文章编号:1000-1441(2009)01-0076-04

# 声波完全匹配层吸收边界条件的改进算法

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**摘要**:传统位移形式的声波完全匹配层(PML)吸收边界条件以三分裂位移参量来构建,需要求解时间 3 阶导数,计算量大,计算时间长。为此,提出了一种改进的声波分裂 PML 吸收边界条件。阐述了传统和改进的 PML 吸收边界条件的构建原理,通过数值模拟讨论了改进和传统的 PML 吸收边界以及低阶 Higdon 吸收边界对边界反射的吸收效果。结果表明,低阶 Higdon 吸收边界条件吸收效果较差,在波场快照和模拟记录中存在较强的边界反射;改进的 PML 吸收边界条件与传统的 PML 吸收边界条件效果相当,均能有效地吸收衰减任意角度的边界反射波。改进算法用褶积近似运算代替时间 3 阶导数的求解,因此简化了计算过程,减少了计算量,是一种高效稳健的算法。

**关键词**:完全匹配层;吸收边界条件;声波波动方程;高阶有限差分;算法改进

**中图分类号**:P631.4 **文献标识码**:A

在进行数值模拟时,为了消除由人为截断而产生的边界反射,人们提出了多种吸收边界条件,并得到了广泛应用[1~5]。构建吸收边界条件的思路主要有两种:一种是从外行波方程出发构建透射边界条件,如 MUR 吸收边界条件[6],MTF[7]和 Higdon[8]多次透射边界条件等;另一种是在边界上引入一定厚度的吸收材料,如完全匹配层(PML)吸收边界条件和阻尼吸收边界条件[9]。当前研究比较广泛的吸收边界条件是 PML 吸收边界条件,它最初被 Berenger[10]应用于 FDTD 麦克斯韦电磁场方程的数值模拟,后来又被许多研究者扩展到声波和弹性波等波场数值模拟中,并取得了较好的效果。如 Hastings 等[11]和 Collino 等[12]把 PML 吸收边界条件应用到 1 阶速度-应力弹性波方程中;Zeng 等[13]在粘弹性介质的波动方程模拟中对 PML 吸收边界条件做了进一步扩展;在将弹性波 PML 吸收条件应用到 1 阶双曲系统方程的基础上,Komatitsch 等[14]提出了 2 阶弹性波动方程 PML 吸收边界条件的分裂方法;朱兆林等[15]提出了各向异性介质 2 阶弹性波动方程分裂 PML 吸收边界条件。

声波波动方程 1 阶系统的 PML 条件分裂算法是把位移场分为 2 项,2 阶系统分裂为 3 项[16],两者均占据较多的内存空间,其中后者还需求解一个 3 阶时间导数式。在此项研究的基础上,本文借鉴各向异性分裂 PML[15]思想,提出了一种改进的声波 PML 分裂算法,并进行了数值模拟。

## 1 计算原理

三维声波波动方程有如下形式:

$$u_{tt} = v^2(u_{xx} + u_{yy} + u_{zz}) \tag{1}$$

式中:$u$ 为位移;$v$ 为地震波速度。

### 1.1 传统分裂 PML 吸收边界条件

在 $x$ 方向进行坐标变换(此处只考虑 $x$ 方向 PML 吸收边界条件的构建,其它方向依次类推):

$$\hat{x} = x - \frac{\mathrm{j}}{\omega}\int_{x_0}^{x}\beta(s)\,\mathrm{d}s$$

式中:$\hat{x}$是复数空间坐标;$\beta$ 为边界衰减因子,是随 $x$ 变化的实函数。根据坐标变换式,可得

$$\frac{\partial}{\partial \hat{x}} = \frac{1}{\xi}\frac{\partial}{\partial x}$$

$$\xi = 1 + \frac{\beta}{\mathrm{j}\omega} \tag{2}$$

且

$$\xi^{-1} = \frac{\mathrm{j}\omega}{\mathrm{j}\omega + \beta}$$

$$\frac{\partial(\xi^{-1})}{\partial x} = \frac{-\mathrm{j}\omega\beta_x}{(\mathrm{j}\omega + \beta)^2} \tag{3}$$

用(2)式和(3)式替换波动方程(1)式中的 $x$ 导数项,得

$$-\omega^2 u = v^2\left(\xi^{-1}\frac{\partial(\xi^{-1})}{\partial x}\frac{\partial u}{\partial x} + (\xi^{-1})^2\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{4}$$

由(4)式将位移波场 $u$ 分裂为三部分,即

$$u = u_1 + u_2 + u_3$$

**收稿日期**:2008-07-11;**改回日期**:2008-08-15。

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分裂结果如下：

$$\begin{cases}(\mathrm{j}\omega+\beta)^2 u_1 = v^2\dfrac{\partial^2 u}{\partial x^2}\\(\mathrm{j}\omega+\beta)^3 u_2 = -v^2\beta_x\dfrac{\partial u}{\partial x}\\-\omega^2 u_3 = v^2\left(\dfrac{\partial^2 u}{\partial y^2}+\dfrac{\partial^2 u}{\partial z^2}\right)\end{cases} \tag{5}$$

对(5)式进行傅里叶逆变换，得到传统位移形式的声波波动方程分裂 PML 吸收边界条件：

$$\begin{cases}(\partial_t+\beta(x))^2 u_1 = v^2\dfrac{\partial^2 u}{\partial x^2}\\(\partial_t+\beta)^3 u_2 = -v^2\beta_x\dfrac{\partial u}{\partial x}\\\partial_t^2 u_3 = v^2\left(\dfrac{\partial^2 u}{\partial y^2}+\dfrac{\partial^2 u}{\partial z^2}\right)\end{cases} \tag{6}$$

(6)式的第 2 项需要求解 3 次时间导数，这就需要消耗额外的计算时间，占据一定的计算空间。

### 1.2　改进的分裂 PML 吸收边界条件

对传统位移形式的声波波动方程分裂 PML 吸收边界条件进行了改进，将(5)式中的前两项合并，并采用褶积近似算法，因此无需求解时间 3 阶导数。(5)式合并后的频率域方程为

$$\begin{cases}(\mathrm{j}\omega+\beta)^2 w_1 = v^2\left(\dfrac{\partial^2 w}{\partial x^2}-\dfrac{\beta_x}{(\mathrm{j}\omega+\beta)}\dfrac{\partial w}{\partial x}\right)\\-\omega^2 w_2 = v^2\left(\dfrac{\partial^2 w}{\partial y^2}+\dfrac{\partial^2 w}{\partial z^2}\right)\end{cases} \tag{7}$$

由傅里叶逆变换

$$\mathrm{F}^{-1}\left[\frac{-\beta_x}{\mathrm{j}\omega+\beta}\right] = -\beta_x \mathrm{e}^{-\beta t} \tag{8}$$

将(8)式变换到时间域，得

$$\begin{cases}(\partial_t+\beta)^2 w_1 = v^2\left(\dfrac{\partial^2 w}{\partial x^2}-\beta_x \mathrm{e}^{-\beta t} * \dfrac{\partial w}{\partial x}\right)\\\partial_t^2 w_2 = v^2\left(\dfrac{\partial^2 w}{\partial y^2}+\dfrac{\partial^2 w}{\partial z^2}\right)\end{cases} \tag{9}$$

其中，符号“ * ”表示褶积。对于(9)式的褶积项，若

$$P = -v^2\beta_x \mathrm{e}^{-\beta t} * \frac{\partial w}{\partial x}$$

采用积分近似[17]后，则

$$P^n = \mathrm{e}^{-\beta\Delta t}P^{n-1} - \frac{v^2\beta_x\Delta t\left(\mathrm{e}^{-\beta\Delta t}\dfrac{\partial w^{n-1}}{\partial x}+\dfrac{\partial w^n}{\partial x}\right)}{2} \tag{10}$$

由(9)式可见，新算法将原波动方程分裂为两项，并且与传统的 PML 吸收边界条件在理论上有同样的精度。采用高阶有限差分[18~20]计算(9)式和(10)式中的空间导数项。对比(6)式和(9)式可知，对于 $x$ 方向的边界吸收问题，改进算法只需求解 1 个时间和空间的 2 阶导数；传统算法则需求解 1 个时间的 3 阶和空间的 2 阶导数，同时还需求解 2 个方程，因此计算量要比改进算法大。

## 2　模型试验

模型尺寸为 1 000 m×1 000 m，空间步长为 5 m，速度为 2 000 m/s；震源采用主频为 60 Hz 的雷克子波，置于模型中央；接收器位于(990 m，10 m)处(考察大角度入射情况下对边界反射的吸收效果)，时间步长为 1.767 ms，计算时间为 1 767 ms。采用高阶有限差分算法[21,22]通量校正技术[23,24]以及 1 阶 Higdon、2 阶 Higdon、传统 PML 和改进 PML 吸收边界条件进行了波场数值模拟(图 1)。

分析图 1 可知，在低阶 Higdon 吸收边界的数值模拟结果上存在边界反射(图 1a、图 1b、图 1e 和图 1f，为了观察边界反射细节，做了振幅增强处理)，在传统 PML(图 1c 和图 1g)和改进 PML 吸收边界条件(图 1d 和图 1h)的数字模拟结果上几乎没有边界反射，两者的吸收效果基本相同。

边界条件的吸收效果可以通过接收器的时程分析和全域误差分析来判别。由接收器的时程图(图 2)可见，低阶 Higdon 吸收边界条件的模拟信号出现了尾波，与精确解之间存在较大的误差，这是由大角度入射时的边界反射所致；传统和改进 PML 吸收边界条件的模拟信号与精确解之间的误差很小，可以忽略不计。

定义任一时间步长中 $n$ 时刻的全域误差为

$$E(n) = \sqrt{\sum_{i=2}^{199}\sum_{j=2}^{199}\left(U^n(i,j)-U_0^n(i,j)\right)^2} \tag{11}$$

其中，$U_0^n$ 是无边界条件下空间节点$(i,j)$处的声波振幅值。图 3 是全域误差图，可将全域误差分为 4 个区域，区域 1 代表波在介质中的传播过程，区域 2、区域 3 和区域 4 分别代表 1 次、2 次和 3 次边界反射波在介质中的传播过程，每个区域中部出现的波动代表边界反射波的叠加过程。分析图 3 可知，改进 PML 和传统 PML 吸收边界条件的全域误差在整个计算时间内近似为零，低阶 Higdon 吸收边界的全域误差非常大，说明边界反射能量很强。由此可见，改进算法在降低计算量的同时，得到了非常好的吸收效果，而且边界计算稳定。

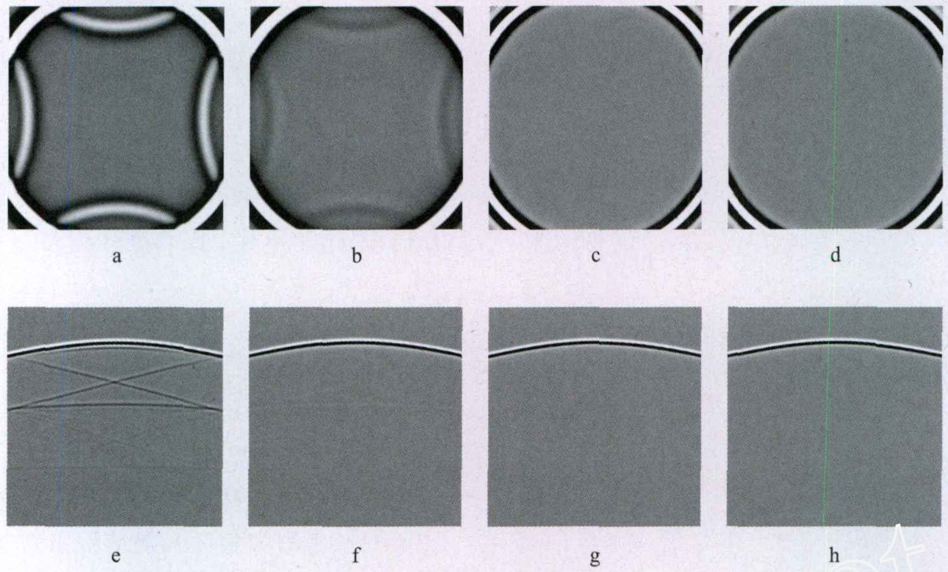


图1 4种吸收边界条件的波场快照和模拟记录

a 1阶 Higdon 的波场快照；b 2阶 Higdon 的波场快照；c 传统 PML 的波场快照；d 改进算法的波场快照；e 1阶 Higdon 的模拟记录；f 2阶 Higdon 的模拟记录；g 传统 PML 的模拟记录；h 改进算法的模拟记录

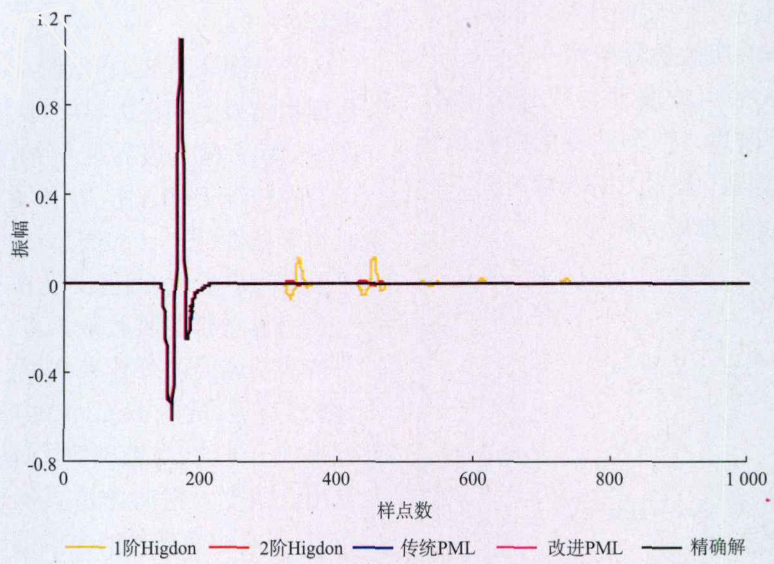


图2 接收器时程分析曲线

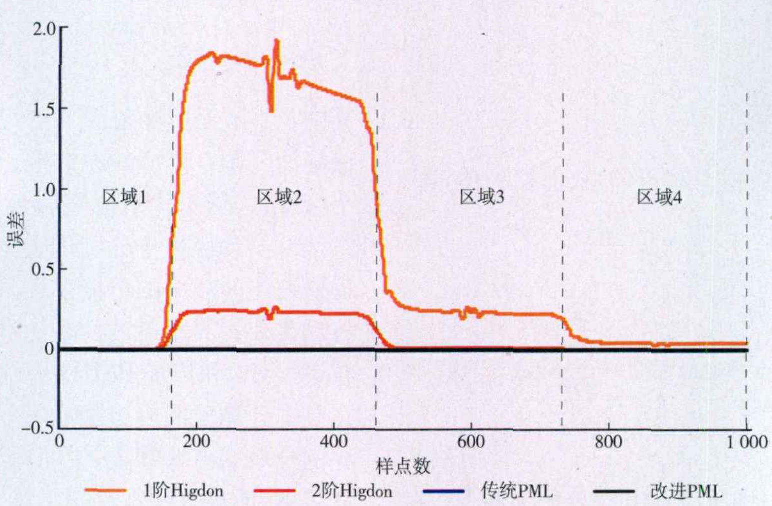


图3 全域误差分析结果

## 3 结束语

从理论上推导了三维声波方程传统位移形式的完全匹配层控制方程，并在此基础上提出了改进的声波分裂 PML 吸收边界条件。采用高阶有限差分法进行了数值模拟，并利用时程图方法和全域误差分析方法对传统和改进 PML 吸收边界条件的吸收效果进行了分析对比，由于改进算法不需要求解时间3阶导数，从而减少了计算量，而吸收效果与传统的 PML 吸收边界条件相同，能有效地吸收衰减边界反射，不受边界反射角度限制，且计算不发散。

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（编辑：邵　瑛）

the recognition of reservoirs. Therefore, an index identification method for recognizing oil layer and gas layer was proposed. Firstly, all discriminant indexes are extracted from conventional log, that is extracting discriminant indexes of reservoir from gamma ray log, extracting discriminant indexes of productive layers from natural potential log, extracting discriminant indexes of oil layers from synthetic resistivity and acoustic log, extracting discriminant indexes of gas layers from three porosity log. Then, the synthetic index for recognizing oil layers and gas layers were proposed based on the indexes. The synthetic index can stress the logging response of reservoir fluid. Actual application shows that the method can effectively distinguish oil layer and gas layer.

**Key words**: low porosity & permeability reservoir; conventional log; oil layer; gas layer; discriminant index

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**Wavelet replacement technology and analysis on its application effect. Li Dawei, He Yan, Tang Shu'an. GPP, 2009, 48(1):61~65**

For ideal deconvolution, spectrum whitening should be carried out on seismic signal to make it returning theoretical impulse condition. In actual processing, due to the restraints of objective conditions, deconvolution changes into the compression of seismic wavelet to improve the vertical resolution, but does not change the phase properties of wavelet. Based on the conventional algorithm, after obtaining deconvolution factor by signal self-relevant Zoeplitz matrix, the wavelet replacement deconvolution algorithm was proposed. Through establishing replacement matrix with the given ideal wavelet, we perform this algorithm for wave replacement during signal deconvolution to change the frequency and phase characteristics of wavelet and to make the vertical resolution reach optimal situation without increasing extra noise. Moreover, the phase processing technology was applied during computing deconvolution factor, which is no longer necessary to assume minimum phase in conventional deconvolution, without the restraint of phase during computing deconvolution factor, the blind deconvolution for any signal can be genuinely realized.

**Key words**: deconvolution; wavelet replacement technology; spectrum whitening; resolution; S/N; phase

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**Study on starting datum of wave equation wave field continuation for rolling surfaces. Yang Haisheng. GPP, 2009, 48(1):66~71**

In data processing of rolling surface regions, whether the prestack forward modeling or the pre-stack depth migration is used, the conventional one-way wave equation wave field continuation starts from the peak of the whole seismic line, and most of the wave field continuation is in the form of single-shot. Therefore, a wave field continuation method starting from the peak of single-shot spread was proposed. Since single-shot spread is a part of the whole seismic line, the peak of the single-shot spread is not always the peak of the whole seismic line, the continuation of zero-amplitude wave field between the two points can be omitted. The testing results of theoretical model and actual seismic data shows that with the same precision, comparing with the "step by step summation" wave equation wave field continuation method (starting from zero depth), the wave continuation starting from the peak of single-shot spread has smaller calculated amount, the larger the difference of elevation is, the higher the computational efficiency is.

**Key words**: rolling surface; forward modeling; pre-stack depth migration; computational efficiency

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**Application of fractional order derivative in analyzing seismic singularity. Song Jianguo, Liu Lei, Li Hui, Liu Liyun. GPP, 2009, 48 (1):72~75**

Traditional seismic data interpretation focuses on changes of amplitude and phase. However, amplitude in most cases cannot reflect the actual geologic situation. Seismic interface can be either a lithologic interface or a lithologic transitional zone. The reflection of lithologic transitional zone is the fractional order derivative of incident wavelet. So the fractional order derivative is introduced into the calculation of seismic attribute to establish a new attribute called singularity which is sensitive to waveform but insensitive to amplitude. The singularity can be used to describe the lateral changes of seismic reflection interface. The principles of this method are as follows: firstly, fractional derivatives of various orders are calculated from a given seismic wavelet; then, matching pursuit algorithm is used to decompose seismic data into different orders of fractional derivatives of wavelet and then to obtain the fractional order of reflection events. This method was applied to preprocess the 2-D seismic data of Shengli oilfield, showing that the fractional order derivative profile can effectively describe the unconformity and reflect the lateral changes of actual interface.

**Key words**: fractional order derivative; singularity; matching pursuit; seismic attribute

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**Improved algorithm for absorbing boundary condition of acoustic perfectly matched layer. Chen Keyang. GPP, 2009, 48(1):76~79**

The absorbing boundary condition of acoustic perfectly matched layer (PML) in traditional displacement form should be established by three splitting displacement parameters and the third-order time derivative needs to be solved, which leads to a large computation amount and long computation time. Aiming at this problem, we proposed an improved acoustic splitting PML absorbing boundary condition. The establishment principles of traditional and improved PML absorbing boundary condition were described. Through numerical simulation, the absorbing effect of improved and traditional PML absorbing boundary and low-order Higdon absorbing boundary on boundary reflection was discussed. The results show that the absorbing effect of low-order Higdon absorbing boundary condition is undesirable and relatively strong

boundary reflection exists in wave field snapshot and analog recording; the effect of traditional and improved PML absorbing boundary conditions are similar, which can effectively absorb and attenuate the boundary reflections from any angle. In the improved algorithm, the computation of three-order time derivative is replaced by convolution approximate calculation, which simplifies the computation process and reduces computation amount, and is high effective and robust.

**Key words**: perfectly matched layer; absorbing boundary condition; acoustic wave equation; high-order finite difference; improvement of algorithm

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**An improvement for frequency-dominated fast matching pursuits algorithm. Chen Fayu, Yang Changchun. GPP, 2009, 48(1):80~83**

Matching pursuits (MP) algorithm is a specific implementing method for signal self-adapted decomposition. With the prior-knowledge that the seismic signal is composed of certain limited frequency band, the frequency-dominated fast MP algorithm creates dictionary index which regards frequency as main matching target, so that it can decrease the amount of dictionary index size and iteration computation, and promote the efficiency and computation speed of signal MP decomposition. By taking the instantaneous frequency at the supreme points of complex seismic signal as original frequency and establishing the relation of linking frequency with scale parameters, the MP iteration process tightly relates with the effective attenuation of residual signal, which improves the pertinence for identifying original frequency.

**Key words**: fast matching pursuits algorithm; atom dictionary; dictionary index; frequency; computation efficiency

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**Wave equation based secondary positioning method for shot point. Huang Longze, Liu Huaishan. GPP, 2009, 48(1):84~90**

In seismic exploration, lots of factors might cause the inaccurate positioning of shot point, which seriously affects the sequent processing of seismic date. Therefore, it is necessary to relocate the shot point. The secondary positioning method of shot point based on wave equation is similar to conventional seismic migration. After preprocessing and removing the interference wave, Kirchhoff integral was utilized to inversely extrapolate wave field and make it gradually converge. At last, the wave field is converged to the position where the shot point is. That is the secondary positioning of shot point. Both the simulation and actual application results show that the method can better realize the secondary positioning of shot point with relatively high S/N, the distance between calculated and actual position of shot point is in the accepted range.

**Key words**: shot point; secondary positioning; wave equation; wave field extrapolation; Kirchhoff integral

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**Experimental study on piezoelectric geophone in high resolution seismic exploration. Shan Gangyi, Han Liguo, Zhang Lihua, Dong Shixue. GPP, 2009, 48(1):91~95**

With the increase of complexity of exploration area and targets, high resolution seismic exploration has achieved a fast development. The acquisition of high-quality seismic data is regarded as the source of high resolution seismic exploration and the traditional electromagnetic velocity geophone cannot meet the requirement. Therefore, land piezoelectric acceleration detector which is more suitable for high resolution seismic exploration attracts much attention of scholars. From the basic structure and operational principles, the response characteristics of the two geophones on oscillatory are described in detail. In the equal field conditions, acquisition testing and comparison have been carried out on the two geophones. The results show that the build-in wide frequency width and high sensitivity of land piezoelectric acceleration can satisfy the demands of high resolution seismic exploration.

**Key words**: high resolution seismic exploration; piezoelectric acceleration detector; traditional electromagnetic velocity geophone; sensitivity; inherent frequency; response characteristic

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**Gravity-magnetic multi-parameter simulation technology and its application: case study of LJ line in Huangqiao area. Wang Huaisheng, Guo Yongchun. GPP, 2009, 48(1):96~103**

The precision of gravity and magnetic data interpretation depends, to a great extent, on the validity of physical properties and the rationality of structure's geometric shape. In the area with limited rock samples, gravity-magnetic-seismic multi-parameter simulation technology can be adopted to improve the interpretation accuracy of gravity-magnetic data. The principles of the technology are as follows: ①the initial space structure of geologic model is established by horizons interpreted for seismic profiles; ② the spatial density is obtained by the equation of seismic wave velocity and formation density; ③the occurrence of igneous rock and the fluctuation of magnetic basement are judged by magnetic source depth estimating method; ④ by fitting different physical elements, the gravity-magnetic multi-parameter simulation technology is used to adjust the density difference, magnetic capacity difference, and boundary of modeling geologic body and to identify the geologic structures as well as its attributes details. The method was used to do integrated fitting of physical elements of LJ line in Huangqiao area, including gravity-magnetic observation field, high-frequency filtering field, low-frequency filtering field, pass-frequency filtering field, derivative and gradient, etc. The fitting greatly restricted the range of solutions and improved the accuracy and credibility of gravity-magnetic data interpretation.

**Key words**: gravity-magnetic data; interpretation precision; multi-parameter simulation; complex physical elements; rock physical property

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