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Effects of slurry on stickiness of excavated clays and clogging of equipment in fluid supported excavations

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ABSTRACT

Mechanized excavation of tunnels and fabrication of deep foundation elements in soft ground often requires a fluid support of the temporarily created openings. The supporting fluids are generally mixtures of bentonite with water, enhanced by chemical additives for difficult geological conditions. The properties of the slurries are chosen to guarantee the stability of the excavation, in particular providing sufficient support to the coarse grained soil layers. When these are interlaid with clayey layers, excavation can be hindered by clogging problems, requiring time consuming cleaning works and causing construction delays. Clogging is caused by the stickiness of the excavated clay, which can be affected both by the clay mineralogy and the composition of the supporting slurry. The paper investigates these effects by means of a laboratory experimental study using novel stickiness tests: the mixing test and a model TBM cutter-head test. For bentonite slurries, the stickiness of the excavated soil was found to correlate with the shear resistance of the slurry. Therefore, increased slurry strength, while beneficial for excavations in coarse soils, may lead to increased susceptibility to clogging under mixed face conditions. In contrast, some pure polymer slurries can help to combine high slurry resistance with low clogging potential by protecting clay aggregate surface from penetration of water.

1. Introduction

Efficient fluid support is necessary for slurry-supported wall and pile excavations and mechanized tunneling. In particular tunneling excavations under the ground water table, where the support of the tunnel face is of major importance, require reliable assessment of the risks and benefits related to the selection of a fluid supported Tunnel Boring Machine (slurry TBM or slurry shield).

The requirements for the properties of the supporting fluid are determined by the process of the specific excavation. Besides the most essential function of supporting the excavated opening, other properties, such as a fast and low-energy transport process without settling of particles through the pipelines and fast separation process of the excavated material enabling a reuse of the slurry, are also of utmost importance.

In many cases sodium bentonite clay slurries are used as supporting fluids, because of their rheological properties (shear-thinning) and their ability to build a gel strength (yield strength). For enhancement of the slurry properties, especially for extreme cases of either very coarse or clayey conditions, the slurry is in some cases treated with additives (mainly polymers). The high number of products available on the market includes natural polymers (starches, guars), cellulose ethers (e.g. carboxymethyl cellulose), polyacrylamides and polyacrylates (Milligan, 2000; EFNARC, 2005). Polyacrylates are used as dispersing agents for conditioning of the soil during excavations with Earth Pressure Balanced Machines (EPBM; Zumsteg et al., 2013) as well as for slurry conditioning of a fluid supported TBM drive (AFTES, 2005). Cellulose products are expected to control and reduce the fluid loss when added to bentonite slurries (AFTES, 2005). Application of polymer-treated bentonite slurries could not always solve the prevailing clogging problems (Mauroy, 1998; Jefferis and Merritt, 2013) and can lead to difficulties for the disposal of excavated soil and slurry.

In some cases, alternative slurries consisting purely of polymers have been successfully used to tunnel through mixed strata or for construction of bored piles (Jefferis and Lam, 2013; Lam et al., 2014). Polymer slurries build an interesting alternative, especially in environmentally sensitive areas and construction sites with limited space conditions (Anonymous, 2001, 2004; Beresford et al., 1989).

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One basic risk, when excavating with a slurry support in clayey soils or in mixed strata with clay layers of high plasticity, is clogging. Depending on the excavation tools used, the problems can occur at different stages of the excavation process and may lead to slower excavation rates, cleaning works or standstills. For slurry shield tunneling the main hazard locations are cutter-head, slurry pipeline and separation facilities (Thewes and Burger, 2005). Although various critical aspects of the excavation procedures and influencing soil parameters contributing to clogging problems have been identified (e.g., Thewes, 1999; Hollmann, 2014), there is still a lack of knowledge concerning the detailed mechanisms. Analyzing clogging problems of several TBM drives, Braun (1997) concluded that the process of clogging is a continuous accretion of sticky material. Several authors state that the disintegration and behavior of the excavated clay lumps is of major importance (Leshchinsky et al., 1992; Hollmann and Thewes, 2013; Jefferis and Merritt, 2013). The recent investigations of Zumsteg et al. (2013) showed the possible benefit of chemically induced clay aggregate protection on the stickiness of soft clay pastes for the application in EPB tunneling.

Whereas it is believed that clogging is caused by the stickiness of the excavated clay, which can be affected both by the clay mineralogy and the composition of the supporting slurry, these effects have not been properly quantified. In particular, it is not known if and to what extent can the yield strength of the slurry and/or the bentonite content affect the stickiness and clogging, and what are the potential benefits of polymer additives and polymer slurries. In this paper an attempt has been made to provide answers to these basic questions by using novel experimental methods and devices for studying the stickiness of conditioned clays for EPB-operation, which were originally proposed by Zumsteg and Puzrin (2012) and further developed for the purposes of the current study.

2. Background: slurry support and clogging potential

2.1. Role of slurry

For successful excavation in soft soils below the groundwater table, the supporting fluid has to fulfill the following essential requirements (e.g., Jefferis, 1992; Guglielmetti et al., 2007; Maidl et al., 2012):

- Stabilization of the excavation and prevention of the water inflow.
- Optimization of the excavated material transport through the pipeline system (low pumping pressures and low abrasion).
- Optimization of separation of the excavated material from the slurry with the reuse of the slurry (reduction of fines content dissolved in the slurry).
- Durability against chemical contamination.

Excavation stabilization requires a pressure transfer from the slurry to the ground (Anagnostou and Kovàri, 1994), which is generally guaranteed by slurry forming an impregnation cake. Therefore, in coarse soils, the main requirement for the slurry is filling the pores with minimized slurry loss into the ground. In clayey soils, the ideal composition of the slurry dependents on mineralogical composition and the detailed chemical interactions between soil, slurry and slurry additives (AFTES, 2005). Ideally, slurry TBMs and slurry excavations are used in coarser soils with relatively low fines content. However, in real life ground conditions (e.g., glacial tills) the soils are not homogeneous and mixed layer or very frequently changing conditions at the tunnel face or in the slurry trench are not avoidable. In the worst case scenario, the slurry

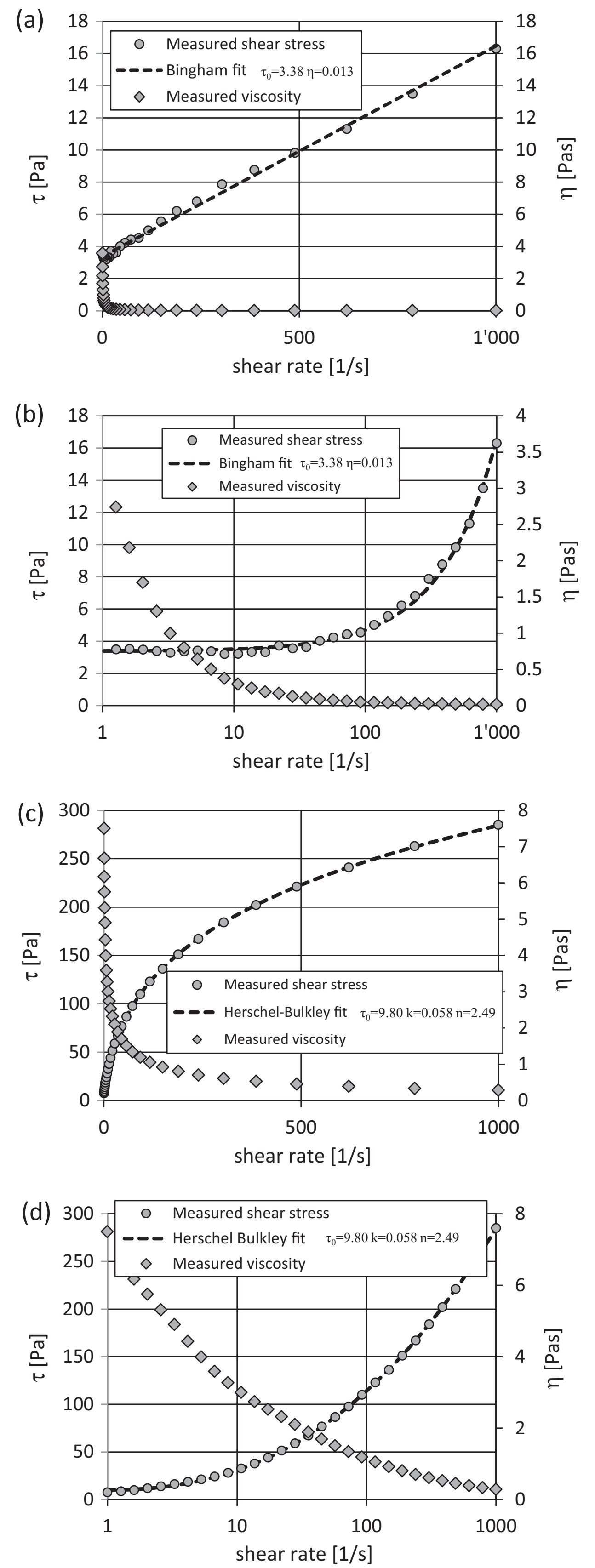

Fig. 1. Examples of the flow curves (shear stress, viscosity) determined in this study using the rheometer device: (a) a bentonite slurry, linear scale; (b) a bentonite slurry, logarithmic scale; (c) a polymer slurry, linear scale; (d) a polymer slurry, logarithmic scale.