Seismicity of rock rupture filled with fluid

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Abstract. The task of generation of seismic radiation by ruptures of rocks filled with a fluid is considered in the work. Possible causes of the occurrence of seismic waves due to the interaction of rock and fluid are considered. Examples of phenomena are given where the observed seismicity is associated with fluid motion. The models describing these phenomena are analyzed. Conclusions are drawn about the possibility of generation of seismic waves by rock ruptures with fluid and about radiation characteristics.

1. Introduction

Ruptures of rock, filled with fluid, can be a source of seismic radiation. In this case the observed radiation arises due to interaction between the fluid and the rock. Numerous studies show that the interaction generates signals with one or more dominating fundamental harmonics, i.e. the signal is harmonic. Under certain conditions periodic oscillations can be observed, for example, when the fluid flows through a rupture. In other cases, a decaying harmonic signal can be observed, for example, when a crack filled with fluid gets in resonance by the action of a impulse source of unknown nature.

There are many examples in which the recorded seismic signals are associated with the result of the interaction of a fluid and rock. For instance, fluid-induced oscillations of channel walls or excitation and resonance of fluid-filled cracks are possible causes of volcanic tremor and long-period (LP) events [1]. These phenomena are observed during seismic monitoring of volcanoes. Tremor and LP events have similar spectral characteristics of the signal, but differ in their duration. LP event is a single low-frequency event, the duration of which can reach up to 3 minutes. The duration of volcanic tremor can range from several minutes to several days or months. For these phenomena a steady periodic low-frequency signal with a spectral peak of 0.1-7 Hz is observed. There have been many works studying the dynamics of cracks filled with fluid and the dynamics of ruptures with a fluid flow to explain the volcanic tremor and LP events [2, 3, 4, 5, 6].

Another example is the signals observed during seismic monitoring of subglacial flows, which are similar to volcanic tremor by their characteristics. A number of studies have established a correlation between the existence of a subglacial water flow and the presence of a harmonic signal [7, 8,9]. Thus, for example, work [9] deals with low-frequency radiation (3-11 Hz) observed in the Greenland glaciers area. The work presents observations of harmonic oscillations under the moving ice of MacAyeal (MacAyeal Ice Stream) in the western Antarctic. There were two recorded events of a tremor with a steady frequency of 3 Hz energy arrival lasting for 10 minutes. The harmonic nature of the tremor is interpreted as the result of the resonance of the subglacial cracks and channels filled with water. Duration, monochromatic character and tremor dynamics indicate that the source mechanism is

most likely associated with the water flow in the subglacial water system, which flows from a small subglacial lake.

Harmonic signals are also observed during seismic monitoring of hydraulic fracturing. Usually, such signals are low-frequency and, in certain cases, they are associated with oscillations of the hydraulic rupture.

Work [10] reports on the recorded harmonic low-frequency signals during hydraulic fracturing at Fenton Hill in New Mexico. The authors use a three-dimensional crack model filled with fluid [3] to explain the spectral characteristics of the signal. In the model the occurring seismic waves are a consequence of crack resonance, which is maintained by very slow dispersion waves on the crack surface ("crack waves"). A comparison of the seismograms of the fracturing and volcanic tremor leads to the conclusion that the two signals are similar. The only difference is in scale. So the spectral peaks registered during hydraulic fracturing at Fenton Hill are approximately at frequencies equal to 112 Hz, 185 Hz, 268 Hz and higher, while the spectral peaks of volcanic tremor can be at frequencies ranging from a few tenths Hz.

Work [11] also includes the study of hydraulic fracturing experiments at Felton Hill. As well as in work [10] the causes of long-period events are associated with the action of the source, and not with effects arising from the seismic waves' transition through the medium. There is a source proposed to explain the spectral peaks of the signal. It consists of two cracks of different sizes with different fluid pressures and the channel connecting them, which suddenly opens. Each peak in the spectrum is associated with one of the cracks, and one or more peaks may correspond to each crack.

Work [12] studies two hydraulic fracturing processes during seismic monitoring of which steady-state periodic signals are recorded. It is said that a reason for the observed signal is the resonance of cracks filled with fluid. But in the case of the first hydraulic fracturing, the most probable cause of oscillations in the range 8-11 Hz is the pumping equipment and / or vibration within the vertical part of the injection well. For the second hydraulic rupture the situation is more complicated. Spectrograms show peaks at frequencies of 17, 35 and 51 Hz. The authors explain the results by the stationary, but not laminar flow inside the open fracture, which can be performed near the injection well. Such a flow leads to resonance of the crack. Less likely causes are related to fluid properties and regular crack growth.

It is important to note that the registered harmonic low-frequency signals can not always be associated with the source mechanism (oscillation of the rupture). Such signals can be formed after elastic waves pass through a complex medium, or they can arise due to the oscillations' excitation on surface or in a wellbore with installed receivers.

In recent years a number of works describing another group of low-frequency events registered during seismic monitoring of hydraulic fracturing have been written [13, 14]. They are called long period, long-duration (LPLD) seismic events and can be observed both during and after the fracturing. The LPLD event is characterized by a low-amplitude tremor-like signal lasting from 10 seconds to a minute with dominant frequencies between 10 and 80 Hz. In this case seismicity is similar to the tectonic tremor occurring during subduction but different from volcanic tremor. The main difference is in the signal spectrum. Spectrum of volcanic tremor has dominant harmonics. The spectrum of the LPLD tremor is flat at low frequencies, and it drops like the spectra of regular earthquakes. For this reason, it is impossible to create connection between these events and oscillations in the rupture filled with fluid. Works [13, 14] make hypotheses that the possible causes of LPLD events are slow shifts along already existing ruptures. The above studies are important for the development of microseismic monitoring technologies [15, 16].

2. Mathematical models of fluid-filled ruptures' dynamics
Work [2] is one of the first studies on the dynamics of a crack filled with fluid. This paper considered a dry or fluid-filled two-dimensional crack of finite size located in an unbounded elastic space. The excitation of a crack is initiated by its sharp opening at the apex. The study of the crack behavior was carried out using numerical methods, where the elasticity equations were solved by finite-difference

methods. A seismic field in a long distance from the crack was calculated using a numerical solution of the crack surface motion and analytical formulas. Also, the author calculated the spectral radiation peaks in the far zone, depending on the size of the crack and properties of the fluid (the bulk modulus) and the elastic medium.

The study of the dynamics of a crack filled with fluid continued in [3, 17]. Work [17] develops Aki's studies [2] by improving the boundary conditions and studying a viscous fluid supporting the propagation of acoustic waves. The study of the crack dynamics is carried out by simultaneous solution of the equations of the fluid motion inside a crack and the elasticity equations outside a crack using numerical methods, similar to that used in [2]. In contrast to [17] work [3] investigates the dynamics of a three-dimensional fluid-filled crack excited to resonance by effect on the surface element. The paper studies the crack response to the impulse action for various ratios of width to crack length and for different values of crack stiffness ($C=(b/mu)/(L/d)$), where b – the bulk fluid compression modulus, mu – the medium rigidity, L and d are the length and width of the crack, respectively.

A similar problem is solved in [18], where a numerical method is proposed for modeling the dynamic response of a crack filled with fluid. In case of this method, the motion of the fluid inside the crack and the motion of the solid elastic body outside the crack are registered in the form of boundary integrals in the frequency domain. It is noted that this method is more effective than the finite-difference method, which was used in [2, 3, 17]. Advantages of the proposed method are the ability to conduct research for a wide range of parameters and the possibility of immediate calculation of the damping factor for the crack resonance.

The observed waves mentioned above are surface waves, and they are called Stoneley waves. They can make a crack the source of low-frequency radiation. The waves run along the crack's surface, reflecting from the peaks to maintain its resonance. Due to the exponential attenuation of the Stoneley wave, it is difficult or impossible to record them at a great distance. But due to their presence volumetric waves can be generated, which makes it possible to register the crack oscillations. As the results of numerical simulation [19] show, volumetric waves can form at the crack ape, when a surface wave is reflected.

The source of seismic oscillations can be the fluid flowing through a crack in the rock. In this case, it is possible to lose stability of the system with the formation of self-oscillations of the crack walls. The resulting oscillations are maintained by the energy of a uniform constant fluid flow.

Julian [5] proposed a model of the harmonic oscillations' occurrence in the course of a uniform fluid flow through a crack in the rock. Julian suggested that instability may be caused by the interaction of the moving flow and the walls of the crack. Instability is achieved at certain threshold values of the system parameters, which leads to an self-oscillating process. The paper considers a model with lumped parameters, where a layer of fluid lies between two walls of finite length. The walls simulate a crack and have such parameters as elasticity, mass and damping. At the edges of the crack pressure difference is maintained, so that the fluid that fills the crack is set to flow. The width of the crack opening does not depend on the spatial coordinates. Due to the simultaneous solution of the equations of fluid motion and the elasticity equations, Julian obtained a system of nonlinear ordinary differential equations describing the dynamics of the crack wall. The solution of the system presents stable harmonic oscillations of the walls when a certain threshold value of the flow velocity is reached. The resulting system, in addition to modeling linear resonances, shows additional nonlinear effects, such as the doubling period.

The problem of the interaction of a moving fluid and an elastic body is solved in [6]. In contrast to [5], we study not a crack, but a cylindrical cavity in an elastic three-dimensional space. As in [5] the motion of the wall does not depend on the spatial coordinates. The statement of the problem makes it possible to obtain a seismic field from a system of connected cylindrical cavities with different diameters. Nonlinear differential equations describing the motion of the cavity wall and the fluid in it are derived. The obtained mathematical model shows that the interaction of a moving fluid and an elastic body generates oscillations.

The possible way of generating oscillations in the interaction of a moving fluid and an elastic body is also studied in [4, 20]. In contrast to [5], in works [4, 20] they adhere to a more rigorous mathematical approach. Another difference is that the width of the crack opening depends not only on time, but also on the spatial coordinate. The paper considers a two-dimensional model in which a relatively thin layer of a viscous fluid is located between two elastic half-spaces. The authors determine the conditions for the occurrence of instability of the flow. Also, they study the oscillations of the crack walls caused by the instability. A linear analysis of the stability of the system shows that the oscillations induced by the flow can occur at arbitrarily low Reynolds numbers. Moreover, the stability of the system depends on the size of the crack, the velocity of the fluid, the velocity of the elastic waves in a continuous medium, and does not depend explicitly on the fluid viscosity.

The obtained results confirm that the mechanisms of harmonic oscillations proposed by Julian are plausible. In addition, a cylindrical cavity with fluid passing through it is considered in [4]. The stability of the obtained system is studied in a similar way, and conclusions are made about the possibility of oscillations' occurrence.

Another approach to modeling of the oscillations associated with the flow of fluid through a channel is proposed in [21]. The paper considers a model of a one-dimensional flow of fluid moving through a crack with a partition. The partition opens if the fluid pressure becomes higher than a certain threshold value and closes in all other cases. The proposed model neglects the deformation of the crack walls and the thickness of the partition. The constant flow velocity at one end of the crack and the constant pressure at the other end are boundary conditions imitating the fluid flowing from the reservoir into the free space. Numerical calculations show fluctuations in the fluid pressure, and the frequency of the oscillations depends on the flow velocity.

3. Conclusion

Taking into consideration results of the work, it can be concluded that rock ruptures filled with fluid can be sources of seismic radiation. This is confirmed by the numerous examples given in the article. The paper shows that the observed seismic signal is harmonic and its characteristics depend on the parameters of the rupture, the parameters of the rock and the fluid. The source mechanisms of seismicity mechanisms may vary. The article presents many models explaining the mechanisms generating oscillations of the ruptures and the characteristics of the signal generated by them.

The results of the presented work can be used to develop technologies for seismic monitoring of rock ruptures with fluid and fluid filtration zones.

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