



移动扫码阅读

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三分量 TEM 在坚硬顶板水力压裂效果检测中的应用

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摘要:矿井水力压裂技术在坚硬顶板卸压和瓦斯高效抽采领域得到的广泛应用,但对于长钻孔水力压裂效果的检测评价一直缺乏较为理想的物探方法,传统探测方法存在成本高、效率低与探测距离短的不足。为实现坚硬顶板定向长钻孔水力压裂效果高效直观地检测这一目标,采用一种煤矿井下在压裂孔内施工的动源动接收瞬变电磁探测方法,探测装置天线是由收发间距固定的极小发射线圈和三分量接收探头组成,在钻孔内沿钻孔逐点移动进行三分量接收。为了弥补有缆装置探测距离的不足,采用孔外定时同步、孔内发射接收的探测装置,采用钻机推送的方式对神东某矿井 2 号压裂钻孔 40~315 m 段进行压裂前、压裂后分别探测。首先对垂直分量数据进行预处理,采用水平分量数据实现探头姿态变化影响校正,并提取纯异常场进行分析,最终实现充水裂缝三维成像技术。试验结果表明:纯异常场等值线图中有明显条带状低阻异常分布,综合分析压裂前、后视电阻率分布情况认为该条带状低阻异常即为压裂形成裂缝所致,异常走向即为裂缝延伸方向,异常延伸范围即为裂缝延伸范围。三分量瞬变电磁探测技术是矿井物探、钻探和水力压裂技术的有机结合与相互补充,对裂缝走向和延展范围进行有效圈定,能够有效应用于坚硬顶板定向长钻孔水力压裂效果评价。

关键词:三分量瞬变电磁;定向长钻孔;坚硬难垮顶板;水力压裂

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Application of three-component TEM in hydraulic fracturing effect detection of hard roof

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Abstract: Mine hydraulic fracturing technology has been widely used in the fields of hard roof pressure relief and high-efficiency gas drainage. However, there has been a lack of ideal geophysical prospecting methods for the detection and evaluation of hydraulic fracturing effects in long boreholes. Traditional detection methods have the shortcomings of high cost, low efficiency and short detection distance. In order to achieve the goal of efficient and intuitive detection of the hydraulic fracturing effect of long directional drilling in hard roofs, a dynamic source-dynamic receiving transient electromagnetic detection method was adopted for the construction of fracturing holes in coal mines. The antenna of the detection device is composed of a minimum transmitting coil with fixed transceiver spacing and a three-component receiving probe, which moves point by point in the borehole to perform three-component receiving. In order to make up for the lack of the detection distance of the cable device, a detection device with timing synchronization outside the hole and transmission and reception inside the hole was used to detect the 40~315 m section of the No. 2 fracturing borehole in a Shendong mine before and after fracturing. Firstly, the vertical component data was preprocessed, and the horizontal component data was used to correct the influence of probe attitude change, and the pure anomaly field is extracted for analysis. Finally, the three-dimensional imaging technology of water filling cracks was realized. The test results show that there are obvious strip-shaped low-resistivity anomalies in the contour map of the pure anomaly field. By comprehensively analyzing the distribution of apparent resistivity before and after fracturing, it is considered that the strip-like

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low-resistivity anomalies are caused by fractures formation, and the abnormal strike is the fracture extension direction, and the abnormal extension range is the fracture extension range. The three-component transient electromagnetic detection technology is an organic combination and complementation of mine geophysical exploration, drilling and hydraulic fracturing technology. It can effectively delineate the fracture trend and extension range, and can be effectively applied to the evaluation of hydraulic fracturing effect of directional long borehole with hard roof plate.

Key words: three-component TEM; directional long borehole; hard and stable roof; hydraulic fracturing

0 引言

我国煤矿地质较为复杂,据统计,现有煤层中具有致密完整、回采后难以及时垮落的坚硬顶板的煤层约占总量的1/3,这些煤层一旦垮落很容易造成冲击矿压等灾害,对矿井安全生产带来严重威胁^[1-2]。针对此类坚硬岩层,目前使用较多的技术有炸药爆破和水力压裂泄压等方法,其中水力压裂技术通过将高压流体注入煤层,使岩石中原生裂缝扩张或形成人工裂纹,并逐渐扩展延伸形成新的裂缝网络系统,从而达到破坏岩层结构的作用。相较于炸药爆破方法,水力压裂技术具有,安全性高、且在泄压的同时可达到预先释放煤层瓦斯的作用,因此近年来该项技术在我国部分煤矿处理坚硬顶板过程中得到了较为广泛的应用,并取得了良好的效果^[3-6]。

受行业趋势的影响,对压裂所形成的裂缝的几何形态(方位、缝长和缝高等)的研究受到越来越多学者的重视^[7-8]。目前压裂效果评价的方法主要有数值模拟法和裂缝监测法,前者是通过数值软件结合工程参数对理想地层进行模拟研究,目前主要应用于实验室研究;在实际的工程应用中采用裂缝监测法较多,该方法通过电透视法、微震法监测和井温测试等方法对裂缝进行评价,在部分工程应用中无法提供巷道供透视法、微震法监测方法布设传感器进行探测,而井温测试方法测量参数单一,探测效果不明显^[9-12]。此外井下钻孔中视频测井技术可以有效地看清裂缝的开口位置,但无法判断裂缝的几何形态^[13]。刘盛东等^[14]、李世宇^[15]在全空间瞬变电磁探测的基础上,受传统测井方法的启发,提出了钻孔瞬变电磁探测方法,并在不同工程环境对该方法效果进行检验,准确定位了钻孔周边的低阻异常。范涛等^[16-18]利用三分量钻孔瞬变电磁探测方法对裂缝进行探测,该方法应用于陕西韩城某煤矿瓦斯抽采孔水力压裂效果检测中,对钻孔60~110 m区间分别进行压裂前、压裂后探测,划定了裂缝空间形态,取得了良好的应用效果,但是由于采用人力推送的工艺,无法适用于长距离定向钻孔中水力压裂效

果检测。

因此,笔者采用一种钻孔内三分量动源动接收瞬变电磁装置,采用钻机推送的方式对某矿坚硬顶板定向长钻孔水力压裂效果进行试验研究,对压裂段进行压裂前、压裂后分别探测,并提取纯异常场对裂缝发育规律进行分析。

1 三分量钻孔瞬变电磁探测基础

1.1 理论基础

在瞬变电磁探测中,Maxwell的微分表达式为

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1)$$

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (2)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (3)$$

$$\nabla \cdot \mathbf{E} = 0 \quad (4)$$

其中,

$$\mathbf{B} = \mu \mathbf{H} \quad (5)$$

$$\mathbf{J} = \sigma \mathbf{E} \quad (6)$$

式中, \mathbf{B} 、 \mathbf{H} 、 \mathbf{E} 分别为磁感应强度、磁场强度和电场强度; μ 和 σ 分别为介质体的磁导率和电导率; \mathbf{J} 为传导电流密度。

由式(3)可知,上述方程组中关于磁场的3个分量中仅有2个分量彼此独立,因此存在下列方程:

$$\frac{\partial B_x}{\partial t} = \frac{\partial B_y}{\partial z} - \frac{\partial B_z}{\partial y} \quad (7)$$

$$\frac{\partial B_y}{\partial t} = \frac{\partial B_z}{\partial x} - \frac{\partial B_x}{\partial z} \quad (8)$$

$$\frac{\partial B_z}{\partial t} = \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} \quad (9)$$

式(7)一式(9)是计算三分量响应的理论基础^[19-21]。

矿井三分量钻孔瞬变电磁探测原理如图1所示,其中T为发射线圈;R为相互正交的3个接收线圈,是由与发射线圈同轴的Z分量接收线圈R_z,与发射线圈正交的X分量接收线圈R_x,以及与发射线圈正交的Y分量接收线圈R_y共同组成。发射线圈添加阶跃激励向周围岩层发射脉冲电磁信号,通过三分量接收线圈采集,实现全空间地质异常体的距离探测和方位识别^[14-15]。

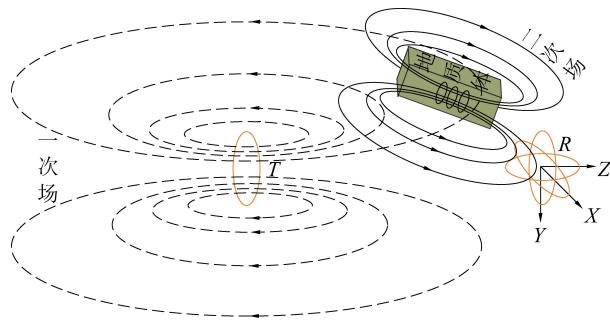


图 1 三分量钻孔瞬变电磁探测原理示意

Fig.1 Three-component drilling transient electromagnetic detection principle

1.2 探测装置

设计的钻孔三分量探测装置如图 2 所示,包括孔中探管和孔口同步机 2 部分。孔中探管由电池主机、发射线圈和接收探头 3 个模块组成,是装置的核心电路部分;孔外同步机主要是用来下发测量参数以及测量过程中时钟同步。探测时,钻机推送探管沿钻孔延伸方向按一定点距测量 2 次场信号。

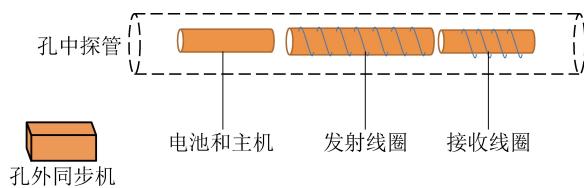


图 2 三分量钻孔瞬变电磁探测装置示意

Fig.2 Three-component drilling transient electromagnetic detection device

2 数据处理方法

2.1 Z 分量数据处理

钻孔瞬变电磁 Z 分量数据处理方法与矿井瞬变电磁探测相同。将装置至于物理模型中进行数据采集,钻孔装置与常规装置接收信号对比如图 3 所示,信号衰减规律基本相同,因此数据处理方法可参考常规矿井瞬变电磁,采用预处理技术对电感影响进行校正,对校正后的数据则可应用多种反演成像方法进行处理解释^[22-24]。

2.2 XY 分量数据处理

常规瞬变电磁探测中仅探测了与发现线框轴向同向的 Z 分量数据,对于三分量钻孔瞬变电磁中 XY 分量的数据处理方法,通过数值模拟计算,在分析响应特征的基础上,总结了一套 XY 分量的数据处理方法^[25]。

2.2.1 装置旋转角度校正

三分量瞬变电磁探测装置在钻孔中施工时,由于受推送工艺影响,装置必然会在钻孔内发生旋转,

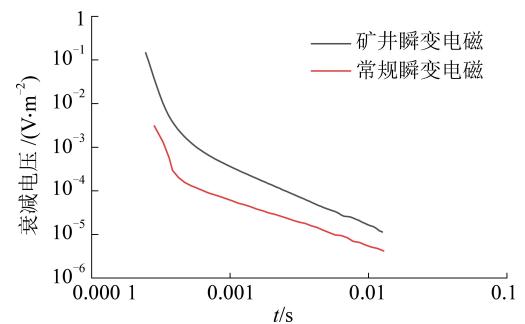


图 3 矿井瞬变电磁装置与钻孔装置实测曲线对比

Fig.3 Comparison of measured curves of mine equipment and drilling equipment

因此,实际地层 XY 分量数据需要通过工具面角进行相应变换得到。

为了方便分析,记开孔处装置工具面角为 α_0 ,孔中 α_0 第 i 个测点位置的工具面角为 α_i ,则仪器在钻孔内的旋转角度为

$$\Delta\alpha = \alpha_i - \alpha_0 \quad (10)$$

装置在第 i 个测量点处校正后的 X 和 Y 分量感应电动势为

$$V_{i,x} = V_{i,x'} \cos \Delta\alpha + V_{i,y'} \sin \Delta\alpha \quad (11)$$

$$V_{i,y} = V_{i,x'} \sin \Delta\alpha + V_{i,y'} \cos \Delta\alpha \quad (12)$$

式中, $V_{i,x'}$ 和 $V_{i,y'}$ 为装置在第 i 个测量点处实测的水平分量感应电动势。

2.2.2 异常方位计算

三分量瞬变电磁探测中异常方位角度与 XY 水平分量的探测信息密切相关,因此探测可以从水平分量信息着手研究异常的方位。采用 COMSOL 有限元软件建立数值计算模型如图 4 所示,规定 X 分量与 Y 分量正方向之间区域为第 1 象限,逆时方向依次定义为二、三、四象限。

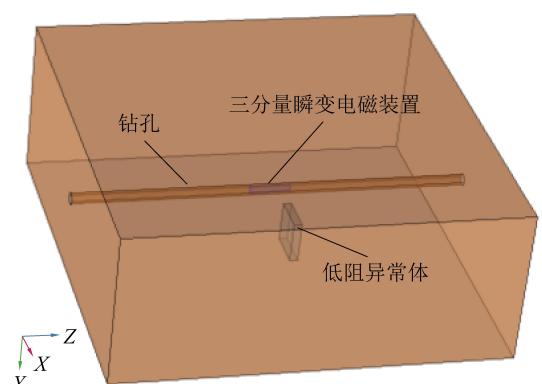


图 4 三维有限元数值计算模型

Fig.4 Finite element numerical calculation model

钻孔瞬变电磁检测水力压裂效果时采用压裂前和压裂后分别探测,由于 2 次探测的主要环境差异

为压裂所致,因此认为两次探测成果差异即为纯压裂场效果。相对固定板状低阻异常体位置,通过移动探测装置的方式分别计算无异常体和有异常体XY水平分量和异常体位置关系,并提取纯异常场导致的信号变化特征。

产生的瞬变电磁XY分量探测曲线会发生波“正弦”或“反正弦”形态(图5)。模拟不同象限异常时纯异常场曲线特征,可归纳为如图6所示“正弦”与“反正弦”形态的组合,因此可根据图7判断异常体所在象限。

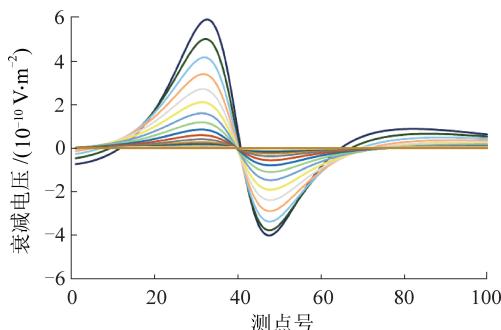


图5 水平分量异常场形态组合

Fig.5 Horizontal component abnormal field combination

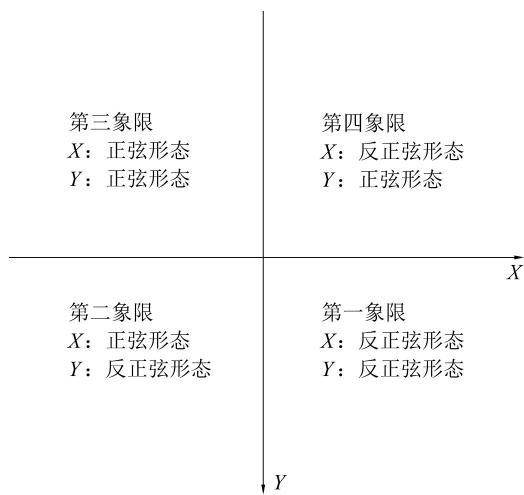


图6 异常位于不同象限时水平分量响应形态

Fig.6 Horizontal component response curve in different quadrant

水平分量异常场幅值之间的三角函数关系(图5),按照下式计算出异常体在该象限内的偏转角度 θ 。

$$\theta = \arcsin\left(\frac{|V_n^A|}{\sqrt{(V_n^A)^2 + (V_n^B)^2}}\right) \quad (4)$$

最后根据异常体所在象限,求出异常体中心的方位角 α :①异常体在第1象限: $\alpha = \theta$;②异常体在第2象限: $\alpha = \pi - \theta$;③异常体在第3象限: $\alpha = \pi + \theta$;④异常体在第4象限: $\alpha = 2\pi - \theta$ 。

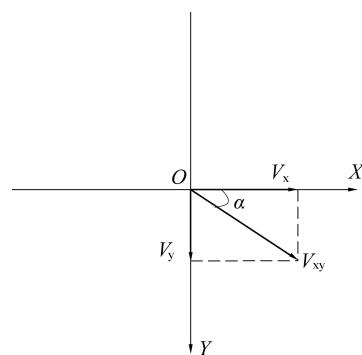


图7 异常体偏转角度

Fig.7 Abnormal body deflection angle

2.3 三维成像方法

三分量钻孔瞬变电磁水力压裂检测方法提供了丰富的裂缝坐标信息,为了更直观显示裂缝沿钻孔轨迹分布情况,对异常体进行三维立体成像^[26]。

通过散点坐标空间旋转后,可以借助Voxler软件散点绘图功能实现立体成像,具体步骤如下:

1)绘制钻孔轨迹。

2)将视电阻率成像图沿钻孔轨迹展开,并根据视电阻率分布划分出几个明显的条带状异常区段,标记为主裂缝。

3)每一区段通过2.2节的方法计算的有异常中心方位,根据方位角度计算实际空间中裂缝几何形态,并用Voxler软件以散点图立体成像显示主要裂缝的形态。

上述步骤中,采用散点空间旋转的方式按指定角度旋转。为了方便计算,忽略钻孔高程变化,因此钻孔轨迹主要由方位角度决定。以对应钻孔轨迹点为旋转中心进行旋转可得探测成果坐标,方法如图8所示。

3 探测应用

神东某矿2号钻孔深417 m,采用水力压裂技术拟提高坚硬煤体裂隙发育程度、降低煤层整体强度,压裂段布置如图9所示。为了检测压裂的效果,采用三分量瞬变电磁法探测了钻孔深度40~315 m区间。

图10为压裂前后的钻孔瞬变电磁Z分量处理结果,其中图10a为压裂前的处理结果,图10b为压裂后的处理结果,成果图中横坐标为钻孔深度,纵坐标为钻孔径向距离。由图10a中看出,压裂前的视电阻率等值线分布比较均匀,在成果中零星分布圈闭低阻区,这与压裂前,测区内围岩的视电阻率分布

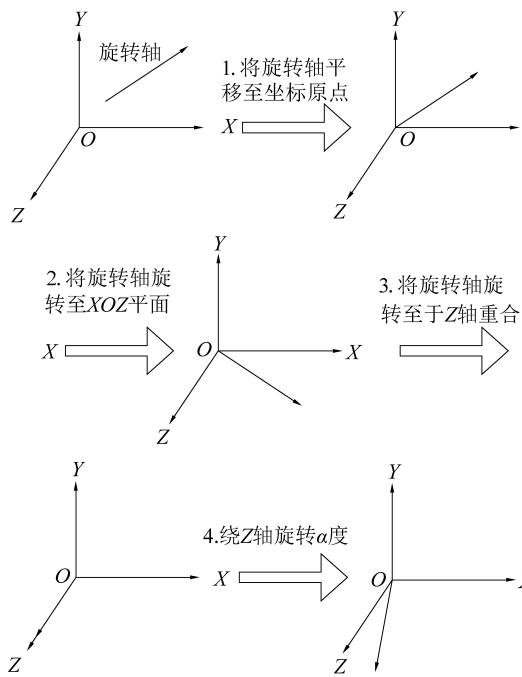


图 8 散点空间旋转方法

Fig.8 Scattered space rotation method

2号钻孔压裂段						
坐封位置	第8段压裂	第7段压裂	第6段压裂	第5段压裂	第4段压裂	
40 m	91.74~96.12 m	150.74~155.12 m	195.74~200.12 m	242.14~246.52 m	279.84~284.22 m	

图 9 钻孔压裂段布置

Fig.9 Borehole fracturing section layout

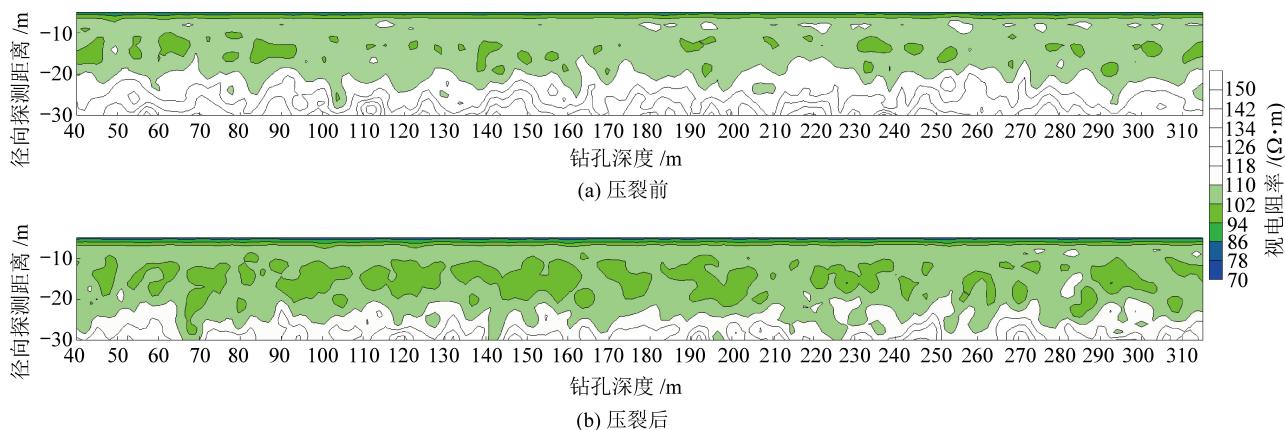


图 10 Z 分量压裂前后对比

Fig.10 Comparison of Z component before and after hydraulic fracturing

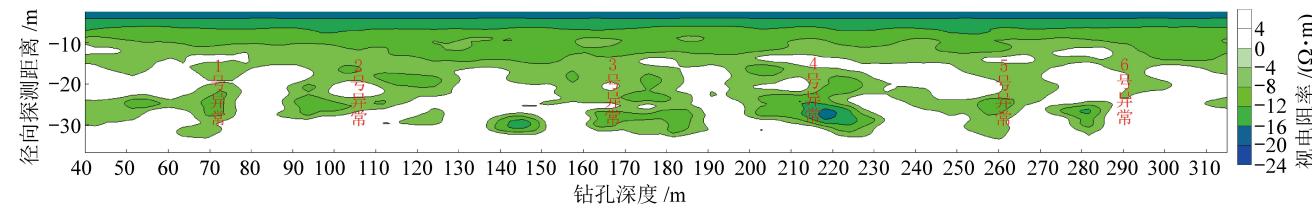


图 11 纯异常场探测平面成果

Fig.11 Results of pure anomaly field detection plane

相对比较均匀、规律吻合。从压裂后的图 10b 可以发现,测区中出现了局部较大区域的低阻异常,这与压裂导致岩层局部充水吻合,但无法从成果图中直观看出裂缝的发育规律。

为了更清楚的识别异常分布与发育情况,将压裂前的探测成果当做背景场,在压裂后的探测成果中减去背景场,提取出纯异常场,计算成果如图 11 所示,成果图中横坐标为钻孔深度,纵坐标为钻孔径向距离。通过对纯异常的提取,可以看出钻孔径向距离 0~10 m 整体视电阻值较低,且异常发育最远距离约为 30 m。按照异常强弱和条带状不同,可将图中异常分为 6 个区域。综合分析图 9—11 发现,6 个异常区,均与实际压裂点存在良好对应关系。

根据前述异常方位计算方法,可得 6 个异常方位位于钻孔的径向的不同方位,将探测成果进行立体成像,成果如图 12 所示。图 12 中可以清晰展示裂缝空间分布位置,便于对水力压裂效果进行评价。

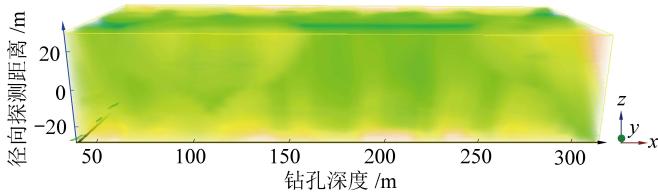


图 12 异常空间分布展示

Fig.12 Display of abnormal spatial distribution

4 结 论

1)采用三分量钻孔瞬变电磁技术分别在水力压裂前和压裂后进行孔旁探测,压裂后视电阻率值较压裂前有明显较低,可以看出压裂导致视电阻率发生变化,但无法直观显示裂缝的方位。

2)纯异常探测成果图中,异常区域与压裂段布设位置吻合,且异常条带性明显,因此可以认为纯异常成果中的异常区域即为水力压裂诱导所致裂缝。

3)矿井钻孔中的探测实例通过对坚硬顶板水力压裂钻孔压裂前后的对比探测,成果直观显示出了压裂的影响范围和裂缝的空间发育情况。基于钻机推送的三分量钻孔瞬变电磁技术可以有效对水力压裂诱导所致裂缝进行探测,成果可用于分析裂缝位置与发育情况,对坚硬顶板灾害治理具有重要意义。

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