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RESEARCH PAPER

Seismic forward and inverse simulation in a tight reservoir model of loess plateau region

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Abstract: To find out the seismic wave field propagation principles in loess plateau near surface of the Ordos Basin and the seismic response characteristics of tight oil reservoirs, this study established a geological-geophysical model under the real conditions of ground surface of loess plateau, and launched full elastic seismic wave equation forward modeling and pre-stack elastic seismic inversion study. Comparison of modeling and real seismic data shows that, the loose and wavy loess plateau surface is the main reason for causing the problems of seismic static correction and interference wave. Tomographic static correction method with the constraint of traces near shot point can effectively solve the problem of seismic static correction in the loess plateau and enhance seismic imaging accuracy, S-wave impedance obtained from pre-stack seismic inversion can identify sandstone effectively, and Poisson's ratio can identify oil-bearing reservoirs. The seismic forward and inverse simulation and rock physical analysis provide a solid theoretical and experimental basis for the seismic prediction of tight oil reservoir, and have worked well in the oil exploration and development in the loess plateau of the Ordos Basin.

Key words: loess plateau surface; tight reservoir; wave equation forward simulation; tomographic inversion static correction; pre-stack elastic inversion

Introduction

Abundant tight oil has been found in the Triassic Yanchang Formation of the Mesozonic, Ordos Basin, generally located in the center of the lake basin on the plane, and middle section of Yanchang Formation in the vertical profile[1–2]. The near surface condition and reservoir properties there pose great challenges to seismic exploration of tight oil. First, because the near surface of the target area is rugged mountainous area with ravines, gullies, and drastic undulation, the seismic interference wave is well developed, posing great challenge to static correction, and making seismic imaging very difficult; second, the tight oil reservoir in the Chang 7 Member has poor physical properties, high heterogeneity, small difference in seismic characteristics from surrounding rock, making it hard to identify "sweet spots". Therefore, figuring out the seismic wave propagation pattern in the complicated near surface and geophysical properties of tight oil reservoirs are the key to seismic imaging for the loess plateau and tight oil reservoir prediction. Conducting seismic forward and inversion simulation with geology-geophysics model is an important means to find out the seismic wave propagation pattern and testify the effectiveness of geophysical method. Currently, wave equation method is commonly used in forward modeling. Many peer researchers have made massive researches on theoretical methods of forward seismic wave modeling and wave propagation pattern[3]. However, most of the researches are algorithms based on theoretical model, few dealing with wave propagation pattern in actual complex surface conditions. In terms of application study, Wang and Zhang et al., primarily delved into the seismic wave numerical modeling in complicated near surface conditions, and discussed the numerical challenge of topographic case[4–5]; Pei et al performed the elastic wave equation modeling on the complicated topographic model, and found that rugged terrain can cause wave field difference and static correction[6]; Wang and Qin used the optimized wave equation finite difference method to simulate the seismic data acquisition system, which has provided a scientific basis for the design of seismic data acquisition[7]; modeling the seismic low frequency shadow with the viscoelastic equation, Lan et al., verified that the seismic attenuation of low Q value reservoir is the main cause of the low frequency shadow[8], providing a theoretical basis for oil and water prediction; Wang and Zhang et al., through the seis-

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mic forwarding on the wedge model of tight oil reservoirs and pre-stack elastic parameters inversion, selected elastic parameters good for characterizing tight oil reservoirs, and made sure seismic elastic parameter can distinguish the reservoirs[9].

This study builds a whole profile geology-geophysics model considering actual near surface of loess plateau and tight oil reservoir feature. Meanwhile, the high order finite difference algorithm is applied to simulate the forward model. The seismic wave field feature and wave propagation are identified by the comparison of field seismic record and numerical record. The proposed data processing and tight oil reservoir prediction techniques are verified by comparing the actual seismic shot with numerical one under the loess plateau condition.

1. Building of geology-geophysics model for the tight oil reservoir in loess plateau

A topographic near surface model was built by surveying the surface structure, rock properties and measuring velocity; meanwhile, a tight reservoir model was built by analyzing geophysical parameters of the tight oil reservoir. Finally, the whole profile geology-geophysics model was built to characterize the tight oil reservoir in the loess plateau condition. The model building principles are: (1) the actual seismic profile can reflect the classic topographic feature of loess, and the wells through the seismic line can represent the general characteristics of tight oil reservoir; (2) the near surface structure (elevation, velocity and density) and reservoir parameters (thickness, velocity and density) are totally obtained from field measurement and well log data; (3) the stratigraphic framework is set according to logging data, while reservoir parameters are interpolated from Logging data.

1.1. Near surface structure parameter model

The building of near surface model strictly refers to the survey data of line HCX of Xinanbian in the south of Ordos Basin. Fig. 1 shows the near surface structure parameter model. It can be seen that the loess has abrupt variations of elevation, with an elevation range from –1 800 m to –1 400 m, low velocity layer of 10 to 300 m thick, The near surface structure of the four layer is weathered layer, low velocity layer, decreasing velocity layer and high velocity layer from top to the bottom, and dry loess, loess, mudstone and sandstone, respectively. Although the velocity of actual loess layers varies in a gradual and continuous manner, to make the model building easier, the velocity of the four layers in the model were taken as 600 m/s, 800 m/s, 1500 m/s and 2500 m/s respectively.

1.2. Parameters distribution of tight oil layers and reservoirs

Under the constraint of the Cenozoic, Cretaceous, Jurassic and Triassic sequences, the geological geophysical model is built by extrapolation and interpolation from the logging data of 7 wells (H223H231, H232, X71, S544, S581, S582) survey line HCX crosses. Fig. 2 shows the geology-geophysics model of formation and reservoir in the tight oil area, with consideration of the surface structure. 60 000 m long, over 2 500 m deep, with Chang 7 Member as the main target, the model is 10 m (vertical) by 2 m (horizontal) in grid size, (see the Tables 1 and 2 for strata and reservoir parameters).

2. Numerical modeling of wave equation in the complicated media

2.1. 2D elastic equation in the homogenous media

When performing the numerical simulation in the homogenous media, the velocity-stress equations can be deduced by reducing order of wave equation expressed as parameter displacement.

$$\begin{cases} \dfrac{\partial \tau_{xx}}{\partial t} = (\lambda + 2\mu)\dfrac{\partial v_x}{\partial x} + \lambda \dfrac{\partial v_z}{\partial z} \\ \dfrac{\partial \tau_{zz}}{\partial t} = \lambda \dfrac{\partial v_x}{\partial x} + (\lambda + 2\mu)\dfrac{\partial v_z}{\partial z} \\ \dfrac{\partial \tau_{zx}}{\partial t} = \mu\left(\dfrac{\partial v_x}{\partial z} + \dfrac{\partial v_z}{\partial x}\right) \\ \dfrac{\partial v_x}{\partial t} = \dfrac{1}{\rho}\left(\dfrac{\partial \tau_{xx}}{\partial x} + \dfrac{\partial \tau_{zx}}{\partial z}\right) \\ \dfrac{\partial v_z}{\partial t} = \dfrac{1}{\rho}\left(\dfrac{\partial \tau_{zx}}{\partial x} + \dfrac{\partial \tau_{zz}}{\partial z}\right) \end{cases} \tag{1}$$

If vector of wave field is $\boldsymbol{Q} = (v_x, v_z, \tau_{xx}, \tau_{zz}, \tau_{xz})^{\mathrm{T}}$, then the elastic wave equation expressed by velocity and stress can be written as

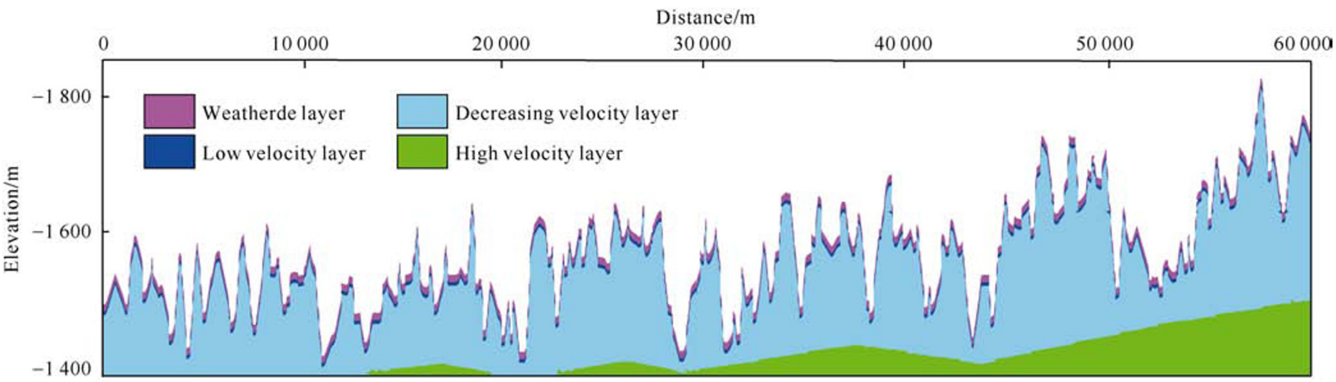

Fig. 1. Parameter model of near surface structure in the loess region.