# Chapter 11

# THE PENETRATION RATE BASELINE DILEMMA

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## THE PENETRATION RATE BASELINE DILEMMA

The penetration rate is the instantaneous advance rate of a TBM in a rock tunnel. Normally expressed in feet per hour. The production rate is the penetration rate multiplied by the number of hours worked and then factored by the actual utilization of the TBM.

In a given rock formation, the actual production rate is a result of many factors some of which are within the control of the contractor and some of which are based on the route selected. Factors that are within the contractors control are cutter profile, frequency of cutter changes, thrust, rotation speed, cutter spacing and the efficiency of the operation. Factors that are site (route) specific are compressive strength, fracture orientation, fracture frequency, micro- fracturing, quartz content, Moh's hardness, Cerchar Abrasivity Brazilian Tensile Strength and Youngs Modulus of the rock. In addition the following route specific conditions are beyond the contractors control; rock jointing, rock stress fault zones, water inflow and rock decomposition; all of which effect production rate

Any one of the above defined rock properties, equipment specifications and actual operating usage will change the penetration rate. Furthermore, since the rock formation changes both in content and orientation as the tunnel advances, the penetration rate is constantly varying

The current industry practice in bidding tunnels is for each contractor to individually evaluate the rock hardness and other properties and from this information develop a penetration rate. All other factors being equal, the contractor using the most optimistic penetration rate will be the low bidder and be awarded the project. As this view is by definition optimistic, invariably the rock will be harder than the low bid assessment and the contractor will request additional compensation for the changed condition. The contractor will attempt to justify his optimistic assessment as reasonable by using expert supporting analysis.

The above described example which is quite common at present in the industry tends to make the most optimistic contractor (at time of bidding) the contractor selected for the project whereas it is in the owners interest to contract with the most efficient contractor not the most optimistic.

This situation is similar to the Geotechnical analysis that was prevalent in the industry over twenty years ago.

Many projects have experienced a significant reduction of penetration rate from that which was originally estimated. In these cases the contractor often makes a claim for extra compensation based on the difference between the actual rock encountered and the rock as presented in the GBR These differing site condition claims (DSC) often involve the fracture orientation, foliation of the rock, quartz content and compressive strength Both owner and contractor retain experts to show the similarities and differences in the rock encountered. The end result of the geologic engineering analysis is a proported change in the penetration rate from the original expected rate to that actually experienced on the project.

The actual fact is that the instantaneous penetration (the depth of penetration into the rock) rate of a hardened steel disc cutter using a given force is solely a function of the rock formation which has been selected by the owner, as such it (the penetration rate) is no different than the geotechnical or permeability interpretation These are all facts pertaining to the work that are specific to the site which has been selected by the owner It is certainly the owners' prerogative to request that the contractor make his own evaluation of the physical conditions at the site but given that situation, it is then unreasonable for that same owner to then reject the "reasonable interpretation by the contractor."

With the enormous risk involved in determining the penetration rate of a TBM it is not reasonable to place all that risk with the contractor (who in turn will attempt to pass some portion on to the equipment manufacturer) when the penetration rate in fact, excluding the equipment and its operation, is completely dependent on the rock formation.

Is it in the industry's best interest to select as the contractor the one who has the most optimistic view of the penetration rate and then when those unreasonably optimistic projections are not realized then negotiate a claim for additional compensation?

Interpretive Geotechnical Reports have been used for about twenty years to contractually define soil and rock conditions and the expected engineering properties for construction These reports have also defined the ground water condition and the expected permeability of the formation.

The initial baselines were contained in Geotechnical Design Summary Reports (GDSR) which evolved into Geotechnical Baseline Reports (GBR) about ten years ago. The concept, report guidelines and general discussion are presented in the excellent ASCE publication "Geothechnical Baseline Reports for Underground Construction" 1997 In the case of rock tunnels, the rock core samples have been laboratory tested and the results provided in the contract documents Typical tests results that are provided in the documents include Unconfined Compressive Strength, Moh's hardness, Cerchar Abrasivity Index, Brazilian Tensile Strength and Youngs Modulus By using these test parameters, a bidder can compare these rock qualities to similar rock with known performance data using a TBM and then interpolate a penetration rate.

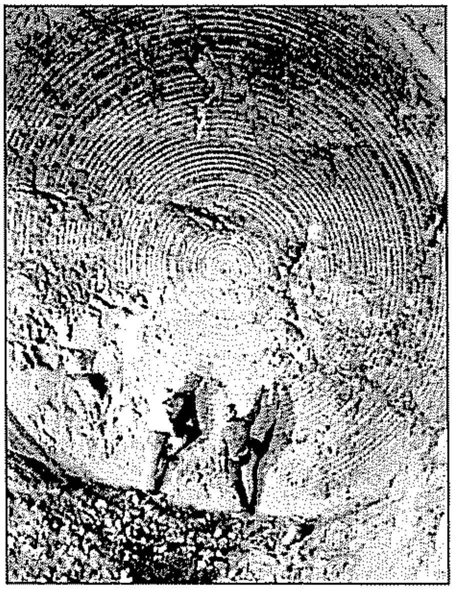
Rock core samples are also provided to equipment manufacturers who perform their own testing Equipment manufacturers also factor their experience in similar formations and then modify the expected results for the actual proposed TBM, taking into account all the variable operating parameters The manufacturers then quote a specific TBM for the project and provide the bidders with the expected operating results On a particular project; a bidder may have two to three equipment manufacturers quotations as well as his own experience to arrive at a penetration rate estimate.

Many factors actually affect the penetration rate in addition to the rock to be bored such as load per cutter, cutter spacing, cutter width, cutter changes, cutterhead RPM and others. Some of these factors are fixed once the equipment (TBM) is selected for the project and others are a function of the actual operation of the machine.

The following TBM features or operational events all affect rate of penetration.

### Load Per Cutter

Increased load per cutter is normally the most important factor. As the load is increased, the advance increase normally is a ratio ranging from $A^{1\,2} = L$ to $A^2 = L$,



Varying rock condition which affects penetration

where A is the advance and L is the Load. In other words, it can be if you double the load, the advance goes up as the square of the increase.

Excess loading can also cause negative affects such as early flattening or mushrooming of cutting structure, premature cutter bearing failure, machine component failure, or excess vibration.

### Cutter Spacing

Generally, reduced spacing with constant cutter load increases penetration. Spacing is probably the most complicated factor because there are physical restrictions in fitting the cutters on the cutterhead to obtain a very tight or close spacing. Generally, the larger the cutter (capable of exerting a higher cutter load) the wider the spacing has to be. This of course offsets the advantage of a larger cutter which can withstand a higher load.

### Disc Tip Width and Cutterhead Diameter

Without surprise, the narrower the tip width the greater the penetration rate. In other words, the lower the cutting contact area for a given load, the higher the penetration rate. Obviously there are limits on the width of tip. Narrow discs wear faster and spall at high loads.

To a great extent, a disc gets wider (cutting contact areas increase) as it wears. Therefore, it effectively penetrates less each hour of use. This negative effect is less with so called constant section discs. Also the greater diameter of the disc, the greater the cutting contact area. This fact means the cutting load must increase to maintain constant penetration as the diameter of the cutter increases.

### Cutterhead Revolution Per Minute (RPM)

The rate of penetration is linear to the RPM of the cutterhead while under constant cutter load This means if you can obtain 5 ft per hour at 7 5 RPM, and if you are capable of turning at 15 RPM with the same cutter load and capable of removing the muck from the cutterhead, you will advance at 10 ft. per hour.

When maintaining a constant cutter load, as the RPM increases the horsepower (HP) demand increases in direct relationship to the RPM Therefore, the TBM must have sufficient H P. to operate at a maximum RPM The maximum RPM is that speed whereby the muck has not had time to exit the buckets because of being held in by centrifugal force

Today most TBMs have variable speed, so the proper choosing of base speed by the manufacturer is important and, more important is the training of the operators in the effective use of variable speed

### Inefficient Muck Removal

Cuttings left in the cutterhead reduce rate of penetration. This can be caused by: a) too much shielding or breasting on the cutterhead face; b) too small of bucket openings; c) choking in the muck chute; d) muck buildup on the bucket throats and chute; e) too fast of RPM; f) too fast advance or; g) incorrectly designed buckets and muck chute

### Stability of the Cutterhead

The stability of the cutterhead has a great affect on rate of penetration. The greatest penetration rate is achieved when the disc stays as close as possible to 100% in their respective grooves or disc path. This stability is achieved in different ways, depending on the machine design

A Robbins style main beam is stabilized by activated roof shield and side supports. Over stabilizing can inadvertently reduce cutter load and therefore penetration.

On a Kelly type machine, stabilization is maintained by the sliding surface of the main beam within the main body, and rigidity of the main beam Generally, as the machine strokes out, stability decreases. Also, the stabilizing contact areas wear with use, decreasing stabilization.

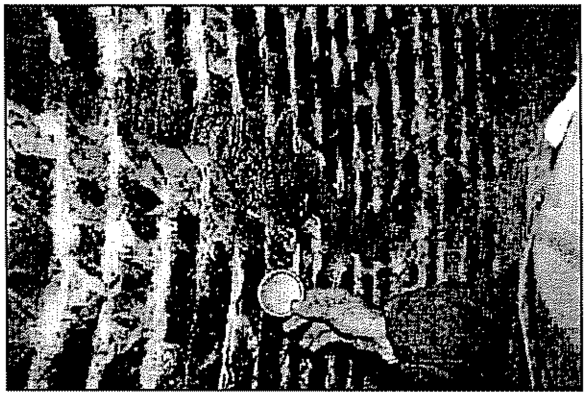
With shield machines, stabilization is usually obtained with front sliding stabilized pads. These stabilizers are generally not as effective as with hard rock TBM stabilization. Many shields that have been used in hard rock TBM's are drastically deficient in stabilization.

### Non-Compensated Machine Drag

TBMs and shields have drag to a lesser or greater degree. This drag, if not compensated, will decrease the penetration rate by decreasing the effective load on the cutters. The drag can and does occur from:

- Stabilization of the cutterhead, and especially over-stabilizing of the cutterhead
- Friction from the weight of the TBM or shield
- Build-up of fines or ground pressure between the shields and the rock
- Towing of backup if not isolated by a tow cylinder

Normally TBM design has built-in extra thrust to overcome drag However, operators sometime do not recognize the extent of the drag and under-thrust, or the



Cutter spacing

machine does not have sufficient total thrust to overcome drag and apply optimum cutter load.

### Binding of the Front Shield

The binding of the front shield will decrease penetration rate by decreasing the effective load on the cutters. Raked or skewed cylinder TBMs are especially prone to this problem. This problem also occurs in steering through curves.

### Improper Operation of the TBM

Obviously the improper operation of the TBM can reduce penetration rate. The operator is usually given three parameters not to exceed while operating:

1. Cutter load
2. Amperage of main motor
3. Rate of advance due to mucking system capacity.

The recommended cutter load may not be maintained even if 2 and 3 are within limits, for the following reasons:

- Excess drag not recognized by operator
- Excess vibration which causes the operator to reduce thrust in order to reduce vibration
- Excessively high RPM
- Lack of diligence by the operator

Over amperage can be caused by blocky ground; too high RPM; too high a cutter load for the chosen RPM; or clogging of cutterhead. If the operator reduces the RPM or the cutter load, the penetration rate is decreased.

Given the number of variables associated with the rock which combine to produce the penetration rate, is it not time to include in the GBR an expected penetration rate in the various rock formations to be excavated?

By defining the penetration rate as a baseline parameter, the contractor with the equipment manufacturer can decide on the most efficient TBM for the project. The possibilities of TBM selection vary from a poorly designed low horsepower, low thrust TBM that will be the minimum initial cost to the contractor to a well designed, high horsepower, high thrust TBM which will cost significantly more but produce higher production This is an analysis the contractor can make with a degree of certainty. Also the onus to properly train and instruct the TBM operators will be more directed at the contractor accurately.

The GBR penetration rate would be a contractual baseline similar to the geologic baselines and would be predicated on a specific cutter load and spacing. By providing this as a baseline the actual differential of the penetration of the actual rock encountered and the baseline penetration rate would be reduced to an analysis of the equipment provided, the actual operation of that equipment and a correlation to the baseline provided. A simple but effective starting point for a standard would be the penetration rte of a 3/8 inch (tip width) 17 inch cutter, loaded to 55,000 lbs. of thrust and traveling at 10 RPM.

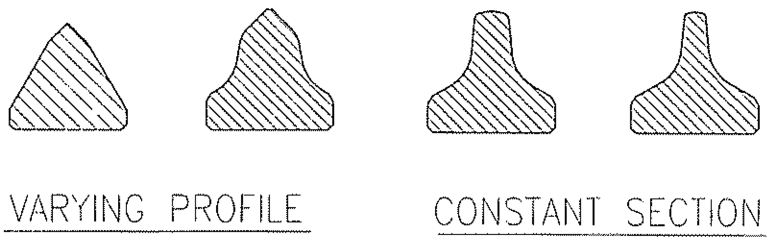



**Figure 1. Cutter disc design**

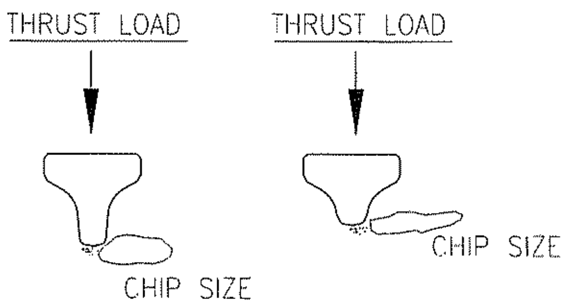



**Figure 2. Effect of disc wear on penetration**