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Theoretical basis of slurry shield excavation management systems

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ABSTRACT

Slurry shields are commonly used not only in Singapore but worldwide. As these are often used in very challenging nonhomogeneous ground conditions, it is crucial to understand and improve the processes which will help to prevent over-excavation, sinkhole and settlement risks. Slurry shields utilize a bentonite suspension to provide support to the tunnel face and to transport spoil to the surface. By comparing the measured inflow and outflow rates it is possible to calculate and display on real time basis the amount of excavated material. For this purpose there are flow meters and density meters installed in the slurry circuit. Based on the measurements there are different methods to calculate the quantity of excavated material. These can be presented as excavated volume, mass or dry mass following different formulae. As the calculation methods differ slightly in their approach, the sensitivity to the various influences on the slurry circuit depends on the chosen calculation approach. Such influences can be measurement errors, mechanical, electrical and hydraulic issues, the influence of time as well as changing geology. Also in case there is over-excavation of solids, ingress of ground water or bentonite loss into the ground, the different formulae will reflect these effects through different results. While one approach may be more suitable under certain conditions, another approach will be more appropriate in other conditions. In order to provide the industry a clear view of the advantages and disadvantages of the various approaches under different conditions, this paper presents a set of definitions for all the parameters involved. The different calculation approaches are then compared on the basis of the unified definitions. The focus of the study centres on the behaviour of the different calculation methods, during situations such as a face collapse, calibration error of sensors, water inflows or compressed air interventions. A simulation tool in Excel is presented which allows defining several real life examples and the different calculation methods. Subsequently the behaviour of different calculation algorithms is shown and explained. This analysis and comparison allows not only the improvement of practical excavation control systems in the future but also helps the various stakeholders to better understand and interpret the measurements and calculation results obtained by the different systems available in the market.

1. Introduction

The slurry shield, previously known as bentonite tunnelling machine, was invented and full scale trials were conducted in the UK in the early 1970s for the sole purpose of achieving better control of excavation in difficult ground conditions (Bartlett et al., 1974). At the time the challenge was to excavate safely through submerged sand and gravels without causing over-excavation or instability of the tunnel face. Slurry shields are nowadays used in a variety of ground conditions which include hard rock and stiff clays primarily to take advantage of their superior ability to respond to sudden variations in the grounds conditions. The monitoring of the slurry circuit is an important task for quality control of tunnelling processes; this includes the continuous monitoring during tunnelling as well as regular reviews of the latest progress but also the back analysis after project completion of incidents which require investigation. The main parties concerned are the contractors under whose responsibility TBMs are operated but also project owners, authorities, consultants and TBM suppliers (McChesney et al., 2008). There are several different approaches to measure and calculate the amount of excavated material. The calculation formulae used in the industry have been developed by suppliers of TBMs, slurry circuits and monitoring systems. There are typical solutions developed by individuals for their employers and as a result different TBM suppliers use different approaches.

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There are also specific approaches requested by contractors and implemented by the suppliers. Although these approaches are all based on the same underlying principles, they vary in terms of hardware, signal processing and calculation procedures. There are several simplified formulae which are theoretically not correct but have been used successfully on site. The theoretical target value of excavation quantity is difficult to determine because of the variations in specific gravity, moisture content, pre-existing voids etc. in the ground. The user interface and visualization of the systems available in the market can differ quite a lot so results are not necessarily comparable. On top of all this, there are claims by some suppliers about the high level of accuracy of their system which when examined closely could be classified best as technically incorrect if not fictitious.

This paper gives an insight into the implications arising from the use of different formulae and clearly defines the theory of excavation management which can be used as a reference for future work and discussions. The authors intend to present a unified theoretical basis which is unbiased towards any single individual developer and built on the standards set by the large industry associations such as ITA, DAUB or BTS. To make the results tangible, an Excel based simulation tool is presented which allows the comparison of different formulae. This tool is then used with input data which corresponds to experiences from actual projects. The tool simulates one ring of advance and it can process the input data for different scenarios and produce the measurement results for each type of calculation formula.

1.1. Contractual framework for mass balance systems

The contractual framework for excavation management systems is usually set in the TBM specifications by the project owner. In the Singapore context this is usually LTA, SPPA or PUB. This is a requirement under most industry standards (BTS/ICE, 2005; DAUB, 2006; Japan Society of Civil Engineers, 1984). For the last major infrastructure projects there were slight variations in the excavation management requirements stated in the specifications. Table 1 gives an overview of past projects and requirements regarding the excavation management system. As can be seen, the requirements have changed over time and sometimes there are even contradictory or illogical statements in different parts of the specification.

1.2. The slurry circuit

To understand the theory of excavation management, it is necessary to explain the general setup of a slurry circuit. Fig. 1 shows an overview of the slurry circuit. The slurry circuit using bentonite is a pipeline loop that connects the TBM to the Slurry Treatment Plant (STP) at the surface. In front of the machine is the tunnel face, where the ground is excavated by the cutting wheel. The excavated material enters through openings into the excavation chamber, where it is mixed with the incoming bentonite slurry. The slurry has two different functions during the tunnelling process (Eichler, 2007). The first function is face support. Through pressurizing the slurry, support pressure can be applied to the ground to compensate for the earth and hydrostatic pressure. The slurry either penetrates into the ground (filter cake model) or forms a membrane on the face (membrane model) to clog the soil pores (Wehrmeyer, 2000). In the excavation chamber the bentonite slurry is mixed with the excavated soil material and both are pumped to the surface. A pressure bulkhead separates the working chamber from the rest of the rear machine. The transportation of the loaded slurry to the STP is done by pumps in the slurry discharge pipe line. In the STP the excavated material is separated from the slurry to discharge the muck and reuse the slurry. Fresh bentonite slurry can also be added to the circuit. After this process the separated bentonite slurry is fed back into the excavation chamber with pumps via the slurry feed line. During the whole process the pipes of the slurry feed and slurry discharge line need to be extended. Both in the slurry discharge and the slurry feed line sensors are installed to determine the flow rate and density. Different valves regulate the flow into the chamber. Another part of the circuit is the bypass. The bypass maintains the flow in the slurry circuit during stoppage of the TBM without flushing through the excavation chamber (Maidl et al., 2001).

1.3. Possible external and internal influences on the slurry circuit

There are a number of influences on the slurry circuit as well as on the measurement process. Some of these can be quantified easily whereas others are hard to determine directly (Duhme, 2015). Indirect methods have to be chosen to deal with these influences. The following overview in Table 2 allows an understanding of the mechanisms behind many of these influences.

2. Definitions

The parameters and expressions describing excavation management vary between different countries and different publications. This causes a lot of misunderstanding when technical information is communicated between different parties in the industry. This Section introduces the input and output parameters for excavation management and provides a precise foundation for further work by setting out exact mathematical definitions for all relevant parameters. Where possible the definitions follow the Geotechnical Engineering Handbook (Smoltczyk, 2002) as well as the typical industry standards.

2.1. General definitions

The following definitions apply to the operational and geotechnical parameters which are relevant for the excavation management system:

Table 1
Overview of contractual specifications from past projects in Singapore.

Project	Extract
Downtown Line	• "typical" excavated volume from average value shall be taken as reference volume for comparable ground conditions • Measurement of excavated volume based on flow and density readings from slurry feed and slurry discharge line
Cable Tunnel	• Materials from all separation stages are to be collected and their volume of solids and material type measured • The dry mass shall be measured against theoretical excavated mass • All slurry treatment plant (STP) components to be monitored including volumes and weights removed as well as after secondary treatment
Thomson Line	• Advance rate shall be determined by the dry mass of removed material • Volume and mass in the slurry line • Quantity of excavated material for each ring
Thomson East Coast Line	• Advance rate shall be determined by the dry mass of removed material • "typical" excavated volume from average value shall be taken as reference volume for comparable ground conditions