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Experimental modelling on tunnel boring

Abstract

Dutch experience in TBM tunneling is relatively recent. The knowledge development during the nearly ten bored tunnels up to now, was supported by experimental modeling on different scales. We will give two examples of the effectiveness of experimental modeling. The first concerns laboratory experiments at a 1:1 scale on a small part of the system, particularly the bleeding behaviour of the grout from the tail void.
The second example is a centrifuge experiment at scale 1:65 on a tunnel subjected to consolidation forces from the soft soil overburden.

Introduction

Dutch experience in TBM tunneling is relatively recent. In the early 1990s, Dutch engineers were uncertain whether the soft saturated soil in the western parts of their country was suitable for TBM tunneling. The first tunnelling projects were therefore accompanied by a research programme, with extensive monitoring during construction. The experience gained in every tunnel project was applied in the next one.
The measurement results were analysed at a later date, and discrepancies with the predictions were explained where possible. Experimental research at a laboratory and model scale appeared to be crucial in understanding the observed phenomena.

The abovementioned research programmes were aimed mainly at the processes at, in and around the TBM, like front stability, tail void grouting and flow of bentonite and grout around the TBM. A second important issue, however, in the soft saturated soil in the western parts of the Netherlands is the long term behaviour of the tunnel lining. Construction of the tunnel in the shallow clay layers gives inevitably rise to differential settlements of the soil surrounding the tunnel, and possibly also of the tunnel itself.

Grout bleeding or grout consolidation

Consolidation of the tail void grout is an important process to understand the loading on the tunnel lining and the soil pressures in the direct vicinity of the tunnel. When the tail void grout is applied, the tunnel lining floats in a liquid with a density of up to 2100 kg/m^3, since the average density of the tunnel itself (lining and air) is generally less than 1000 kg/m^3. The flotation force has to be compensated by the yield stress in the grout, the weight of the TBM in front and by friction forces between the lining in the liquid grout and the part of the lining a bit further from the TBM in the solid grout.
To minimize the forces and moments in the 'floating' lining the liquid grout zone should be as short as possible The consolidation properties of the grout determine how long the grout will remain a liquid (chemical hardening due to the cement is a process with a longer time scale) and thus what will be the loading on the lining.

It is important to consider that the thickness of the grout layer in a test should be identical to that in the field. This is to avoid scaling effects that occur because hardening of the grout is independent of the sample size. Some consolidation tests performed in a standard oedometer device with a sample thickness of 0.02 m over-predicted the maximum settlement with a factor of 4 compared to tests where a sample thickness of 0.2 m was applied, comparable to the thickness of the grout in the tail void. The volume loss found in these consolidation experiments was 3 to 8 %. Such a volume loss will lead to an unloading of the soil around the tunnel, possibly generating settlements of footings and pile foundations.

The composition of the grout is also important in compensation grouting. Experiments have shown that the fracturing behaviour in compensation grouting depends on the specification of the grout. If more cement is added, the permeability of the grout is higher and there will be more consolidation and leak-off during grout injection. At Delft University of Technology, the density of grout bodies made in two compensation grouting experiments was analysed in a CT-scan (X-ray Computerized Tomography). Such a CT-scan can be used to determine the density of the material tested. This was done with two grout mixtures, having a water-cement ratio of 1 and 10.

The results of the CT-scans are shown in figures 1 and 2. The results of the first grout mixture show an increase in density from the injection pipe in the middle, to the outside boundary of the grout, from 1500 to more than 2100 kg/m^3. Grout at the boundary of the sample is consolidated during the grout injection process.
The grout body made with the second cement-rich mixture has a more constant density across the fracture. The black lines in the figure are various contour lines showing the sharp increase in density at the boundary of the sample *(figure 2)*. The more homogeneous density of the grout body in the second test is understandable

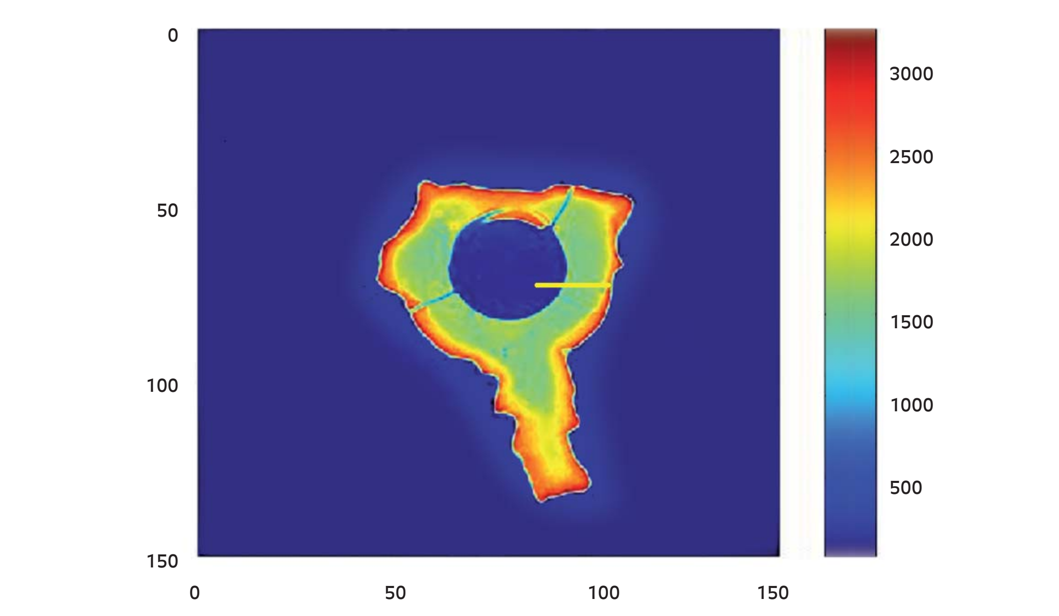

Figure 1 *Attenuation of x-rays over a grout sample with a WCR of 1. The surrounding air is blue. Red is the highest density (2100 kg/m³), green the lowest (1500 kg/m³).*

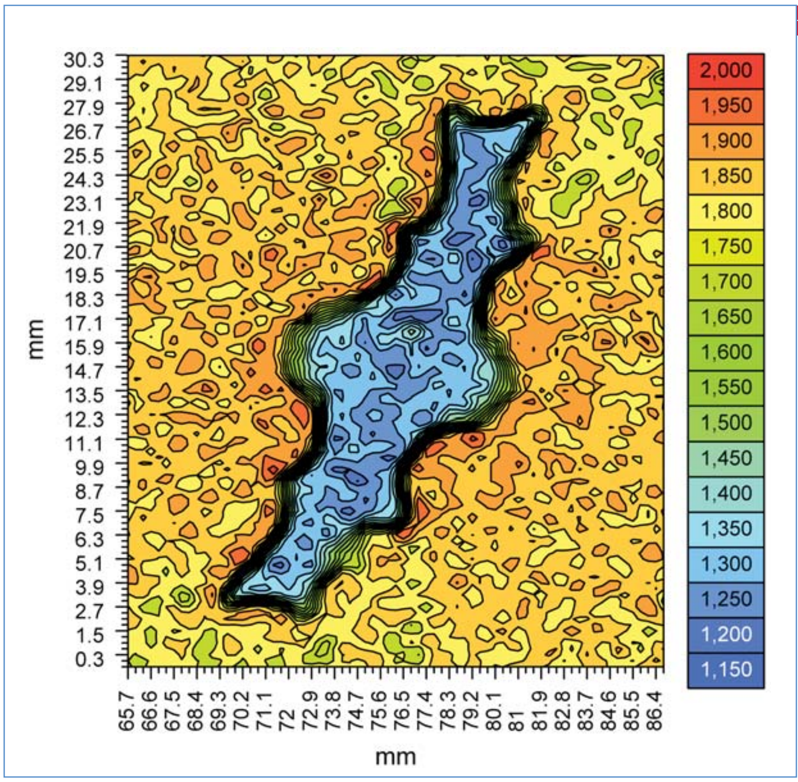

Figure 2 *Density of a fracture in sand with a WCR of 10. The blue is the fracture, the orange-yellow-green the sand.*

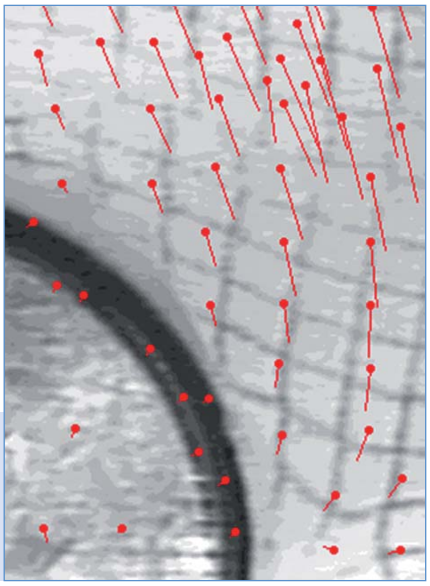

Figure 3 *Movement of consolidating clay around a tunnel. Result of centrifuge test.*

if the permeabilities of the grout are considered. The second sample has a lower permeability which results in much less grout consolidation within the limited injection time.

Consolidation pressure on the tunnel lining

RandstadRail is a future light-rail link between Rotterdam, The Hague and Zoetermeer in the Netherlands. Building the Rotterdam section of RandstadRail involves the construction of two bored single-track tunnel tubes in the city area of Rotterdam. On several parts of the alignment the tunnel tubes are located at the boundary between the soft Holocene clay and the stiff Pleistocene sand, about 15 m below surface.
It is expected that the top of the soft Holocene layers will settle 1.5 m due to consolidation and creep during the lifetime of the construction (100 y). Therefore the external loading on the tunnel lining will increase. The time dependent additional loading has been analyzed analytically as well as numerically. Since the mechanisms working on the tunnel wall and around the tunnel are known in principle but only partially in a quantitative sense, physical modeling using the Delft GeoCentrifuge, was performed in order to verify the design approach.

Scaling rules

The basic purpose of centrifuge modelling in geotechnics is to increase the gravity artificially, such that the stress levels in the model are the same as in the real situation. This is an important issue because material behaviour of soil (stiffness, strength) is strongly dependent on the stress level.
For consolidation processes centrifuge modelling has an interesting side-effect. When the artificial gravity equals N times the natural gravity (Ng), the consolidation time is accelerated by a factor N^2. This makes consolidation processes accessible for experimental study. Processes normally taking e.g. 10 years are at 100g accelerated by a factor of 10^4 implying a scaled process of about half a day. It should be kept in mind that it is not the time itself that is being scaled, but that geometrical effects cause an acceleration of processes.

Settlement is not only created by consolidation, but also by creep: time-independent deformation under constant stress. Creep is basically a material property and only governed by the stress level, so the creep velocity is the same in model and in reality. Creep is therefore not sped up, and the settlement during the centrifuge experiment is caused by consolidation alone.

The model was built at a scale of 1:65 in a strong box with a perspex window, through which a grid, applied on the clay, was observed with 2 video cameras. The model tunnel was made of an aluminum tube, for the lower part embedded in a dense sand layer. The tube was instrumented with pore pressure gauges and total pressure gauges. After placement of the tunnel in the sand, a layer of Spesswhite clay slurry was applied and subjected to self weight consolidation.

After self weight consolidation had taken place in the GeoCentrifuge, a sand layer was applied in flight on top of the clay. To this purpose a special device has been designed that can be actuated hydraulically in flight. It is important to not stop the artificial gravity temporarily because stress release leads to deformations which are not realistic. This sand layer caused an overburden pressure of about 55 kPa. After consolidation of the clay a second layer of sand was applied leading to further consolidation of the clay layer. *Figure 3* shows the deformation of the clay at the end of the consolidation of the first sand layer.

The centrifuge tests allow seeing the processes in one day that will occur in the coming decades in the field. In these tests we checked the failure mechanism that was assumed in the design calculations. Although the assumed mechanism appeared to be right, the loading on the tube appeared to be smaller than expected, because the stiffness of the clay on top of the tunnel during consolidation was lower than the stiffness used in the calculations. With the results of the tests, the effects in the field can be predicted. When the field data corroborate these results, this implies that no steel lining is necessary when building a tunnel partly in soft Holocene soil layers. This would mean a significant reduction in lining and drilling costs. ■