Tunneling in Cobbles and Boulders

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1 INTRODUCTION

During the past two decades, significant advancements have occurred in subsurface investigation, baselining, excavation methods and risk management for tunneling in bouldery ground conditions. Review of a bibliography on tunneling in cobbles and boulders indicates that only seven papers-references existed prior to 1985. Most of the tunneling in bouldery ground references have been published since 1999. As a result of these advances, we can now better manage boulder risks with fewer differing site conditions impacts than before.

At the same time, boulder risks and uncertainties still cannot be eliminated. 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)
- Cutter retraction capability
- Cutterhead opening size, shapes
- Abrasion resistance of equipment
- Cutter types, configuration
- Prescriptive specification extent
- Cutter change options, effort
- Mucking system type
- Subsurface investigation limits
- Redundant excavation methods
- Potential consequences
- Contract method, compensation
- Prescriptive specification extent

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

1.1 Cobble and boulder ground conditions and occurrence

Cobbles and boulders are commonly found in glacial till, glacial outwash, alluvial and residual soils. Erratic cobbles and boulders are clasts that are generally composed of the harder, stronger parent rocks that better resisted transportation and weathering. In order to properly assess the probable occurrence of cobbles and boulders, the geologic setting of the tunnel alignment should be carefully evaluated.

In North America, the following sizes are used to describe clast sizes:

- **Cobbles:** 3-12 inch (75-300 mm)
- **Boulders:** 1-10 feet (0.3 to 3.3 m) with 1 to 3 feet (0.3 to 1 m) being most common
- **Blocks:** > 10 ft (3.3 m)
- **Floaters:** > 10 ft (3.3 m) occurring as large, often elongated rock blocks near bedrock

Cobble and boulder properties of most interest are considered to be [24]:

1. **Frequency** – volumetric density, occurrence per foot of microtunnel.
2. **Distribution** – random (scattered) or geologically concentrated (lags or nests).
3. **Size** – approximate diameter or maximum length.
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, lithology, compressive strength, and degree of weathering all affect fracturing by TBM cutters, energy required for commutation 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 the ground and wear to cutters, cutterhead, crushers, chamber and mucking system increases as the percentage of hard minerals in matrix soil and clasts encountered increases. Abrasiveness can be estimated from the relative percentage of minerals of different Moh’s hardness classes and by tests on both the clasts and soil matrix. Angularity of the clasts also increases abrasiveness.

7 Matrix soil composition – density, strength, grain-size distribution, and permeability affect ease of dislodgement by cutters, disc cutter effectiveness, ability to push boulders aside, and stand-up time or ground improvement required for manual drilling and splitting.

Cobbles and boulders may be isolated and scattered or in small to large clusters (nests) or lag zones. Cobble and boulder clusters are more common along 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 distribution.

1.1. Geologic Setting

The distribution, quantities and properties of cobbles and boulders within a soil unit should be assessed in conjunction with the geology of the formations involved. Baselining of boulders based on soil type, e.g. silty clay or gravelly sand, may not result in reasonable correlations. Instead, boulder occurrence should be assessed for individual geologic soil units with consideration of common geologic characteristics and anomalies. The importance of using a geologic framework when assessing 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 [14][21][22][24][33].

Typical characteristics of 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 to better understand the regional structure and typical characteristics of the units and formations that are likely to be encountered. Boulder occurrence can be better understood and baselined if the subsurface exploration data is presented in a geologic context.

1.1. Boulder Volume Ratio

Boulder concentrations may be expressed as number of boulders per length of tunnel, but this does not address size ranges and volume, both of which are important. Boulder volume ratio (BVR) is the volume of boulders as a percentage of the excavated volume. BVR combined with an estimated distribution of sizes is a better method of expressing occurrence. BVR has been used on many tunnel projects, including Toronto [2][36] and Milwaukee [24][25][26]. While a specific quantity such as BVR is preferred to describe concentrations, descriptive terms are still in common use. Figure 1 lists relative descriptive terms for ranges of BVRs.

In order to show typical average boulder concentrations, BVRs encountered at 20 projects across the world are shown in Figure 2. The majority (63%) of projects encountered only trace amounts 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 [26] found that BVRs 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 [24][25]. Sheppard tunnel in Toronto had an average BVR of 0.14 percent [7]. Storebaelt tunnel in Denmark had an average BVR of 0.09 percent [10][11]. The Downriver Regional Storage and Transport System tunnels in Wayne County Michigan encountered an overall average BVR of 0.14 percent [8]. Average BVR values for Brightwater Conveyance tunnels were less than 0.3 percent.

Higher BVR values are commonly found within talus, within ~ 5 ft from bedrock and in alluvial deposits down gradient from mountain ranges. For example, the Folsom East IIB project near Sacramento encountered estimated BVRs between 2 and 4 percent [4][38]. Bradshaw 8 in Sacramento 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 encountered average BVRs of 4 to 9 percent [7]. Local zones within most of the tunnels studied had much higher BVRs than the overall average, which is why correlations to geologic units are essential for baselining and planning.
Cobble quantities and volume ratios are generally higher than those for boulders. In Milwaukee, 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. In Sacramento, the cobble volume ratios were much greater due to fluvial sorting and typically ranged from 5 to 10 times greater than the BVRs. In Columbus, 157,021 cobbles and 5,429 boulders were estimated for 20,770 ft of 14 ft diameter tunnel [17]. A back analysis by S. Hunt indicated an approximate cobble volume ratio (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 [8]).

In summary, quantities and frequencies of cobbles and boulders are highly variable and dependent on geologic conditions. Methods for investigating quantities and baselining boulders are discussed later in this paper.

1.2 Cobble and boulder risks, hazards and potential consequences

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

- Subsurface conditions – ground, groundwater permeability and head, depth.
- 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 optimization of all four categories.

Cobble and boulder condition risks are many, but concentration and location are of utmost importance. Concentrated cobbles and boulders in lag zones or nests are much more difficult to excavate than isolated cobbles and boulders. Concentrations may choke a microtunnel boring machine (MTBM) or TBM excavation chamber causing the cutterhead torque to become excessive and the MTBM or TBM to stall. Cobble and boulder concentrations may also form a mixed-face condition and may cause steering problems [20].
The location of boulders is another factor. Boulders, particularly large ones that extend past the perimeter are much more difficult to cut and more likely to be plucked or pushed. 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) [28]. Table 1 provides a summary of potential hazards related to cobbly-bouldery ground and potential consequences.

### Table 1 – Boulder encounter hazards and potential consequences

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

Contractual risk almost always involves advance rates, schedule and ultimately cost. Cobbles and boulders encountered during tunneling almost always increases tunneling cost. Cobbles and boulders generally reduce advance rates [1][4][5][7][9][13][25][26][32][42][43]. Higher tunneling costs result from:

- More expensive TBM equipment requirements
- Slower TBM advance rates
- Delays to remove boulder obstructions
- Cost of rescue shafts and tunnels
- Delays to repair abrasion damage
- Costs to repair worn or damaged cutters, cutterhead, rock crusher or mucking system
- Higher project risk

Higher tunneling costs may result from: higher bid prices, unit rate bid items for boulders or boulder obstructions encountered or as compensation for differing site condition claims.

### 1.3 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 [25]. Compensation (pay item) for boulder removal is viable and should be considered when:

- Open face tunneling in stable ground with a manual splitting option;
• For large boulders or cobble-boulder concentrations that “obstruct” TBM advance as defined in the specifications; and
• When 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 is also appropriate for just about any tunneling method where the BVR is less than 1 percent, maximum boulder sizes are expected to be less than about 25 percent of the excavated diameter and the TBM is equipped with appropriate cutters and face access.

Even if the vast majority of cobble 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 and large boulders should be considered. Experience indicates that paying for defined obstructions as bid is 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. 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 [25]. 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, 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 to the contractor to enhance tunnel risk mitigation [27]. 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 [14][16][22][24][27][34]. In an effort 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, Table 2 was developed. 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 are seldom cost effective at depths over about 15-20 feet. Large diameter auger borings are much more difficult and expense below the water table in cohesionless ground and at depths over approximately 50 feet.
In most cases, phased and multiple methods of exploration will be much more effective than single or double methods [16][27]. For example, a desk study combined with both conventional rotary wash or hollow stem auger borings with Standard Penetration tests will be much more effective if rotosonic or large diameter auger borings are also completed.

**Table 2 – Subsurface investigation options for cobbly-bouldery ground**

<table>
<thead>
<tr>
<th>Subsurface Investigation Methods</th>
<th>Subsurface Investigation Method Selection Factors</th>
<th>relative cost</th>
<th>some method references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desktop study</td>
<td>+*</td>
<td>+*</td>
<td>Very Low [25]</td>
</tr>
<tr>
<td>Quarry/outcrop mapping</td>
<td>+</td>
<td>0</td>
<td>Very Low [16]</td>
</tr>
<tr>
<td>Rotary wash/HSA w SPT</td>
<td>0</td>
<td>0</td>
<td>Low [16]</td>
</tr>
<tr>
<td>Cone penetration test</td>
<td>-</td>
<td>0</td>
<td>Low [34]</td>
</tr>
<tr>
<td>Becker percussion borings</td>
<td>0</td>
<td>0</td>
<td>Low [45]</td>
</tr>
<tr>
<td>Rotosonic borings</td>
<td>+</td>
<td>+</td>
<td>Moderate [16]</td>
</tr>
<tr>
<td>Large diam. bucket auger</td>
<td>+</td>
<td>+</td>
<td>High to Very High [16]</td>
</tr>
<tr>
<td>Large caisson boring</td>
<td>+</td>
<td>+</td>
<td>High [16]</td>
</tr>
<tr>
<td>Borehole GPR (radar)</td>
<td>0</td>
<td>-</td>
<td>Low to Moderate [46]</td>
</tr>
<tr>
<td>Cross-hole seismic</td>
<td>0</td>
<td>0</td>
<td>Moderate [46]</td>
</tr>
<tr>
<td>Test pits</td>
<td>0</td>
<td>0</td>
<td>Moderate to High [6]</td>
</tr>
</tbody>
</table>

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

* If previous tunnel case histories, subsurface investigations exist

In summary, successful subsurface investigation of cobble and boulder occurrence 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 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 the majority of more traditional exploration methods is that cobble and boulder samples are not recovered and indications of cobbly-bouldery ground are seldom adequately documented [24].

In an effort to overcome these challenges, a method for estimating relative drilling resistance (RDR) between sample intervals was developed by the senior 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 all drilling intervals and record values on the boring logs. Subsequently, RDR values in combination with Standard Penetration Test and other conventional boring data significantly help improve interpretations of cobble and boulder occurrence.
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 [14][16][24][27][34]. One of the most complete studies of multiple methods and their cost effectiveness is reported in a Frank & Chapman 2001 paper [16] 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 roto-sonic coring technique, which costs less than double the cost of conventional hollow stem auger borings.” The authors agree with Frank & Chapman based on similar experience at other projects in North America.

Table 3 – Relative Drilling Resistance Criteria

<table>
<thead>
<tr>
<th>RDR</th>
<th>Term</th>
<th>Criteria</th>
<th>Typical Ground Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Easy</td>
<td>No chatter, very little resistance, very fast and steady drill advance rate</td>
<td>Very soft to soft silts and clays; very loose to loose silts and sands; no gravel, cobbles, boulders or rubble</td>
</tr>
<tr>
<td>2</td>
<td>Easy</td>
<td>No chatter, some resistance, fast and steady drill advance rate</td>
<td>Firm to stilt silts and clays; loose to medium dense silts and sands; little or no gravel, no to very few cobbles, boulders or pieces of rubble</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Some chatter, firm drill resistance with moderate advance rate</td>
<td>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)</td>
</tr>
<tr>
<td>4</td>
<td>Hard</td>
<td>Frequent chatter and variable drill resistance, slow advance rate</td>
<td>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)</td>
</tr>
<tr>
<td>5</td>
<td>Very Hard</td>
<td>Constant chatter, variable and very slow drill advance, nearly refusal</td>
<td>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</td>
</tr>
</tbody>
</table>

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);
- Clast mineralogy and rock types;
- Clast unconfined compressive strength ranges; and
- Soil matrix types, strength and density.

Additional aspects to consider baselining include: shapes and abrasivity of both the clasts and 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 muck train. With most pressurized face
tunneling, the TBM is generally equipped with cutters capable of fracturing boulders to a much smaller size that can pass through the cutterhead and be crushed and ingested into a slurry mucking system or pass 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 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 penetration rate, torque, cutterhead rotation speed, thrust and angularity of rock fragments. Boulder sizes cannot be reliably determined except for open face tunneling with face access. Distinguishing between cobbles and boulders is also impractical.

As a result the limitations given above, a pay item for excavation of all boulders encountered is seldom used and would only be viable for open face tunneling with face access. Pay items are more frequently used to compensate for a defined cobble and boulder obstruction. An example obstruction definition is given below. Obstruction definitions should depend on the owner’s risk sharing position, tunnel size, anticipated tunneling method and cobble and boulder conditions.

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 by an excavation made from outside of the tunnel.

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.

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 subsurface investigation data that considers geologic settings. The other two methods of boulder baselining are discussed below.

### 3.2 Boulder volume ratio methods

Boulder volume ratio methods involve semi-empirical correlations of geologic and 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 [2]. They used borehole, excavation, outcrop and other data to determine average boulder volume ratios (boulder volume as a percent of excavation volume) for anticipated geologic units. A boulder number ratio was also determined from the investigation data and then used with the boulder volume ratios to

![Figure 3 – BVR vs % bouldery ground in borings (2002) [25]](image-url)
determine estimated quantities of anticipated boulder sizes. During tunneling, they found that design predictions correlated well with the boulders encountered [36].

Hunt & Angulo [24] developed a semi-empirical correlation method similar to that used in Toronto. A chart was developed in 1999 and updated in 2002 (Figure 3 above) that correlates BVR or boulder volume as percent of excavated volume data from eight completed tunnels to conventional borehole indications of percent bouldery ground for total boring length drilled in potentially bouldery ground [24] [25]. 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 4. Since inception, the method has been used successfully on over ten tunnel projects within glacial and alluvial soils to predict boulder occurrence.

3.3 Probabilistic methods

Attempts to predict boulder quantities from conventional borehole records date back to at least 1976 when Stoll [39] attempted to use a random probabilistic method. Around 1986, Tang & Quek [41] 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 [10] [11] and recently for a planned tunnel in Italy [15].

The most extensive study of subsurface exploration for tunneling in bouldery ground [16] 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 [40]. 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 [9][40].

### 3.4 Baselining Recommendations

Which aspects of cobbled and boulder conditions to baseline depends on the ground conditions, anticipated methods of construction and project owner’s preferences for risk sharing. 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. The boulder volume ratio 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 5. 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 and require a rescue shaft or tunnel to remove the boulder obstruction and repair damaged cutters and cutterhead.

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 [26].

#### 4.2 Cobble and boulder cutting, crushing or ingestion considerations

In order to tunnel through cobbled-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 crusher), and the mucking system. Boulders must be excavated and possibly fractured by one or more of the following methods:
- Plucked from the ground using scrapper and/or roller cutters on a MTBM cutterhead and then passed through the cutterhead into the excavation chamber to be crushed before entering the mucking system.
- Plucked and pushed aside if not passable though cutterhead and matrix is soft or loose enough.
- Fractured and broken using ripper, scrapper and/or roller cutters on a TBM cutterhead before being plucked and passing through the cutterhead to be crushed.
- Accessed from the excavation chamber or from a rescue shaft-tunnel and then manually split or blasted and removed.
- Pushed into a temporary shaft drilled below microtunnel invert at the heading.

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

- Cobble and boulder strengths, sizes, shapes, 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 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 control to fracture and remove obstructing cobbles and boulders.
- Settlement damage risk if excess lost ground occurs at the heading.
- Cutter life and cutter cost - disc cutters generally have longer cutter life [35], but are much more expensive [9].
- 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 6.

Second, more energy is required to commutate rocks to gravel size than to small boulder or cobble size as shown in Figure 7. When higher commutation energy is required, the MTBM or TBM power must 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 15 foot diameter earth pressure balance TBM that can pass 15-inch rocks through to a conveyer or train car mucking system than a slurry or mix-shield TBM that must crush cobbles and boulders to 6-inches or less in order to be pumped. 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 be less in ground with cobbles and boulders than the same ground without them. Advance rate reductions may be due to three factors:

- Lower instantaneous penetration rate to cut or pluck boulders.
- Delays to manually split or remove boulders resulting in lower utilization.
- Delays to replace worn cutters or repair the cutterhead and mucking system.

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 4.6m diameter open mode shield tunneling [7]. 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 8.

Data from another open-face shield [18] and a microtunnel project [42] 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 off 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][44]. 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 [9][44]. The contractors on both projects elected to use rippers and scrappers instead of disc cutters. These cutters were successful at breaking boulders as discussed below.
4.4 **Cutter considerations**

Cutter selection should depend on boulder strength and size, expected frequencies, matrix, cost of wear and replacement 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 [19][31][35]. A study published in 2008 better explains degree of cutting versus plucking for ranges in boulder to matrix strength [19]. 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 [35]. 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 [31][32]. 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-scaper cutters is generally more effective than all disc cutters or all scraper type cutters in bouldery ground, particularly for microtunnel boring machines. The 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 [26][32][43].

**BWARI and Brightwater West with Rippers**

Although a combination head is often best, a cutter head with only or primarily 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) [9][44]. For example on the BWARI project in Columbus, Ohio, a 16 ft (4.9 m) diameter earth pressure balance TBM was used to bore through very bouldery till and outwash (BVR ~ 0.34%) [40]. 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. 4. 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.

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 on 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 [44] – Figure 5. 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 with boulders 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 [37]. 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 6 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 [37]. Figure 6 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. 6 (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 cutter breakage from cobble and boulder impacts.

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.”

Figure 6 – Ripper cutter life from BWARI [9] and Brightwater West [37]
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%) [5]. 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). In order to get an indication of the influence of BVR on cutter life, some available average cutter change interval data from these projects and others with both back calculated and estimated BVR values is plotted in Figure 7. The plot includes data for cutterheads with all rippers (conventional and robust), all disc cutters (conventional and with carbide inserts) and a combination (all the cutterheads had scraper cutters acting as scoops at cutterhead openings). Fig. 7 shows that cutter life as indicated by average cutter change intervals decreases as the BVR increases. Better curves may result once more data is added and distinctions between cutter types are plotted separately.
Microtunneling

When microtunneling, a combination cutterhead with scraper and disc cutters is essential to minimize risk of getting stuck from severe cutter wear [26]. 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 [29]. A recently 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 [20]. 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.

In summary, many factors should be considered when selecting cutters for cobbly-bouldery ground. Heavy, block type scraper cutters protected with carbide inserts may be the most cost effective where face access is available and a stable face in free air is expected. A combination head of ripper-scraper and disc cutters may be most cost effective for microtunneling and for pressurized face tunneling 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 BVR greater than 5 percent in open, high permeability gravel or 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 [23].

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 [3][38]. When cobble and boulder volume ratios exceed approximately 10 percent and very abrasive matrix soils are present, microtunneling should be avoided or special measures and pay items provided to manage the likely advance rate and abrasion challenges.

5 SUMMARY AND CONCLUSIONS

During the past twenty years, the tunneling industry has made considerable improvements in capability to successfully microtunnel and tunneling in cobbly-bouldery ground. Subsurface investigations have gotten more varied and focused to obtain necessary data. A database of typical boulder volume ratios for glacial and alluvial 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 risk of excavating through cobbly-bouldery ground. Risk management methods should be used to
assess cobbles 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 MTBMs (or TBMs) 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.

Many useful papers on subsurface investigation, baselining, tunneling method selection and case histories have been published, particularly within the past 20 years. A bibliography of papers on tunneling in cobbly and bouldery ground follows the cited references.

6 REFERENCES


7 BIBLIOGRAPHY

Papers shown in bold type are considered by the authors to be better references and higher priority for suggested reading on tunneling in cobbly-bouldery ground.

7.1 References on subsurface investigation and boulder baselining


7.2 References on tunnel excavation methods, cutters in bouldery ground


7.3 References on compensation for boulder encounters or obstructions


7.4 Case histories with references to boulder encounters


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