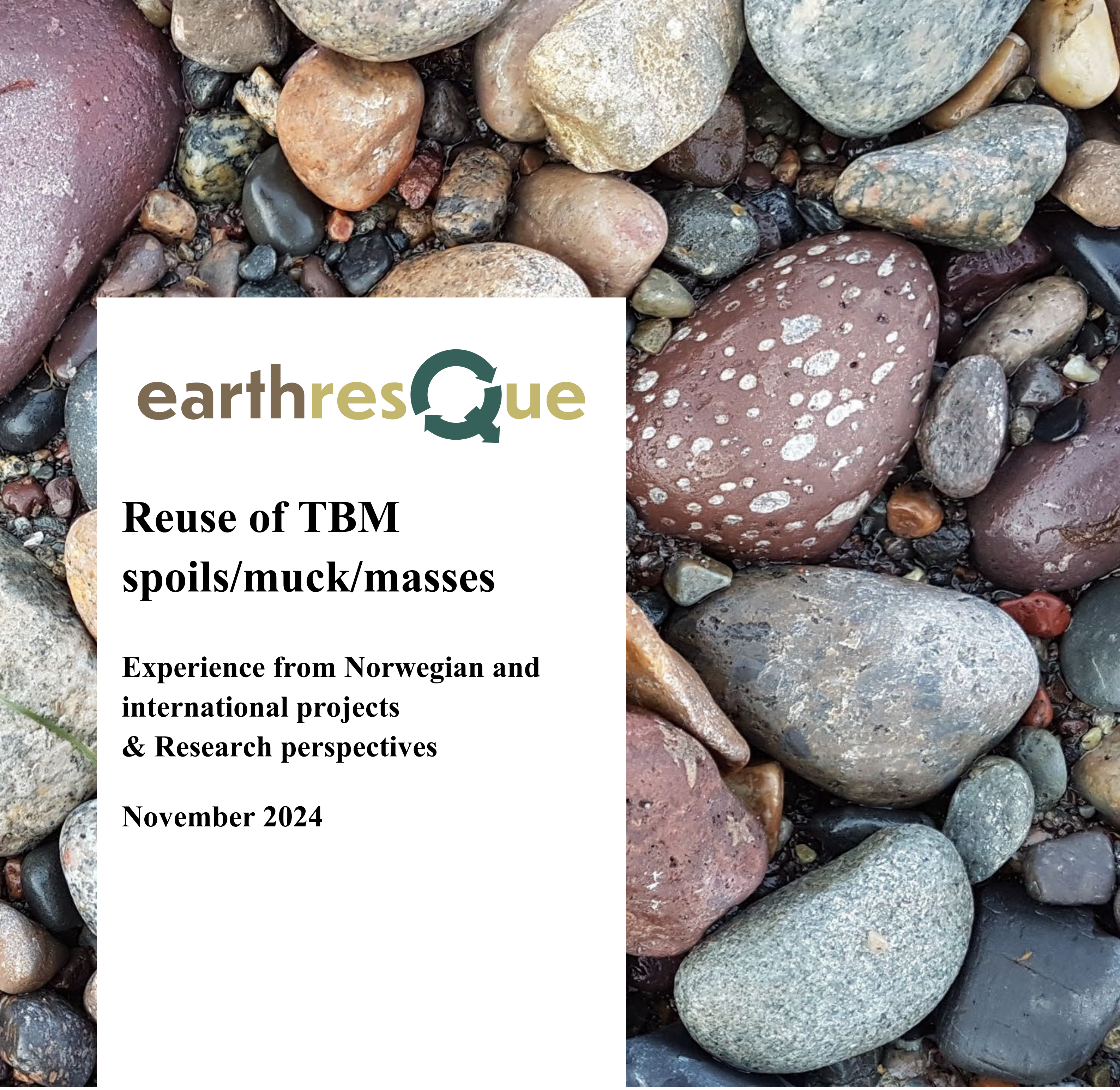

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Reuse of TBM spoils/muck/masses

Experience from Norwegian and international projects & Research perspectives

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Reuse of TBM spoils/muck/masses - Experience from Norwegian and international projects & Research perspectives

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Sammendrag

This literature review investigated the properties and reuse potential of Tunnel Boring Machine (TBM) muck. Properties of TBM spoils depends on geology and equipment used but are typically well-graded coarse-grained materials with strong geotechnical properties and high permeability.

The reuse of TBM muck has been successfully implemented in various projects, notably in road construction, for concrete production (aggregates or filler), and for different types of fillings. For instance, around 80% of TBM spoils produced in the Gothard Tunnel project were recirculated. However, challenges such as heterogeneity, local conditions, and effect of storage duration, necessitate case-by-case characterization and somewhat limit their valorisation.

Improvement techniques like grinding, crushing, and sieving can make TBM spoils more suitable for specific uses. Removing potentially problematic minerals using sorting or flotation techniques can also contribute to improve the long-term stability of the material. The development of temporary storage methods is also necessary to optimize reuse and maintain material properties over time between production and potential reuse.

Further research could focus on the effects of particle elongation on hydrogeotechnical properties, the influence of crushing, and the role of larger particles in characterization and sampling.

Innhold

1 Properties of TBM spoil

1.1 Particle size distribution

Particle size distribution of TBM masses varies significantly from a project to another and is a function of the rock geology (mineralogy, weathering grade), equipment used and disk spacing, among other factors. The variability/heterogeneity within a same project (see for example Dahl, 2018) can be significant and could originate from either natural variability in the rock, variations in the production and/or sampling methodology.

Particle size distribution is usually determined using dry and wet sieving, but image analysis coupled with machine learning techniques can also be used for on-line characterization/sorting.

In general, TBM spoils are well graded gravels or sands (ASTM 2487) and have a maximum diameter around 60 mm (which may be estimated as twice the disk spacing). Maximum particle size is, however, often affected by sample preparation (large particles are often removed or crushed to fit lab equipment). Gravel particles often represent more than 50% of the material, around 30% sand (< 4,75 mm), less than 20% silt (< 80 µm), and clay content (< 2 µm) is generally below 1% (except in claystones/mudrocks).

Atterberg limits, including liquid limit (LL), plastic limit (PL) and plasticity index (PI) were determined in several projects (table 1). These tests are, however, usually conducted on the finest fraction of the materials, which, in many cases, represent only a small part of the entire material. Their relevance to field behaviour could therefore be limited. Based on the available results, the fine fraction of TBM masses is usually slightly (7 < PI) or medium (7% < PI < 17%) plastic.

Table 1. Literature value for liquid limit (LL), plastic limit (PL) and plasticity index (PI) of TBM masses.

Reference	LL	PL	PI
Alnuaim (2021)	20,0%	16,9%	3,1%
Gertsch et al. (2000)	< 425 mm non plastic		
Haller et al. (1972)1	15-25%	13-21%	0,7-5,4%
Oggeri et al. (2014) F1	35,4%	20,7%	14,7%
Oggeri et al. (2014) F2	34,8%	22,0%	12,8%
Oggeri et al. (2014) F3	26,9%	16,1%	10,8%
Taqa et al. (2021a)	51%	36%	15%

[1] As reported by Gertsch et al. (2000)

Proctor test is a standard approach to evaluate and compare the compressibility of materials and is particularly useful to plan and design material placement in the field. Optimum density depends, however, on particle relative density (also called specific gravity) and is therefore not always directly comparable between projects.

Table 2. Literature value for particle size distribution (D_{max}, D_{10}, D_{60}, < 4,75 mm, <80 mm, <2 mm and petrography of TBM masses.

Reference	Dmax	D10	D60	< 4,75 mm	< 80 mm	< 2 mm	Petrography
Alnuaim (2021)	40 mm	<10 mm	8 mm	50%	20%	-	Tertiary / Quaternary deposits
Gertsch et al. (2000)	125 mm	0,4 mm	19 mm	32%	4,5%	-	Tuff
Dahl (2018)	50 mm	0,02 – 0,2 (0,06) mm	2 – 20 (10) mm	20 – 75% (45%)	5–15%	< 1-2%	Gneiss
Oggeri et al. (2014) F1	50 mm	< 2 mm	0,6 mm	80%	35-40%	32-36%	Argilites
Oggeri et al. (2014) F2	50 mm	< 2 mm	0,15-1,5 mm	75%	45-55%	26-28%	Claystones, clayish sandstones
Oggeri et al. (2014) F3	50 mm	1-70 mm	3 mm	70%	12-26%	3-13%	Ophiolitics, basaltic boulders
Riviera et al. (2014) S6 Bellopede & Marini (2011)	63 mm	0,1 mm	10 mm	46%	9%	< 1%	Granite
Riviera et al. (2014) S7 Bellopede & Marini (2011)	63 mm	0,02 mm	7 mm	52%	21%	< 1%	Calcareous schist
Taqa et al. (2021a) 1	40 mm	0,8 mm	8 mm	45%	< 1%	< 1%	Limestone
Taqa et al. (2021a) 2	63 mm	< 75 mm	30 mm	18%	12%	-	Limestone
Tokgoz (2013) 1	250 mm	16 mm	51 mm	< 1%	-	-	Sandstone
Tokgoz (2013) 2	250 mm	22 mm	76 mm	< 1,5%	-	-	Weathered diabase
COWI (2015)1	80 mm	0,3 mm	0,8 mm	46%	7%	-	Ulriken tunnel
ITA (2019)1	100 mm	0,2 mm	20 mm	22%	5%	-	Limestone
ITA (2019)1	100 mm	1 mm	22 mm	24%	2%	-	Mica schist
ITA (2019)1	100 mm	0,1 mm	8 mm	50%	8%	-	Amphibolite
ITA (2019)1	100 mm	0,12 mm	12 mm	40%	8%	-	Gneiss, christaline
Syversen (2021)	100 mm	0,05 mm	7 mm	55%	12%	< 1%	Gneiss

The usual objective to limit settlement is to reach at least 95% of Proctor optimum in the field, but in practice, greater densities are often achieved (depending on the equipment used and the thickness of compacted layers). Results should also be corrected for field conditions because particles greater than 19 mm are removed in the laboratory. Generally, Proctor results showed significant variations between materials, with optimum water contents varying from 5 to 15% (probably directly linked to particle size distribution).

Large oedometer tests were conducted by Dahl (2018) and Syversen (2021), but the relevance of such tests is questionable considering TBM masses are usually compacted partially saturated. Risks of settlement was also further assessed using plate load tests in the field (Dahl, 2018). California Bearing Ratio (CBR) test is a standard method to evaluate strength and surface stiffness for road design.

Table 3. Literature value for standard Proctor, modified Proctor and Calefornia Bearing Ratio (CBR) of TBM masses.

Reference	Std Proctor		Mod Proctor		CBR
	$r_{d,opt}$	w_{opt}	$r_{d,opt}$	w_{opt}	
Alnuaim (2021)	1968 kg/m3	11,2%	2050 kg/m3	8,8%	
Gertsch et al. (2000)	1848 kg/m3	14,2%	1869 kg/m3	13,7%	49-71%
Riviera et al. (2014) S6	2204 kg/m3	4,7%	-	-	317%
Riviera et al. (2014) S7	-	-	-	-	215%
Dahl (2018)	2150 kg/m3	8,2%			
NGI (1986)	2180-2270 kg/m3	6-8%			

Few measurements of the hydraulic conductivity of TBM masses have been reported, and even fewer for the entire/original material, probably because of operational constraints (cf. size of typical permeability cells). Also, few references to infiltration tests in the field, exception made of Dahl (2018). Based on the other characteristics of the materials, a hydraulic conductivity similar to that of a sand or a gravel can be expected. Predictive models (especially those developed for waste rock) could be used to predict the saturated hydraulic conductivity of TBM spoils but were not evaluated in the reported literature. Significant anisotropy of hydraulic conductivity can be expected in the field but is difficult to measure in the laboratory.

Table 4. Literature value for hydraulic conductivity (k_{sat}) of TBM masses.

Reference	ksat (m/s)	Comment/details
Alnuaim (2021)	1×10-8	< 4,75 mm, 95% Proctor
	2×10-5	< 19,05 mm
Dahl (2018)	[1×10-6 ; 8×10-5]	Field pit test

Friction angle of TBM masses is generally relatively high and often above 40°, but around 10° smaller than equivalent blasted rock. Cohesion values around 75 to 145 kN/m^2 are reported (Dahl, 2018), but these results were most probably obtained on the finest fraction of the masses. Mechanical properties of TBM masses are anisotropic.

Table 5. Literature value for friction angle of TBM masses.

Reference	Int. frict. angle	Comment
Alnuaim (2021)	44°	Shearing rate 0,3 mm/min, 95% opt, ASTM D3080
Dahl (2018)	40-50°	Triaxial
NGI (1986)	35-45°	Triaxial, reported by Dahl (2018)

TBM spoils are, by nature, elongated particles. A rough estimate usually consists of considering that the long axis is twice the size of the short axis, but a more accurate estimation can be obtained by measuring the shape index and flakiness index. These indexes, however, only apply to particles larger than 6,3 mm, and the elongation of finer particles (and their impact on the hydro-geotechnical behaviour of TBM masses) is unknown.

Table 6. Literature value for shape index and flakiness index of TBM masses.

Reference	Shape index	Flakiness index
Bellopede & Marini (2011a)1	53%	44%
Bellopede & Marini (2011b) 2	36%	22%
Taqa et al. (2021a)		4,3% (4-10 mm) 8,3% (10-20 mm)

TBM crushability may affect the *in situ* properties of the TBM masses, especially in filling and/or road structures. Crushability can be evaluated using Los Angeles or Micro Deval abrasion test, and field tests (Barbieri, 2019). In that case, representative and characteristic equipment can be used to compare particle size distribution before and after compaction (using, for example, particle breakage factor $B_{10} = 1 - D_{10,f}/D_{10,i}$). Empirical relations exist between these different parameters. Maximum acceptable loss is 45% for the base course of the road, and 35% for the surface course, which was the case in most tested samples. Also, large oedometer tests did not appear to significantly modify the particle size distribution of the TBM masses (Syversen, 2021).

Table 7. Literature value for crushability (Los Angeles, Micro Deval) of TBM masses.

Reference	Los Angeles	Micro Deval
Bellopede & Marini (2011a) 1	-	9%
Bellopede & Marini (2011b) 2	24%	-
Gertsch et al. (2000)		
Taqa et al. (2021a)	40%	
Tokgoz (2013) 1	21%	29%
Tokgoz (2013) 2	12%	15%

Overall, TBM masses are therefore coarse-grained materials with strong geotechnical properties, high permeability, and good suitability to filling and road construction. Their behaviour, however, strongly depends on rock mass, production method and potentially treatment approaches (see below) and should therefore be characterised case by case.

A few questions remain and may be investigated in a research project:

- What does sieving measure and what is the effect of particle elongation on the determination of the particle size distribution? What is the influence of the method (sieving in the laboratory, in the field, image analysis) on the results? And more importantly, what is the influence of the approach chosen on the determination/prediction of the material hydrogeotechnical properties.
- Material heterogeneity and variability is probably one of the most significant challenges regarding the reuse (and the characterization) of the material. Statistical approaches are recommended (rather than averages or intervals) and should be evaluated (e.g., k-th percentile).
- Prediction models for permeability, water retention capacity and other properties, are probably little suited for elongated particles. Would more adapted models be useful? A more thorough analysis of anisotropy and its effect on hydrogeological behaviour could also be useful.
- The effect of crushing on hydrogeotechnical properties may be useful to investigate depending on the applications and for long-term performance (so far, the effect of crushing has been qualitatively observed, but not quantified).
- Scale effect, in particular the role of larger particles on characterization and sampling, would be interesting to evaluate further (typical question expected when planning reuse: how many samples and what size of samples are required to determine representative properties?).

Characterization techniques are well documented and may not require significantly more work/research. Online characterization tools/equipment would be very useful for operationalization, but NGI has little to contribute to in this field. Using a case-by-case approach is recommended rather than trying to determine general trends and behaviours/properties.

2 Reuse of TBM spoil

TBM spoils have been largely reused in many different projects around the world (including Norway, since the 80s), and successful examples are widely available in the literature. For example, around 80% of TBM muck produced in the Gothard Tunnel project were (reportedly) recirculated. Typical applications include road construction, aggregates in concrete and shotcrete, filler, all types of fillings (also in the sea), sometimes using the spoils alone, sometimes mixing them with other materials, and sometimes using them as a (partial) replacement of other products. In several cases the use of TBM spoils has contributed to increase the performance of the final product (e.g., replacing a part of bentonite with inert, low plasticity TBM fine spoils have contributed to controlling the compressibility and reducing the swelling index). These applications usually imply the validation of standardized properties (e.g., particle size, particle shape, particle size distribution, mineralogy, brittleness) specific to each country and there is little research to do in that field (except if the objective is to change standards and practices).

There are, in theory, many potential applications of TBM spoils, but in practice, reuse will mostly depend on local situation, conditions, and needs. Also, there are limited environmental or economical benefits in transporting TBM masses over too long distances so potential applications should rather be evaluated using a case-by-case cost-benefit analysis.

Despite all reuse potentials, some amounts (either a fraction of the total masses or a specific part/fraction of the original material) will most probably always have to be disposed of in a long-term storage site/landfill. Very little research has been conducted regarding the long-term hydrogeotechnical and geochemical stability of such storage facilities and their potential optimization to reduce environmental footprint.

Finally, a usual challenge regarding the recirculation of construction wastes/excavated masses concerns the time frame difference between production and potential reuse. Maximizing reuse would, in practice, require storing the produced masses (potentially after treatment; see below) until further use. Because of the widely graded particle size distribution of TBM spoils, short-, medium- and long-term storage may significantly alter the material properties. For example, cementation may create clogs/agglomerates and coarser (but weaker) aggregates. Chemical weathering may alter the classification of the material and contribute to generating contamination during storage. A potential research topic could therefore consist in studying the evolution of TBM spoils during storage and developing temporary reclamation/storage/cover methods to maintain their properties in the long-term. These techniques should also be adaptable (for a minimum cost) to long-term closure solutions in case the material would never be reused/repurposed. Temporary reclamation options should be economical and require a minimal amount of material because cover may have to be removed later to get access to the spoil. A reusable cover would be highly beneficial.

3 Improvement of TBM muck properties

Properties of TBM spoils can be (and often are) modified using conventional (mobile or not) aggregate-processing techniques. Grinding, crushing, and sieving are usual improvement techniques used to adjust/adapt the TBM spoils to specific uses. Several crushers can be found on the market, and some of them (e.g., VSI crusher, impact crusher) are particularly adapted to reduce the angularity of TBM particles (which may be necessary for reuse as aggregates). Other approaches involve removing sulfides, sulfates or micas, using sorting or flotation techniques.

Based on the many examples reported in the literature, improving TBM spoils to make them more appropriate for reuse seem quite common and little challenging. In practice, however, potential users may be reluctant to use such approaches considering the risks and costs involved, especially if well-documented alternative materials are available.

Improvement of TBM spoils appear therefore relatively straightforward and presents little potential for innovative research.

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Forskning

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