Abstract

Tunneling under soft ground conditions often requires active face support to prevent face instability. Foam in an Earth Pressure Balance (EPB) shield Tunnel Boring Machine (TBM) and slurry in a slurry shield TBM are the most common materials for the realization of this support pressure. During ring building at standstill, there will be a filter cake formed at the tunnel face in a slurry shield TBM that could effectively transfer the fluid pressure to the soils. For an EPB shield the foam will have roughly the same function as the slurry in a slurry shield TBM, however, the details of supporting mechanisms are still not fully understood.

The first part of this work aims to study the foam infiltration behavior that may influence the pressure development during standstill. Experiments on pure foam infiltration into saturated sand with different influencing factors such as foam expansion ratio (FER), and sand types were examined. The infiltration characteristics were compared with slurry infiltration and the mechanisms are discussed. Results suggest that the pressure drop can be realized over the foam infiltration zone during foam spurt. There is a maximum infiltration depth by foam during foam spurt. Development of pore pressures shows that the foam infiltrated area functions similarly to an internal cake at the tunnel face of a slurry shield. Verification tests indicate that the permeability of the whole system is determined by the foam infiltrated sand instead of the foam on top of the sand, which is different to the filter cake in a slurry infiltration. Further infiltration that is comparable to the deep bed filtration in a slurry infiltration was found to be the main process after foam spurt. Experimental results were compared with the results field measurement data from the Botlek Rail Tunnel.

Following the improved understanding on the mechanisms during pure foam infiltration, a theoretical study was carried out to interpret the experimental results. The numerical model is based on an infiltration model for slurry infiltration, which considers foam spurt during foam infiltration. The maximum penetration depth by foam bubbles was first estimated by a simplified micro stability model which is based on the limit equilibrium analysis due to capillary resistance. Results from the numerical model were in accordance with the measured discharge behavior during

foam spurt from experiments. The general agreements suggest that the model can explain the foam flow behavior and can be used to describe foam spurt during foam infiltration that can be expected in EPB shield tunneling.

With the improved understanding on pure foam infiltration mechanisms, the infiltration characteristics of sandy foam infiltration into saturated sand were experimentally investigated. Influencing factors including foam injection ratio (FIR) and water content of the foam-sand mixture were studied. Consolidation of the foam-sand mixture is the dominant process as found by comparing the permeabilities at different locations during the test. No foam infiltration could be expected with a FIR lower than 40 Vol % for the fine sand used in the experiments. While foam infiltration with a higher FIR results in a foam infiltration layer that has a lower permeability than the consolidated mixture. It was found that the sand matrix plays an important role in determining the permeability of a sand-foam mixture. As the permeability of the consolidated mixture close to the sand surface is smaller than that far away from the sand surface. Since the consolidated mixture close to the sand surface is subjected to considerable foam loss due to foam infiltration, the sand grains are more compacted than the consolidated mixture far away from the sand surface. Combining the micro stability model for pure foam penetration, the criteria for bubble penetration during sandy foam infiltration were discussed. Based on the analysis, the theoretical value for the permeability of a foam-sand mixture was derived and compared with the recommended values from EFNARC (2005). General agreements were obtained.

In field applications during tunneling, foam is usually injected into the excavation chamber where pore water from the excavated soils will dilute the concentration of foam. This dilution effect will influence the surface tension of foam which may further influence the engineering properties of the foam-soil mixture. The values of surface tension at different concentrations were measured with the capillary rise method. Consequences for the volume change and the compressibility were theoretically investigated while the consequences for the infiltration behavior were experimentally investigated. Results suggest that, during tunneling, the surface tension of the diluted foam can be twice the value of original foam. The influences on the volume change and the compressibility can be negligible for the foams used in tunneling. While it may have a negative influence on the formation of a foam infiltration layer that has a lower permeability. Results suggest that the dilution of foam by pore water should be considered when studying the foam infiltration behavior. Further foam-soil interaction could also be influenced by this dilution effect which is worth further investigation.

In the second part of the thesis, a new model for predicting the Marsh funnel (MF) test was proposed and validated through experiments. The new model aims at evaluating the bentonite slurries for the slurry shield TBM or Horizontal Directional Drilling (HDD). The physical model accounts for the pressure drop in the upper conical section due to the yield stress of the fluids as well as the dynamic pressure in the lower capillary tube. Results show that for bentonite slurries with a small MF value, the dynamic pressure in the test plays a dominant role that must be taken into consideration. Further discussions show that the two-point measurement in field tests can be used as a fast estimation of the rheological parameters for the bentonite slurries.