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Modeling and locating underground water pipe leak with microseismic data

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ABSTRACT

Traditional pipeline leak locating methods require that geophones have to be placed on the pipe wall. While if the exact location of the pipeline is unknown, the leaks may not be identified accurately. To solve this problem, considering the characteristics of pipeline leak, a continuous random seismic source model is proposed and geological models are established. Based on the two dimensional (2D) viscoacoustic equations and the staggered grid finite-difference (FD) algorithm, the microseismic wave field generated by a leaking pipe is modeled. Cross-correlation analysis and the simulated annealing (SA) algorithm are employed to obtain the time difference and the leak location. Analysis and discussions of the effects of number of recorded traces, survey layout, and offset and trace interval on the accuracy of the estimated location are also conducted. Simulation and data field experiment results indicate that: (1) A continuous random source can realistically represent the leak microseismic wave field in a simulation using 2D viscoacoustic equations and staggered grid FD algorithm. (2) For the leak microseismic wave field, the cross-correlation method is effective for calculating time difference of the direct wave relative to the reference trace. However, outside the refraction blind zone, accuracy of the time difference is reduced by the effects of refracted wave. (3) The SA algorithm based upon time difference, helps to identify the leak location effectively, even in the presence of noise. Estimation of the horizontal distance is more accurate than that of the depth, and the locating errors increase with increasing number of traces and offset. Moreover, in the refraction blind zone, trace interval has almost no impact on the accuracy of the location estimate. And the symmetrical array provides a higher estimate accuracy than the asymmetrical array. (4) The acquisition method of time difference based on the microseismic theory and SA algorithm has a great potential for locating underground pipelines leak from an array located on the ground surface.

1. Introduction

Pipeline is a common and effective means of transportation and plays an important role in economic development. However, pipeline leakage can lead to immeasurable waste of resources as well as severe economic and environmental damage. Therefore, pipeline leak detection and location techniques have been developed over years. The cross-correlation method is a widely used method of leak detection that calculates the acoustic-wave time difference between two geophones on the pipe wall (Fuchs and Riehle, 1991; Hunaidi et al., 2000; Gao et al., 2004; Yong et al., 2011). This method requires the geophones to be placed on the pipe wall, which is difficult to implement and maintain. Additionally, detection of leak may fail in that the geophones are on the pipe wall. In this paper, a novel pipeline leak detection method is proposed based on the microseismic monitoring theory, in which leak location is detected by recording the leak signals on a geophone array located on the ground surface.

To accurately locate a leak, characteristics of the microseismic wave field caused by leaking should be investigated at first. The finite difference (FD) scheme was originally applied to seismic wave simulation around the 1970s (Alterman and Karal, 1968; Alford et al., 1974; Kelly et al., 1976). Madariaga (1976) proposed a first-order velocity–stress staggered grid FD scheme for elastic waves, which improved the accuracy and stability of the modeling. To simulate wave propagation in geologic strata, Carcione et al. (1988) and Robertsson et al. (1994) developed an FD scheme that simulated the propagation of viscoacoustic and viscoelastic waves, respectively. For the boundary conditions, the perfectly matched layer (PML) introduced by Bérenger (1994) has become widely used. In recent years, some approaches to improve the behavior of PML at grazing

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incidence and stability calculating, such as the complex frequency shifted PML (CFS-PML) (Komatitsch and Martin, 2007) and the multi-axial PML (M-PML) (Meza-Fajardo and Papageorgiou, 2010), have been proposed and proven to be more efficient than the original PML. However, these methods were applied to traditional seismic prospecting, while few of these studies were related to wave modeling of continuous seismic sources, such as the leak wave field, which is the focus of this study.

Research on seismic source location began in 1912 (Geiger, 1912). The essence of this method is to linearize the nonlinear equations, and solve these equations by the least square method. Subsequent related research includes Aki et al. (1977), Spence (1980), Lienert et al. (1986), Nelson and Vidale (1990), Kummerow (2010), and Maxwell et al. (2010). Some nonlinear inversion techniques such as Newton's method, the simulated annealing (SA) algorithm, and the genetic algorithm have also been successfully applied to locate seismic sources (Thurber, 1985; Menke, 1999; Kennett and Sambridge, 1992). To solve the noise issue, some methods without arrival-time picking have also been proposed, such as emission tomography (Duncan and Eisner, 2010), the migration algorithm (Rentsch et al., 2007) and the statistically optimal algorithm (Kushnir et al., 2014). However, most of these methods were used to locate discontinuous and instantaneous seismic sources such as earthquakes, oil field fracturing, few of which have systematically examined methods for locating continuous low-energy sources such as gas or liquid leakage of a pipeline.

In this study, without loss of generality, a water supply pipeline is taken as an example, meanwhile leaking source and geological models for various field situations are established. Microseismic wave field generated by the leak is simulated based on the 2D viscoacoustic equations and the staggered grid FD algorithm. Characteristics of the wave field are also analyzed. By using cross-correlation method and the SA algorithm based upon time difference, direct-wave time difference relative to the reference trace are computed, and the pipeline leak is located. The effects of number of traces, survey layout, and trace offset and interval on accuracy of the location process is analyzed and discussed, providing a basis for the design of a leak microseismic location observation system and further theoretical research.

2. Basic theory

2.1. Wave field modeling

In seismic prospecting, the layer is not a perfect elastic medium, in which seismic energy decays when the seismic wave propagates. Therefore, it is more accurate to model the layer as a viscoelastic medium. In the proposed method, the ground layer is modeled as a 2D Kelvin-Voigt viscoelastic medium, where the first-order velocity–stress acoustic wave equation is given by

$$\begin{cases} \rho\dfrac{\partial V_x}{\partial t} = -\dfrac{\partial P}{\partial x} \\ \rho\dfrac{\partial V_z}{\partial t} = -\dfrac{\partial P}{\partial z} \\ \dfrac{\partial P}{\partial t} = -\rho v^2\left(\dfrac{\partial V_x}{\partial x}+\dfrac{\partial V_z}{\partial z}\right) - \dfrac{\rho v^2}{Q\omega}\left(\dfrac{\partial^2 V_x}{\partial x\partial t}+\dfrac{\partial^2 V_z}{\partial z\partial t}\right) \end{cases} \tag{1}$$

where P is the acoustic pressure, v is the acoustic wave velocity, and the medium density is given by ρ. Q is the quality factor and ω represents the angular frequency. V_x and V_z denote the horizontal and vertical components of the velocity, respectively.

In numerical simulation, Eq. (1) is converted to a discrete form by using a staggered grid FD algorithm, obtaining the acoustic wave equation of high order difference schemes in a 2D viscoelastic medium:

$$\left\{\begin{array}{l} P_{i,j}^{k+1/2} = P_{i,j}^{k-1/2} - \dfrac{\Delta t\rho v^2}{\Delta x}\Bigg\{\sum\limits_{n=1}^{N} C_n^N[U_{i+(2n-1)/2,j}^{k} - U_{i-(2n-1)/2,j}^{k}] + \\ \dfrac{1}{Qw}\sum\limits_{n=1}^{N} C_n^N[U1_{i+(2n-1)/2,j}^{k} - U1_{i-(2n-1)/2,j}^{k}]\Bigg\} - \dfrac{\Delta t\rho v^2}{\Delta z}\Bigg\{\sum\limits_{n=1}^{N} C_n^N \\ \left[V_{i,j+(2n-1)/2}^{k} - V_{i,j-(2n-1)/2}^{k}\right] + \dfrac{1}{Qw}\sum\limits_{n=1}^{N} C_n^N\left[V1_{i,j+(2n-1)/2}^{k} - V1_{i,j-(2n-1)/2}^{k}\right]\Bigg\} \\ U_{i+1/2,j}^{k} = U_{i+1/2,j}^{k-1} - \dfrac{\Delta t}{\Delta x\rho}\left\{\sum\limits_{n=1}^{N} C_n^N\left[P_{i+n,j}^{k-1/2} - P_{i-(n-1),j}^{k-1/2}\right]\right\} \\ V_{i,j+1/2}^{k} = V_{i,j+1/2}^{k-1} - \dfrac{\Delta t}{\Delta z\rho}\left\{\sum\limits_{n=1}^{N} C_n^N\left[P_{i,j+n}^{k-1/2} - P_{i,j-(n-1)}^{k-1/2}\right]\right\} \\ U1_{i+1/2,j}^{k} = -\dfrac{1}{\Delta x\rho}\left\{\sum\limits_{n=1}^{N} C_n^N\left[P_{i+n,j}^{k-1/2} - P_{i-(n-1),j}^{k-1/2}\right]\right\} \\ V1_{i,j+1/2}^{k} = -\dfrac{1}{\Delta z\rho}\left\{\sum\limits_{n}^{N} C_n^N\left[P_{i,j+n}^{k-1/2} - P_{i,j-(n-1)}^{k-1/2}\right]\right\} \end{array}\right. \tag{2}$$

where Δx and Δz denote the spatial sampling interval in the X and Z axis, respectively. Δt is the time sampling interval. P, U, and V denote the discrete forms of the acoustic pressure, the horizontal velocity component V_x, and the vertical velocity component V_z, respectively. $U1$ and $V1$ denote the discrete forms of the acceleration components $\partial V_x/\partial t$ and $\partial V_z/\partial t$, respectively. In this paper, we use a staggered FD algorithm with second-order accuracy in the time domain and fourth-order accuracy in space for the numerical simulation. A convolutional perfectly matched layer (CPML) boundary condition is applied to absorb the artificial reflection waves.

The quality factor Q is used to measure the medium's capacity to attenuate the seismic wave. Since pipelines are generally buried at a shallow depth, the medium around the pipeline is often loose quaternary overburden and shows high attenuation of the wave field. In the proposed model, the quality factor Q is estimated by using an empirical equation (Li, 1994) based on extensive field data:

$$Q = \beta V^{\alpha} \tag{3}$$

with parameters $\beta = 14.0$ and $\alpha = 2.2$; V denotes the velocity of the compressional wave in *km/s*.

2.2. The seismic source function

Effectiveness of the wave field simulation is greatly related to the choice of seismic source function. Leak sources are continuous in time as well as stochastic in amplitude and polarity. Hence, conventional seismic source functions are not suitable for leak wave field and a new seismic source function that can represent the leak needs to be constructed.

The discretization equation of the Ricker wavelet in the time domain is (Ricker, 1944)

$$s(n\Delta t) = \left[1-2\pi^2 f^2 (n\Delta t - t_0)^2\right] * \exp\left[-\pi^2 f^2 (n\Delta t - t_0)^2\right] \qquad n = 1, 2, \ldots, N \tag{4}$$

where Δt is the temporal sampling interval, f is the basic frequency, t_0 is the delay time, and N is the sampling number in the time domain. We denote $s(n\Delta t)$ as $s(n)$.

To construct the seismic source function of a leak, a random number is introduced into the source function, multiplying the seismic wavelet by which to simulate the randomness of the leak source. For temporal continuity of the source, the Ricker wavelet is loaded at different times; the wavelets have the same frequency, but different amplitudes and polarities.