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Apparent density evaluation methods to assess the effectiveness of soil conditioning

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ABSTRACT

A study was performed on the University Link and Northgate Link projects in Seattle, WA, to investigate the use of apparent density evaluation methods for the identification of air pockets and plugging issues in the chamber of EPB TBMs. Both air pockets and plugging issues can result from improper soil conditioning and the TBM's inability to mix the soil properly with the conditioning agents. An apparent density below unity indicates the formation of an air pocket in the top part of the chamber and an apparent density above the virgin soil density points to developing plugging issues in the cutterhead bays and pressurized chamber. From the conducted study it can be concluded that the presented apparent density evaluation methods are an effective way to identify issues in the excavation chamber of an EPB TBM and can be used as a mean to improve the soil conditioning process.

1. Introduction

Proper soil conditioning in EPB tunneling offers many advantages to the quality and productivity of the project. There are few operational parameters that can be used to clearly assess the soil conditioning performance such as advance rate, torque, thrust, and chamber pressures. One of the other parameters that potentially can be used is the apparent density. The apparent density of the material in the chamber was introduced by Guglielmetti et al. (2003) as the vertical chamber pressure gradient calculated from the physical relation between the horizontally measured excavation chamber pressures and the vertical distance between the pressure sensors. Guglielmetti et al. (2003) introduced apparent density as a measure to ensure the excavation chamber is filled with material. To guarantee face stability, the authors suggest to keep the apparent density over a certain limit so the material is able to transfer effective stress to the virgin soil, and thus provide support of the excavation face. This method was implemented in the Metro project in Porto, Portugal.

Bezuijen et al. (2005) compared the vertical gradient of the horizontal bulkhead pressures to the total density of excavation chamber material and discovered that the gradient is not necessarily representative of the muck total density. The authors assumed that the yield stress of the muck as well as the adhesion between the muck and the cutterhead and bulkhead material have an influence on the vertical gradient. They simplified the resulting pressure gradient to Eq. (1).

$$\frac{dp}{dz} = \rho g \pm 2\frac{\tau_a}{L} \tag{1}$$

where $\frac{dp}{dz}$ is the vertical pressure gradient, p is the horizontal bulkhead pressure, z is the elevation, ρ is the total muck density, g is the gravitational acceleration, τ_a is the yield stress of the muck, and L is the length of the excavation chamber. In this equation, term $2\frac{\tau_a}{L}$ is added or subtracted depending on the direction of the muck flow in the chamber.

Alavi Gharahbagh et al. (2013) suggest that if muck contains an excessive amount of foam, the excessive foam will travel to the top of the chamber and an air pocket will form. This pressurized foam pocket is able to counteract the face pressure temporarily until the released air dissipates into the surrounding ground. This is a bigger problem during mining stops, where foam is not constantly added compared to the mining cycles. Possible issues that can arise from the formation of such an air pocket are: support pressure drops, water and muck flow into chamber, overexcavation, surface settlements, and blowouts through screw conveyor and to surface. The authors used apparent density to identify the existence of an air pocket in the excavation chamber of the University Link Light Rail Tunnel project in Seattle, WA. They suggest that an apparent density below the density of water indicates an air pocket in the chamber. Alavi Gharahbagh et al. used a port through the top of the bulkhead and a ball valve to bleed the accumulated air from the chamber. Another method that was suggested by the authors was to reduce the amount of injected foam into the chamber by modifying the

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Nomenclature

Symbol	Description (Unit)
∇	vertical chamber pressure gradient (kN/m^3)
FIR	foam injection ratio (%)
F_T	thrust force (kN)
g	gravitational acceleration (m/s^2)
K	coefficient of lateral earth pressure (–)
L	length of excavation chamber (m)
p	pressure; horizontal bulkhead pressure (kPa)
p_1	pressure measured by chamber pressure sensor #1 (kPa)
p_{16}	average of p_1 and p_6 (kPa)
p_2	pressure measured by chamber pressure sensor #2 (kPa)
p_3	pressure measured by chamber pressure sensor #3 (kPa)
p_4	pressure measured by chamber pressure sensor #4 (kPa)
p_5	pressure measured by chamber pressure sensor #5 (kPa)
p_6	pressure measured by chamber pressure sensor #6 (kPa)
$p_{ambient}$	ambient pressure of surrounding ground (kPa)
T	cutterhead torque (kN-m)
u	pore pressure (kPa)
v	advance rate (mm/min)
z	vertical distance; elevation (m)
z_B	vertical distance between bottom two chamber pressure levels (m)
z_T	vertical distance between top two chamber pressure levels (m)
γ	total unit weight of material in chamber (kN/m^3)
γ'	buoyant unit weight of the chamber soil (kN/m^3)
γ_f	unit weight of chamber fluid (kN/m^3)
ρ	total muck density; total density of material in chamber (g/cm^3)
ρ_f	density of chamber fluid (g/cm^3)
ρ_S	density of in-situ soil (g/cm^3)
ρ_w	density of water (g/cm^3)
ϱ	apparent density (g/cm^3)
ϱ_B	bottom chamber apparent density (g/cm^3)
ϱ_T	top chamber apparent density (g/cm^3)
σ_x	horizontal stress in tunneling direction (kPa)
σ_x'	effective horizontal stress in tunneling direction (kPa)
σ_z'	effective vertical stress (kPa)
τ_a	yield stress of muck (kPa)
*1 bar	100 kPa

foam injection and expansion ratios.

Bezuijen and Talmon (2014) compared the vertical gradient of pressures measured on the front and backside of the cutterhead to the gradient of pressures measured on the bulkhead of the Botlek Railway EPB TBM. They found that the vertical gradient of the horizontally measured pressures increases slightly from the front to the back of the cutterhead and increases significantly from the cutterhead to the bulkhead. The gradients also fluctuate over time and can reach levels higher than the in-situ soil density, which indicates the presence of effective stress. The gradient of pressures measured on the bulkhead is higher in the bottom of the chamber than at the top, which indicates a separation of the muck in the chamber.

Maidl and Stascheit (2014) integrated active density control of muck in the excavation chamber in their process control software for mechanized tunneling. The authors determine the density of the material in the chamber from the advance rate, the volume of conditioning agents injected, and the quantity of material leaving the screw conveyor. The goal is an optimal consistency of the muck and a reduction of soil conditioner usage.

Mosavat and Mooney (2015) examined the vertical gradient of horizontally measured chamber pressure (at six elevations on the chamber bulkhead) for a 17.5 m diameter EPB TBM during the early portion of a tunneling project in Seattle. The average or global vertical chamber pressure gradient was found to be 10–20% less than the total density (unit weight) of the samples taken from the belt conveyor during tunneling through the cohesive clay/silt and till deposits. They also show that the gradient varied locally within the chamber. The local gradient near the top of the chamber was consistently smaller in magnitude than the gradient near the bottom of the chamber. Mosavat and Mooney (2015) proposed that the vertical gradient of horizontal chamber pressure measurements is a function of both density and the coefficient of lateral earth pressure in the excavation chamber (derivation presented in Section 2.1). They speculate that the underestimation of total muck density using the gradient suggests that the lateral earth pressure coefficient in the excavation chamber is less than unity. The vertical chamber pressure gradient was found to be similar in magnitude to the density of conveyor belt samples during tunneling through predominantly granular soils, suggesting the lateral earth pressure coefficient equals unity and the gradient serves as a measure of muck unit weight. Like Bezuijen et al. (2005), Mosavat and Mooney (2015) presented data to illustrate differences in chamber pressure magnitude and gradient depending on whether muck was flowing upward or downward. They were not able to rationalize the difference.

Dobashi et al. (2007) and Dobashi et al. (2013) introduced and discussed a system for visualizing the muck flow inside the excavation chamber of an EPB TBM that was used on the SJ51 and SJ53 sections of the Metropolitan Expressway Central Circular Shinkjuku Route. Four flappers were installed in the excavation chamber of the EPB TBM and were rotated during the excavation. A relationship between flapper torque and muck flow velocity and deformation rate in the excavation chamber was established via numerical analysis. Muck flow velocity and deformation rate are indicators for the condition of muck in the excavation chamber (e.g., a high flow velocity but low deformation rate indicates clogging). Dobashi et al. (2007) used the measured flapper torque to identify regions of poor plastic muck flow and adjusted the injected additive volume in these regions to improve the muck flow.

This paper presents apparent density evaluation methods to assess the effectiveness of soil conditioning. In this context the term apparent density is defined as the vertical gradient of the horizontally measured chamber pressures divided by the gravitational acceleration. However, as shown in previous research summarized above, the apparent density is not necessarily equal to the actual density of the material in the chamber. Several factors can influence the relationship between apparent and actual density and a theoretical relationship can be formulated which will be discussed in more details in Section 2.1.

2. Background

The theoretical relationship between the apparent density and the chamber pressures can be established by taking the muck density in the excavation chamber as well as the coefficient of lateral earth pressure into account (see Section 2.1). However, the apparent density is not only influenced by these factors but also by soil conditioning and operational parameters as described in Section 2.2.

2.1. Relationship between apparent density and chamber pressure gradient

Mosavat and Mooney (2015) proposed that the vertical chamber pressure gradient is a function of total muck and fluid unit weights as well as the coefficient of lateral earth pressure. The horizontal pressure p ($p = \sigma_x$ where x is oriented in the direction of tunneling) measured by the chamber pressure sensors is theoretically a total pressure composed of pore fluid pressure u and lateral effective earth pressure σ'_x as shown in Eq. (2). The vertical effective stress σ'_z is related to the horizontal