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An experimental examination of foam stability under pressure for EPB TBM tunneling

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ABSTRACT

Foam as a soil conditioning agent has been extensively employed in earth pressure balanced (EPB) tunnel boring machines (TBM) to change the mechanical and hydraulic properties of soils for effective excavation. Foam stability is a critical parameter that influences the performance of foam and foam-conditioned soils. This paper examines foam stability under pressure through a novel foam generation – pressure chamber – foam capture testing system. A comprehensive suite of foam experiments was performed to examine the physical phenomenon of foam degradation and time-dependent foam properties under pressure. Testing results suggest that foam liquid loss is not an effective indicator for characterizing foam stability, while foam volume loss is a more appropriate measure of foam stability. Results also reveal that foam liquid drainage is significantly retarded at higher chamber pressure because foam bubbles are smaller and more uniform. Bubble size was not appreciably different in dry and wet foams.

1. Introduction

Foam is routinely used to modify the in-situ soil properties during excavation in EPB TBM tunneling. The desired properties of foam-conditioned soil include elasticity, high compressibility, low shearing resistance, low permeability and flowability/workability (Budach and Thewes, 2015; Milligan, 2000; Mori et al., 2018; Peila, 2014; Thewes et al., 2012; Vinai et al., 2008). When foam is homogeneously mixed with soil, the foam bubbles create particle or clod separation that transforms the in-situ soil into a compressible, elastic medium with sufficiently low permeability and greatly reduced shearing resistance. Sufficient compressibility is needed so that unavoidable changes in TBM advance rate or screw conveyor discharge rate does not translate into significant chamber pressure fluctuations (Bezuijen and Schaminee, 1999; Mooney et al., 2016; Mori et al., 2017; Psomas and Houlsby, 2002; Quebaud et al., 1998). Conditioned soil in the chamber is subjected to tens to hundreds of cycles of loading due to such advance rate/discharge fluctuations as well as potential rotation of material from lower pressure in the upper portion of the chamber/cutterhead openings to higher pressure in the lower portion of the chamber/cutterhead openings. It is therefore important that the foam behaves elastically, i.e., that plastic strain does not accumulate with loading cycles. Further, the foam serves to restrict water flow through the soil's pores.

A critical characteristic of foam in conditioned soil is its stability, i.e., the ability of foam to maintain its structure and the aforementioned properties when mixed with soil throughout residency time in the chamber. During normal operations, residency time can vary from 30 to 90 min depending on the diameter of the TBM, depth of the excavation chamber, advance rate, etc. Because foam stability greatly affects foam-conditioned soil behavior in EPB TBM tunneling, it is important to understand the fundamentals of foam stability in the context of EPB TBM tunneling. Schramm and Wassmuth (1994) define foam stability as the resistance to the processes of film (bubble wall) thinning and coalescence (film rupturing). In film thinning, the liquid films that separate bubbles thin and bubbles approach closely together. In coalescence, the films between bubbles rupture and bubbles merge together to form larger bubbles. Schramm and Wassmuth (1994) state that foam stability is largely determined by liquid drainage and rupture of the thin film. Quebaud et al. (1998) describe 'foam persistence' (akin to the meaning of stability) as the capacity to maintain a constant volume and keep the liquid of the matrix from flowing out. As we demonstrate later, maintaining constant volume and limiting liquid drainage are quite different behaviors.

In tunneling, foam stability is typically characterized by its foam liquid half-life, defined as the time necessary for foam to lose one-half of its initial liquid fraction due to drainage. While there is no standardized testing procedure (e.g., ASTM, DIN), the EFNARC (2005)

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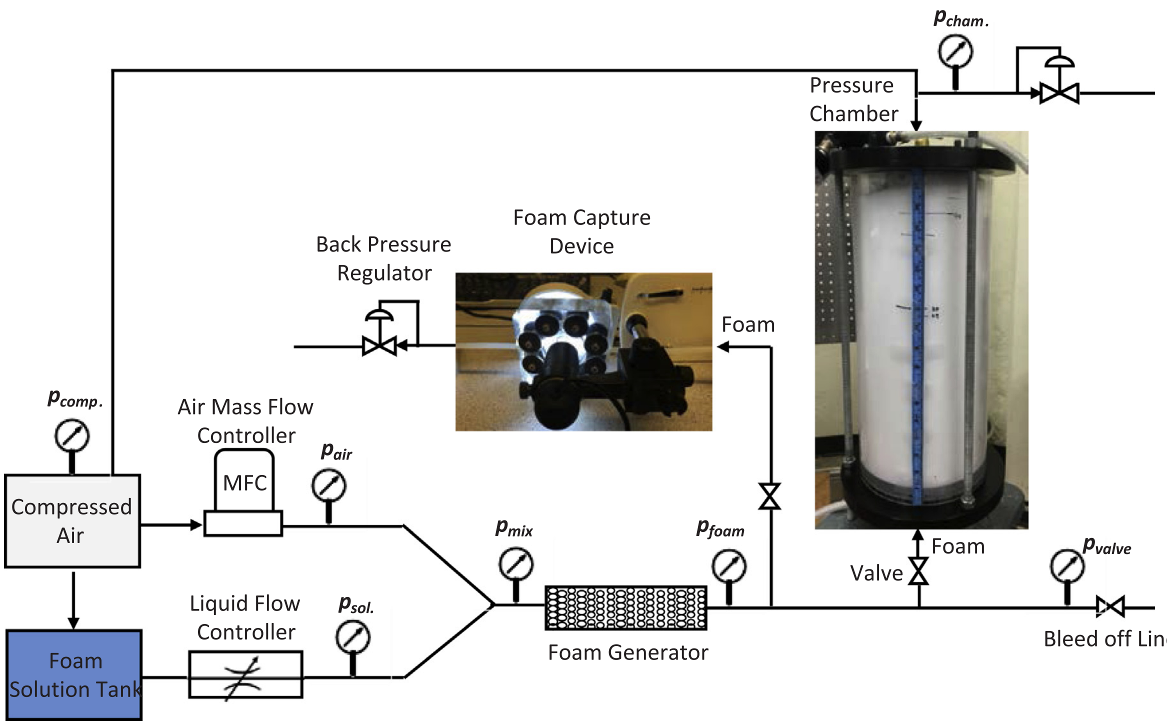

Fig. 1. Schematic of the laboratory foam generation system and foam testing devices (pressure chamber and foam capture device).

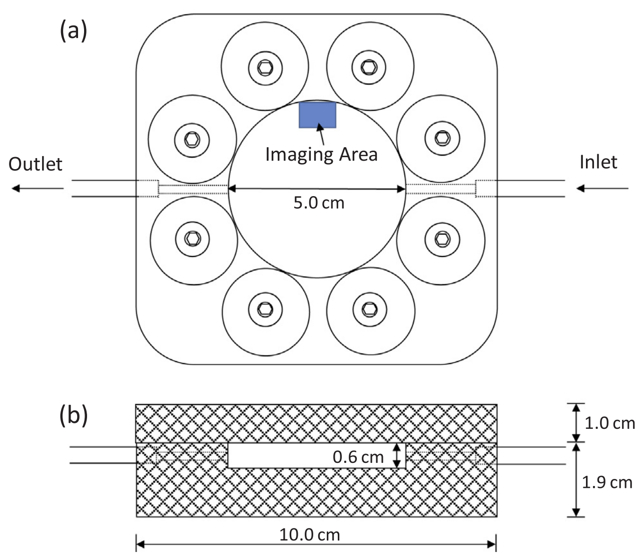

Fig. 2. Schematic of the foam capture device.

recommends using a filter-funnel filled with 80 g foam subjected to atmospheric pressure to measure liquid drainage and determine foam liquid half-life. The EFNARC (2005) half-life (or liquid drainage) method is widely used and referenced in characterizing foam stability for soil conditioning in tunneling (Milligan, 2000; Psomas and Houlsby, 2002; Quebaud et al., 1998; Thewes et al., 2012).

The rationale for using liquid drainage time as a measure of foam stability for EPB soil conditioning is not well addressed in the literature, but perhaps can be related to non-tunneling based fundamental studies of foam (Rand and Kraynik, 1983; Schramm and Wassmuth, 1994). It may be, as alluded to in Quebaud's definition that the prevailing assumption is that significant liquid drainage results in significant foam volume reduction. To the author's knowledge, only one publication, by Langmaack (2009), suggests that the foam volume can be used in addition to liquid drainage since the remaining foam volume is more relevant to judge the stability of the foam-soil mixture. The author reports approximately 5% foam volume loss of two different foams over 30 min. Unfortunately, liquid loss was not reported.

The term 'stability' implies the continuance of desired properties without change. It is unclear whether liquid drainage implies an accompanying degradation in desired engineering properties, i.e., elasticity, compressibility, etc. And, at a fundamental level, it is unclear what is physically happening to foam properties during liquid drainage. Further, the traditional liquid drainage test is conducted under atmospheric pressure, while in practice foam and foam-conditioned soils are almost always subjected to pressure in the tool gap, excavation chamber and screw conveyor of an EPB TBM. This paper addresses these issues by examining foam stability in the context of sustained performance as described above. A comprehensive suite of experiments was conducted using a novel foam generation – chamber pressure – foam capture device testing system that allows the measurement of macroscopic and microscopic foam properties under pressures typically experienced in tunneling. The physical phenomena of liquid drainage is characterized and its relationship to foam performance is examined. Finally, the implications on tunneling practice are discussed.

2. Test equipment

A novel foam generation – pressure chamber – foam capture device testing system was developed to perform a comprehensive suite of foam experiments. Fig. 1 shows a schematic of the laboratory foam generation system and foam testing devices. A liquid flow controller and an air mass flow controller were used to produce a foam solution plus compressed air mixture with the desired foam expansion ratio (*FER*). The foam generator was comprised of closely packed 3 mm glass beads. The foam solution was prepared by mixing water with a commercially available surfactant at a desired concentration (c_f). In this study, c_f = 5% was used for all the foam tests. The foam solution-air mixture then flowed through a 20 cm long and 1.5 cm inside diameter laboratory-scale foam generator.

A 45 cm tall, 11.4 L pressure chamber was used to simulate the pressurized environment that exists in the tool gap, mixing chamber,