TBM-spoil characterization and utilization at the Follo Line project

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Abstract. The potential use of surplus materials commonly considered as waste has been investigated by the project "Geomaterials in the Circular Economy" (GEOreCIRC). TBM spoil is one of the materials which were assessed, based on data from the Follo Line tunnel project in Oslo, Norway. For this tunnel, four TBMs were used simultaneously and the tunnel generated almost 9 million metric tonnes of spoil. The excavated TBM spoil was used to establish a building platform for a new district in the Oslo municipality, by filling a 30 m deep valley. An extensive campaign of laboratory testing, field measurements and monitoring was conducted for the deposit. The geotechnical properties, such as grain size distribution, grain shape, brittleness, density, permeability and friction angle were determined. The optimal water content for compaction and maximum dry density were determined using the Standard Proctor test. Field measurements included plate load tests and nuclear density gauge (Troxler), with several measurements for each layer of the deposit. In addition, the spoil was analysed for a wide range of possible contaminants associated with natural rock minerals and machinery used in the tunnelling process. The results show that the level of contamination is low, and related to background levels from the bedrock itself, with levels below specified threshold values for contaminated soil according to Norwegian regulations.

1. Introduction
During the 1970's and 80's, Tunnel Boring Machines, or TBM's, were used for the construction of several tunnels for hydropower projects in Norway. After a long period where the preferred construction method for tunneling in Norwegian hard rock has been drilling and blasting, the use of TBMs have seen a renaissance in the construction of railways. Construction with TBMs has become commonplace for large projects, where the volume of excavated tunnel spoil is significant. An advantage with excavation using TBM is the reduction of the number of access tunnels in comparison to drill and blast tunnels. In addition, excavation with TBM can also reduce the need for transportation of excavated materials through residential areas.

One of the challenges associated with TBM spoil as a construction material is the grain size distribution. TBM spoil typically contains a higher percentage of fines than blasted rock of the same
bedrock type. However, the potential reduction in environmental impact for a TBM project by utilization of the spoil is considerable, due to the vast amounts of spoil that are generated.

2. Background

Full face TBM's are typically used for larger tunnelling projects, where there is a potential cost benefit compared to regular drilling & blasting (D&B) methods. For a TBM, a rotating cutting wheel with discs break off chips of the bedrock (Figure 1). The spoil is transported out of the tunnel on a system of conveyer belts.

For the construction of hydropower tunnels in the 70's and 80's, the spoil was generally deposited in large landfills in the vicinity of to the hydropower tunnels. Traditionally, TBM spoil was therefore considered a waste material. The increased use of TBMs in urban environments with limited space in landfills and increased focus on sustainability, raises the need to further assess the characteristics and possible use of the spoil. This utilization needs to be evaluated based on the geotechnical characteristics of the spoil.

![Figure 1. Illustration of tunnel boring machine with conveyer belts (left) (illustration: Bane NOR), machine front with rotating discs (right (photo: Bane NOR)).](image)

3. The Follo Line project

The ongoing Follo Line tunnel project in Oslo, is the largest railroad project ever in Norway. The project includes a bedrock tunnel of a total of 20 km, which has been excavated with TBMs from Oslo to the town of Ski. Four TBMs were used simultaneously to excavate the tunnel, which generated almost 9 million metric tonnes of spoil. The contractor is a joint venture between the Spanish company Acciona and Italian Ghella (AGJV), the TBM's are produced by Herrenknecht.

The client, Bane NOR (state-owned company responsible for the Norwegian railway infrastructure), has made an agreement with the municipality of Oslo to utilize the spoil for establishing a new district, by filling a 30 m deep valley, 14 km south of Oslo center. Bane NOR has performed extensive laboratory and field testing to document the geotechnical properties of the spoil and the quality of the fill.

Figure 2 shows a drone picture of the plant depot for the contractor at Åsland, Oslo. The main entrance to the tunnel is on the left-hand side, where the TBM spoil is transported out on conveyer belts, under a blue cover. The spoil is temporarily deposited in a spoil shed, in the right-hand side of the picture. Figure 3 shows the fill, close to its final height.

The fill is placed in 0.7 m thick layers with TBM spoil from the spoil shed. Each layer is compacted with normal compaction energy, with six passes with vibratory compaction roller. No spoil is placed in
the fill during precipitation, to avoid low quality compaction. The filling and compaction is documented with Troxler and plate load testes, described in section 6. For each layer two Standard Proctor tests have been performed on samples from the fill.

![Image of the contractors plant depot at Åsland, Oslo, with conveyer belt transporting the spoil under cover (blue) from the tunnel entrance to the spoil shed (photo: Bane NOR).](image1)

**Figure 2.** The contractors plant depot at Åsland, Oslo, with conveyer belt transporting the spoil under cover (blue) from the tunnel entrance to the spoil shed (photo: Bane NOR).

![Image of overview of the fill of TBM-spoil at Åsland (photo: Bane NOR).](image2)

**Figure 3.** Overview of the fill of TBM-spoil at Åsland (photo: Bane NOR).

### 4. Geotechnical characterization of TBM spoil from the Follo line

An extensive campaign of laboratory testing, field measurements and monitoring was conducted in the Follo line project. The geotechnical properties, such as grain size distribution, grain shape, brittleness, density, permeability and friction angle were determined. The optimal water content for compaction and maximum dry density were determined using the Standard Proctor test. Field measurements included plate load tests and the nuclear density gauge (Troxler), with several measurements for each compacted layer of the deposit.

#### 4.1. Bedrock type

The bedrock in the area consists of precambrian gneisses, with variations between tonalitic to granitic gneiss and quartz-feldspathic gneiss.
4.2. Grain size distribution

Grain size distribution curves from the Follo Line project are shown in colored lines in Figure 4. In the same figure grain size distribution curves from older TBM-projects in Norway are shown within the dashed area [5]. For comparison the grain size distribution curves from drill & blast tunnels are sketched with a light grey area. From the results it is clear that the particle size distribution for TBM-spoil has limited variation and is governed by the method of excavation [5].

The TBM spoil from the Follo Line project (and in general) is characterized as a well-graded, sandy, silty gravel. The spoil from The Follo line has 50-70% gravel (> 2 mm) and 10-18% fines (<0.063 mm silt and clay).

The particle size distribution is close to the ideal distribution for aggregates for fill and lean concrete (Füller's curve). In an ideal fill material, the fine particles shall barely fill the pores between the coarser particles.

However, the relatively high fine-content makes the material somewhat frost susceptible and the structural integrity of the material can be affected to a larger degree by its moisture content. The spoil will not be free draining but will retain water.

![Figure 4. Grain size distribution curves, coloured lines are samples from the Follo line project, dashed area are sieving results from database from Norwegian dam projects [5], light grey area shows sieving results from drill& blast spoil for comparison [3].](image)

4.3. Grain shape and crushing resistance

The spoil has particle shape far from cubic. Most of them can be regarded as 'elongated and very platy' and 'very elongated and very platy' (Figure 5).

The unfavourable particle shape results in a low crushing resistance. Therefore, the spoil does not meet the requirements for materials to be used in base course for roads or for concrete aggregate. However, the grain shape and potential for use can be considerably improved by recrushing and sieving.
Figure 5. Washed and sieved spoil from the Follo line project, illustration the particle shape (right), TBM-spoil dug up from the fill at Åsland.

4.4. Friction angle
Triaxial tests on TBM spoil show that the shear strength is highly frictional. The shear strength of the spoil is similar to medium good rock fill and the angle of friction lies between 40 to 50° (tested on different relative densities, n ≈ 20% or 30%). Figure 6 shows a comparison of the friction angle for TBM spoil and rock from drill & blast tunnels).

Figure 6. Friction angle, $\phi'$ for TBM spoil with varying porosity $n$ [5].

5. Contamination analysis
Excavation using TBM machines will not contain any residues from explosives. In addition, the use of conveyer belts avoids the need for heavy transportation inside the tunnel, and the associated risk of oil leakage from construction vehicles. 38 samples of the TBM spoil at the Follo line project were taken for environmental analysis. The results show that the material is non-contaminated [9] according to the Norwegian regulations [7]. A few samples had concentrations of heavy metals exceeding the threshold values for contaminated soil, but this is related to the mineral contents of the bedrock at hand.
6. Evaluation of the construction fill

TBM spoil is sensitive to water, and the water content of the material varies in the spoil shed. The amount of water in the spoil comes from the drilling process and the natural ground water from the bedrock mass. The variation in water content causes variations in geotechnical performance after compaction of the material. The deposit is designed to provide good geotechnical performance for future construction and development. Compaction control has therefore been an important part of the construction process during placement of the spoil. The compaction control consists of standard Proctor compaction tests, washing and sieving for grain size distribution, *in situ* Troxler compaction tests, measuring water content and density, and *in situ* plate load tests.

The standard Proctor compaction tests are performed on material taken from the spoil shed. Two samples are taken for each layer of the deposit. The test provides data on the maximum compaction of the material, and the optimal water content at which this can be achieved. The tests were conducted by KSR Maskin AS and revealed that the material may be compacted to a maximum value of about 2.15 t/m³ in Standard Proctor and the corresponding optimum water content is approximately 8%. When applying a correction of the maximum dry density with respect to grain size it should be possible to achieve an average dry density of 2.2 t/m³ with this material.

Plate load tests were performed after compaction of each layer to determine the achieved stiffness of the first loading cycle $E_1$. Furthermore, by applying the load twice with complete release of pressure between the two cycles it is possible to evaluate the degree of compaction, $E_2/E_1$. The results from the plate load test showed a less stiff material than expected. To investigate whether the compaction of the fill was acceptable despite these results, additional field excavation/permeability tests were undertaken to evaluate the actual achieved dry density against the standard Proctor maximum. During the tests the permeability was also measured, and the drainage properties of the fill were evaluated.

Field excavations tests were performed in four locations. Each test consisted of digging a pit (about 1.5 m by 3 m, and 1.5 m deep, approximately 6.5 m³) and measuring the exact volume by lining it with plastic and filling it with water as shown in Figure 7. The volume of the pit was also measured using a Lidar scanner (Figure 8). The excavated mass was weighed, and the density was calculated. In addition, the shaft was filled with water which was allowed to dissipate, and the hydraulic conductivity was measured. The tests revealed that the material drains well, however it could take a day or two for the water to dissipate from the newly compacted layer, depending on the weather conditions. Hence, it is possible that excess water is still draining when the plate load tests are performed, resulting in unrepresentative measurements. The Troxler moisture and density gauge measurements were also taken shortly after the compaction of each layer while the field excavation tests were performed several days later.

![Figure 7. Excavation test to measure the density after compaction and permeability [2].](image-url)
The results from the Troxler measurements and the field excavation tests are shown in Figure 9. It is seen that the achieved dry density of the deposit is measured to be significantly higher for the excavation tests than for the Troxler measurements and the maximum dry density found in the Proctor compaction tests. The water content measured in several points during the excavation tests is however in the same range as seen in the other tests. The excavation tests are considered more reliable than plate load tests and the Troxler measurements, as a larger volume of compacted soil is considered in the test.
However, there are some uncertainties related to the measured weight of the excavated soil and the measured water content (which might have been affected by frost and thawing).

To get an evaluation of the quality of the compacted fill, the results from the Troxler tests and excavation tests are plotted in a compaction plot, together with results from Standard Proctor tests, shown in Figure 10. For comparison compaction curves for 100% saturation are plotted, which shows the limit for the maximum theoretical dry density of the material, for the measured solid density $\rho_s=2.69$ t/m$^3$. This line, and the curves from the Standard proctor test, is sensitive to the solid density of the particles, $\rho_s$, and is the probable reason for some of the Proctor curves plotting on the high side, above the line for $S_r=100\%$. In addition, curves for 5 and 10% air filled voids are shown.

In the figure Proctor tests from five different layers are plotted with grey lines. The tests are randomly chosen from tests from the total 30 layers which were laid out at Åsland. The standard Proctor tests indicate an average maximum dry density of $\rho_d=2.15$ t/m$^3$. The highest measured dry density measured in the curves for the layers which are plotted is about $\rho_d=2.2$ t/m$^3$. This density is at the maximum density for 100 % saturation, for a water contents of about 8 %. The average maximum dry densities from the Proctor tests are plotted as 100% standard Proctor, with a purple curve. In addition, lines for 97 and 95 % of maximum dry densities are shown.

![Figure 10](image)

**Figure 10.** Comparison of measured dry densities from test excavation pits and Troxler tests, with Standard Proctor tests.
The calculated density from the four excavation tests are plotted with large triangles, Troxler tests from each of the tests pits are plotted with smaller squares. As stated previously, the density determined for the excavation test are considerably larger than the densities from the Troxler tests. However, the results from excavation test 2 show unrealistically large dry density, and for this test there must have been an error in the measurement for weight. Also, the density from excavation test number 3 is in the high range. This though, can be related to uncertainties in the solid density of the particles. Despite some uncertainty in the excavation tests it is concluded that the achieved dry density after compaction indicates a good quality fill, resulting in high stiffness and low settlement potential. This is also supported by normal compaction control for fills for road construction, where requirements are set to 95 to 97 % of the maximum density in Standard Proctor tests [8]. All Troxler test indicate a dry density in the fill which is larger than 95% of Standard Proctor compaction tests. These findings are also in line with a study by Rivera et al. [6], where densities from field compaction to Proctor tests were measured at 95-98 %.

According to Deutsches Institut für Normung [4] a thin layer of plaster or sand is to be placed beneath the loading plate to level the surface before starting the test. This is not done as a part of the procedure at Åsland. It is plausible that the lack of plaster causes "falsely" low $E_1$ values and as a result increasing the value of $E_2/E_1$. It is assumed that this may be the cause of the inconsistency between the poor plate load results and the achieved compaction which is within 95% of standard Proctor.

7. Summary and conclusions
The test program and data collection for the Follo line project has resulted in broad characterization of TBM-spoil from the Follo line project. Based on grain size distribution curves the spoil is characterized as a sandy, silty gravel, with a fines content of 10-18%. The fine-content makes the material somewhat frost susceptible and the compaction is significantly influenced by the water contents of the material. The spoil will not be free draining but will retain water. The amount of water in the spoil is generated from the drilling process and the natural ground water in the bedrock mass. At the Follo line project, the water content has been controlled by storing the spoil in a spoil shed and not filling material on days with considerable precipitation.

Documentation from the fill at Åsland shows that it is possible to obtain a high-quality fill by placing the spoil in layers and using normal compaction effort (6 over-passes with vibratory rollers). It is concluded that, the fines content in the spoil is close to the ideal fill (Füller curve), and not so high that the coarse particles are "floating" in a matrix of the fines. The coarse particles will be in contact, forming a stiff skeleton with high shear strength and low compressibility.

Projects where TBM is used generally generate enormous amounts of excess mass. Utilizing TBM spoil locally, as has been done at Åsland in Oslo for the Follo line project, results in substantial reduction in transportation, and reduced carbon footprint. Furthermore, the reuse of TBM spoil may reduce the need for virgin construction materials. Utilization of spoil in this manner requires early planning to ensure regulation permits, as well as necessary areal extent for temporary storage and geotechnical testing and planning of the fill.

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