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Numerical simulation for recognition of coalfield fire areas by Rayleigh waves

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ABSTRACT

Effective recognition of a coalfield fire area improves fire-fighting efficiency and helps avoid potential geological hazards. Coalfield fire areas are hard to detect accurately using general geophysical methods. This paper describes simulations of shallow, buried coalfield fires based on real geological conditions. Recognizing the coalfield fire by Rayleigh wave is proposed. Four representative geological models are constructed, namely; the non-burning model, the pseudo-burning model, the real-burning model, and the hidden-burning model. Numerical simulation using these models shows many markedly different characteristics between them in terms of Rayleigh wave dispersion and Eigen displacement. These characteristics, as well as the shear wave velocity obtained by inverting the fundamental dispersion, make it possible to distinguish the type of the coalfield fire area and indentify the real and serious coalfield fire area. The results are very helpful for future application of Rayleigh waves for the detection of coalfield fire area.

1. Introduction

China has some of the most serious coalfield fire issues in the world. The primary area for coalfield fires is located in the arid and semiarid regions like the desert, the Gobi and loess plateau near 35° north latitude, starting from the Pamirs in the west and ending in the Greater Khingan in the east. This coal combustion destroys a considerable mass of coal, pollutes the environment, and endangers the safety of the mine workers even challenges the coal mine design [1]. Additionally, heavy excavators and transport equipment face huge potential safety hazards in an opencast works where they operate along with the coal fire [2]. Therefore, it is necessary to accurately determine the coalfield fire area to reduce fire-fighting costs, improve fire-fighting efficiency, and to finally eliminate the potential safety hazard.

Presently, few reports on coalfield fire area detection exist. There are some qualitative research methods that have been introduced including magnetic prospecting, radon measurement, remote imaging, and Ground Penetrating Radar (GPR) [1,3–5]. These are the main ways, combined with other geological information, to roughly determine the coalfield fire area. Among these methods, magnetic prospecting, radon measurement, and remote imaging have too low a resolution and cannot satisfy the requirements of firefighting. GPR has higher resolution but it penetrates to a depth that is too shallow and cannot detect problems in the deeper strata.

Other significant geophysical methods like seismic reflection, seismic refraction, or seismic cross well tomography and Rayleigh wave are also widely used in geotechnical investigations. For the detection of shallow buried coalfield fires the Rayleigh wave method should be regarded as a good choice in terms of the exploration target and specific field conditions. Nevertheless, there are few works that study Rayleigh waves as a way to recognize coalfield fire area.

This paper discusses a theoretical analysis and simulation related to the feasibility of recognizing shallow buried coalfield fires using a method based on Rayleigh wave theory. Valuable theoretical guidance for the accurate recognition of coalfield fire area by Rayleigh wave method is provided.

2. Geophysical properties of the coalfield fire area

Oxygen penetration into the coal seam through the rock crevices may lead to a series of complex physicochemical reactions where the heat created may cause the coal to spontaneously combust [6,7]. Coal combustion then changes the crustal stresses, which can cause further development of rock fractures or even the collapse of the overburden rock mass and coal seam. This vicious circle links the level of coal combustion to the amount of fractures in the overburden rock and the coal seam.

The velocity of propagating sound waves is one main parameter that reflects the level of rock fracture. The level of rock fracturing

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can be predicted, and the primary coalfield fire area determined, by the velocity within these strata. In this case, the use of Rayleigh waves is theoretically appropriate for an investigation of the coalfield fire area. Numerical simulations are provided below to illustrate this.

3. Theory of Rayleigh waves

3.1. Propagation of Rayleigh waves

In 1885 Rayleigh predicted the existence of surface waves on the free surface of half-space, which subsequently were named Rayleigh waves [8]. Later, these waves were shown to exist in natural seismic records. The amplitude of the Rayleigh wave decays exponentially with depth and the propagation velocity is less than that of both the P-waves and S-waves. The particle motion in a Rayleigh wave is elliptical in a plane perpendicular to the surface. Rayleigh waves can also form in layered earth and, in this case, unlike the case of a free surface, homogeneous half-space, these waves show obvious dispersion characteristics [9]. The difference in phase velocity creates an Eigen displacement that shows the surface waves traveling along a higher velocity interface and creates a guided wave property where wave travel is limited in the lower velocity layer. These properties of Rayleigh waves allow geophysicists to develop a way to find the shear wave velocity profiles from inversion of the dispersion curves that were extracted from Rayleigh wave records [10].

3.2. Modeling of Rayleigh waves

About the modeling of Rayleigh waves for layered earth, many research works have been reported calculating the multiple mode phase velocity dispersion curves for specific geological models. In the 1950's, Haskell's propagator matrix was regarded as a valuable systematic method but this approach does have a problem with unstable solutions in the range of higher frequencies [11]. Several newer methods have been proposed to improve numerical stability, such as the Schwab–Knopoff, the δ matrix, the Abo-Zena, or the RT matrix methods. An improved RT matrix suggested by Yoshiaki Hisada is used in this paper [11–18]. This method allows the calculation of the Green's function no matter if the source is close the receivers, or not. Also, the displacement and stress may be derived from the Green's function for a viscoelastic layered half-space medium.

3.3. Inversion of Rayleigh waves

The approximately equal velocities of Rayleigh and S-waves allow the half-wavelength theory to provide an initial interpretation of the Rayleigh wave dispersion curves. This method is based on the penetrating depth of the Rayleigh waves, which is approximately equal to one half of the wavelength [19]. Dispersion calculation theory allows the fundamental mode dispersion curves to be inverted to give the velocity profiles. A least square method, the simulated annealing method, genetic algorithms, an artificial neural network algorithm, or a quasi-Newton method can be used to do the inversion [20–22].

The inversion of the Rayleigh waves was solved herein using a local-search procedure where the stationary point in the solution space was sought by a constrained optimization technique known as Occam's algorithm [23]. This method avoids the ill posed problem of unreasonable parameters that results from classic least square inversion and it provides a first order, differentiable result.

4. Numerical simulations of typical models in coalfield fire area

According to the general geological characteristics of coalfield fire area, this paper tries to sum up four types of representative models and study their Rayleigh wave Eigen displacements and dispersions. Velocity information is inverted from dispersion curves and the feasibility of recognizing a coalfield fire area by Rayleigh waves is discussed.

4.1. Model building

Four representative, simple geological models of shallow, buried coalfield fire areas are presented.

The first is a "non-burning model" that features great integrity of both the coal seam and the overburden rock mass. The wave velocity in the overburden rock mass will generally be greater than in the coal seam. The second type is a "pseudo-burning" model where developed fractures in the overburden rock mass create galleries for oxygen support of the neighboring burning coal seam. Coal under this rock mass may be smoking but has not yet caught fire. In this case the wave velocity in the overburden rock is often less than that in the underlying unbroken coal seam. The third typical model features an underlying burning coal seam with a slightly higher wave velocity compared to the seriously fractured overburden rock mass; this is a truly burning model. The last type is called the "hidden-burning" model and is characterized by burning coal covered by an intact rock mass with a relatively high wave velocity.

There are five schematic possibilities shown in Fig. 1. Cases 1 and 5 both belong to the non-burning group but have different coal seam and overburden thickness. Cases 2, 3, and 4 are the pseudo-burning, real-burning, and hidden-burning models respectively. Some important parameters concerning these models are shown in Fig. 1, where the thickness, S-wave velocity, P-wave velocity, and density for each layer are shown. The media are simply classified into five types. Mudstone and fractured mudstone are the model overburden rock. Sandstone is the underlying rock. The coal consists of either burning or unbroken coal here.

4.2. Dispersion and Eigen displacement

The frequency range of the forward calculations is from 10 to 200 Hz with a frequency interval of 9.75 Hz. Dispersion for only the fundamental, second, and third modes have been calculated for each model. The results are shown in Fig. 2a–e. Fig. 2f–j are the Eigen displacement diagrams at a frequency of 146.5 Hz for

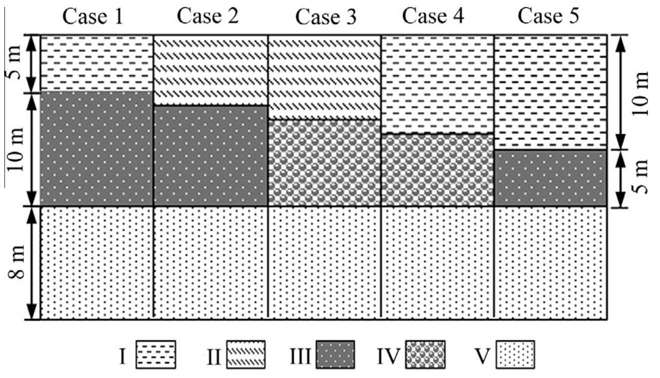

Fig. 1. Geological possibilities for shallow, buried coalfield fires field (I. Mudstone, $v_s = 1500$ m/s, $v_p = 2500$ m/s, $\rho = 2.2$ g/cm^3; II. Fractured mudstone, $v_s = 900$ m/s, $v_p = 1600$ m/s, $\rho = 1.5$ g/cm^3; III. Unbroken coal, $v_s = 1200$ m/s, $v_p = 2000$ m/s, $\rho = 1.8$ g/cm^3; IV. Burning coal, $v_s = 1000$ m/s, $v_p = 1800$ m/s, $\rho = 1.6$ g/cm^3; V. Limestone, $v_s = 2000$ m/s, $v_p = 3500$ m/s, $\rho = 2.5$ g/cm^3).