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Tunneling in Cobbles and Boulders

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ABSTRACT

The impact of cobbles and boulders within a soil matrix on tunneling may be from negligible to severe depending on the volume and characteristics of the cobbles and boulders and method of tunneling being used. To properly assess the risk of cobble and boulder impacts requires a customized subsurface investigation program that allows cobble and boulder volume ratios, sizes and properties such as unconfined compressive strength and abrasivity to be determined. In addition, soil matrix properties including cohesion, strength, density, grain size distribution, permeability and abrasivity should be determined. The resulting field and laboratory test data may be used alone and with local tunneling experienced to baseline cobble and boulder conditions, assess impact risks, and determine better tunneling methods to mitigate and manage the risks.

1 INTRODUCTION

Since the 1990's, significant advancements have occurred in subsurface investigation, baselining, excavation methods and risk management for tunneling in cobbly-bouldery ground conditions. Review of a bibliography on tunneling in cobbles and boulders indicates only 12 out of 176 or 7 percent of the listed references existed prior to 1985. Most of the relevant tunneling in bouldery ground references have been published since 1995. As a result of the advances reflected in these papers, we can now better manage boulder risks with fewer differing site conditions impacts than before.

Better knowledge of potential cobble and boulder occurrence allows cobble and boulder risks and uncertainties to be better managed. Management of cobble and boulder risks for tunneling requires consideration and optimization of factors including:

Ground type-geology
Geologic variability
Cobble and boulder quantities
Boulder sizes, shapes, strengths
Matrix type, strength/density/perm.
Face stability in free air
Excavation method options
Face/excavation chamber access
Tunnel diameter
TBM power (torque-thrust-speed)
Cutterhead retraction capability
Cutterhead opening size, shapes
Abrasion resistance of equipment
Cutter types, configuration
Cutter change options
Mucking system type
Subsurface investigation limits
Redundant excavation methods
Potential consequences
Contract method, compensation
Prescriptive specification extent

This paper provides an overview of factors and issues for assessing risks of tunneling in cobbly-bouldery ground. It cites relevant references for more detailed study and emphasizes key risk issues and approaches to mitigate them.

1.1 Cobble and boulder ground conditions and occurrence

Cobbles and boulders are commonly found in alluvium, glacial till or ice-margin deposits, recessional or interglacial outwash, beach-shoreline erosion zones, talus and within residual soils weathered from bedrock. Cobbles and boulders are also commonly found in fill deposits. Generally, cobbles and boulders are composed of the harder, stronger, more abrasive rock clasts that resisted wear from geologic transportation and weathering processes. These clasts are the surviving pieces of rock. Cobbles and boulders often have higher strength, higher abrasivity and hardness than neighboring bedrock, particularly if deposited after significant transportation. To properly assess the probable occurrence of cobbles and boulders, the geologic setting of the ground along the tunnel alignment should be carefully evaluated and understood to an extent practical.

Cobbles and boulders may be isolated and scattered, or present in small to large clusters - nests, beds or erosional lag zones. Cobble and boulder clusters are more common in high water energy alluvial or outwash deposits, eroded geologic contacts, within talus and near the bedrock surface. Careful determination of the geologic setting is essential for proper assessment of likely cobble and boulder concentrations and distributions. Spaced borings are often inadequate for assessment of cobble and boulder clusters and supplementary information from geophysical methods and tests pits or excavations may be required. Clusters of cobbles and boulders often result in the highest impact risk and are very important to properly address.

In North America, the following sizes are used to classify and describe cobble and boulder clast sizes:

Cobbles:	3-12 inch (75-300 mm)
Boulders:	1-30 feet (0.3 to 9.1 m) with 1 to 3 feet (0.3 to 1 m) being more common

In addition, very large rock clasts may be described as blocks or floaters:

Blocks:	> 30 ft (9.1 m)
Floaters:	> 30 ft (9.1 m) occurring as large, often elongated rock blocks near bedrock

Cobble and boulder properties considered to be of most importance are [33]:

1 Frequency – cobble and boulder volume ratios or quantities per length of tunnel.

2 Distribution – isolated (scattered) or concentrated (clusters, lags or nests).

3 Size range – anticipated distribution of sizes or ranges in sizes.

4 Shape – spherical, cubic, slabby, or irregular; and angularity or roundness of corners. Shape affects fracturing by TBM cutters, passage through grizzly bars, crushing after ingestion and abrasion of the cutters and mucking system. Flatter clasts are generally easier to split than round clasts. Angular clasts are generally more abrasive than rounded clasts.

5 Composition – rock mineralogy (particularly quartz content), lithology, hardness, toughness, compressive strength, and degree of weathering all effect fracturing by TBM cutters, energy required for commutation (crushing or breaking to smaller size) of clasts and abrasion of the cutters and mucking system. Mineral grain size, fabric, crystal arrangement, foliation and sedimentary sub-bedding also generally affect the energy required for splitting and crushing as well as abrasiveness of the clasts.

6 Abrasiveness – Abrasiveness of both the rock clasts and soil matrix causing combined wear to and breakage of cutters, cutterhead, crushers, chamber and mucking system. Total abrasiveness requires assessment of soil matrix abrasivity, cobble and boulder volume ratios and abrasivity of the rock clasts.

7 Soil matrix composition – density, strength, grain-size distribution, grain shapes, mineralogy, and permeability of the soil matrix around rock clasts affects soil matrix abrasivity and affects cuttability or ease of dislodgement by cutters, potential to push boulders aside, and stand-up time or ground

improvement required for manual drilling and splitting.

1.2 Geologic Setting

The distribution, quantities and properties of cobbles and boulders should be assessed for each soil unit anticipated in a tunnel zone along with the geologic setting of the soil units. Baselining of cobble and boulder conditions based on soil type, e.g. silty clay or gravelly sand without geologic units may not result in reasonable correlations. Instead, cobble and boulder occurrence should be assessed for individual geologic soil units. The importance of using a geologic framework when assessing cobble and boulder occurrence (and other ground conditions that affect tunneling) has been explained by many authors: Essex (1993), Gould (1995), Heuer (1978), Legget (1979), Hunt & Angulo (1999) and others [20][27][30][33][49].

Typical characteristics of cobbles and boulders and likelihood of occurrence within various glacial units and morphological features are discussed in many geology books. If available, local geologic papers and publications should be studied prior to and during a subsurface investigation program to better understand the regional structure and typical characteristics of the units and formations that are likely to be encountered. Cobble and boulder occurrence can be better understood and baselined if the subsurface exploration data is presented in a geologic context.

1.3 Boulder Volume Ratios

Boulder concentrations may be expressed as number of boulders per length of tunnel, but this does not address size ranges and volume of clasts, both of which are important. Boulder volume ratio (BVR) is defined as the volume of boulders as a percentage of the excavated volume. BVR combined with an estimated distribution of sizes is an effective method of expressing boulder occurrence. BVR baselines have been used on many tunnel projects, particularly in Toronto [5][57] and Milwaukee [33][34][35]. While a specific quantity such as BVR is useful to describe concentrations, descriptive terms are still in common use. Figure 1 indicates relative descriptive terms for ranges of BVRs.

To show typical average boulder concentrations, BVRs encountered at 23 projects across the world are shown in Figure 2. The majority (63%) of projects encountered only ‘trace’ quantities of boulders (BVR <1%). ‘Few’ boulders (BVR = 1-2%) were encountered on 16 percent of the projects. ‘Many’ boulders (BVR = 2-5%) were encountered on 12 percent of the projects. ‘Frequent’ (BVR = 5-10%) and ‘very frequent’ (BVR = 10-50%) boulders were encountered on only 6 percent of the projects. A study of 40 microtunnel and small TBM cases in 2004 [35] found that BVRs generally ranged from 0.01 to 4 percent with an average of approximately 0.8 percent.
Most tunnels in glaciated areas of North America will encounter average BVRs less than 2 percent with many less than 1 percent. For example, a study of eight tunnel projects in Milwaukee and northern Illinois indicated average BVR values between 0.01 to 1.62 percent [33][34]. Sheppard tunnel in Toronto had an average BVR of 0.14 percent [5][57]. Storebaelt tunnel in Denmark had an average BVR of 0.09 percent [14][15]. The Downriver Regional Storage and Transport System tunnels in Wayne County Michigan encountered an overall average BVR of 0.14 percent [12]. On the BWARI project in Columbus, BVR values varied from 0-2.5 percent [22]. Average BVR values for Brightwater Conveyance tunnels were less than 0.3 percent. On two recent projects in Seattle [71], BVR values of 0.3 and 0.4 percent were back-calculated by the author.

Higher BVR values are commonly found within ~ 5 ft above bedrock, within talus, and in alluvial deposits down gradient from mountain ranges or rock ridges. For example, the Folsom East IIB project near Sacramento, California encountered estimated BVRs between 2 and 4 percent [8][59]. Bradshaw 8 in Sacramento, California encountered an overall average BVR of 2.9 percent with reaches of the tunnel having a BVR of ~ 10 percent. The Columbia Slough tunnels in Portland, Oregon encountered average BVRs of 4 to 9 percent [11].

Local zones within most of the tunnels studied had much higher BVRs than the overall averages, which is why correlations to geologic units are essential for baselining and planning.

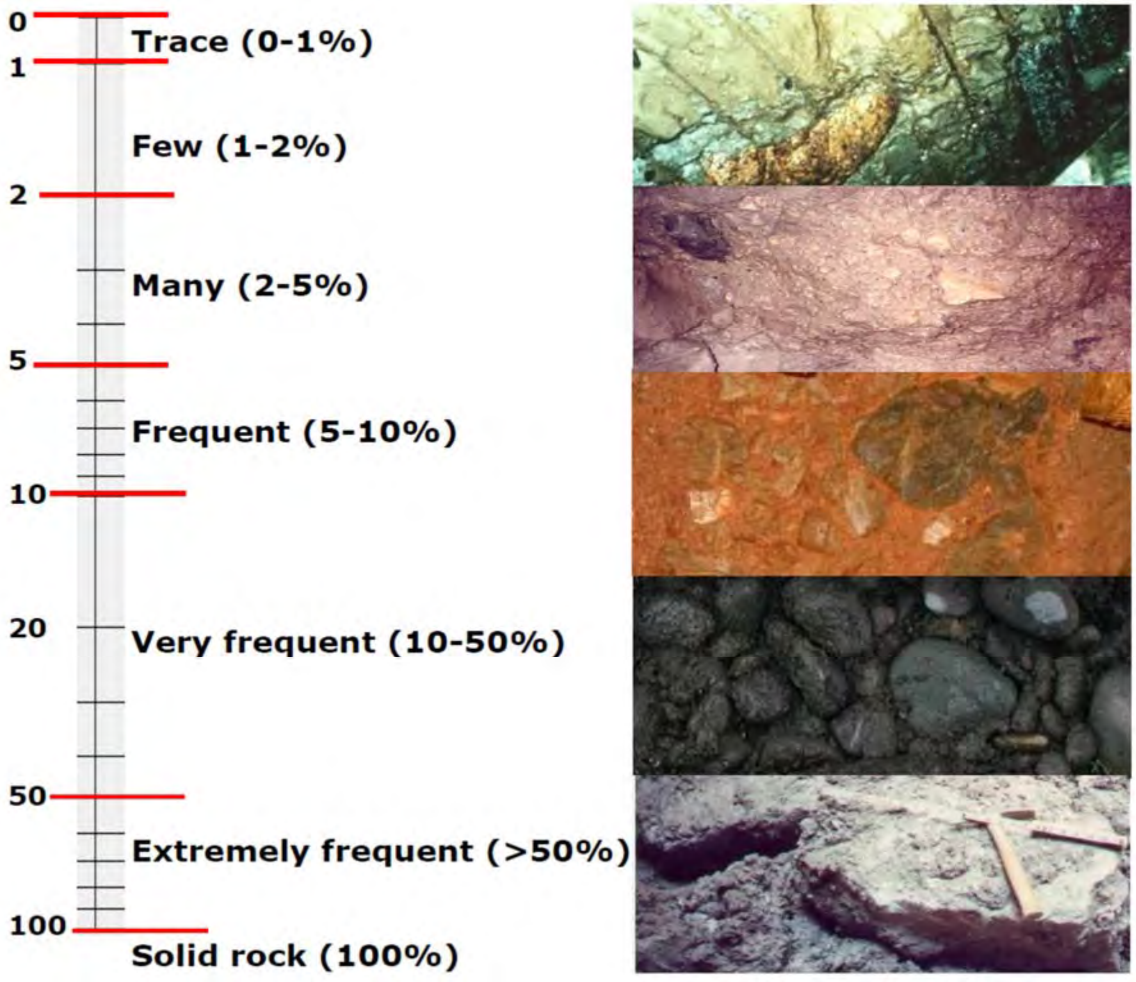


Figure 1 – Relative boulder volume ratios

1.4 Cobble Volume Ratios

Cobble quantities and cobble volume ratios (CVRs) are generally higher than those for boulders. For several Milwaukee projects studied [34], cobble volume ratios were estimated to be approximately 1.5 to 2 times the BVRs which resulted in much higher cobble quantities due to their smaller sizes. On the Bradshaw 8 project in Sacramento, the cobble volume ratios ranged from 25 to 50 percent and were much greater than BVRs due to fluvial sorting – CVRs typically ranged from 5 to 10 times greater than the BVRs. On the Alameda Siphon No. 4 project in California, the interpreted CVR was 16 percent and BVR was 4 percent or 4 times higher [42]. On the Los Angeles, California Regional Connector Transit Corridor Project, the GBR generally baselined CVR at 3 percent and BVR at 1 percent but baselined 5 and 2 percent, respectively at one station. [61]

On the Chengdu Metro Line 1 project in China, gravel, cobble and boulder volume ratios ranged from 50 to 90%, CVRs ranged from 5 to 20 percent and BVRs were 1 to 5 percent [32] [51] [74].

On the BWARI project in Columbus, Ohio, 157,021 cobbles and 5,429 boulders were estimated for 20,770 ft of 14 ft diameter tunnel [23]. A back analysis by the author resulted an approximate CVR of 0.22% and a BVR of 0.34%. The CVR may have been underestimated or the BVR overestimated (the latter according to the contractor [12]).

Estimated total average CVR + BVR values are compared to BVR values for 23 projects are shown in Figure 2. The CVR to BVR ratio generally ranges from 1 to 5 and commonly ranges from 2 to 4.

In summary, quantities and frequencies of cobbles and boulders are highly variable and dependent on geologic conditions and geomorphology. A reasonable rule of thumb is to assume that CVR = 3 x BVR. Methods for investigating quantities and baselining boulders are discussed later in this paper.

1.5 Cobble and Boulder Unconfined Compressive Strengths

Cobbles and boulders deposited in both alluvial and glacial deposits may contain both local bedrock clasts and “erratics” transported from distant upstream sources. In general, cobbles and boulders are stronger, more resistant rock clasts that have survived weathering and transport after erosion geologic processes. Erratics tend to be the strongest, hardest rock clasts. Cobbles and boulders from local or nearby bedrock generally have not been transported as far as erratics and may be weaker depending on the nature and strength of the bedrock. Weak rock cobbles and boulders seldom exist.

Typical unconfined compressive strengths for cobbles and boulders from six North American projects are shown in Figure 3. The cobbles and boulders had maximum unconfined compressive strengths ranging from 22,000 to 45,000 psi (152-310 MPa) and minimum unconfined compressive strengths ranging from 5,000 to 25,000 psi (34 to 172 MPa). The data also reflects that most clasts were stronger than 10,000 psi (69 MPa) from the projects reviewed. Draney 2012 [18] suggested that disc cutters are not needed for ground with strengths less than 2,900 psi (20 MPa). For rock tunneling, 10,000 to 15,000 psi (69 to 103 MPa) UCS is typically used as guideline for when disk cutters should be added to a TBM cutterhead.

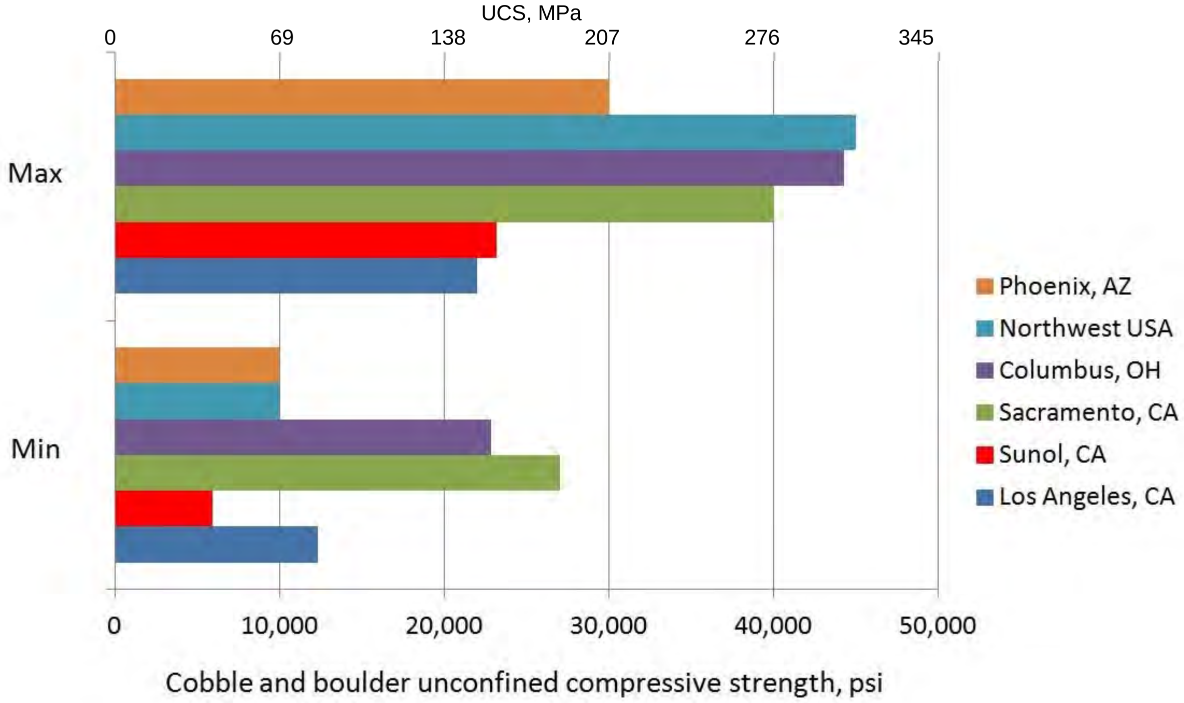


Figure 3 – Typical cobble and boulder unconfined compressive strengths

1.6 *Cobble and boulder risks, hazards and potential consequences*

A comprehensive risk management program is essential to properly manage cobble and boulder risks for tunneling. Cobble and boulder risks can be evaluated within four broad categories:

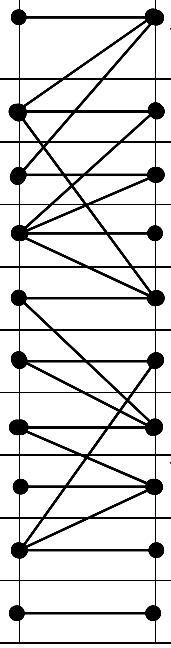
- Subsurface conditions – ground - groundwater.
- Construction equipment – tunnel boring machine, mucking system, etc.
- Facility constraints – line and grade limits, drive lengths, settlement sensitivity, etc.
- Contractual – risk sharing, compensation, schedule, etc.

A successful tunneling project requires that risks from all four categories to be managed.

There are many cobble and boulder condition risks, but concentrations and locations are of the utmost importance. Concentrated cobbles and boulders in lag zones or clusters are much more difficult to bore with a TBM than isolated cobbles and boulders. Concentrations of cobbles and boulders may choke a microtunnel boring machine (MTBM) rock crusher [40] or TBM excavation chamber causing the cutterhead torque to become excessive and the MTBM or TBM to stall. Cobble and boulder concentrations may also behave like a mixed-face condition and may cause steering and face instability problems [26].

The location of boulders is another factor. Boulders that extend past the perimeter, particularly large ones, are much more difficult to cut and more likely to be pushed aside or plucked resulting in excess lost ground and potential settlement or lining damage. Uncut pushed or partially cut boulders may obstruct or deflect a TBM shield and may damage trailing pipe or a segment lining by point loading (high contact stress) [37]. Table 1 provides a summary of potential hazards related to cobbly-bouldery ground and potential consequences.

Table 1 – Boulder encounter hazards and potential consequences

Hazard or Condition		**Potential consequence**
Boulder(s) over ~ 20-30% diameter, no face-chamber access or disc cutters		Stuck MTBM, rescue shaft or shaft-tunnel required or MTBM-tunnel abandoned
Boulders composed of much harder, stronger rock than expected		Severe pump and slurry line wear resulting in pump failure or line rupture
Cobble and boulder quantities much greater than expected		Severe cutter wear, higher tool replacement cost potential stuck MTBM
Ground is much more abrasive than anticipated		Severe intake port wear resulting in enlarged holes, jammed slurry lines
Boulders in weak-loose matrix resulting in plucked boulder rolling on cutterhead		Severe cutterhead wear or rock crusher bar wear, reduced advance rate, stuck
Mixed face heading weak soil zone adjacent to hard bouldery ground		Steering difficulty, MTBM/TBM deflected beyond line or grade limits
Advance rate higher than allowed for disc cutters causing plucked rock		Broken cutters or cutter housings and/or cutter arms from high impact forces
Attempt to blast or split boulders at heading in free air and unstable soil		Voids, excess lost ground, sinkholes, damaging settlements
Perimeter boulder(s) not cut by gage cutters or plucked from perimeter		Pipe or lining damage from passed perimeter boulder contact stresses
Large oblong boulders pass through cutterhead opening		Boulders jam against EPB screw conveyor intake

Contractual risk almost always involves advance rates, equipment wear, maintenance and ultimately schedule and cost. Tunneling costs (directly or indirectly) are generally higher when combined CVR+BVR values exceed a few percent. A single large isolated boulder can result in significant extra cost. Large boulders and high cobble and boulder concentrations generally reduce advance rates [1][8][9][11][13][17][34][35][41][48][64][65]. Higher tunneling costs due to cobble and boulder volumes over a few percent result from:

- More expensive TBM equipment requirements
- Slower TBM advance rates
- Delays and cost of equipment and excavations to remove boulder obstructions
- Cost of rescue shafts and tunnels
- Delays and costs to repair abrasion damage to cutters, cutterhead, rock crusher, mucking system, gears and/or bearing

Higher tunneling costs from cobbles and boulders may also result from:

- Higher bid prices in lump sum or unit rate items
- Larger quantities than estimated for unit rate items
- Boulder obstructions encountered with payment items or as compensation for differing site condition claims.

Section 4 provides more detail on the hazards and risks associated with tunneling in cobble and boulder ground conditions.

1.7 Compensation for tunneling in cobbles and boulders

Since tunneling through cobbly-bouldery ground costs more than tunneling through soil without boulders, an important question is how best to properly compensate contractors for tunneling through cobbly-bouldery ground. This topic was addressed in a 2002 paper by Hunt entitled Compensation for Boulder Obstructions [34]. Compensation (pay item) for man or intervention access boulder removal is sometimes viable and should be considered for:

- Open face tunneling in stable ground with a manual splitting option;
- Large boulders or cobble-boulder concentrations that “obstruct” TBM advance as defined in the specifications; and
- Tunneling methods where boulder quantities and sizes can be measured.

For most other conditions, separate compensation is not practical and the cost of cobble and boulder excavation is generally incidental and paid as part of the unit rate for tunneling. This is particularly true when using a pressurized face TBM that fractures and ingests rock fragments with no reasonable ability to measure quantities or sizes. Making boulder excavation incidental may also be appropriate where the estimated CVR + BVR is less than ~1 percent and where the maximum boulder sizes are expected to be less than about 25 percent of the excavated diameter and where the TBM is equipped with appropriate torque, cutters, rock crushers, wear protection or face access.

Even if most of cobbles and boulders can be fractured and ingested into the mucking system and are considered incidental, a compensation method for obstruction due to nested cobbles and boulders or large boulders or blocks should be considered. Experience indicates that paying for defined obstructions as bid is generally more cost effective than paying for them as part of a differing site condition claim.

Two methods of compensation for cobble-boulder obstructions are most common. One method is to bid a unit price per obstruction. This might vary with ranges of boulder obstruction size, face access from the tunnel, tunnel depth and rescue shaft restrictions. Another method is to bid a unit rate for delay time to access and remove qualifying cobble and boulder obstructions. The specifications must clearly define what advance rate reduction and other conditions qualify. An estimate of total obstruction hours would be baselined in a Geotechnical Baseline Report (GBR) and listed as a pay item quantity in the contract. Either way, what constitutes a qualifying boulder size and boulder obstruction and how it would be measured in the field must be carefully defined. Experience has shown that the removal time method is generally more equitable if face access is available – it reduces contractor risk resulting in better bid prices than the unit price per obstruction method [34]. The additional cost of tunneling in bouldery ground will be minimized if cobble-boulder risks are properly baselined and managed by TBM-MTBM selection including face access, cutterhead design, cutter types and power (torque-thrust).

2 SUBSURFACE INVESTIGATION OF BOULDERY GROUND

A case can be made that cobbles and boulders result in more cost and schedule overruns than any other single geologic condition encountered during soft ground tunneling. To exasperate the situation, tunneling risks and costs typically increase as the cobble and boulder quantities, size, hardness and frequency of occurrence increase. A focused, boulder-sensitive subsurface investigation and proper baselining are essential information to communicate risks to the contractor and allow better tunnel risk mitigation [36].

The basic problem faced by a designer in attempting to predict the geological and geotechnical risks (and costs) during construction of a tunnel is the adequacy of the information obtained from the site investigation program. Many subsurface investigation programs fail to collect sufficient cobble and boulder data resulting in inaccurate information or insufficient data to establish a baseline.

2.1 Effectiveness of Available Methods

Several authors have presented thorough discussions on the challenges of developing a subsurface investigation scope that is appropriate for cobble and boulder laden ground [1][20][22][30][33][36][39][54]. Table 2 was developed to synthesize the recommendations made in these papers and provide an update on the latest approaches to cobble and boulder detection in a subsurface investigation,. The methods identified in this table are key considerations in an appropriate subsurface investigation program for cobbly-bouldery ground. Some of the methods are limited by available previous data and depths. Test pits or trenches may not be cost effective at depths over about 15-20 feet and may be destructive in the ground disturbance caused. Large diameter auger borings are much more difficult and expense below the water table in cohesionless ground and at depths over approximately 50 feet.

Table 2 – Subsurface investigation options for cobbly-bouldery ground

Subsurface Investigation Methods	**Subsurface Investigation Method Selection Factors**				
	cobble and boulder frequency	**cobble and boulder size**	**cobble and boulder location**	**relative cost**	**some method references**
Desktop study	**+***	**+***	**+***	Very Low	[36]
Quarry/outcrop mapping	**+**	**+**	**0**	Very Low	[22]
Rotary wash/HSA w SPT	**0**	**-**	**0**	Low	[22]
Cone penetration test	**-**	**-**	**0**	Low	[54]
Becker percussion borings	**0**	**0**	**+**	Low	[69]
Rotosonic borings	**+**	**+**	**+**	Moderate	[22]
Large diam. bucket auger	**+**	**+**	**+**	High to Very High	[22]
Large caisson boring	**+**	**+**	**+**	High	[22]
Borehole GPR (radar)	**0**	**-**	**0**	Low to Moderate	[73]
Cross-hole seismic	**0**	**0**	**+**	Moderate	[73]
Surface seismic refraction	**-**	**-**	**0**	Low	
Surface electrical resistivity	**-**	**-**	**0**	Low	
Test pits	**0**	**0**	**0**	Moderate to High	[10]

Notes: **+** = Method Effective; **0** = Slightly Effective; **-** = Method Ineffective

* If previous tunnel case histories, subsurface investigations exist

In most cases, phased and multiple methods of exploration will be much more effective than single exploration methods [22][36]. For example, a desk study combined with both conventional rotary wash and hollow stem auger borings with Standard Penetration tests will be much more effective if test pits, rotosonic or large diameter auger borings are also completed.

In summary, successful subsurface investigation of cobble and boulder occurrence requires a phased program using multiple exploration methods with careful geologic monitoring and documentation of conditions encountered. Conventional borings alone such as commonly used for building foundation and earthwork investigations are generally not sufficient.

2.2 Conventional Borings

Despite limited effectiveness, conventional hollow stem auger and rotary wash drilling and sampling should be an exploration method utilized to obtain relative density data and samples for lab testing. This method can provide information on cobble and boulder occurrence if improvements are made to the information collected. The problem with most of the more traditional exploration methods is that cobble and boulder samples are not recovered and indications of cobbly-bouldery ground are seldom adequately documented [33].

To overcome these challenges, a method for estimating relative drilling resistance (RDR) between sample intervals was developed by the author on tunnel projects in Milwaukee. Table 3 summarizes criteria and typical ground conditions for RDR values ranging from 1 to 5. The boring logger with input from the driller should determine a RDR value for each drilling interval and then record values on the boring logs. Subsequently, RDR values in combination with Standard Penetration Test data and other conventional boring data should significantly improve interpretations of cobble and boulder occurrence.

Table 3 – Relative Drilling Resistance Criteria

RDR	Term	Criteria	Typical Ground Conditions
1	Very Easy	No chatter, very little resistance, very fast and steady drill advance rate	Very soft to soft silts and clays; very loose to loose silts and sands; no gravel, cobbles, boulders or rubble
2	Easy	No chatter, some resistance, fast and steady drill advance rate	Firm to stiff silts and clays; loose to medium dense silts and sands; little or no gravel, no to very few cobbles, boulders or pieces of rubble
3	Moderate	Some chatter, firm drill resistance with moderate advance rate	Stiff to very stiff silts and clays; dense silts and sands; medium dense sands and gravel; occasional cobbles or rubble pieces (2-3 occurrences per 10 ft)
4	Hard	Frequent chatter and variable drill resistance, slow advance rate	Very stiff to hard silts and clays with some gravel and cobbles; very dense to extremely dense silts and sands with some gravel; dense to very dense sands and gravel; very weathered, soft bedrock; frequent cobbles and boulders or rubble pieces (3-4 per 10 ft)
5	Very Hard	Constant chatter, variable and very slow drill advance, nearly refusal	Hard to very hard silts and clays with some gravel; very dense to extremely dense gravelly sand or sandy gravel; very frequent cobbles and boulders (at least 5 per 10 feet); weathered, very jointed bedrock

Standard penetration test N-values that are corrected for energy and depth can provide an indication of cobbles and boulders. Table 4 suggests N values that are likely to indicate cobbles and boulders for various soil matrix relative densities in geologic units where cobbles and boulders are likely. Since N values are also used to estimate relative density, the relative density for the soil matrix should be based on the lower ranges of N-values encountered within a geologic unit with the presumption that the higher values are more indicative of cobble and boulder presence than relative density.

Table 4 – SPT N-value Indications of Cobbles and Boulders

Approximate Average Relative Density of Soil Matrix	Corrected N value indicating probable cobbles and/or boulders (blows/ft)
Loose	> 25
Medium dense	> 50
Dense	> 75
Very Dense	> 100

2.3 Non-Conventional Borings

Several authors provide good overviews of exploration methods to supplement conventional boring and sampling methods for ground with cobbles and boulders [20][22][33][36][54]. One of the most complete studies of multiple methods and their cost effectiveness is reported in a Frank & Chapman 2001 paper [22] regarding the subsurface investigations in Columbus, Ohio prior to earth pressure balance tunneling projects. After completion of conventional borings, rotosonic borings, large diameter auger borings and quarry sampling, they concluded: “For this project, the use of several specialized investigation methods has enhanced the geotechnical characterization. Most successful was the rotosonic coring technique, which costs less than double the cost of conventional hollow stem auger borings.” The author agrees with Frank & Chapman based on similar experience at other projects in North America. At least two methods of subsurface investigation should be used to characterize cobble and boulder conditions.

Where rotosonic drilling is not practical, large diameter auger boring, test pits or other methods should be used to supplement conventional drilling and sampling. Confidence in cobble and boulder data should be higher were multiple methods provide consistent indications.

In summary, successful subsurface investigation of cobble and boulder conditions requires a phased program using multiple methods and careful geologic monitoring and documentation of conditions encountered. Conventional borings such as commonly used for building foundation and earthwork investigations are generally not adequate alone unless previously correlated to cobble and boulder volume ratios for the same geologic units encountered in completed shaft, cofferdam and tunnel excavations in the vicinity.

3 BOULDER BASELINING

3.1 What to baseline

Generally, properly baselined items should be measurable in the field, particularly if boulders or cobble-boulder obstructions encountered are a pay item. Proper baselining requires a thorough subsurface investigation program and then use of an effective method to correlate investigation data into boulder size and frequency predictions for each geologic unit to be encountered in a tunnel. The primary aspects to baseline include:

- Quantities and ranges of anticipated boulder sizes;
- Cobble and boulder distributions along tunnel (isolated vs. clustered) for each geologic unit;
- Clast mineralogy and rock types;
- Clast abrasivity, i.e., Cerchar Abrasivity Index;
- Clast unconfined compressive strength ranges; and
- Soil matrix types, strength, density permeability and abrasivity.

Additional aspects to consider baselining include: shapes of the clasts and Tunnelman’s Ground Classification of the matrix.

When open-face tunneling or closed-face tunneling with face access is used, cobbles and boulders may be at least partially observed at the heading. With open-face tunneling, intact boulders or rock fragments may also be observed in the tunnel muck.

When pressurized face tunneling is used, the TBM or MTBM is often equipped with cutters capable of fracturing boulders to a much smaller size that can pass through the cutterhead openings (or grizzly bars for EPBMs). The excavated material is then either: 1) crushed and ingested into a slurry mucking system or 2) passed through a screw conveyor (auger boring, pilot tube and earth pressure balance systems) into a conveyor belt or rail mucking system.

Unless obstructed, generally all of the boulders encountered by a pressurized face TBM or MTBM will be fractured to gravel or smaller sizes making assessment of boulder size and quantity very difficult. Similarly, larger boulders (all but cobbles and small boulders) will be fractured before passing through the mucking system. While intact boulder data is often not available, boulder encounters can be roughly inferred from analysis of vibration data [70], penetration rate, torque, thrust and angularity of rock fragments [19] [64], but boulder sizes cannot be reliably determined. Distinguishing between cobble clusters and boulders is also very difficult.

Due to difficulties in measuring quantities, a pay item for general cobble and boulder occurrence is not commonly used with pressurized face tunneling or microtunneling. Pay items are more frequently used to compensate for a defined cobble and boulder obstruction. An example obstruction definition is given below.

> A boulder obstruction occurs when a large boulder or cluster of cobbles and boulders is encountered at the heading of a tunnel that stops or significantly inhibits forward progress to less than 10 percent of normal progress for at least 30 minutes under normal thrust and torque with properly functioning cutters, and because boulders are too large or cobbles and boulders are too congested to be broken or ingested through the TBM cutting wheel and tunnel mucking system. In addition, the obstructing boulder or cobbles and boulders require removal by supplementary means such as drilling and splitting from the excavation chamber or removal within an excavation made from outside of the tunnel.

Obstruction definitions should depend on the owner's risk sharing position, tunnel size, anticipated tunneling method and cobble and boulder conditions.

Whether cobbles and boulders or obstructions are a pay item or not, cobble and boulder baselining is still recommended to help bidders determine tunneling methods, estimate advance rates, and estimate cutter wear and replacement costs. Cobbles and boulders should also be baselined for pressurized face tunneling where face access is limited and tunnel muck has been reduced in size resulting in inability to determine cobble and boulder content. While measurement to assess if quantities encountered are different than the baselined is very difficult, measurements can be obtained during periodic interventions, by supplementary borings or shafts and by evaluation of TBM operation parameters such as cutterhead speed and torque [64] and by geophysical or TBM vibration monitoring. Colorado School of Mines investigators monitored TBM vibrations to attempt to determine boulder encounters and general ground conditions on Sound Transit University Link, Contract U230 [53][70] and Northgate Link [29]. The method has promise for future use in assessing boulder encounters.

Boulder sizes and quantities can be baselined by one or more of three methods:

- Guessing or estimating from past local experience.
- Boulder volume ratio methods.
- Use of statistical or probabilistic methods.

Guessing is very risky and not advised. Past local experience is valuable, but must be analyzed with project specific subsurface investigation data that considers geologic settings. Three viable methods of boulder baselining are discussed below.

3.2 Boulder volume ratio (BVR) methods

Boulder volume ratio (BVR) methods involve screening of larger volume samples of ground than possible with conventional borings to determine cobble and boulder volumes. Sampling methods to obtain larger volumes include: deep excavations including shafts and tunnels, test pits, large diameter auger borings, and roto-sonic coring.

BVR values may also be estimated using semi-empirical correlations of geologic and subsurface investigation data to previous tunnel and excavation experience in the same geologic units.

Around 1997, designers in Toronto completed a major study of boulders for the Sheppard subway tunnel project [5]. They used borehole, excavation, outcrop and other data to determine average BVRs for geologic units expected within the tunnel zone. A boulder number ratio was also determined from the investigation data and then used with the BVRs to determine estimated quantities of anticipated boulder sizes. During tunneling, they found that design predictions correlated well with the boulders encountered [57].

Hunt developed a semi-empirical correlation method similar to that used in Toronto. A chart (Figure 4) was developed in 1999 [33] and that was updated in 2002 that correlates BVR data from eight completed tunnels to conventional borehole indications of percent bouldery ground for total boring length drilled in potentially bouldery ground [33] [34].

After determining anticipated BVR values for tunnel reaches based on all available data and geologic setting assessment, boulder quantity-size distributions can be made with an Excel spreadsheet that was developed using a negative exponential distribution function to estimate quantities of boulders for a range of geologically expected sizes – Figure 5. Since inception, the method has been used successfully on dozens of tunnel projects within glacial and alluvial soils to predict boulder occurrence.

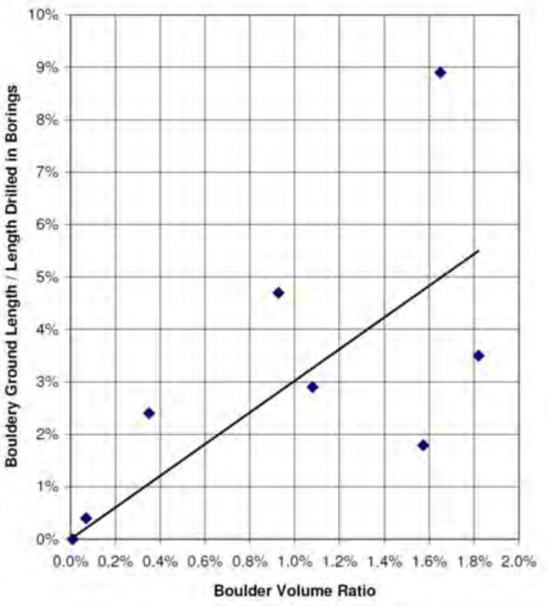
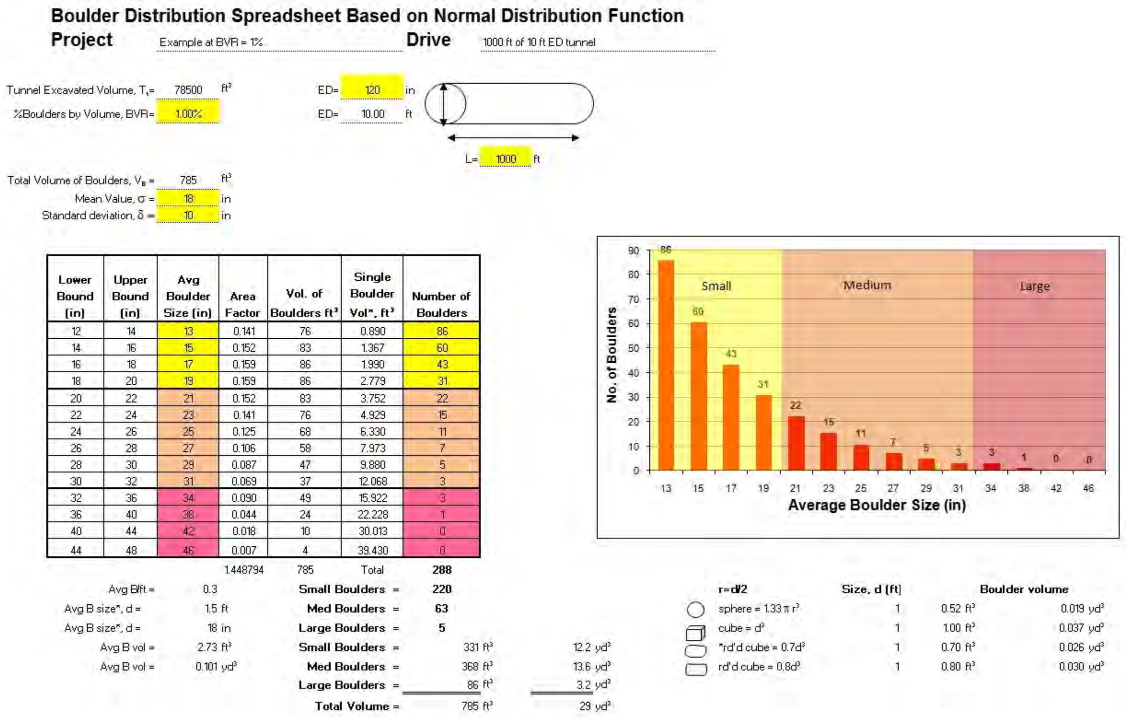


Figure 4 – BVR vs. % bouldery ground in borings (2002) [34]

3.3 Probabilistic methods

Attempts to predict boulder quantities from conventional borehole records date back to at least 1976 when Stoll [60] attempted to use a random probabilistic method. Around 1986, Tang & Quek [63] statistically evaluated the lengths of boulders taken from boreholes in sedimentary deposits in Singapore to show a statistical correlation with excavated boulders. Probabilistic methods were also used for the Storebaelt Tunnel in Denmark [14] [15] and for a planned tunnel in Italy [21].

The most extensive study of subsurface exploration for tunneling in bouldery ground [22] and development of an approach to predict boulder quantities and sizes for baselining was completed by Frank & Chapman during the early to mid-2000's for the BWARI project in Columbus, Ohio [62]. They developed an exponential distribution relationship similar to that used for the Storebaelt Tunnel. The number of clasts (boulders) expected is computed as $N=C/V^d$ where: N = no. clasts, V = volume excavated, C is a constant correlated with sample size data, and d is a constant correlated with clast size distribution. The method requires a significant amount of reliable sample data from the subsurface investigation. The constant d is evaluated from boulder sizes found in the investigation. The constant C is calculated from boulder volume data. The number of clasts for selected sizes is then computed using the formula with these constants. Tunneling results indicated that boulder quantities were slightly over-predicted, but accurate estimates of actual boulders encountered were difficult to make from the broken rock and very large quantities of muck [12] [13][62].



Boulder Distribution Spreadsheet Based on Normal Distribution Function

Project Example at BVR = 1% **Drive** 1000 ft of 10 ft ED tunnel

Tunnel Excavated Volume, T_t= 78500 ft^3

%Boulders by Volume, BVR= 1.00%

ED= 120 in

ED= 10.00 ft

L= 1000 ft

Total Volume of Boulders, V_B = 785 ft^3

Mean Value, σ = 18 in

Standard deviation, δ = 10 in

Lower Bound (in)	Upper Bound (in)	Avg Boulder Size (in)	Area Factor	Vol. of Boulders ft^3	Single Boulder Vol*, ft^3	Number of Boulders
12	14	13	0.141	76	0.890	86
14	16	15	0.152	83	1.367	60
16	18	17	0.159	86	1.990	43
18	20	19	0.159	86	2.779	31
20	22	21	0.152	83	3.752	22
22	24	23	0.141	76	4.929	15
24	26	25	0.125	68	6.330	11
26	28	27	0.106	58	7.973	7
28	30	29	0.087	47	9.880	5
30	32	31	0.069	37	12.068	3
32	36	34	0.090	49	15.922	3
36	40	38	0.044	24	22.228	1
40	44	42	0.018	10	30.013	0
44	48	46	0.007	4	39.430	0
			1.448794	785	Total	**288**

Avg B/ft = 0.3

Avg B size*, d = 1.5 ft

Avg B size*, d = 18 in

Avg B vol = 2.73 ft^3

Avg B vol = 0.101 yd^3

Small Boulders = **220**

Med Boulders = **63**

Large Boulders = **5**

Small Boulders = 331 ft^3 12.2 yd^3

Med Boulders = 368 ft^3 13.6 yd^3

Large Boulders = 86 ft^3 3.2 yd^3

Total Volume = 785 ft^3 29 yd^3

r=d/2	**Size, d (ft)**	**Boulder volume**	
sphere = $1.33\pi r^3$	1	0.52 ft^3	0.019 yd^3
cube = d^3	1	1.00 ft^3	0.037 yd^3
*rd'd cube = $0.7d^3$	1	0.70 ft^3	0.026 yd^3
rd'd cube = $0.8d^3$	1	0.80 ft^3	0.030 yd^3

Figure 5 – Boulder size distribution for anticipated BVR value

3.4 Functional Baselines

When cobble and boulder quantities and sizes cannot be reasonably measured, functional baselines may be an alternative to consider [19]. Functional baselines for cobbles and boulders might be for advance rates and cutterhead interventions. Edgerton et al 2012 explain this concept and give an example where an advance rate of reduction of 20 percent might be baselined as an indication of cobbly-bouldery ground. Payment could be by unit rate or as an allowance for an estimated length of tunnel in ground with reduced advance rates.

Functional baselining of advance rates or reduced advance rates in cobbly-bouldery zones should only be considered after careful evaluation of the geology and potential influences of means and method options. For example, it would not be appropriate to compare a non-boulder ground advance rate from tunneling in stiff-hard clay to a bouldery ground advance rate in a sand and gravel matrix. In some cases, the advance rate may actually be higher in the bouldery ground [66]. Other factors such as TBM type (open-face rotary wheel, earth pressure balance, slurry or digger shield), cutterhead opening ratio, cutterhead configuration, cutter types and cutter wear may have more influence on instantaneous advance rate than a change in ground type to cobbly-bouldery ground. Another very important factor would be utilization and down time or intervention time required to change cutters or make repairs. Utilization will likely decrease as CVR and BVR magnitudes increase. There are advantages and disadvantages to functional baselines. Careful consideration of both should be made before choosing this method of baselining.

3.5 Quantity Baselining Recommendations

Which aspects of cobble and boulder conditions to baseline and whether or not to directly baseline conditions or use functional baselines depends on the ground conditions, anticipated methods of construction and project owner's preference for risk sharing. Article 3.1 above gave recommendations for which ground conditions to baseline.

The method to use for evaluating data to predict quantities for baselining should depend on the size of the project and the quality and quantity of data available. When desired to baseline quantities, the volume method is generally more practical than probabilistic methods for most projects. Probabilistic methods are viable for larger projects with a significant amount of quality data. In either case, the method should consider the geologic setting, geologic variability and local experience.

4 TUNNEL EXCAVATION METHODS IN BOULDERY GROUND

4.1 Relative boulder size risk

Risk of tunnel advance being obstructed increases with relative boulder size. An illustration of this risk is shown in Figure 6. A 6. A closed (pressurized) face MTBM or TBM without face access or roller cutters has a much higher risk of being obstructed than with excavation by other methods.

When relative boulder sizes are greater than approximately 20 to 40 percent of the excavated diameter, the risk rapidly increases due to limits on the size of boulder than can pass through cutterhead openings and be either crushed or ingested (e.g. pass through a screw or belt conveyor). A single large boulder may obstruct a MTBM or TBM and require a rescue shaft or tunnel to remove the boulder obstruction and repair damaged cutters and cutterhead.

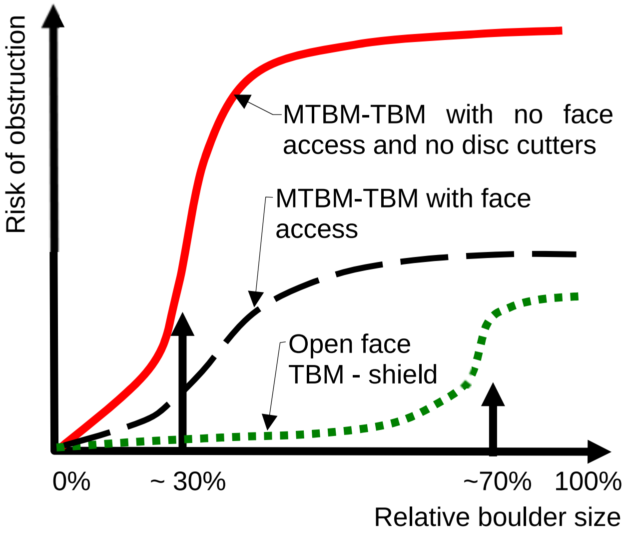


Figure 6 – Risk of boulder obstruction

A previous study of 40 pipe jacking cases revealed that MTBMs and small TBMs without face access or disc cutters became obstructed and stuck about 2.5 times more frequently than machines with face access or disc cutters [35].

4.2 Cobble and boulder cutting, crushing or ingestion considerations

In order to tunnel through cobbly-bouldery ground, the cobbles and boulders must be appropriately handled at three locations: the heading, the excavation chamber (which may or may not have a rock crusher), and the mucking system: screw conveyor, belt conveyor, slurry pumps and pipelines, etc.. Boulders must be excavated and possibly fractured by one or more of the following methods:

- Plucked from the ground using ripper, scrapper and/or roller cutters on a cutterhead and then passed through the cutterhead openings into the excavation chamber to be crushed before entering the mucking system. This method applies to slurry MTBMs and TBMs.
- Plucked and pushed aside if not passable though cutterhead and matrix is soft or loose enough. Boulders may roll on the cutterhead for a long distance before being pushed aside.
- Fractured and broken using ripper, scrapper and/or roller cutters on a cutterhead before being plucked and passing through the cutterhead to be crushed or passed through a screw or discharged onto a belt conveyor.
- Accessed from the excavation chamber or from a rescue shaft or tunnel and then manually split or blasted and removed.
- Pushed into a temporary shaft drilled below the tunnel invert at the heading.

Factors that should be considered when selecting the excavation tools and mucking methods include:

- Cobble and boulder strengths, sizes, shapes, abrasivity, distribution and quantities anticipated.
- Type, consistency and strength of the soil matrix with an assessment if sufficient cutting or fracturing is viable before clasts are plucked from the matrix.
- Assessment of potential inflows and if the stand-up time of the ground is sufficient to provide safe, free air access to fracture and remove obstructing cobbles and boulders.
- Assessment if ground improvement or compressed air will be required to provide sufficient stand-up time and water isolation to fracture and remove obstructing cobbles and boulders.
- Settlement damage risk if significant lost ground occurs at the heading.
- Cutter life and cutter cost - disc cutters generally have longer cutter life [55], but are much more expensive [13] Heavy rippers with hard, abrasion resistant inserts will have more cutter life than lighter, smaller steel rippers or scrapers.
- Energy and associated tool wear required to commutate boulders to gravel or cobble size for passage through a slurry shield mucking system if used, or through screw conveyors if used.

The commutation energy, E_c, required to crush rocks to gravel size has been studied extensively by the aggregate industry and TBM cutter researchers. Two commutation energy facts are important to recognize. First, rocks with higher unconfined compressive strengths require significantly more commutation energy than weaker rocks as shown in Figure 7.

Second, more energy is required to commutate rocks to gravel size than to small boulder or cobble size as shown in Figure 8. It shows that energy consumption increases rapidly to commutate rock clasts to fractions less than ~3 inches (75 mm). When high commutation energy is required, the MTBM or TBM power needs to be greater. The energy lost during commutation will result in higher rates of cutter, cutterhead and mucking system wear.

Commutation energy should be carefully considered when selecting an excavating- crushing-mucking system, particularly for ground with boulders stronger than ~ 138 MPa (~ 20 ksi) and BVRs exceeding ~ 2 percent. For example, the commutation energy and associated wear should be less for a 5-m (15-foot) diameter earth pressure balance TBM that can pass 395 mm (15-inch) rocks through to a conveyor or train car mucking system than for a slurry or mix-shield TBM that must crush cobbles and boulders to 180 mm (6-inches) or less in order to be pumped. MTBMs require crushing clasts to 75 mm (3-inches) or less requiring a lot of energy. This fact may provide a significant advantage to earth pressure balance TBMs in cobbly and boulder ground if conditioning is viable and cost effective to provide suitable face stability.

4.3 Advance rate impacts

As mentioned earlier, microtunnel and tunnel advance rates will generally be less in ground with cobbles and boulders than the same soil matrix type without clasts. Advance rate reductions may be due to four factors:

- Lower instantaneous penetration rates that are generally required to cut cobbles and boulders into smaller clasts rather than pluck them or sustain high cutter impact forces.
- Reduced advance rate to allow rock crushers to crush clasts and the mucking system to remove clasts from the excavation chamber and prevent choking or TBM cutterhead stalling.
- Delays to manually split or remove boulders resulting in lower utilization.
- Delays to replace worn cutters or repair the cutterhead and mucking system.

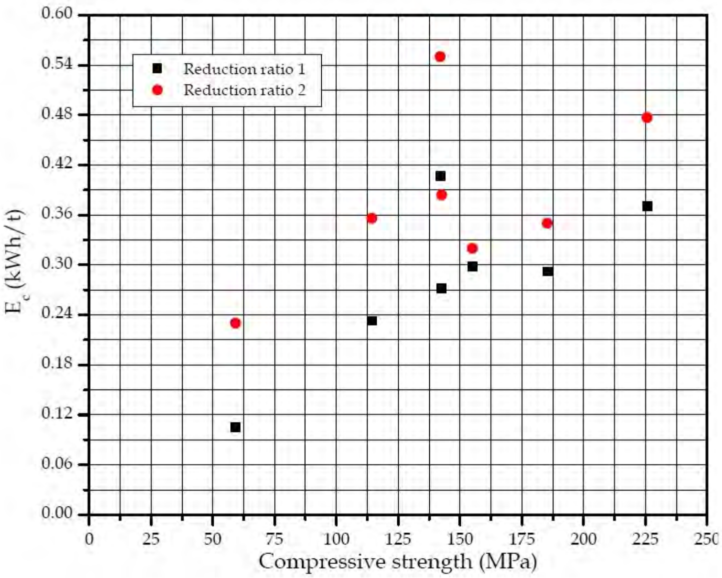


Figure 7 – Commutation energy vs. UCS, [16]

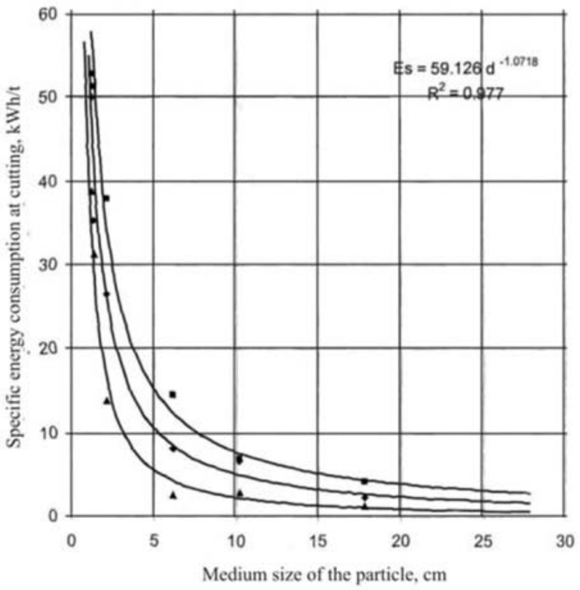


Figure 8 - Commutation energy vs. particle size, adopted from [55]

The effect of boulder quantities on advance rate using an open-face TBM was determined on the Columbia Slough project in Portland Oregon. Approximately 34,300 boulders were encountered within 2.5 km of 4.6 m diameter open mode shield tunneling [11]. The average advance rate per shift decreased by 14 and 22 percent for the East and West drives, respectively, as boulder volume increased from 0 to 18 percent of the excavated volume – Figure 9.

Data measured in Singapore on DTSS-1 Contract T-05 showed advance rate reductions of up to 75 percent as the BVR or hard ground volume varied from 0 to over 60 percent [67].

Data from another open-face shield [24] and a microtunnel project [64] indicated higher advance rate reductions ranging from 30 to 65 percent for boulder volumes ranging from 0.1 to 0.7 percent of excavated volume.

The TBM penetration rate in bouldery ground depends on TBM type and power, cutter types and configuration, ground conditions and operation strategy. If the penetration rate is too high, cutters may be excessively damaged by dynamic impact forces and the cobbles and boulders will likely be ripped out of or plucked from the soil matrix instead of cut. Studies and experience have shown that in order to achieve disc cutter rock chipping instead of boulder plucking, the penetration rate must be reduced down to a rate typical for rock TBMs (<10-12 mm/rev) [1][68]. The penetration rate used should balance the impacts of more frequent cutting tool replacement with an acceptable tunnel advance rate.

On some recent projects (BWARI in Columbus and Brightwater West in Seattle) where earth pressure balance TBMs were used, the target and achieved advance rates were greater than practical for disc cutters to cut boulders [13][68]. The contractors on both projects elected to use rippers and scrappers instead of disc cutters and achieved higher advance rates. Similar findings were made in China on the Chengdu Metro [50][51]. The section below entitled Cutter Considerations will show that for some ground conditions, a spoke type cutterhead with a higher opening ratio and use of rippers will be much more effective than a plate type cutterhead with smaller opening ratios and where disc cutters are primarily used.

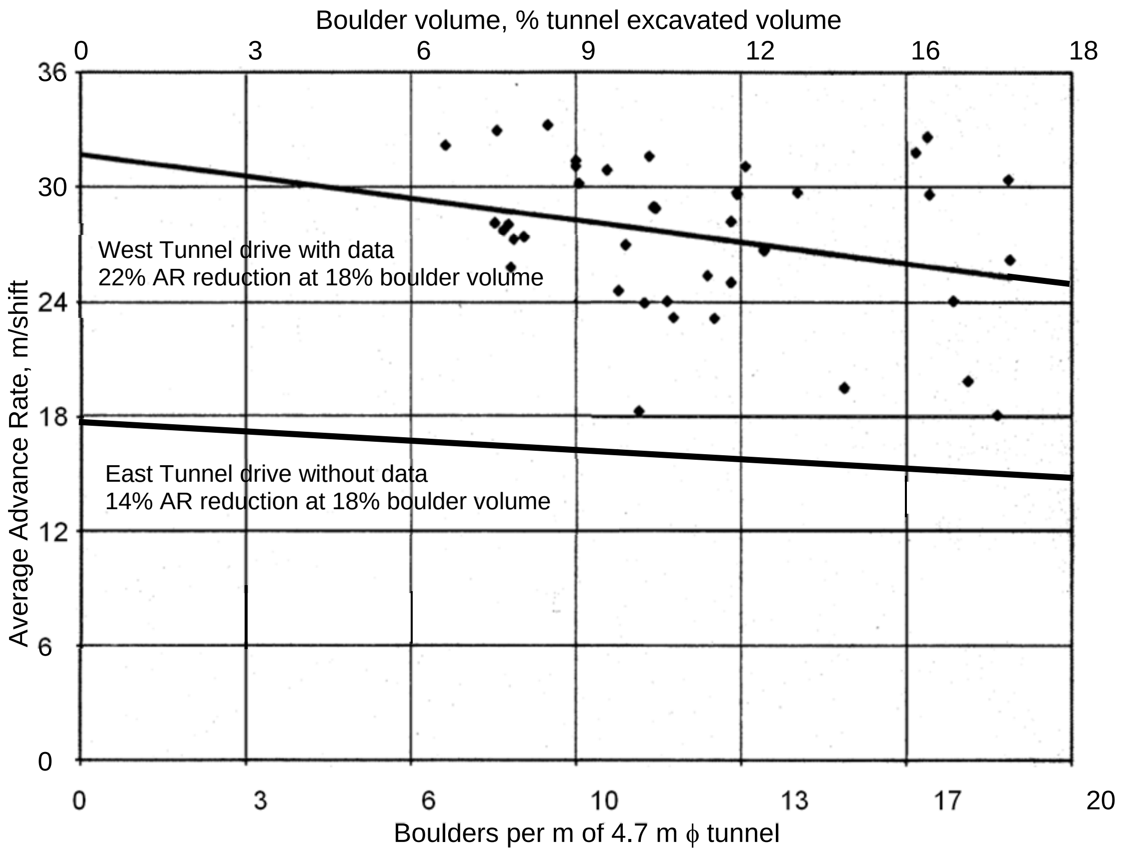


Figure 9 – Advance rate reduction with boulder quantity, Columbia Slough, after [11]

4.4 Cutter considerations

Cutter selection should depend on cobble and boulder volume ratios; boulder sizes; clast unconfined compressive strengths and abrasivity; matrix soil type, strength and abrasivity; cost of cutter replacement (cutter material cost and cost of cutter replacement time); and anticipated instantaneous advance rates. Colorado School of Mines researchers have extensively studied cutter type effectiveness and particularly the use of disc cutters in bouldery ground [25][45][55]. A study published in 2008 better explains degree of cutting versus plucking for ranges in boulder to matrix strength [25]. The study showed that plucking is likely to occur in weak soil with little or no splitting and that plucking is likely after partial cutting for most matrix soils. If the penetration rate is low enough and the matrix strength sufficiently high, disc cutters can chip and fracture boulders to small sizes (small cobble, gravel or smaller) for ingestion and mucking. After evaluating hundreds of cutters and TBM types, Dr. Ozdemir found single disc cutters to be the most efficient tool for chipping and boring hard rock [55]. While single disc cutters are generally most effective for full face rock, multi-kerf disc cutters (2 to 3 disc rows) with carbide inserts have been generally found to be more effective in bouldery ground [45][48]. The wider multi-kerf disc cutters provide a larger area to engage boulders and help to minimize premature plucking. They are also easier to keep rotating and more resistant to skid and impact damage.

A combination of disc and ripper-scraper cutters is generally more effective than all disc cutters or all scraper type cutters in ground where the total CVR + BVR is in the 1 to 10 percent range and where boulders are small, particularly for microtunnel boring machines. When BVR is over 5 percent and when boulder sizes are over ~30-40% of the excavated diameter, then disc cutters should be used as the primary cutter type.

When used, disc cutters are usually positioned 25-30 mm ahead of the scraper bits to allow chipping or fracturing of boulders before contact with the ripper-scrapers [1]. Evaluators have found that combination cutterheads are not only effective for optimal penetration rate, but significantly reduce the risk of catastrophic cutter damage and becoming obstructed [35][48][65].

Experience with projects such as Chengdu Metro in China and Columbia Slough in Portland Oregon that had high volumes of gravel, cobbles and small boulders (CVR + BVR >10%) has shown that a spoke type cutterhead on an open-face or earth pressure balance TBM with a higher opening ratio and use of rippers will be much more effective than a plate type cutterhead on a slurry or earth pressure balance TBM with disc cutters and smaller opening ratios. The larger cutterhead opening ratios will allow larger clasts to flow through the cutterhead. Larger diameter and ribbon type screw conveyors will allow those larger clasts to pass through the excavation chamber will faster advance rates, less energy spent crushing clasts with less wear and tear on the cutters, cutterhead and mucking system. The case histories below will explain some of this experience.

4.4.1 BWARI and Brightwater West with Rippers

Although a combination head is often best, a cutterhead with only or primarily heavy block rippers and scrapers may facilitate a higher rate of advance with less cutter cost (cutter material and the labor-delay cost for replacement after wear or breakage) [13][68]. For example, on the BWARI project in Columbus, Ohio, a 16 ft (4.9 m) diameter earth pressure balance TBM was used to bore though very bouldery till and outwash (BVR ~ 0.34%) [62]. The contractor, Jay Dee, Michels, Traylor JV, had better advance rates and cutter cost effectiveness after replacing the cutterhead face disc cutters with heavy block rippers – Fig. 10. Using a high cutterhead rotation speed and advance rate, the heavy block rippers were able to “bash” most of the boulders and break them into sizes less than ~ 305 mm (12-inch) in size that could pass through grizzly bars and screw conveyors for the EPB TBM used.

Figure 10 – Heavy block rippers, BWARI Project, Columbus, Ohio [13]

Heavy block type scraper cutters were also used to bash boulders on Brightwater West. The contractor, Jay Dee-Coluccio-Tasai, elected to use only heavy tungsten carbide insert, chromium carbide plated ripper and block scrapers and no disc cutters in soil primarily consisting of cobbly-bouldery glacial till and outwash (BVR ~ 0.03 percent eastern third of drive) under groundwater heads up to 5 bar [68] – Fig. 11. This cutter selection was found to be successful. The heavy enhanced scraper cutters resulted in an average tunneling distance of ~1030 m (3,380 ft) within the western two thirds of the drive and ~280 m (920 ft) within the more abrasive bouldery ground of the eastern third. One of the keys to this success was that only one of 12 cutter change interventions was in hyperbaric conditions – the other 11 were in free air.

A detailed evaluation of ripper cutter use on BWARI and Brightwater West was given in a 2011 RETC paper [58]. The authors discuss both gradual cutter wear from travel through the ground as well as cutter (ripper) breakage from impacts with boulders. They describe methods used to attempt to predict cutter life – average radial travel distance before sufficient wear to require replacement. Figure 12 shows the reported cutter life results for rippers on BWARI (left) and Brightwater West (right). Both plots show that cutter wear increases with distanced traveled.

On BWARI, the average interval advanced before cutter changes was ~ 500 ft when conventional rippers were used and ~ 3,000 ft after the heavy block rippers were installed [58]. "Figure 6" on the right side of Figure 12 shows the cutter wear and distances traveled varied from ~ 0.5 inches wear at ~ 50,000 ft to ~ 3.5 inches wear at 500,000 ft of radial cutter travel.

On Brightwater West, very little cutter wear (<0.5 inches) was observed within the western two thirds of the drive where the ground was predominantly less abrasive pre-glacial lacustrine silt, clay and sand – see flat, lower line in Fig. 12 (note that a distance scale was not shown, but is assumed to be 0 to 125,000 ft). Wear significantly increased within the eastern third of the drive where the ground changed to glacial till and outwash sand and gravel with cobbles and a trace of boulders. Wear of ~ 2.5 inches is shown at travel distances of ~ 125,000 ft. The considerable scatter in the data was partly attributed to cutter breakage from cobble and boulder impacts.

Figure 11 – TBM with tungsten carbide insert, chromium carbide plated ripper scrapers, Brightwater West [68]

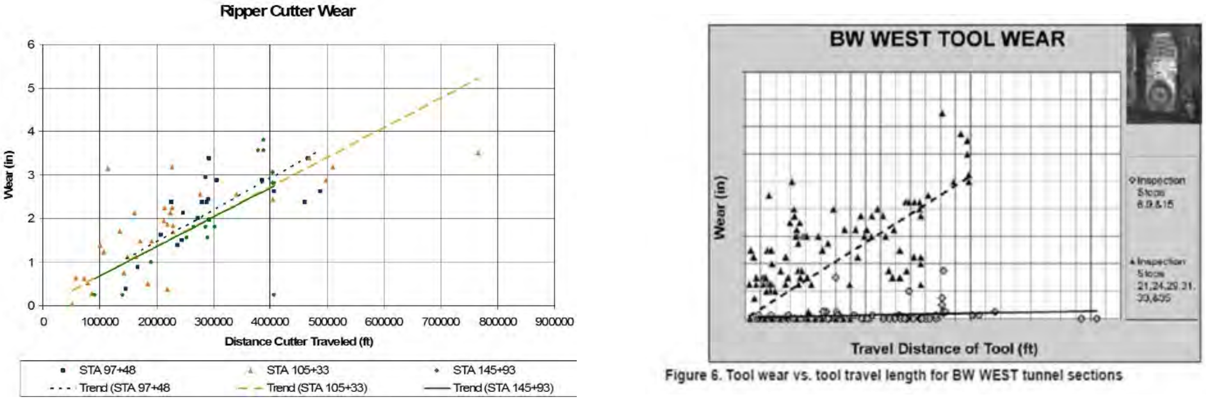


Figure 12 – Ripper cutter life from BWARI [13] and Brightwater West [58]

The authors provide a detailed discussion of abrasion and TBM operation factors and found that advance prediction of cutter life is very difficult. Some of their conclusions related to cobble and boulder factors include:

> "This leads to the conclusion of other system components than the chosen abrasiveness descriptors and cutterhead energy consumption to be more relevant causal factors for the observed tool wear. As discussed, the fact that ripper-type tools are subject to significant impact forces in boulder conditions points to the possibility of non-gradual material loss of the cutting tools and thereby to a wear mechanism not covered by the above evaluation."
>
> "Predicting the consumption of TBM cutting tools based on these soil abrasiveness descriptors alone, however, appears not possible."
>
> "The correlation of normalized tool wear and counts of coarse components [gravel, cobbles and boulders] encountered points to those components being a dominant factor in causing material loss of cutting tools."

4.4.2 Chengdu Metro Line 1

Chengdu Metro Line 1 included 18.5 km of twin running tunnels excavated with EPBMs in multiple lots. Tunneling for the initially bid lots encountered several problems related to cobbly-bouldery ground. The average advance rates using primarily disc cutters on plate type cutterheads with cutterhead opening ratios in the range of 20 to 30 percent were unsatisfactory.

Much of the ground for Chengdu Metro Line 1 is Quaternary fluvial and alluvial deposits with cobbles and boulders in a loose to medium dense, cohesionless sand or gravel matrix [7][50][51] [74]. The EPB TBMs on Lot 1 had predominately disc cutters with scrappers at cutterhead openings. Problems were experienced with improper disc cutter rotation and stalling, uneven and excessive cutter wear and lower than expected advance rates. To mitigate these problems, the cutterhead configuration was modified for the Lot 3 and subsequent tunnel bores. Most of the disc cutters were replaced with rippers and "pick tools". This modification stopped the problem of cutter stalling and uneven wear, reduced cutter changes and significantly increased advance rates [7].

Disc cutters were found to be mostly plucking cobbles and boulders, experience frequent jamming or roll stoppage resulting in excessive flat wear and had levels of wear and breakage. Rippers gave higher advance rates but were also ineffective at breaking hard, large boulders (over 500 mm in size) within a loose sand and gravel matrix. Larger boulders were often pushed aside with associated high wear. Those that obstructed advance had to be manually split during a hyperbaric intervention.

When interventions were attempted in high permeability gravel matrix soils, problems were experienced with excess air loss and face instability. Modifications included injection of bentonite slurry into the chamber and pressurized filter cake formation prior to starting hyperbaric interventions [7].

A study of experience at Chengdu and other locations in China with similar cobbly ground led to similar conclusions [50]. Although plate type cutterheads with CORs in the range of 20-30 percent helped improve face stability and the success of hyperbaric interventions, they did not allow high enough advance rates – higher CORs combined with ripper cutters and a large ribbon type screw conveyor resulted in higher advance rates. Li et.al 2017 [50] concluded: "The spoke type cutterheads equipped with precut bits, shell bits, scrapers and a center fish-tail bit are strongly recommended for the shield tunneling in loose coarse grain soils without groundwater." and "The spoke type and spoke-plate type cutterheads with high opening ratios of 39-75.5% are favorable to passing of the ripped-off big stones into the rear mixing chamber without the need of a substantial pressure drop, thus mitigating wears and damages of cutting tools and other components as well as reducing interventions of changing tools."

4.4.3 Canada Line with Rippers and Disc Cutters

While boulder bashing with heavy block cutters may be a viable boulder excavation method for tunnels over 10 ft (3 m) in excavated diameter and where low groundwater heads and ground conditions allow mostly free air interventions to remove obstructions or replace cutters, boulder bashing is probably not appropriate if groundwater heads prevent free air interventions or on projects where lost ground must be minimized, e.g. in settlement sensitive urban conditions. The contractor, SNC-Lavalin Constructors Pacific and SELI (SSJV), on the Canada Line tunnel in Vancouver, BC found that ripper cutter wear was excessive on Drive 1 upon advance into glacial till with cobbles and boulders (estimated BVR ~ 0.3%) [9]. To reduce cutter wear, they replaced the ripper cutters with twin kerf disc cutters. To further improve cutter performance on

Drive 2, disc cutters with carbide inserts were used resulting in fewer cutter wear problems. Average advance intervals before cutter changes ranged from 615 to 1230 ft.

A comparison between BWARI, Brightwater West and Canada Line projects shows that cutter life is highly variable and depends on many factors including cutter type, cutter robustness and armoring with carbide inserts, TBM advance rate, abrasiveness of the soil matrix and cobble and boulder volume ratio (CVR and BVR).

4.4.4 Cutters for Microtunneling

When microtunneling, a combination cutterhead with scrapper and disc cutters is essential to minimize risk of getting stuck from severe cutter wear [35][42]. When the anticipated maximum boulder sizes are greater than approximately 50 percent of the MTBM diameter, conditions rapidly approach those encountered during rock microtunneling. A single boulder greater than 50% of the excavated diameter can cause a stuck MTBM unless it is equipped with cutters and power suitable for rock. A 2009 overview of rock microtunneling experience provided many useful guidelines that are applicable to microtunneling in cobbles and boulders [38]. A completed project in Milwaukee successfully used two adequately powered MTBMs with combination heads (scraper and disc cutters) to bore through cobbly-bouldery glacial till and outwash (BVR ~ 0.1 to 10%) and a dolomite rock ridge over 400 feet wide [26]. Drives lengths of 405 and 800 feet were achieved without cutter changes and severe damage in the extremely difficult bouldery till, mixed-face and full face rock conditions encountered.

4.4.5 Cutters Conclusions

In summary, many factors should be considered when selecting cutters for cobbly-bouldery ground. Heavy, block type ripper and scraper type cutters that are protected with carbide inserts may be the most cost effective cutter for maximizing advance rate and minimizing cutter tool change costs where face access is available and a stable face with little or minor inflows can be achieved in free air. Ripper and scraper cutters are also effective if boulder volume ratios are less than about 2 percent and in a loose matrix that allows easy plucking and passing or pushing aside. Where boulder volume ratios are over 2 percent or where large boulders over 1.5 m are common, particularly in a dense or hard soil matrix, rippers and scrapers will likely be ineffective and boulder access interventions would be required. A combination head with ripper-scraper and disc cutters or mostly disc cutters may be more cost effective for microtunneling and for pressurized face tunneling in wet ground with over 2-3 bar of water pressure, particularly where hyperbaric interventions may be required to change cutters.

4.5 Problematic Ground

While robust MTBMs with combination heads, particularly if face access is also provided, significantly increase the chances of good advance rates and avoidance of stuck drives, some combinations of cobbles, boulders and soil matrix type remain very risky. Probably the most treacherous condition for MTBM or pressurized face TBM tunneling is a combination of cobbles and boulders with a CVR+ BVR greater than 10 percent in open, high permeability gravel or a sand-gravel matrix with fines less than 3 percent. Bentonite slurry at the face may flow excessively into the gravel and may not have sufficient viscosity to form a filter cake and prevent excess flowing ground. With earth pressure balance tunneling, such ground is very difficult to properly condition and may result in inadequate face pressure and excess flow through the screws. If cutterhead openings are excessive, the excavation chamber may quickly become filled with gravel, cobbles and boulders that resist crushing and flow through the intake ports or screw conveyor resulting in a blocked chamber and a stalled MTBM or TBM. Significant reductions in the cutterhead opening ratio to less than 20 percent may be required to obtain face stability and reduce risk of stalling an adequately powered MTBM in these conditions [31][42].

Another high risk is that very abrasive ground and cobble and boulder impact damage may result in excessive cutter-cutterhead-crusher-intake port wear severely reducing the average advance rate or resulting in a stuck MTBM and possibly inability to complete the project with the selected MTBM [6][59].

When cobble and boulder volume ratios exceed approximately 10 percent and very abrasive matrix soils are present, microtunneling should be avoided or special measures implemented and pay items provided to manage the likely advance rate and abrasion impacts.

Hunt & Del Nero 2012 [40] and Hunt et al 2013 [42] provide a detailed discussion of considerations and potential measures for microtunneling in cobbles and boulders in a gravel matrix. The risks of microtunneling in gravel with cobbles and boulders can be mitigated by a variety of potential measures. To microtunnel in high-permeability gravel and to reduce risk of choking and stalling and the risk of severe overmining and sinkholes, flow of ground through the cutterhead into the excavation chamber must be restricted to a rate manageable by the crusher and slurry mucking system by one or more of the following methods:

- Pre-excavation grouting to reduce permeability and increase strength.
- Required use of bentonite conveyance slurry and not allow water-soil slurry.
- Thickening of the bentonite slurry and addition of additives if necessary to allow a “filter cake” to form or at least significantly reduce slurry flow into gravel-cobble pores, thereby increasing face stability.
- Application of a slurry pressure at the face equal to at least the hydrostatic groundwater pressure and estimated active earth pressure.
- Reduce cutterhead opening size and cutterhead opening ratio to less than normal.
- Require minimum MTBM torque – or torque-cutterhead speed combinations.

5 ABRASION AND CUTTER WEAR

5.1 Total Ground Abrasivity

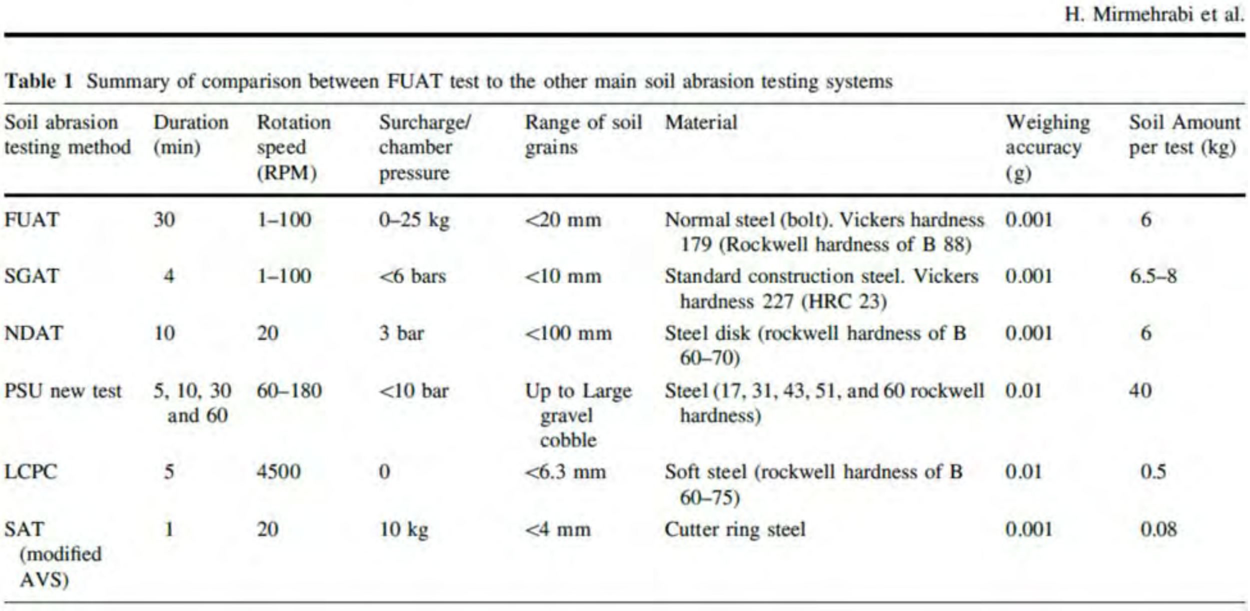
The total abrasivity of tunnel zone ground is due to the combined effects of the soil matrix, gravel, cobbles, boulders and any mixed-face ground or rock encountered. An assessment of tunnel zone ground abrasivity to estimate wear of cutters, cutterhead, rock crusher and mucking system is a very important component of risk management for tunneling in ground with gravel, cobbles and boulders or mixed-face conditions. Total ground abrasivity not only includes the primary wear of cutters and secondary wear of the cutterhead and mucking system, but also includes cutter breakage from impacts with cobbles and boulders or hard rock in a mixed-face.

5.2 Soil Abrasion Testing

During the past 10 years, significant advancements on soil matrix abrasion tests have been made by researchers in France, in Norway at the Norwegian University of Science and Technology (NTNU), in the United States at Penn State University and Colorado School of Mines, in Iran and recently in South Korea. The early soil matrix abrasion testing methods were limited to grains smaller than 20-mm (0.8-inches), which do not allow assessment of abrasion risk from gravel, cobbles and boulders. The more recently developed methods now allow testing of soil mixtures with gravel and very small cobbles up to ~100-mm (3.9-inch) in size. None of the soil matrix abrasion tests consider the effects of cobbles and boulders, which is a significant limitation for ground with CVR + BVR over ~ 2 percent.

Mirmehrabi et.al. 2015 [52] present a new soil abrasion testing method called Ferdowsi University Abrasion Test (FUAT) and summarized the key features of it and the other soil abrasion testing methods as shown in Table 5.

Table 5 – Summary of Six Soil Abrasion Testing Methods from Mirmehrabi et.al. 2015 [52]



H. Mirmehrabi et al.

Table 1 Summary of comparison between FUAT test to the other main soil abrasion testing systems

Soil abrasion testing method	Duration (min)	Rotation speed (RPM)	Surcharge/ chamber pressure	Range of soil grains	Material	Weighing accuracy (g)	Soil Amount per test (kg)
FUAT	30	1–100	0–25 kg	<20 mm	Normal steel (bolt). Vickers hardness 179 (Rockwell hardness of B 88)	0.001	6
SGAT	4	1–100	<6 bars	<10 mm	Standard construction steel. Vickers hardness 227 (HRC 23)	0.001	6.5–8
NDAT	10	20	3 bar	<100 mm	Steel disk (rockwell hardness of B 60–70)	0.001	6
PSU new test	5, 10, 30 and 60	60–180	<10 bar	Up to Large gravel cobble	Steel (17, 31, 43, 51, and 60 rockwell hardness)	0.01	40
LCPC	5	4500	0	<6.3 mm	Soft steel (rockwell hardness of B 60–75)	0.01	0.5
SAT (modified AVS)	1	20	10 kg	<4 mm	Cutter ring steel	0.001	0.08

5.3 Rock Clast and Rock Abrasion Testing

The abrasivity of rock clasts or rock can be assessed by completing Cerchar Abrasivity Tests per ASTM D7625, Laboratory Determination of Abrasiveness of Rock Using the Cerchar Method. Many references are available on rock abrasivity testing, but it is not discussed here. The focus of the remaining abrasivity discussion will primarily be the combined abrasivity effects of the soil matrix and cobbles and boulders.

5.4 Abrasivity from Cobbles and Boulders

The abrasivity of cobbles and boulders should always be considered and particularly when concentrations exceed approximately 2 percent by volume. Abrasivity of cobbles and boulders involves the intact rock abrasivity indicted by Cerchar testing and cobble and boulder conditions including concentration (combined cobble and boulder volume ratio), size, angularity and distribution within the soil matrix. A method is proposed below that will allow better assessment of cutter wear and breakage and frequency of cutter changes and associated interventions for ground with cobbles and boulders.

Kloppl & Thuro 2013 [47] and Kim et.al. 2017 [46] (and others) define and utilize a term called cutting distance, Sc, as the ground surface distance traveled for the cutter life – before it wears to an extent requiring replacement. The cutting distance estimate for cutters can be used to estimate the cutter change interval, Li, for the anticipated ground conditions, which determines where interventions may be needed and the extent of effort and cost to mitigate abrasive cutter wear and breakage.

Kloppl & Thuro 2013 also define a term called Soil Abrasivity Index, SAI, and provide equations and correlations of cutting distance, Sc, to Equivalent Quartz Content, EQC, and other soil abrasion testing results. For example, Figure 13 shows cutting distance Sc versus SAI for both disc cutters and scrapers.

Kim et.al. 2017 [46] determined the Sc values shown for six soil types Based on a study of 17 projects in Table 6. The Sc values ranged from <250 to over 1500 km/cutter for the soil types. These values may be used as a guideline or check against soil abrasion test results and cutting distance calculations being used to estimate Li values (estimated distances between cutter change interventions).

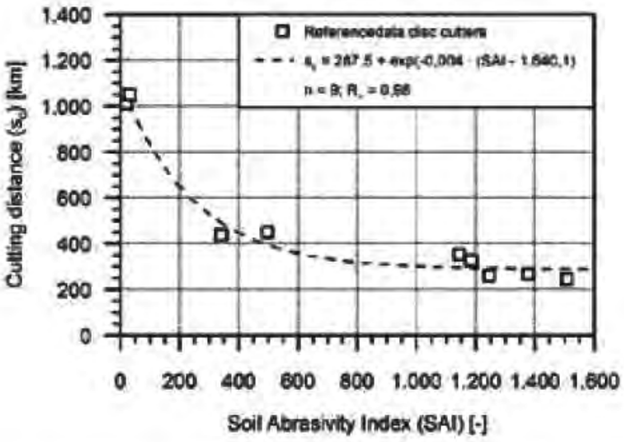


Figure 1. Correlation of the Soil Abrasivity Index (*SAI*) and the cutting distance s_c of disc cutters in different geotechnical conditions.

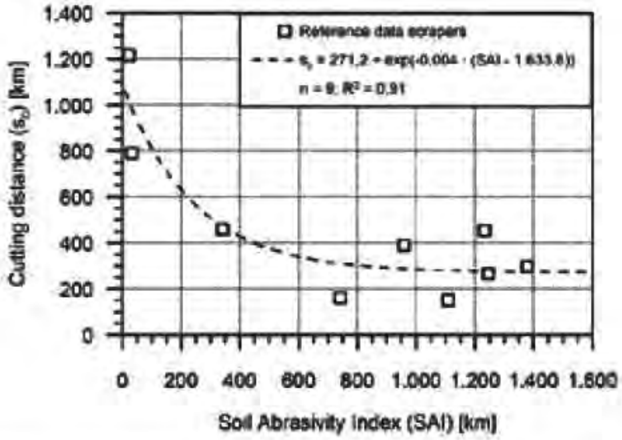


Figure 2: Correlation of the Soil Abrasivity Index (SAI) and the cutting distance s_c of scrapers in different geotechnical conditions.

Figure 13 – Cutting distance, Sc, versus Soil Abrasivity Index from Koppl & Thuro 2013 [ ]

Table 6 – Cutter life, Sc, values in km/cutter for six soil types from Kim et.al. 2017 [ ]

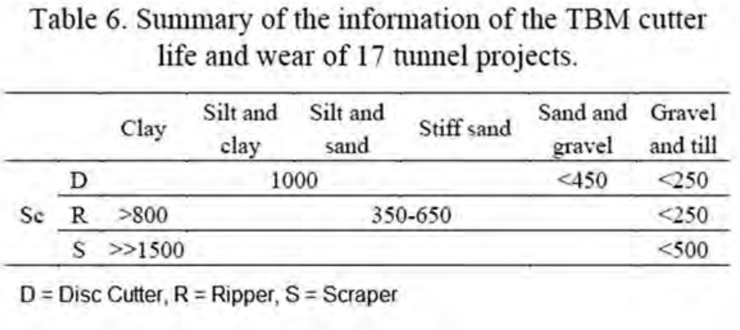


Table 6. Summary of the information of the TBM cutter life and wear of 17 tunnel projects.

		Clay	Silt and clay	Silt and sand	Stiff sand	Sand and gravel	Gravel and till
Sc	D		1000			<450	<250
	R	>800	350-650				<250
	S	>>1500					<500

D = Disc Cutter, R = Ripper, S = Scraper

Another approach to estimating Li values is to obtain estimate of cutter tool life, Vc, as cubic meters of tunnel bored divided by the number of worn or broken cutters that must be replaced over a tunnel interval or Li interval. Vc values can be used to estimate Li values for the anticipated ground conditions. Jakobsen et.al 2013 [43] and Jakobsen 2014 [44] provide charts that relate Vc in m^3/cutter to EQC, SAI, and SAT (Soil Abrasion Test from NTNU). Figure 14 shows a relationship between Vc and EQC for various soil types and shows that Vc values for soil matrix generally ranges from about 50 to 1400 m_3/cutter with most of the data between 200 and 1200 m^3/cutter.

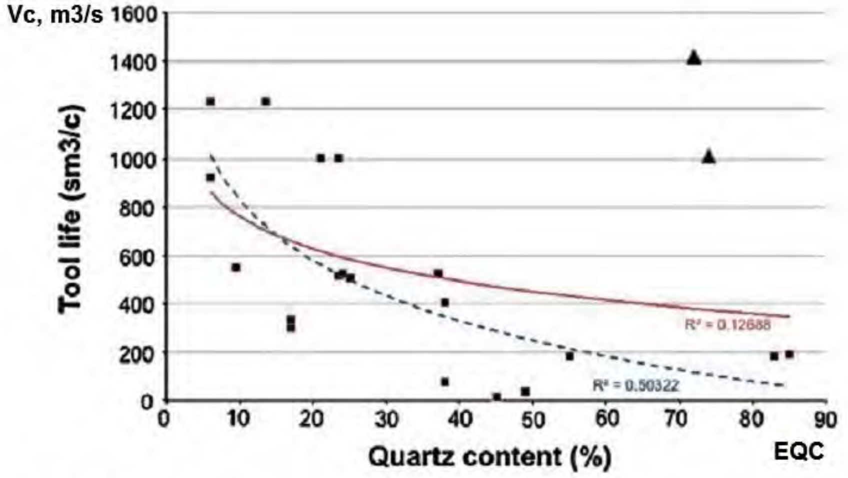


Fig. 14. Correlation between quartz content and recorded soft ground tool life. The

[From Jacobsen 2013]

Figure 14 – Tool live, Vc, versus EQC for various soil types per Jakobsen 2013 [43]

For comparison, Vc values for seven bores in rock are shown in Table 7. The Vc values range from 42 to 1661 m^3/cutter. By combining both the Vc values from the soil matrix and rock, an indication of cutter tool live from cobbles and boulders might be assessed.

For example, if the soil matrix is primarily clay with a EQC of 10%, a Vc value of of ~800 m^3/cutter may be estimated. If the ground contains cobbles and boulders with a CVR+BVR of 10 percent or more, the rock abrasiveness may control and if the rock is hard granitic rock (common for boulders) with an EQC of 80%, a Vc value of 100 m^3/cutter may be assumed for the rock clasts.

Table 7 – Cutter life, Sc, Vc values in m/cutter for rock and mixed face ground

Project	Ground	Vc, m^3/cutter	Li, avg intervention length, m	Reference
HEPP, Turkey	Limestone	1661	552	[1]
Busan Line II, Korea	Mixed face	295	212	[4]
Busan Line II, Korea	Granodiorite, andesite	91	73	[4]
Tuzla WW, Turkey	Sandstone conglomerate	42	79	[28]
Yinhanjiwei, China N	Phyllite, amphibolite schist	1048	218	[72]
Yinhanjiwei, China S	Quartzite, granite	121	13	[72]
Tsuen Wan, Hong K.	Tuff, granodiorite	88	-	[56]

The previous discussion provides abrasivity and cutter wear or life information for soil and for rock with one example of mixed face conditions. To relate this information to abrasivity and cutter wear due to cobbles and boulders, the author used a database of soft ground tunnel projects with various percentages of cobbles and boulders. Figure 15 is a plot of average cutter change intervention interval, Li, versus BVR. It shows that impacts on Li are small for BVR values less than ~ 0.5 percent and are slightly more than Li values experienced for soil without cobbles and boulders. The impacted of boulders rapidly increases at BVR values over 0.5 percent and approaches the Li values for rock at BVR values over 1-2 percent which would correspond to CVR + BVR values of ~3 to 6 percent.

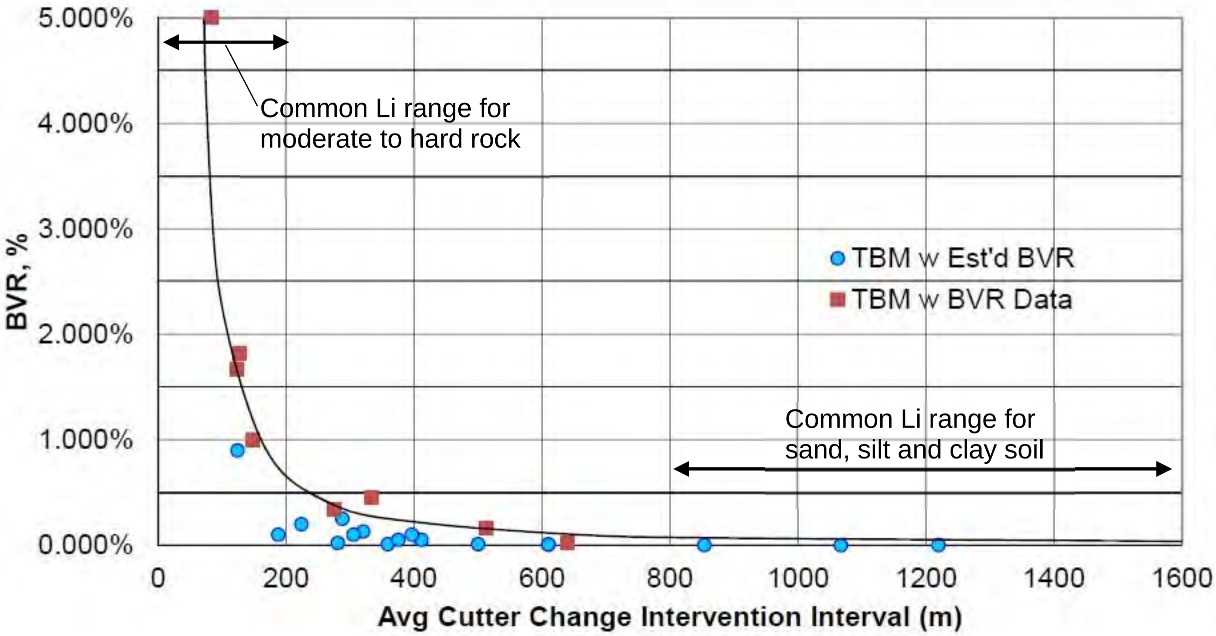
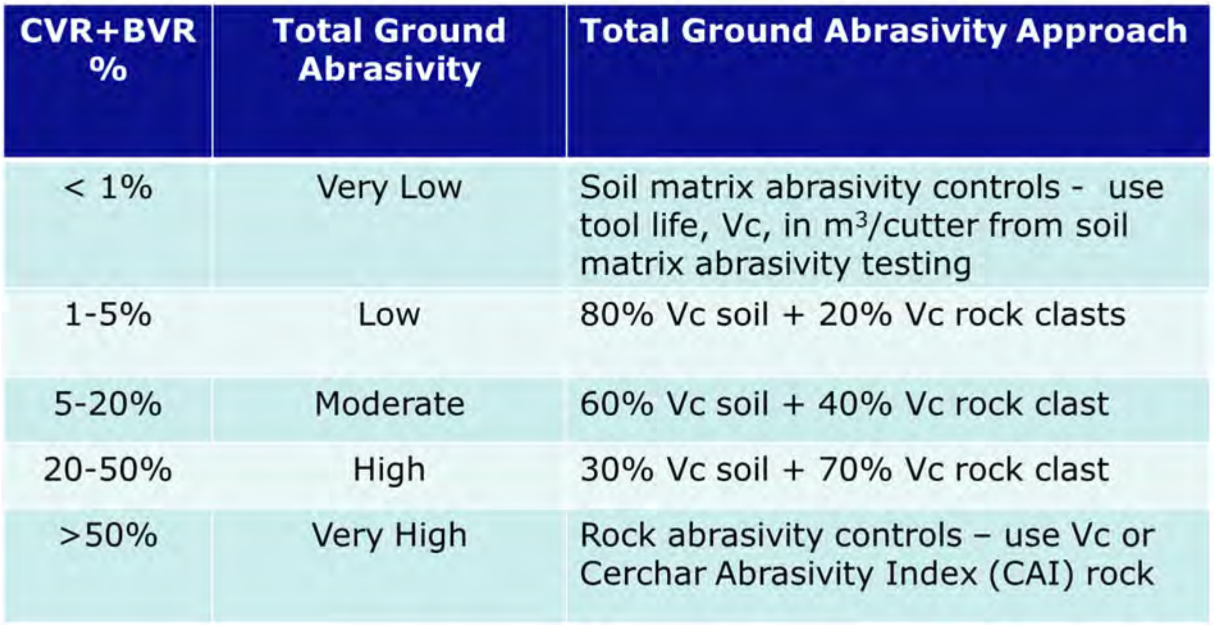


Figure 15 – Boulder volume ratio versus Li = average cutter change intervention interval

Based on all the previous discussion, the total ground abrasivity might be estimated using the preliminary chart provided in Table 8. The table provides the authors preliminary opinions on how tool live, Vc, in m3/cutter may be estimated for ranges in BVR using combinations of Vc from soil and rock clast data.

For example, it suggests that for the preceding case where a CVR+BVR of 10 percent was assumed, that the total ground abrasivity may be estimated as 60 percent of the soil matrix VC plus 40 percent of the rock Vc = 0.6 x 800 + 0.4 x 100 = 480 + 40 = 520 m^3/cutter. This is a preliminary experimental approach to be further researched, but it should provide a better estimate of total ground abrasivity due to cobbles and boulders than present methods which ignore the impact of cobbles and boulders. The method might be used in conjunction with the relationship between BVR and Li shown in Figure 13 to better estimate the impact of cobbles and boulders on cutter wear and life.

Table 8 – Preliminary suggested total ground abrasivity approach



CVR+BVR %	Total Ground Abrasivity	Total Ground Abrasivity Approach
< 1%	Very Low	Soil matrix abrasivity controls - use tool life, Vc, in m^3/cutter from soil matrix abrasivity testing
1-5%	Low	80% Vc soil + 20% Vc rock clasts
5-20%	Moderate	60% Vc soil + 40% Vc rock clast
20-50%	High	30% Vc soil + 70% Vc rock clast
>50%	Very High	Rock abrasivity controls – use Vc or Cerchar Abrasivity Index (CAI) rock

6 SUMMARY AND CONCLUSIONS

During the past twenty years, the tunneling industry has made considerable improvements in capability to successfully microtunnel and tunnel in cobbly-bouldery ground. Subsurface investigations have gotten more varied and focused to obtain necessary data. A database of typical cobble and boulder volume ratios for common soil types has grown. Designers have developed practical and statistical methods to predict boulder occurrences. These methods have been used with reasonable success on well over 50 projects and perhaps in the hundreds.

Baselining and pay items (where applicable) have helped to significantly reduce the contractual and cost risk of excavating through cobbly-bouldery ground. Risk management methods should be used to assess cobble and boulder risks along all portions of the alignment. Where the consequences of getting stuck are high or where the cost of interventions to change cutters is excessive, contract documents might require more robust TBMs or MTBMs with face access and combination roller and scraper cutters. Where conditions are bad and risks are high, redundancy and backup plans should be designed with appropriate pay items to manage uncertainties and risks.

Abrasivity of cobbles and boulders needs to be considered, particularly when cobble and boulder occurrence has a boulder volume ratio, BVR, over ~ 0.5 percent or CVR + BVR over ~2 percent. These and higher concentrations of cobbles and boulders are expected to have impacts on advance rate, cutter life and the average cutter change intervention interval and may also cause more severe impacts such as obstruction and cutterhead or mucking system damage. A preliminary method was given that would allow cutter life estimates for soil matrix to be combined with cutter life estimates for rock clasts to estimate total ground abrasivity and Li, the average cutter change intervention interval.

Many useful papers on subsurface investigation, baselining, tunneling method selection and case histories have been published, particularly within the past 20 years. An extensive bibliography of papers on subsurface investigation, baselining and tunneling in cobbly and bouldery ground and on abrasivity of soil is provided after the references.

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