frequencies). The signal decay defines energy absorption in a given medium, geometrical divergence and dispersion. Plane wave absorption is described by a well known relation [Clay&Medwin, 1997]:

$$I(x)=I_0 \exp(-\beta x), \qquad (5)$$

where β is an attenuation factor, I_0 is the wave energy in the source, and I(x) is the wave energy if the source-receiver distance equals x. The signal absorption in rocks and sediments is proportional to frequency (f, Hz): $\beta=k*f$. k values (1/km) are: 0.0023 for rocks; 0.023 for sediments and 0.1152 for sands. But as a rule there is mixed media, re-refracted at the medium boundary waves, and combinations of plane spherical and cylindrical waves. Hence, real decay will be considerably larger.

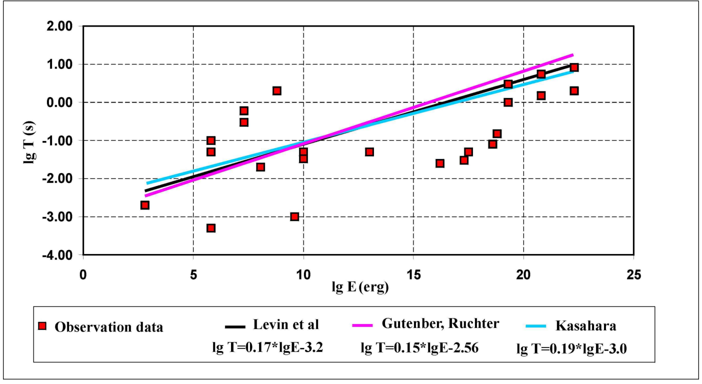

Figure 2. Scatter diagram of the relationship between seismic signal period and energy (T=f(E) of observational data and empirical functions in a log-log scale for T=f(E), obtained by different researchers.

Fig. 3 shows the dependence of signal decay level on source-receiver distance. Therefore, signals with frequencies of 200 Hz or higher will not be able to travel even through a sedimentary layer.

Thus, the signals whose frequencies f=200 Hz must be recognized as decaying completely at a 2 -3 km distance. If receivers were deployed in water layers, the registered signal radiates from the nearest under bottom area. If we record the seismic acoustic emission signals with f>200 Hz before an EQ, then these signals do not radiate from EQ source, but from a big area surrounded by the future epicenter zone. And these signals may be registered only if the receivers are deployed directly in this zone.

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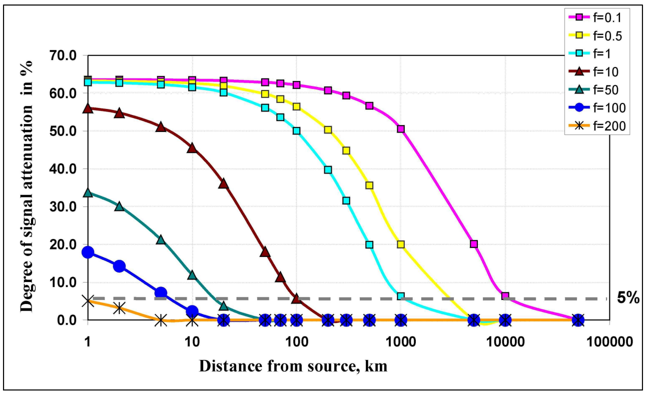

Figure 3. Signal attenuation dependence for mixed medium on source-receiver distance for various frequencies, taking into account geometrical divergence. Distance is in log scale. Thick dotted line corresponds to 95% signal attenuation.

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