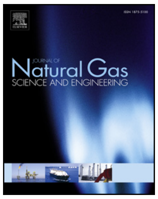
Journal of Natural Gas Science and Engineering 56 (2018) 212–221

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse



# Factors affecting received signal intensity of electromagnetic measurement-while-drilling during underground in-seam horizontal drilling

Chun Shao[a], Lin Xu[a,*], Xiaojun Chen[a], Zhiwei Chu[b], Baolin Yang[a]

[a] Faculty of Earth Resource, China University of Geosciences, Wuhan, 430074, China
[b] R&D Center of Drilling Technology and Equipment, Xian Research Institute of China Coal Research Institute, Xian, 710077, China

ARTICLE INFO

*Keywords:*
Underground in-seam horizontal drilling
Electromagnetic measurement-while-drilling
Received signal intensity
Influencing factors
Finite-element simulation

ABSTRACT

Electromagnetic measurement-while-drilling (EM-MWD) is a real-time monitoring technology for bottom-hole engineering parameters, and applied to underground in-seam horizontal drilling to obtain high accuracy borehole trajectories for enhancing the output of coal bed methane. However, the received signal intensity of EM-MWD is affected significantly by many factors. In this study, a finite-element model for simulating the signal transmission was proposed based on the quasi-static electric field theory, and the reliability of the model was proved by performing a sensitivity analysis and scale-model experiment. Then, factors including full-dimension signal channel, coal seam resistivity and thickness, surrounding rock resistivity, borehole location, electrode location, and bit drilling into surrounding rock were investigated. Results indicate that higher resistivities of coal seam and surrounding rock imply stronger intensity of the received signal, and the coal seam resistivity is the primary influencing factor. When the resistivity of coal seam is less than that of surrounding rock, the intensity of received signal increases with rising the receiving distance and decreasing the distance between borehole and surrounding rock. The received signal intensity of electrode in surrounding rock is higher than that in coal seam under the above condition. Moreover, a sudden change in the received signal intensity will be observed as the bit drills from coal seam into surrounding rock, which is an indicator for determining whether the bit has drilled into surrounding rock. The finite-element model and the findings in this research are helpful for the design, feasibility evaluating and application of the EM-MWD in coal mines.

## 1. Introduction

Coal bed methane (CBM), a main component of natural gas, is a kind of high quality, high thermal efficiency, and low pollution energy (Zou et al., 2015; Wang et al., 2015a,b). However, owing to serious disasters such as gas explosion and gas discharge, CBM is also a threat to coal mining construction as well as production (Chen et al., 2016). To cope with these challenges, pre-extracting CBM via a borehole is applied worldwide as the most effective and economical measure (Liu et al., 2014; Zhai et al., 2015).

Among the techniques for pre-extracting CBM, ground drilling and underground in-seam horizontal drilling are used in coal mine. The schematics of ground drilling and underground in-seam horizontal drilling for pre-extracting CBM are presented in Fig. 1. Compared with the ground drilling, the underground in-seam horizontal drilling shares many advantages such as wider coverage area of coal seam, higher extraction efficiency and lower cost (Zhou et al., 2016). Moreover, the underground horizontal drilling is also used for tectonic exploration, groundwater exploration and release (Yao et al., 2014). At present, the application of underground in-seam horizontal drilling is more widespread than ground drilling in coal mine with roadway. Actually, the underground drilling is also widely used in other mining fields such as gold mines and salt mines for prospecting mineral abundance.

Generally, the borehole trajectory is required to be carefully controlled to ensure that the borehole can extend effectively and predictably across a long distance within the coal seam to enhance the capacity of the CBM extraction. Electromagnetic measurement-while-drilling (EM-MWD) can transmit the engineering parameters from the downhole to the hole top (i.e., the mouth of the borehole), and assist in controlling the borehole trajectory for underground in-seam horizontal drilling.

The schematics of the EM-MWD working principles for ground drilling in homogeneous formation and underground in-seam horizontal drilling are presented in Fig. 2. As shown, the drill pipe is divided into two asymmetrical parts (i.e., upper and lower drill pipes) by a short electrically insulated special drill pipe called the insulated gap.

---

[*] Corresponding author.
*E-mail addresses:* shaochun_74@163.com (C. Shao), xulin@cug.edu.cn (L. Xu), chenxj@cug.edu.cn (X. Chen), chuzhiwei@cctegxian.com (Z. Chu), yangbaolin.123@163.com (B. Yang).

https://doi.org/10.1016/j.jngse.2018.06.002
Received 13 September 2017; Received in revised form 29 May 2018; Accepted 3 June 2018
Available online 06 June 2018

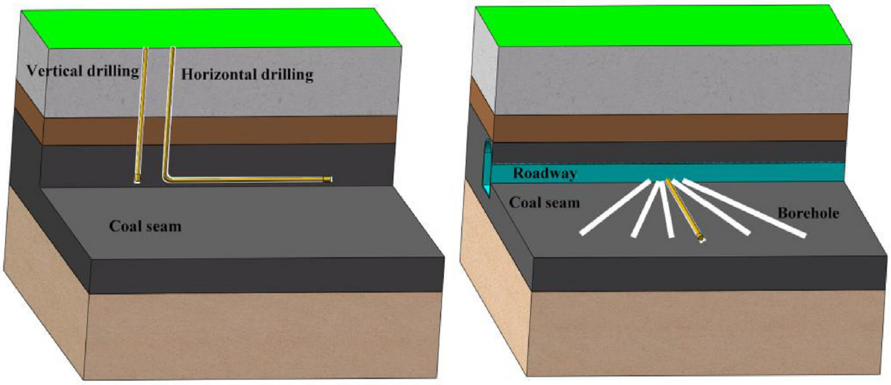
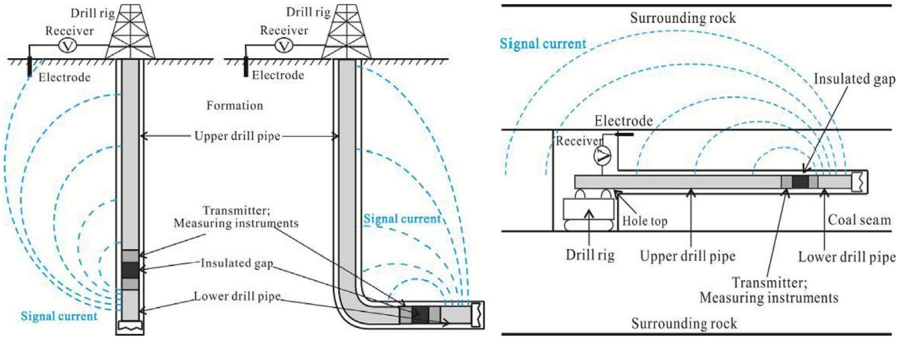


**Fig. 1.** Schematics of ground drilling and underground in-seam horizontal drilling for pre-extracting CBM.



(a) ground drilling in homogeneous formation (b) underground in-seam horizontal drilling

**Fig. 2.** Schematics of the EM-MWD working principles of two different drilling methods.

The measured data in the downhole are encoded as an extremely low-frequency electromagnetic signals by the transmitter and transmitted to the hole top through the formation (or coal seam and surrounding rock) and drill pipe. The receiver detects the signals by measuring the potential difference between the top of the upper drill pipe and electrode. The data measured in the downhole are obtained by filtering and decoding the received signals, and then used to adjust the borehole trajectory as necessary. However, there is a limitation of EM-MWD in terms of the application depth because the received signal intensity is affected significantly by many factors, and hence, it remains undetected in certain conditions. To better guide the development and application of EM-MWD, it is necessary to develop a numerical model and investigate the influencing factors of the received signal intensity (Schnitger et al., 2009).

On this issue, many factors such as the signal frequency, formation resistivity, lengths of the drill pipe and insulated gap, resistivities of the drill pipe and drilling fluid, and casing have been investigated for ground drilling in homogeneous formation (Fig. 2a). A high signal frequency causes severe attenuation of the received signal intensity, and hence, a low signal frequency (generally less than 30 Hz) should be selected for a deep borehole (Bhagwan and Trofimenkoff, 1983; Chen and Jin, 1991; Wang and Zhang, 1991; Maekawa et al., 1992). Formation resistivity is the primary factor, and low formation resistivity leads to a significant attenuation of the received signal intensity (Trofimenkoff et al., 2000; Yu and Ding, 2008). Longer length of the lower drill pipe (i.e., the drill pipe between bit and insulated gap) and insulated gap, and shorter length of the upper drill pipe (i.e., the drill pipe between insulated gap and hole top) imply stronger intensity of the received signal (Li et al., 2014). A low resistivity of the drill pipe and high resistivity of the drilling fluid can enhance the received signal intensity (Bhagwan and Trofimenkoff, 1983; DeGauque and Grudzinski, 1987; Vong et al., 2006). In addition, the casing has two opposite effects: the received signal is shielded when the insulated gap is in the casing, whereas it is enhanced when the insulated gap is outside the casing (Xiong and Hu, 1997; Vong et al., 2005, 2006).

For underground in-seam horizontal drilling (Fig. 2b), there are two significant differences in the signal channel with ground drilling (Fig. 2a). On the one hand, the signal current of underground in-seam horizontal drilling inflows to the opposite-side formation of the upper drill pipe (i.e., the coal seam and surrounding rock on the left of the drill field in Fig. 2b), whereas that of ground drilling are reflected into the formation by the air on the ground, so that the former is full-dimension signal channel, whereas the latter is half-dimension signal channel. On the other hand, considering the difference in resistivities of the coal seam and surrounding rock, the signal channels of underground in-seam horizontal drilling and ground vertical drilling are non-axis-symmetry and axis-symmetry, respectively. Therefore, there are some distinct influencing factors for underground in-seam horizontal drilling such as full-dimension signal channel, coal seam resistivity and thickness, surrounding rock resistivity, borehole location, electrode location, and bit drilling into surrounding rock. Wang et al. (2015a,b) performed some work related to this type of drilling, the signal channel that they investigated had the feature of axis-symmetry because the coal seam and surrounding rock were set to have the same resistivity. However, this is not a realistic case, and factors, except for the full-dimension signal channel, have not been researched. At present, there are very limited studies on the factors affecting the received signal intensity of underground in-seam horizontal drilling.

In this study, we have investigated the distinct factors for underground in-seam horizontal drilling by performing a finite-element simulation. In section 2, the simulation theory of signal transmission was introduced. Based on the quasi-static electric field theory, a three-dimensional (3-D) finite-element model that considers the full-dimension and non-axis-symmetric signal channel was established. Following this, the sensitivity analysis and scale-model experiment conducted to verify the reliability of the model was presented. In section 3, the influencing