Study on seismic response characteristics and prediction methods of fracture

Introduction

The seismic response characteristics of fractures are the basis of using seismic method to study fractures. However, the complexity of fracture scale and development law limits the forward modeling, inversion and other series of technologies for fractures to a certain extent, and the seismic response characteristics under different characterization parameters are not clear and systematic. Therefore, it is still necessary to study the seismic response mechanism of fractures.

In order to study the mechanism of seismic response of fractures, it is necessary to have a fracture model which is more consistent with the development and distribution of fractures, and then a high-precision and efficient forward modeling method matching with the fracture model. For microfracture, most of them are continuous modeling, mainly including Hudson model, Schoenberg linear sliding model et al. However, the correctness of these theoretical models still needs to be studied, and there is no effective numerical simulation method to realize the analytical description of micro scale fractures.

In addition, the microfracture prediction method is mainly based on the azimuth anisotropy caused by fractures. Using pre stack data or sub azimuth stack data, the calculation time is long and the memory is large, while the detection methods using post stack data are mostly focused on large-scale fractures, which can't do anything for microfracture.

In this paper, a random discrete fracture modeling method is proposed, furthermore, the multi-level variable grid idea is introduced, and the optimized staggered-grid space-time dual variable finite difference simulation method is used. Finally, through the systematic study of seismic response characteristics of fractures, the fracture prediction based on post-stack data is carried out.

Multi-level variable grid forward modeling

The first-order velocity-stress equation of 2D elastic wave based on isotropic inhomogeneous medium is used. The algorithms of space variable-grid step and time variable-grid step have been discussed in detail [1], no more details here.

The conventional variable grid algorithm will introduce large human error when the grid changes at high times, and it is easy to be unstable. The idea of multi-level variable grid is to achieve the final multiple of change through the gradual change of multiple grid series, so as to avoid the disadvantages of large mutation of grid times. The basic principle is as shown in Figure 1.

![Figure 1 The Schematic diagram of multi-stage variable grid](image)

Lanczos Filtering

In the variable grid algorithm, the wave field transfer error between the coarse and fine grids is the main reason for the instability of the algorithm. Through comparative analysis, it is found that Lanczos filter operator has a greater advantage in solving such problems [2].

Assuming that the grid change multiple is $k$ times, and then Lanczos filter coefficient can be expressed as,
\[ \omega_{mn} = A \text{sinc} \left( \frac{\pi m}{k} \right) \text{sinc} \left( \frac{\pi n}{k} \right) \text{sinc} \left( \frac{\sqrt{m^2 + n^2}}{k} / 2 \right), |m| \leq 2k, |n| \leq 2k. \]  

(1)

Where, the value of \( A \) is determined by \( \sum_{m=-2k}^{2k} \sum_{n=-2k}^{2k} \omega_{mn} = 1 \).

**Random discrete fracture modelling**

Fracture modeling contents three parts: background model, random discrete fracture model and variable grid fracture model. The background model is the same as the conventional geological model, the random discrete fracture model is divided into two steps: the single fracture modeling and multi fracture modeling.

The idea of variable grid fracture modeling is corresponding to the multi-level variable grid algorithm.

**Single fracture modelling**

The single fracture modeling is the first step of random discrete fracture modeling. The fracture characterization parameters used are fracture location \((i_0, j_0)\), fracture length \(L\), fracture width \(D\), fracture dip angle \(\theta\) and fracture tendency \(\alpha\). The description equation of single fracture is given as follows,

\[
\{(i, j) \mid i_0 - L/2 \leq i \leq i_0 + L/2 \}
\]

\[
\left\{ \begin{array}{l}
i_0 + \tan(\theta) \cdot (i - i_0) \leq j \leq j_0 + \tan(\theta) \cdot (i - i_0 - 1) \\
\end{array} \right. 
\]

(2)

**Multi fracture modeling**

Multi fracture modeling is the second step, it’s a collection of many single fractures combined in a certain way, of which the combination mode is the key. At present, it is applied to fracture modeling in forward simulation, generally assuming fracture arrangement rules. In this paper, random function is introduced, so that the above fracture characterization parameters are randomly distributed according to the statistical rules, making it consistent with the core and logging statistics (Figure 3).

**Analysis of seismic response characteristics of fractures**

The background model used for fracture seismic response analysis in this section is shown in Figure 4. It is a thin interbed of sandstone and mudstone in a certain area. The thickness and velocity parameters of sandstone and mudstone are set according to a real drilling, so as to ensure that the background model is consistent with the lithology change trend of the actual formation.

To study the seismic characteristics of fracture, we change the fracture parameters respectively, the characteristics are divided into two categories:
1) The fractured zone composed of fracture units with fracture scale of $Ka > 0.01$ presents chaotic seismic response characteristics in the migration profile, and the waveform changes irregularly, as shown in Figure 5 (a).

2) The fractured zone is composed of fracture units with fracture scale of $Ka < 0.01$. Due to the existence of fractures, the velocity of the fracture location decreases. In the migration profile, with the increase of fracture density, the wave field at the reflection interface becomes stronger and stronger from weak to strong, and the axis of reflection in phase gradually cuts down, and then the discontinuous lower section is formed at the fracture zone boundary, but the internal axis of reflection in phase is uniform as shown in Figure 5(b) (c).

$Ka$ is the normalized wave number, $Ka = \frac{2\pi a}{\lambda}$ ($a$ is the non-uniform scale, $\lambda$ is the seismic wavelength).

**Figure 4** (a) The background model with conventional grid  (b) The first level variable grid model  (c) The second level variable grid model

**Figure 5** (a) The seismic section of large-scaled fracture  (b) The seismic section of microfracture with fracture density is 0.05(c) The seismic section of microfracture with fracture density is 0.1

**Examples**

By summarizing the variation law of fracture seismic waveform, the paper uses the waveform clustering method with post-stack data to predict the development of fracture for T3x Formation, as shown in Figure 6. Different colors are marked on the upper left corner to represent the waveform, while gray is the background waveform when there is no fracture development in the target formation; red is the large-scaled fracture; and green is the micro fractured zone with uniform distribution.

Compared with the drilled wells: Well 1, well 2 and well 6 encounter faults; well 3, well 4 and well 5 encounter micro fractured zones; the core of well 7 does not develop fractures according to statistics. The result coincidence rate is more than 85%.
Figure 6 The map of fracture distribution predicted by the waveform clustering method

Conclusions

According to the summary of numerical simulation, there are two main factors that affect the seismic response characteristics of fractures: fracture density and fracture length, which correspond to two types of wave field characteristics respectively. This recognition uses waveform clustering method to carry out fracture prediction on the actual data, and the prediction results can detect large-scale fractures and microfracture zones at the same time, with a high coincidence rate. It is verified that the feasibility of fracture prediction using post-stack data.

References