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Experimental investigation on gas migration in saturated Shanghai soft clay

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ABSTRACT

Understanding of gas migration behavior in saturated soft soil is of great importance for designing and construction activities involving applications of pneumatic caisson method and compressed-air tunneling technique in soft ground. For further investigation of mechanical effect on gas migration behavior in such applications, including gas flow rate, gas permeability, as well as the gas breakthrough pressure, step-wisely gas injection tests were conducted on Shanghai soft clay under different vertical loads in this paper. Results show that gas flow rate will increase as the injection pressure increases. The conventional two-phase flow theory, which is mainly governed by capillary pressure, can be used to model gas flow under lower gas injection pressures, but fails to describe gas flow under higher gas injection pressures, due to the significant influence of mechanical stress. As effective stress increases, gas permeability decreases sharply at the initial stage followed by a gradually stabilization stage due to the dissipation of mechanical effect. The mechanical stress has significant influence on gas permeability for specimens with higher compressibilities. Formation of gas flow pathways, either caused by capillary pressure or mechanical stress, can result in gas breakthrough, the corresponding pressure of which is determined according to the evolution of gas flow rate and can be used as the working gas pressure for avoiding significant gas loss in the gas-tight working structures in pneumatic caisson method and compressed air tunneling technique. Gas breakthrough pressure increases with the increase of vertical load.

1. Introduction

The pneumatic caisson method and the compressed-air tunneling technique are of great importance in excavation of deep foundation pits and construction of tunnels in shallow saturated soft clay. During the construction process, groundwater may inflow or even lead to the collapse of deep foundation pit or tunnel. By injecting air into the gas-tight structure of the caisson or tunnel, water inflow could be prevented due to the equal or even higher gas pressure inside the structure than the surrounding water pressure (Dabill et al., 1996; Kodaki et al., 1997; Scheid et al., 2005; Sun et al., 2009; Chinkulkijniwat et al., 2015). As shown in Fig. 1, if the groundwater pressure (P_w) is counter balanced by the gas pressure (P_g) at the bottom of the gas-tight structures, the water-gas differential pressure will increase linearly from the bottom and reach a maximum value at the top of the gas-tight structures, which will result in gas loss into the surrounding saturated soils. Therefore, sound understanding of the gas flow behavior in saturated soils is very important (Javadi and Snee, 2002; Scheid et al., 2005).

Previous experimental researches report that gas migration through a saturated porous medium is a complicated process because of the coexistence of the liquid and gas phases (Ho and Webb, 2006). Moreover, basic properties of geo-materials (i.e. permeability, porosity, pore size distribution, tortuosity of the flow channels, etc.) and the mechanical state (i.e. external load, fluid pressure, effective stress, etc.) also play important roles in controlling gas flow behavior (Hoseman et al., 1999; Zhao et al., 2002; Marschall et al., 2005; Senger et al., 2008; Yu and Weetjens, 2009; Perera et al., 2011; Ye et al., 2014; Xie et al., 2015).

For a porous medium with low permeabilities (usually lower than 10e-16 m^2), gas migration, accompanied by the displacement of pore water, is normally regarded to be driven by the capillary pressure (the differential pressure between gas and water), which is mainly described in the conventional two-phase flow theory (Mualem, 1976; van Genuchten, 1980; Parker et al., 1987; Luckner et al., 1989; Delahaye and Alonso, 2002; Ho and Webb, 2006; Kamiya et al., 2006; Alkan and Müller, 2008; Gerard et al., 2014). With the increase of gas injection pressure leading to the desaturation of the porous medium, more pathways become accessible to gas migration. Using a 1-D soil column testing system, Ng et al. (2015) once conducted a series of stepwise air-injection tests on compacted clay with consideration of the liquid saturation effect. Test results clearly presented non-linear gas flow behavior

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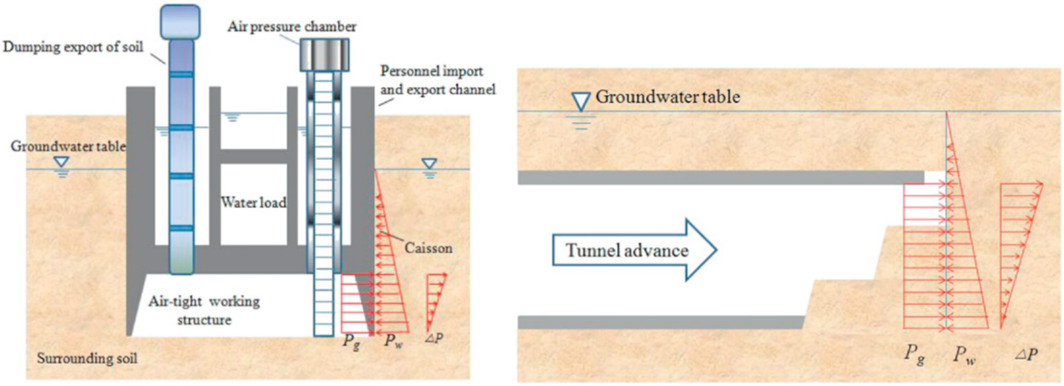


(a) Pneumatic caisson method (b) Compressed gas tunneling technique

Fig. 1. Principle of pressure balance in engineering practices.

or gas breakthrough phenomenon due to the capillarity-induced formation of gas flow pathways during this process (Fig. 2).

Recent researches also reported that for ultra-low permeability materials (permeability < 10e-20 m^2), due to the extremely large gas entry pressure (>15 MPa, Gerard et al., 2014), the capillary pressure plays a limited role in gas migration. When gas injection pressure reaches a critical value, significant increase of gas flux could be observed due to the mechanical-induced dilatancy of the flow pathway or expansion of the pore space, as shown in Fig. 3 (NAGRA, 2008). These observations are supported by numerous other studies (Hoseman et al., 1999; Zhao et al., 2002; Marschall et al., 2005; Senger et al., 2008; Navarro, 2009; Yu and Weetjens, 2009; Ye et al., 2014; Gerard et al., 2014). That is to say, for ultra-low permeability materials, mechanical effect is the main controlling factor on gas migration behavior, while the conventional two-phase flow (capillary flow) theory cannot properly describe gas flow behavior in this situation (Hoseman et al., 1999; Marschall et al., 2005).

It is evident that gas flux will significantly increase once a critical pressure is reached, either induced by capillary or mechanical effects. This critical pressure is termed as gas breakthrough pressure. From an engineering viewpoint, the determination of the gas breakthrough pressure, which is corresponding to the unexpected gas loss in the gas-tight structure, is a fundamental aspect in application of the pneumatic caisson method and the compressed-air tunneling technique. Furthermore, the capillary and mechanical control of gas flow behavior, as well as the suitability of conventional two-phase flow theory in this application, should be investigated in details. Therefore, step-wisely gas injection tests were conducted on saturated Shanghai soft clay under different vertical loads and the test results were obtained and analyzed in this paper.

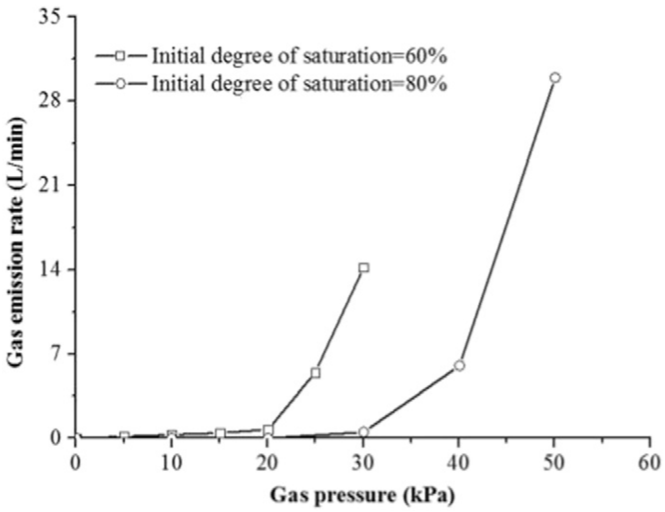


Fig. 2. Non-linear gas flow or gas breakthrough for compacted clay specimens with low permeability (Ng et al., 2015).

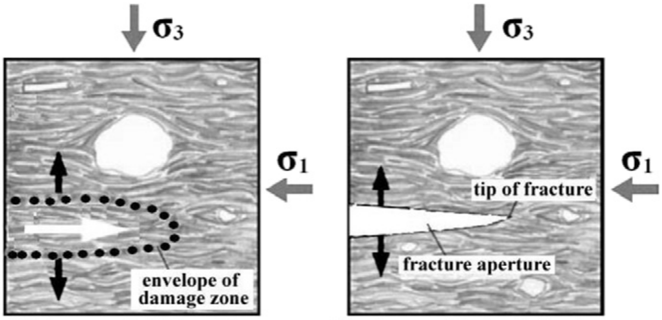
2. Experimental investigation

2.1. Test apparatus

A test apparatus for step-wisely gas injection tests is designed and shown in Fig. 4. It composes of five parts including a loading system, a testing cell, a liquid pressure-volume controller (for water injection), a gas pressurization system and multi-gas flow meters with a data acquisition system.

The loading system, which is designed for applying vertical load on the specimen, mainly consists of a basement, a loading piston and a cell ring. The outlet in the loading piston was designed either for connecting the liquid pressure-volume controller to monitor the volume/pressure evolutions of the deionized water injected during the hydraulic conductivity test, or the multi-gas flow meters to record the gas flow rate during gas injection test. Air was adopted as the injected gas in the tests. Two outlets were designed in the basement, one was connected to a valve for air expulsion during hydraulic conductivity tests and the other one was connected to the gas pressurization system during gas injection tests, which consisted of an air compressor and a pressure regulator for keeping stable gas injection pressure with an accuracy of ±10 kPa.

The liquid pressure-volume controller employed has a measurement accuracy of ±1 kPa in pressure and ±1 mm^3 in volume. For measuring a broad range of gas flow rates, the Sevenstar® CS200A series



Dilatancy controlled gas flow (Pathway dilation) **Gas transport in tensile fractures (Hydro- / gas- fracture)**

Fig. 3. Mechanical stress induced dilatancy of the flow pathway (NAGRA, 2008).