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Solid-fluid-gas coupling prediction of harmful gas eruption in shield tunneling

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ABSTRACT

In some cities in the south of China, a stratum of explosive gas was often be encountered in shield tunneling, as well as in other countries. However there is no function of explosion-proof function in the shield machine, and it is likely to cause a large number of harmful gases gushing out instantaneously. The harmful gas concentration can exceed the safety alarm value and even lead to explosion. Based on the above issues, solid-fluid-gas three-phase coupling is analyzed with relevant theories and assumptions through FISH language programming in FLAC^{3D}, which originally only has the solid-fluid two-phase coupling function. The prediction of harmful gas eruptions in shield construction is realized. On this basis, a set of real-time monitoring systems for the harmful gases is constructed, which realizes staff evacuation warnings. The research achievement has been successfully applied in a practical project.

1. Introduction

Harmful gas eruption has been the nightmare of coal miners, threating to their health and life safety (Zhao et al., 1994; Xu et al., 2006; Chen et al., 2012; Cheng et al., 2012; Wang et al., 2014; Kundu et al., 2016). When the gas concentration is at a certain extent, it is flammable and explosive. This has been studied extensively in underground coal mining because methane is frequently found within the coalbed (Rodríguez and Lombardía, 2010; Peng et al., 2012). An accident prediction and prevention of mine gas explosion in mining are mature enough. An engineering geological environment containing explosive gases is also one of the tunnel geologic hazards that can occurr during tunneling (Peters et al., 1985; Gritchfield, 1985; Proctor and Monsees, 1985; Edwards et al., 1988; Pearson, 1991; Shahriar et al., 2009; Zarei, 2011; Peila et al., 2013; Pearson et al., 2015; Taherian, 2015; Zheng et al., 2016). This is not as frequent as the other tunnel disasters, such as tunnel collapse and water gushing. There have been some methane inflow cases during tunnel construction resulting in construction halt and some casualties (Proctor, 2002; Schafer et al., 2007; Tali et al., 2014). Copur et al. (2012) listed eleven cases on accidents related to tunnel gases during tunnel construction in America, Japan, England, Iran, Spain and Turkey; several lessons learnt from these cases were also summarized. The causes and consequences of the methane explosion case in Selimpasa waste water tunnel are reanalyzed later in detail. In Guangzhou, Shanghai, Hangzhou and other cities in China, an engineering geological environment containing explosive gases, such as methane gas, is very common in subway construction. This will lead to a large number of harmful gases rushing into the tunnel, and the concentration of harmful gas may exceed the safety alarm value. However, the traditional shield machine does not have an additional explosion-proof function. Once the harmful gas concentration exceeds safety alarm value, it is very likely to cause harmful gas explosion. Then it will cause unpredictable economic losses and threaten the safety of workers and construction equipment.

Therefore, some special precautions against methane emission must be taken when tunneling by a TBM (Tunnel Boring Machine) in the gas stratum. They can be summarized as follows. First, detailed information about the area of methane emission and some emergency programs should be included in the project design documents. Second, all of the construction facilities must be fire-proof and explosion-proof, and open flame should be completely prohibited; Third, accurate gas monitoring alarm systems, including a gas detection module and a concentration measurement module, must be installed near the tunnel heading. Last but not the least, tunnels with the danger of gas bursts should be well ventilated and advanced geological forecast is imperative. It has been proven that the best measures to avoid explosion hazards is to keep the gas concentration below predetermined dangerous concentrations by supplying sufficient fresh air with a ventilation system. Thus it is necessary to estimate the gas emissions timely and effectively in tunnel excavation. Based on coal mine experiences, Rodríguez and Lombardía (2010) used the measurements of TBM advancing rate, quantity of air flow and methane concentration to predict the methane inflow into a

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tunnel, which was a very simple and useful way to design a ventilation system, i.e., something that is very significant for safety. Moreover, some mathematical methods were also adopted for gas outbursts in tunnels. Chen (2011) used the set pair analysis and stochastic simulation of triangular fuzzy numbers to conduct a risk analysis for gas burst in a tunnel. Peng (2008) presented a comprehensive evaluation method for gas burst in a tunnel during tunnel construction on the basis of extension theory. In addition, based on a set of laboratory tests, Peila et al. (2013) supposed that the use of an EPB machine in the 'closed mode' was an effective way to prevent explosive gases from the rock mass entering into the machine.

The coalbed and organic-rich strata are the major sources of methane in a tunnel, which can be dissolved in underground water and stored in aquifers. Therefore, methane can be accumulated in the pores and fractures (gaseous phase), in groundwater (solution phase) and in organic strata (adsorbed phase) (Edwards et al., 1988; Zarei, 2011). The local gassy strata can be simplified as an underground gas-storage structure which is a mixture structure, containing the gas, water and soil.

The underground gas-storage bag is most likely formed in the silt clay stratum. In terms of the mechanical mechanism of the underground gas storage structure, experts and scholars have conducted numerous research investigations (Aberg, 1977; Goodall et al., 1988; Liang and Lindblom, 1994; Yu et al., 2013; Li et al., 2014). Prior to the shield tunneling the tunnel underground gas-storage structure is in an undisturbed state consisting of the original equilibrium ground stress and pore pressure. In other words, the soil mass around the gasbag and gas and water in the gasbag are maintained in a balance state under the natural state. It is widely believed that the critical pressure of underground gas storage structure was lower than the natural hydrostatic pressure and the applied water curtain pressure. Similar views are presented in this paper that the water-curtain pressure should be higher than the pressure inside the gasbag. When the shield machine advances near the gasbag, the balance is disrupted and the gasbag breaks and bursts. Then, the gas with water will erupt out and rush into the tunnel through the TBM cutter and soil chamber. In a word, this process is a typical and complicated solid-fluid-gas three-phase coupling problem. Therefore, it is necessary and practical that the prediction of methane inflow during tunnel excavation can be realized by a solid-fluid-gas coupling model.

Currently, the multi-field coupling theory has been greatly developed and applied in various domains of geotechnical engineering, such as unsaturated soil, underground oil and gas storage, earth dam, coal containing methane and nuclear waste repositories. Furthermore, hydro-mechanical coupling and thermo-hydro-mechanical coupling have been widely used in the study of gas flow in rocks and coals and the prediction model of gas outbursts in coal mines (Zhao et al., 1994; Xu et al., 2006; Lv, 2012; Peng, 2008; Tao et al., 2012). However, the prediction and determination of gas concentrations during tunneling are often based on mature experiences of coal mines. There are few quantitative studies based on the solid-liquid-gas coupling theory regarding the migration mechanism of gas in the underground gas-storage structure.

In a solid-fluid-gas coupling study, Laloui et al. (2003) presented three models on multiphase porous material, such as three phase soil based on the thermodynamic mixture theory and the well-known Biot's relations. They included a three-phase pore material solid-fluid-gas three-phase coupling model and two kinds of two-phase pore material coupling models, i.e., solid-liquid and solid-air. They insisted that the air existing in the soil was as either incompressible body or empty space. Nuth et al. (2010) analysed the compaction phenomena due to water injection in reservoirs with a three-phase geomechanical model in the library to study the land subsidence resulting from the industrial pumping of underground fluids. Xiong et al. (2014) developed a finite element–finite difference scheme (FE–FD) program for the soil–water–air fully coupling model for slope failure analysis in unsaturated ground. With the aim of expanding the soil skeleton–water coupled finite deformation analysis code, it was mounted with the SYS Cam-clay model and was capable of accommodating inertia forces to deal seamlessly with soils from the unsaturated to the saturated states. Noda and Yoshikawa (2015) proposed a new soil skeleton–water–air coupled finite deformation analysis method based on the three-phase mixture theory. Elia et al. (2011) studied the seismic behaviour of an existing homogeneous earth dam using a fully coupled finite element effective stress approach in conjunction with a recently developed multi-surface, elasto-plastic constitutive model for structured soils. They stated that the model was calibrated using laboratory test results for the embankment material and the foundation soils.

Although many authors have contributed substantial efforts toward the coupled modeling of interactions among the three phases in unsaturated soil, the coupling process of gas transport in the coalbed is also focused on. The major objective of this paper is to present a more comprehensive modeling strategy for soil-fluid-gas coupling and a numerical solution method for the prediction of gas emission into a tunnel. Based on the analysis of numeral modeling, some guidelines for preventing methane gas explosions during tunnel construction are presented. The engineering application shows that the results of the numerical simulation method of the solid-fluid-gas coupling in this paper are in good agreement with the measured results in the field, and it has been successfully applied in practical projects.

2. Theories and hypotheses

Solid-fluid-gas three-phase coupling refers to the interaction mechanical relations among the soil skeleton, fluid (viewed as water) and gas in the soil layer. Based on Biot's consolidation theory (Biot, 1941), a solid-fluid-gas coupling model is proposed, and the main difference from the model presented by Elia et al. (2011) is that the gas is a compressible body and entity. The effective stress borne by the soil skeleton and pore pressure meet the principle of effective stress (Terzaghi, 1960), and the relation between the gas and water pressure in unsaturated soil is equivalent to that proposed by Bishop using a phenomenological approach (Bishop, 1959).

2.1. Analysis of fluid phase in three-phase body

The fluid flow state in porous media is complex and irregular, affected not only by the characteristics of the pore structure and soil grain but also by the fluid pressure. The Reynold's number is the main index that defines the state of fluid flow. Therefore, the flow equation of the fluid can be determined according to the Reynold's number.

(1) Flow equation of fluid

When the fluid flow is in the laminar state, the flow equation satisfies Darcy's law (Darcy, 1956):

$$v_f = -\frac{k_{fh}}{\rho_f g}\nabla p_f \tag{1}$$

$$\text{in which:}\nabla = \left(\frac{\partial}{\partial x}i + \frac{\partial}{\partial y}j + \frac{\partial}{\partial z}k\right)$$

where v_f is fluid velocity (m/s); k_{fh} is fluid hydraulic conductivity (m/s); ρ_f is fluid density (kg/m^3), for water $\rho_f = 1000$ kg/m^3; p_f is fluid pressure (Pa); and ∇ is the Nabla operator; g is the gravity acceleration (m/s^2), $g = 9.81$ m/s^2.

(2) Judgment of fluid flow state

The fluid flow state is judged based on the Reynold's number. The Reynold's number is defined as: