

# Difficult rock comminution and associated geological conditions

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## SYNOPSIS

Conditions encountered by the authors on several projects (tunnel boring, blast hole drilling, and large diameter pile socket drilling) were unanticipated, undetectable, and even difficult to identify even after they had been encountered. These conditions have caused failure of mechanical components, low penetration rates, and remarkably high cutter wear. Coincidentally, all projects had one or more geotechnical conditions in common. The difficulties encountered, however, could not be attributed to geotechnical factors measurable by classical laboratory or field methods. The difficulties were not discernible or predictable by conventional exploration, rock mechanics testing, or analysis, prior to tender.

A study of common elements and an analysis of these conditions have shed some light on how to avoid similar difficulties. These problems may be avoided using exploration and testing specifically tailored to mechanical excavation, and by investigation for conditions which have been associated with such difficulties in the past.

What can be learned from these widely undocumented and unpublished experiences? How were these conditions missed? What are the underlying causes and motive mechanisms? How can such problems be avoided in the future?

In all case histories presented here, problems or difficulties were encountered. It is the intent of this paper to use these negative experiences to produce new possibilities for avoiding them in the future.

## INTRODUCTION

In 20 years of consulting practice and construction management, we have come to accept the unexpected and the unexplainable, and still complete the project, sometimes without delay. Years after agonizing experiences, we learn from new experiences and ponder possible explanations. This paper is such a speculation, based sometimes on measurable geotechnical conditions, occasional-

ly on quantitative performance and machine parameters, and, now and then, on reports and second hand descriptions.

Not intended as a purely scientific endeavor, this paper is a simple pragmatic approach that merely documents common effects, some geotechnical conditions common to several projects, and possible causes. There may be more than one explanation or other explanations which are not considered here. Extensive references and sources of information are provided to permit independent evaluation of our analyses.

Our purpose is to establish a new distinction that will make it possible to measure TBM rock comminution efficiency. The measure of efficiency must take into account geotechnical characteristics and mechanical variables of the equipment.

Our ambition is to sow the seed here for further investigation and a more rigorous solution to the problem. It is essential to present preliminary findings in order that they may perhaps prevent others from such folly.

When projects experience difficulties such as unanticipated geological conditions, urgency generally dictates that all resources be directed to the solution of the problem and the recovery of unanticipated costs. It is unlikely that a great deal of effort will be expended to establish an understanding of the underlying cause for future benefit. This has been true in many of our projects (Tokes, 1985; Tarkoy, 1981a, 1986a, 1988a, 1989, 1990; Thompson, 1988; Montacie, 1988; Marconi, 1989; and Van Ryswyk, 1990).

With increasing frequency, we have noted common patterns which have provided insight into the problem. Our own experience with rock comminution (rock disintegration), primarily in tunnel boring, have led us to review unexplained similar case histories to find a common thread. These experiences are offered here for the benefit of others, should they find it useful in avoiding similar events.

The appearance of common patterns are the foundation of this paper. The fundamental and

most obvious common thread is difficult tunnel boring or difficult rock drilling, hence the reference to difficult rock comminution.

## THE COMMON THREAD

The investigation at Selkirk railroad tunnel (Figure 1) in British Columbia, Canada, was the first case where detailed operating data was available and suggested that the encountered rock appeared harder to the machine than any of the rock mechanics tests indicated. Rock characteristics, intact or mass properties (uniaxial strength; Total Hardness, Tarkoy, 1973, 1975, & 1986b; jointing; stresses;), and the mechanical variables of the Tunnel Boring Machine (TBM), could not account for the very poor TBM or drilling performance. The loss of performance could not be explained by measurable rock properties or machine variables.

It was general known that *in-situ* stresses were present at Selkirk from the excavation of nearby and parallel tunnels. Speculation about the impact of *in-situ* stresses on rock comminution by mechanical boring brought about discussions with The Robbins Company. Robbins brought to our attention a similar condition encountered many years ago with one of their machines. The investigation of the unusual experience with an earlier Robbins TBM, other tunnel boring projects, drilling experience, experience with rock crushing, and independent research on available project data has provided insight into rock comminution under certain unique conditions. This underlying case history data will form the basis of this paper.

FIGURE 1: ROGERS PASS RR TUNNEL



## THE FIELD PENETRATION INDEX

In an attempt to establish a quantitative

measure of phenomena not represented by conventional rock testing, a field indicator, which would reflect how the machine "saw" or interacted with the rock, was developed and utilized. This field indicator had to take into account the mechanical variables required to produce efficient rock comminution.

The most effective energy expended in tunnel boring and drilling is the force applied normal to the face. The measure of rock comminution efficiency should take into account the force normal to the face and the depth of penetration produced. If measured for each revolution, it allows the scale to be independent of the tool or machine diameter and rotational rate. As a result, the Field Penetration Index (FPI) was defined as follows:

$$FPI, \text{ kg/mm} = \frac{F_n \text{ (kg)}}{\text{Penetration (mm/rev)}}$$

Where:

$$F_n = \text{gross cutter load normal the face in kilograms}$$

$$\text{gross cutter load} = \frac{\text{total applied machine thrust or bit load}}{\text{number of cutting edges or bit contacts}}$$

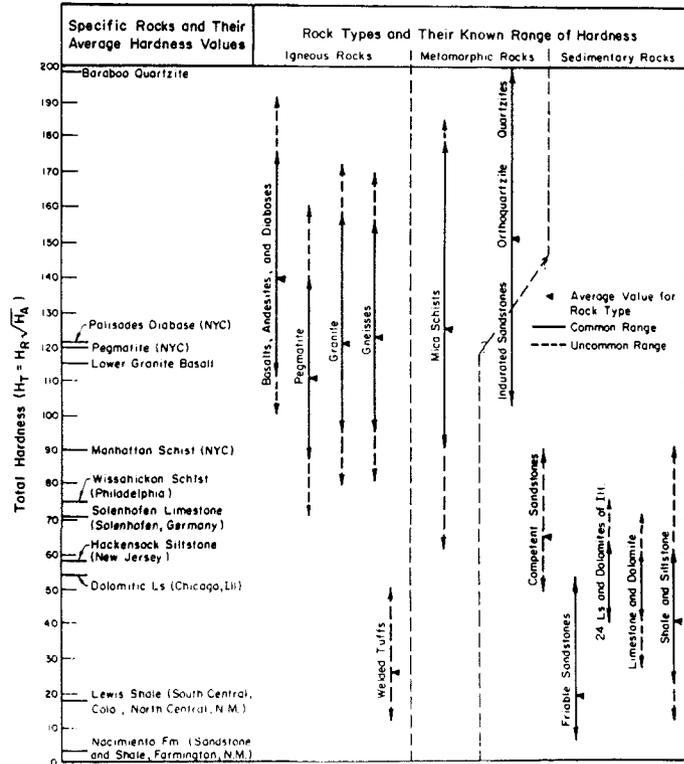
Analyses of TBM performance based on detailed TBM records (machine variables and performance) and comparison with Total Hardness, revealed consistency as well as some extraordinary variation. The results appeared to be particularly sensitive to TBM cutter load, tool condition, and rock "behavior" as seen by the TBM, and reflected by the cutting efficiency (height above the regression line).

Since the Total Hardness is essential to the application of the FPI, it bears defining. The Total Hardness was originally established as a simple, practical, and timely test for predicting boreability (penetration rate and cutter costs) by Tarkoy (1973, 1975, & 1986b). It consists of measurements made with the Shore Scleroscope (D-type), Schmidt (L-type) Hammer, and a Modified Taber Abrasion Apparatus. The tests require that specific and precise procedures be followed according to Tarkoy (1973). The Total Hardness test procedures have been submitted to the American Society for Testing and Materials to assure standardization of equipment and procedures. The Total Hardness is calculated as follows:

$$H_T = H_R \sqrt{H_A}$$

The Total Hardness has been a reliable indicator of boreability for nearly a quarter of a century. Total Hardness for earlier case histories discussed in this report were approximated from typical rock hardness for similar materials. Typical values are illustrated in Figure 2.

FIGURE 2: RANGE OF TOTAL HARDNESS (After Tarkoy, 1975)



The FPI serves as a gauge of cutting efficiency as a function of cutter load and rock hardness based on penetration per revolution. It measures the efficiency of cutting or amount of load required to obtain a unit of penetration.

The FPI had been determined for a number of projects which encountered no difficulties with boreability and are designated as "normal" in Figure 3. These sites include several subway tunnels in Buffalo, NY, sewer tunnels in Chicago, IL, New York City, and Toronto, Canada. These cases were used to develop the basic regression equation for successful or "normal" machine boring. The correlation between Total Hardness (Tarkoy, 1973, 1975, 1986a) and the Field Penetration Index (FPI) for more than a dozen projects represented as "normal" was extraordinary, with a coefficient of 85%.

The correlation between Total Hardness (representing a multitude of intact and some rock mass characteristics) and mechanical variables (cutter condition, machine stiffness, etc.) is excellent (> 75%). This has confirmed the value of Total Hardness in predicting penetration for efficient excavation. Points representing inefficient machining, fall above the line. Large departures from the regression appear to indicate mechanical difficulties or unusual interaction between equipment and rock mass.

One would conclude that inefficient excavation cannot be predicted by conventional rock properties alone or even with known mechanical variables, in each and every case.

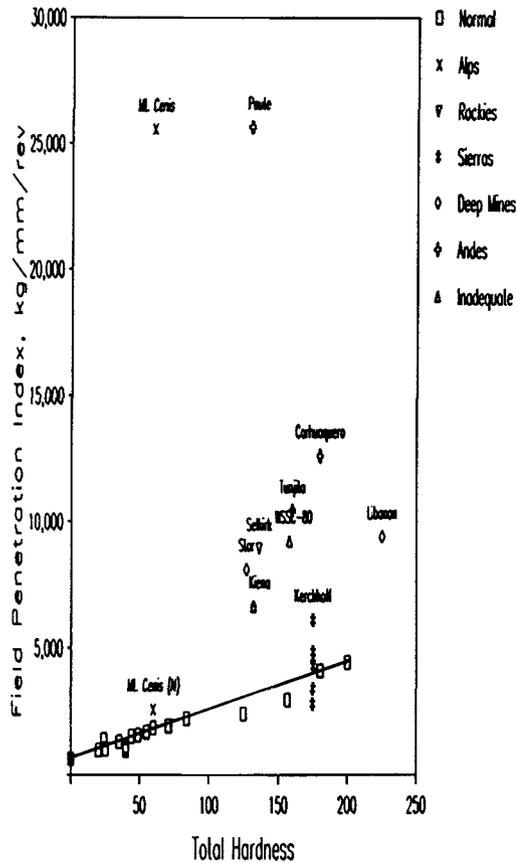
Even though some of the case histories used in this analysis may be over twenty years old, the possible interpretations have only been made recently (Tarkoy, 1988a). These conclusions will be discussed under the section dealing with individual case histories.

#### Significance of a Low FPI

An FPI lower than the regression line indicates what appears to be an unusually high efficiency in rock excavation. This has been related to a variety of geological or tunnel conditions such as highly fractured rock which may actually break out with little contribution from the machine or machine conditions (such as all new cutters) which are superior to the operating average condition.

There is evidence for only one project in Figure 3 where unusually high cutting efficiency (low FPI) was sustained. This occurred during testing, when a completely new cutter dressing had been placed on the cutterhead of the Kerckhoff TBM.

**FIGURE 3: FIELD PENETRATION INDEX**  
(After Tarkoy, 1988a)



#### Significance of a High FPI

Efficient cutting requires higher and higher cutter loads per unit of penetration as rock comminution becomes more difficult. Consequently, for harder rock, small changes in the rock properties may cause a disproportionate decrease in penetration as one crosses below the threshold of efficient cutting. In effect, TBMs operating successfully in hard rock (close to their limitations), can come to a grinding halt with only a small increase in rock resistance to comminution. Similarly, TBMs operating below their capabilities can sustain an increase in rock hardness without suffering an inordinate loss of penetration.

An FPI above the regression line indicates an insufficient cutter load to deal with the encountered rock properties or behaviour. Such conditions have been encountered on several projects and are illustrated in *Figure 3*.

#### Conclusions About the FPI

The Field Penetration Index has been useful in identifying and evaluating difficulties of rock comminution. It has become apparent that the Field Penetration Index can be used as a gauge of a TBM's interaction with the rock. High FPIs appear to have been associated with a conspicuous absence of jointing, high *in-situ* stresses, and microscopic features of the rock mass.

Often, the FPI is sensitive enough to express the loss of cutting efficiency between cutter changes. In such a capacity, the FPI can be used to determine the most cost effective time to change cutters.

These conditions commonly exist in "young" mountain chains, such as the Selkirk Mountains in Canada, the Sierra Nevada in California, USA, in the French Alps on the border between France and Italy, and the Andes in South America.

The Field Penetration Index is a tool which can be used only after the fact. As such, it has been useful to identify, define, and study the effect of difficult rock comminution conditions. A separate means of predicting these conditions will be necessary.

#### **CASE HISTORIES**

Case histories to be discussed in this paper is presented in Table 1 in chronological order of construction. Table 1 summarizes project locations and elements held in common. Table 2 provides a summary of ground conditions and Table 3 summarizes relevant mechanical characteristics of boring equipment used. Data from older projects was limited and less definitive, more general, and utilized average conditions which would not reflect the extremes found in the greater detail of latter projects.

#### Mont Ceniz

Experience in the Mont Ceniz Tunnel in the French Alps during the mid-1960s first illustrated the effect of tectonic and residual stresses on the rock behaviour as "seen" by a TBM. This experience has never been explained or published (Tarkoy, 1988). Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3.

In a section of tunnel about 100 meters long, high tectonic stresses were encountered and the rock was reported to be as hard as "steel."<sup>9</sup> At the beginning of the machine stroke (0.33 m), the TBM bored at rates of 1.8 m/hr (upper Mt. Ceniz point). Beyond the first half meter the Robbins TBM ground to a halt. After a pause of 5-10 minutes (or after re-gripping), during which the stresses were allowed to relieve, it was possible to resume boring at the normal rate. Behind the machine, the rock around the perimeter "exploded" or popped resulting in overbreak of 8-10 cm (Montacie, 1988).

TABLE 1: COMMON ELEMENTS OF DIFFICULT ROCK COMMINUTION

PROJECT	LOCATION	LITHOLOGY	STRESSES OR STRESS FEATURES	QUARTZ SUTURING	INTRU- SIVES	RELIA- BILITY
Mont Cenis	France	MetaSediments	Yes	Unknown	Unknown	Fair
Star Mine	Idaho	Quartzite	Yes	Unknown	Unknown	Fair
Libanon	Africa	Quartzite	Yes	Unknown	Unknown	Fair
Tunjita	Columbia	Quartzite	Yes	Unknown	No	Fair
Carhuaquero	Peru	Igneous	Unknown	Unknown	No	Fair
Kerckhoff	California	Granodiorite&Intr	Yes	Yes	Yes	Good
Selkirk	Canada	MetaSediments	Yes	Yes	No	Excellent
Paute	Ecuador	Granodiorite & Intr	Yes	Yes	Yes	Excellent
Esquimalt	Vanc., Is.	Granodiorite, Etc.	Unlikely	Yes	Yes	Excellent
Quarry	Vancouver	Granodiorite & Intr	Local	Yes	Yes	Excellent

TABLE 2: GROUND CONDITIONS

PROJECT	TOTAL HARD- NESS	UNIAXIAL STRENGTH MPa	OVER- BURDEN meters	GROUND CONDITIONS
Mt Cenis	60	70 - 124	1,200	schist & gneiss; tunnel alignment parallel to foliation; boring tectonic stresses much higher than overburden; encountered popping rock;
Star Mine	128-194	69 - 351	2,225	Revette quartzite; hard, brittle, intensely fractured; encountered popping rock;
Libanon	83-225	125-275	2,100	hard quartzitic rock; high stresses; popping or slabbing rock;
Tunjita	160	68-241	N/A	schist and very hard quartzite (98.8 % silica);
Carhuaquero	160-200	169-210	1,100	very hard and tough igneous lithologies consisting of andesite, dacite, rhyolite, tuff, & agglomerates; very hard aphanitic andesites and welded tuffs exceeded $H_T > 200$ ; rock above tunnel alignment was massive, hard, glistened in the sun, and formed vertical valley walls; Besides the high strength, the rocks were also tough and absorbed a great deal during testing and boring.
Kerckhoff	175	84-140	N/A	massive granodiorite;
Selkirk	111-136	56-211	2,000	metasediments, quartzites, phyllites; high <i>in-situ</i> stresses (documented in nearby tunnels) were anticipated and "popping rock" was in fact encountered.
Paute	130-147	68-313	1,000	very massive granodiorite;
Esquimalt	N/A	43	0	jointed granodiorite with meta-andesite and quartz-plagioclase-porphry;
Quarry	N/A	N/A	0	granodiorite;

TABLE 3: MECHANICAL DATA OF EQUIPMENT USED

PROJECT	Year	TBM	Machine Number	NEW or USED	Dia- meter m	Tunnel Length m	Cutting Edge Load kg	Cutter- Head rpm	Penetration Rate m/hr
Mont Cenis	1965	Robbins	074-115	N	2.2	300	5,500 (avg)	14.	0.18-1.8
Star Mine	1969	Jarva	Mk8-900	U	2.74	125	1,000 (avg)	15.5	0.12
Libanon	1974	Robbins	114-163	N	3.35	N/A	14,500 (avg)	6.9	0.80-2.1
Tunjita	1978	Robbins	145-168	N	4.3	10,500	20,000	6.1	0.7
Carhuaquero	1981	Jarva	Mk-12	N	3.8	8,500	22,700	10.2	1.1-9.0
Kerckhoff	1981	Robbins	243-217	N	7.3	6,700	16,000 (avg)	5.8	.78-2.39
Selkirk	1985	Robbins	222-183-1	U	6.8	8,350	17,600 (max)	6.2	2.2-2.6
Paute	1985	Demag	TV80HA	N	7.8	6,000	26,000 (avg)	5.12	.32-90
Esquimalt	1988	N/A	N/A	N/A	0.5	N/A	N/A	N/A	N/A
Quarry	1989	N/A	N/A	N/A	0.2	N/A	N/A	N/A	N/A

The phenomenon, experienced in terms of TBM penetration and popping rock, illustrated the effect of high tectonic stresses on a relatively low strength rock when bored by a TBM. In effect, the tectonic stresses made the 70-124 MPa rock appear much harder to the TBM than could possibly have been indicated by the uniaxial strength. Some of the difficulty was also attributed to having to break the foliation (parallel to the tunnel) on "edge."

Similar experience was sustained by a Wirth TBM on another section of the project, between Mont Cenis and Grenoble.

The FPI, after the stresses were relieved during re-gripping, designated as Mt. Cenis (N) in *Figure 3*, was consistent with the regression curve. The FPI would increase to infinity as it would grind to a complete halt; however, the FPI at a rate of 0.18 m/hr was over 25,000 kg/mm, higher than any of the other case histories.

The problems associated with this project initiated the development of the Union Industrielle Blanzey-Ouest (Unibo) TBM. The Unibo had three arms, each of which had one cutter mounted on it. The arms would traverse the face from the smallest diameter to the full diameter to cut the entire face. This allowed stresses to be relieved during boring. This TBM is currently known as the "Bouygues Tunnel Boring Machine."

#### **Star Mine, Idaho, USA**

Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3.

At the Star Mine, Idaho, a TBM was chosen for drilling exploratory and development drifts in a gold mine (Hendricks, 1969). High *in-situ* stresses and popping rock were encountered while penetration rates were far below what was reasonable with available cutter loads. The inefficiency of the TBM is reflected by a calculated FPI > 8,000 kg/mm. Popping rock was reported and in some sections where the penetration was less than 0.12 m/hr (Tarkoy, 1975).

The fact that the TBM could apply a cutter load which was barely adequate or at times inadequate for the encountered rock, is now considered the primary cause of the difficulties of boring. Although the quartzite was hard, it contained many micro- and macro- fractures which weakened the rock mass and should have made the rock comminution less difficult.

The stresses, however, held the fractured rock together and the face was relatively impenetrable to the TBM, where the stresses had not been relaxed. However, when the face had not been advanced for a period of time, the stresses caused slabbing and fallout. The slabbing caused problems at the face and the cutter-head. This project illustrates two extreme problems and their effect on the TBM.

The use of the TBM in the Star Mine was considered a failure and it was removed after boring only 125 meters.

#### **Libanon Gold Mine, South Africa**

Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3.

The Libanon Gold Mine in South Africa utilized a TBM to excavate access drifts. Highly stressed rock was encountered and broke loose behind grippers as they were released. Our suspicion that the stresses also affected TBM penetration were confirmed by an analysis of the average penetration rates and typical cutter loads utilized during tunnel boring.

Calculations using average boring conditions (Thompson, 1988) produced an FPI > 9,000 kg/mm, high enough to indicate a considerable departure from the normal values (regression line in *Figure 3*) of about 4,500 - 5,000 kg/mm.

#### **Tunjita Hydroelectric, Colombia**

The Tunjita Hydroelectric Project was excavated between 1978 and 1985 (Marconi, 1990). Two tunnels were driven as follows:

1. a 14.5 km long tunnel with an excavated diameter of 4.3-4.5 m by the 144-151-1 Double Shielded Robbins TBM and
2. a 10.5 km long tunnel, excavated diameter of 4.3-6.0 m, by the 145-168 Robbins TBM.

#### **Robbins TBM (144-151-1)**

The Double Shielded Robbins TBM excavated 5 km in shale and siltstone and 2.5 km in limestone. There were no major difficulties encountered in this tunnel. The remainder of the tunnel was excavated by drill and blast.

#### **Robbins TBM (145-168)**

An open design Robbins TBM excavated 1.5 km in very hard quartzite with a cutter life of only 10 cubic meters (0.7 m of tunnel) per cutter. When drilling 76 mm exploratory boreholes the diamond bit life was only 0.7 meters. The problem of hard abrasive rock was compounded by the inflow of thermal water (> 42°C) in the quartzitic portion of the tunnel which caused problems with machine components, washing away muck fines, and causing breakdown of lubrication components.

The very hard quartzite resulted in low penetration rates and high FPIs (higher than the regression line in *Figure 3*) in spite of very high cutter loads. An analysis of the TBM excavation revealed that the 145-168 Robbins TBM

sustained an FPI > 10,000 kg/mm. Since very little detail of this project is known, additional opinions cannot be formulated.

#### **Carhuaquero Hydroelectric, Peru**

TBM performance was generally satisfactory, except in the harder rhyolites. Analysis of TBM performance data confirms that some of the rock behaviour produced very low penetration rates (Tokes, 1985; Ivan-Smith, 1988; Tarkoy, 1988), requiring an FPI > 12,000 kg/mm. The average encountered FPI, based on average conditions, conceals a far greater inefficiency that could have been identified with more detailed performance data and analysis.

The Carhuaquero project illustrates generally satisfactory performance, some marginal performance, some inefficient performance, and also serves to confirm difficulties encountered elsewhere in young mountain chains such as the Andes of Colombia and Ecuador.

#### **Kerckhoff Hydroelectric, California**

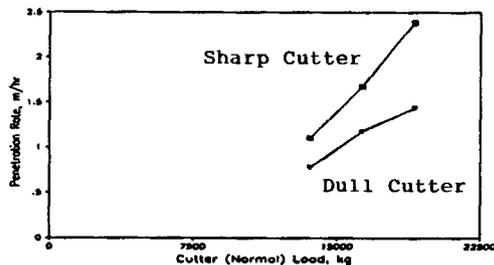
Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3 (Kennedy, 1982; Woodward, 1983; Tarkoy, 1985).

The Kerckhoff 2 Underground Hydroelectric Power Plant Project was bored by a new state-of-the-art Robbins TBM. The rock turned out to be consistently more difficult to cut (harder) than anticipated by anyone, including the manufacturers of the TBM, The Robbins Company.

It was reported that the quartz grains in the diorite were stress sutured, suggesting tectonic stresses had affected the petrofabric of the rock.

The relationship between cutter load and cutter penetration for the granodiorite is illustrated in Figure 4. The curves suggest that a threshold of efficient cutting exists. Below this threshold, the cutting is less efficient and above it, more efficient. The differences in efficiency can be attributed to the differences in the use of energy to produce crushing or chipping.

**FIGURE 4: CUTTER LOAD & SHARPNESS**



Data in Figure 4 illustrate the:

1. sensitivity of penetration rates to cutter load,
2. sensitivity of penetration rates to the cutter profile (state of wear), and
3. reduction of penetration as cutters wear.

The rock hardness encountered at Kerckhoff appears at times to have been close or beyond the efficient cutting limit of the TBM. In effect, the TBM running tests, plotted on Figure 3, illustrate that cutting efficiency decreases (increasing FPI) as the:

1. cutter wears and
2. as the rock hardness increases (illustrated conversely by Figure 3 as the cutter load decreases).

In other words, harder rock causes lower penetration and higher cutter wear. Consequently, lower penetration also increases cutter wear per unit volume of rock cut. Therefore, the cutters are in a duller condition for longer periods of time between cutter changes, even with more frequent cutter changes. As a result, the penetration is decreased even more as a consequence of the dull cutters.

The owner compensated the contractor for extra costs sustained as a consequence of lower penetration rates, higher cutter wear, and delays associated with having encountered harder than anticipated rock (marginal to the efficiency of the TBM).

#### **Selkirk Railroad Tunnel, BC, Canada**

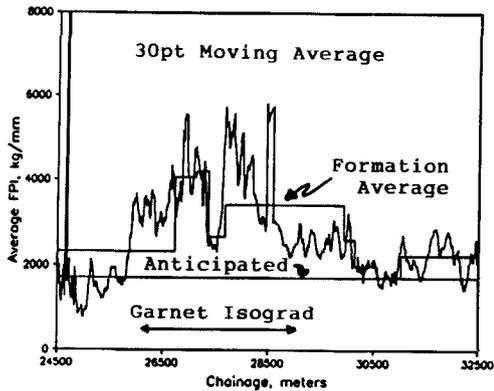
High *in-situ* stresses encountered in various tunnels in the Selkirk Mountains of British Columbia, Canada, suggested that stresses should be anticipated in the nearby Selkirk Railroad Tunnel. Subsequently, "popping rock" was encountered in sections of the Selkirk Tunnel. Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3 (Knight, 1987; Tanaka, 1987; Tarkoy, 1988).

The portion of the Selkirk tunnel excavated with a Robbins TBM sustained less than anticipated penetration rates, penetration rates lower than normal with the available TBM, exceedingly high cutter wear, and a broken main bearing. Penetration rates dropped and cutter wear skyrocketed when crossing into the garnet isograds of metamorphism (a degree of metamorphism typically producing an abundance of garnets). Conversely, penetration rates rose and cutter wear dropped when crossing out of the garnet isograd. No clue, from intact or rock mass properties, was available to indicate that this behaviour should be anticipated within the garnet isograds.

A 30 point moving average, to attenuate

extreme variation of the encountered FPI, is illustrated in *Figure 5*. It is immediately evident that the encountered FPI was significantly higher than the average anticipated value of 2,500 and the highest values occurred between the garnet isograds. The variation in the FPI, even with a 30 point moving average, is still notable. The variation reflects a sensitivity to the condition of the cutters, thereby providing a measure of cutter condition. The curve illustrates the unusually high energy per unit penetration required to excavate the rock.

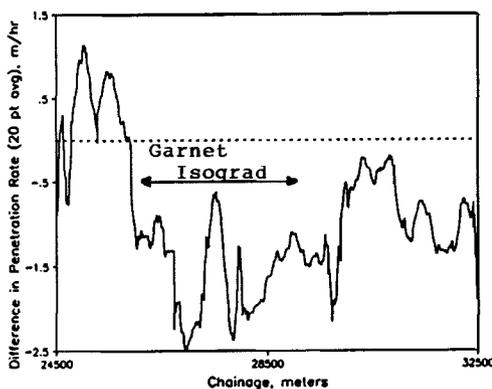
**FIGURE 5: FPI AT SELKIRK**



*Figures 5 & 6* illustrate differences between anticipated and encountered (encountered - anticipated) penetration rates and cutter costs.

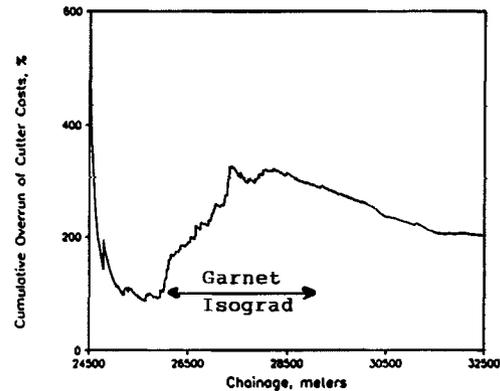
These figures represent performance above or below expectations. Performance as expected, corresponds to zero. As tougher rock was encountered, higher cutter loads were applied (increased from 18,000 to 22,000 kgf) to compensate and maintain penetration. In spite of an increase in cutter load, the difference in penetration increased (dropped) dramatically between chainage 260+00 and 290+00 as illustrated in *Figure 6*.

**FIGURE 6: PENETRATION AT SELKIRK**  
(note the location of the garnet isograd)



Differences between anticipated and encountered cutter costs also skyrocketed between chainage 260+00 and 290+00 as illustrated in *Figure 7*. Cutter costs are normally infinitely high at the start of boring since the original cutter dressing cost has bored no rock (dressing cost, \$/0 meters). As the TBM begins to bore, cutter costs typically continue to drop, approach, and remain near to anticipated costs ("0 on the ordinate is equal to "no cost overrun"). Normal saw tooth movements of the curve represent cutter changes, generally in the outer positions first since these sustain the longest rolling paths in the shortest time. With continued boring, fluctuations of the curve become more subdued since the curve is cumulative. Consequently, the increasing overrun of cutter costs at the garnet isograd (Chainage 260+00) is considered precipitous.

**FIGURE 7: CUTTER OVERRUNS**  
(note the location of the garnet isograd)



The severe reaction of the FPI, penetration rates, and cutter costs at the garnet isograds reflects a prominent change in the nature of the behavior of rock between chainage 260+00 and 290+00. This is consistent with the theory that the formation of garnets in metamorphism represent radical changes of mineralogy and mechanical properties of the rock. Garnets are difficult to nucleate and generally represent conditions of formation far beyond conditions required for stability. Consequently, these changes tend to be radical, as exhibited in *Figures 4 through 6*. Interestingly, these changes do not appear to have been identified by conventional exploration or testing techniques. Further investigation will be required to determine the precise rock characteristics which cause the TBM to react and which were not discovered prior to construction.

In any case, the contractor was compensated for unanticipated conditions; consequently, future investigations no longer have the support of financially interested parties.

### Paute Hydroelectric Project, Ecuador

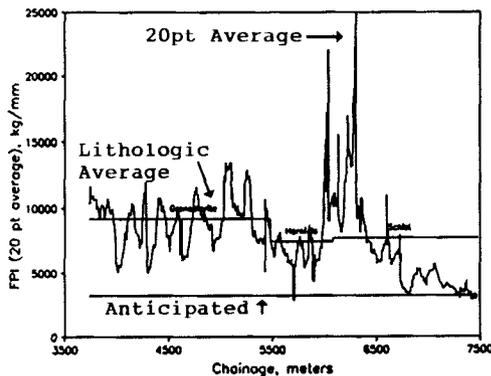
The Paute Hydroelectric Project, Phase A was constructed between 1977 and 1983 and consisted of a concrete dam (1,200,000 cubic meters of concrete, 170 meter high gravity arch, and crest length 400 meters), spillway capacity 7720 cubic meters/sec, reservoir 120 million cubic meters, five 100 MW units with 667 meters of head, and a power tunnel approximately 6 km long and 5 meters in diameter, excavated by D&B (Marconi, 1990).

During excavation popping rock was encountered in a few sections of tunnel. Very little rock support, primarily rock bolts, were required. Water inflow was minimal. The tunnel traversed schists, hornfels, and granodiorite.

The second stage, Paute Phase C, was constructed between 1985 and 1991. It included a total of 9 km of tunnel and shaft excavation and the doubling of the installed generating power in a new powerhouse excavated and built adjacent to the first stage one. The 6 km long, 7.8 meter diameter power tunnel and the 300 meter long access tunnel were excavated by TBM. The alignment of this tunnel was subparallel to the one driven for Phase A at a distance of 80 meters further into the mountain. Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3.

Excavation was started at the downstream end, beginning in schist, traversing hornfels, and ending at the upstream portal in a very tough fine to coarse grained granodiorite. The FPI (Figure 8) and cutter costs increased and penetration rates decreased (boring toward decreasing chainage) with increasing distance from the valley walls.

FIGURE 8: FPI AT PAUTE



A very high Field Penetration Index, sustained between chainage 60+00 and 65+00 as illustrated in Figure 8, reflects damage sustained by the TBM. This damage was repaired and the FPI in the hornfels again became consistent with earlier values in the schist. The FPI first

began to rise in the hornfels and continued to rise in the granodiorite. Ignoring the earlier rise in the FPI due to mechanical problems, an increasing FPI becomes evident in the hornfels and granodiorite, especially when examining the lithological averages in Figure 8 (Tarkoy, 1989).

As a result of encountering the increasing FPI, the contractor carried out extensive site and laboratory investigation. The investigations determined that a high residual horizontal stress field was originated at the time of intrusion of the granitic rock mass and during subsequent tectonism. This state of stress was not relieved in spite of the deep valley erosion.

Even though the first tunnel provided an indication of anticipated conditions, the drill and blast excavation could not foretell the behaviour of the rock as "seen" by the TBM. The FPI anticipated for Paute "C", was expected to be FPI < 4,000 kg/mm. The average encountered FPI for schist, hornfels, and granodiorite, were 7,720, 7,450, and 9,200, kg/mm, respectively.

It is generally known that as the rock hardness and/or the strength increase, a higher cutter load is necessary to maintain efficient cutting above threshold. This phenomenon has been illustrated for rocks of various strengths and thresholds of efficient excavation by Robbins (1972). Consistently high cutter loads, in excess of 23,500 kgf, had to be applied, especially in the granodiorite sections of the tunnel.

Recorded cutter loads confirm that every available bit of TBM capability (over what was anticipated or required) was applied to the rock. The TBM had capabilities far in excess of those required by anticipated rock conditions as indicated by the high cutter load capabilities actually used. However, even this excess capability appears to have been less than adequate to deal with the increased resistance of the rock mass to boring. The TBM was able to deal with the softer and more brittle schist near the valley walls, where stresses are likely to have been relieved by erosion of the valley.

Observations in the tunnel suggested a possible relationship between FPI, joint frequency, increase in cover, stress phenomena, and penetration rates. Consequently, quantitative measurements of joint frequency, stress phenomena, were made for comparison with penetration rates. The raw data showed a trend, however, expected scatter reflected many variables that influenced penetration, including variations in cutter load, cutter condition, jointing, stresses, etc.

It was found that as joint frequency increased, it appeared initially to improve and later decrease penetration rate (Tarkoy, 1989). Penetration rate tends to suffer as jointing becomes more frequent, as in urban tunnel environments, where the rock mass is in an advanced state of degradation compared to conditions

found in young mountain chains. A similar plot (Tarkoy, 1989) illustrated that a decrease in the penetration rate was associated with an increase in stress related phenomena (popping rock, stress slabbing, and stress fracturing).

Based on detailed petrographic examinations and unconfined and confined compressions tests, Buechi (1990) concluded that "*tectonic stresses produce an immediate micro-cracking in the crushed zone area due to relaxation*" and "*This immediate micro-cracking enlarges the crushed zone which means that more thrust will be necessary to build up the pressure level to create further median cracks for penetration and lateral cracks for chipping of the rock.*"

As a result of the high *in-situ* stresses and associated conditions present in a young mountain chain, it is not surprising that the lack of joints, increasing cover, and tectonic stresses appear to have had an impact on penetration rates and comminution efficiency as measured by the FPI.

Coincidentally, the Carhuaquero, Tunjita, and Paute projects are both located in the geologically young Andes mountain chain.

#### **Esquimalt, Vancouver Island**

During the drilling of shallow pile sockets, a problem of very slow drilling rates and high bit wear were encountered at Esquimalt, Vancouver Island, BC, Canada. Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3 (Tarkoy, 1990).

The differences in performance could, in part, be explained by differences between anticipated and encountered uniaxial strengths. However, some of the drilling difficulty and geotechnical conditions had an uncanny resemblance to previous experience. The similarities included unpredictability of comminution behaviour, very low and unanticipated penetration rates, presence of granodiorite, and stress sutured quartz grains.

Since the site geology was in a comparatively advanced state of degradation with well developed jointing and no apparent residual stresses, this project's contribution is limited. However, it serves to illustrate that effects of previous tectonic and stress history reflected in lithology and in the sutured quartz grains may no longer apply when altered.

The discovery of sutured quartz did, however, identify at least one feature, in addition to the presence of granodiorite, which might explain some of the unanticipated drilling difficulty.

#### **Vancouver Quarry**

At about the same time as the work at Esquimalt, a contractor supplying railroad ballast encountered unpredicted and unusually slow drilling rates, high bit wear, and high crusher

wear in one part of his quarry. Common geotechnical elements, geotechnical conditions, and machine characteristics are summarized in Tables 1 through 3.

This project's contribution is that it confirms experience at Esquimalt. The conditions were unanticipated and occurred only in one section of the quarry. However, a geologist (Van Ryswyk, 1990) investigating the unanticipated conditions found stress sutured quartz crystals in the area responsible for the difficulty. The stress suturing of quartz in granodiorite resembled the conditions found at Kerckhoff, Paute, and Esquimalt.

A number of similarities between the local geology and the foregoing projects became evident.

#### **Inadequate TBM Capabilities**

While developing the Field Penetration Index to identify unusual geotechnical phenomena in tunnel boring, it became apparent that it was also useful as a measure of:

1. TBM capabilities (particularly used TBMs),
2. boring efficiency, and
3. condition of the cutters.

In two cases illustrated in *Figure 3*, unanticipated geotechnical conditions (harder than anticipated rock) combined with limited TBM capacity resulted in exceeding the mechanical limits of the machine and efficient tunnel boring. The original investigations of the inefficient behaviour of this TBM on two separate projects provided adequate data to calculate the FPI. On the first project, the FPI confirmed that TBM capabilities were adequate in the anticipated geotechnical conditions. More importantly, the calculated FPI verified that the TBM was operating far beyond its capabilities in the unanticipated conditions.

A number of case histories are therefore presented herein to contrast with the foregoing anomalous geotechnical conditions.

The WSSC-80 project in Bethesda, Maryland, a contract required TBM excavation of only 1000 meters of 2.2 meter diameter tunnel (Tarkoy, 1981b). A relatively old machine, capable of cutting rock having an average Total Hardness of 95, was used. When the machine encountered consistently harder rock on "edge" (at right angles to foliation) averaging a Total Hardness of 125 with a maximum of 160, it was unable to perform efficiently and penetration dropped below 0.3 m/hr.

At penetration rates of 0.24 m/hr, failure of the cutterhead (cracking and bending), a high rate of cutter failure, and failure of hydraulic systems, there was the danger that the TBM could not complete the project. The FPI exceeded 9,000 kg/mm.

Subsequently, the contractor was awarded compensation by a board of arbitrators for decreased penetration rates, increased cutter wear, and delays resulting from encountering unanticipated hardness of rock that was beyond the efficient capabilities of the TBM.

The same TBM was subsequently used at the Kierna Mine, Val D'Or, Canada, to excavate exploratory drifts in a greenstone belt. The Jarva TBM was refurbished and fitted with a new cutterhead (Vanin, 1988).

When encountering hard rock, the FPI increased to nearly 6,000 kg/mm (Tarkoy, 1986b). The available cutting edge loads of 9,000 kgf on the older machine were inadequate to cut hard rock efficiently. Maintaining the cutter loads as high as possible to preserve the penetration rate, the main bearing deteriorated (Vanin, 1988).

Problems encountered on this project were similar to problems experienced on the WSSC-80 project and without the benefit of differing site conditions.

A rigorous evaluation of the TBM thrust, torque, cutter loads, and anticipated geological conditions could have prevented the problem.

## SUMMARY AND CONCLUSIONS

The phenomena of difficult and unexplainable rock comminution have, in several recent cases, been detrimental to project performance and caused considerable cost overruns. Recent case histories with substantial geotechnical and considerable mechanical performance data made it possible to investigate the unanticipated and unusual manifestation of rock comminution phenomena. Investigation into similar behaviour on earlier projects allowed the identification of a number of common elements. These elements have been identified and their effect on rock comminution examined. The investigation was necessarily limited to practical resolution of the problems on a project level rather than on a purely scientific basis. Consequently, studies were limited to the client's immediate concerns.

Detailed studies of two projects and general knowledge of a number of others, cannot lead to definitive or ultimate scientific conclusions. However, our knowledge has been advanced enough to have identified problems and to make recommendations to them in the future, even without fully understanding the underlying cause.

### Summary

The foregoing discussions have documented a number of features that have been associated with unanticipated rock comminution difficulties. The difficulties have not been predictable by classical methods of geotechnical exploration (core borings; D&B tunnel experience;

survey of structural geological;) and testing (uniaxial strength and Total Hardness).

The features in common to several projects may be categorized as follows:

1. Granodiorite Batholith
  - a. with stress deformations (undulous extinction, prismatic walls with preferred orientation, deformation twins, and pressur solution, sutured grain boundaries; Buechi, 1990),
  - b. high tectonic (non-hydrostatic) stresses
  - c. scarcity of jointing, and
  - d. high cover,
  - e. sites found in young mountain chains,
2. Metamorphic Rock
  - a. within a high grade of metamorphism (garnet isograd) and
  - b. sites found in young mountain chains.

Since the phenomena that caused difficult rock comminution are difficult to detect directly, sites in the foregoing two geological domains serve as adequate justification for additional investigations.

### Conclusions

The advance of technology has allowed the boring of increasingly harder rock. With tunnel boring in new domains such as hard rock (granodiorites) and young mountain chains new problems have been encountered. Experience indicates that anomalous geological phenomena may be encountered that are not predicted by currently used typical exploration and testing methods, capable of having a substantial impact (an order of magnitude) on mechanical rock comminution, exceedingly costly and have enormous consequences on project completion and costs.

Reported difficulties with rock comminution caused by geotechnical conditions or mechanical inadequacies have been recognized and quantified with the Field Penetration Index. The Field Penetration Index is an effective and quantitative distinction able to quantify rock comminution efficiency. The FPI is equally effective in anomalous geotechnical conditions and as with substandard performance due to TBM deficiencies.

Since neither classical exploration techniques nor a single test can predict the types of problems and conditions discussed in this paper, an alternate technique must be found. We conclude that the only possibility of detecting

difficult rock comminution is to make further investigations when the conditions common to the discussed projects are found. It is our opinion that sites anticipating granodiorite, high stresses, tunnelling within garnet isograds of metamorphism, or young mountain chains, warrant more intensive investigations. These investigations should include petrographic analyses seeking stress phenomena, micro-cracking, and triaxial compression tests to determine effects of stress relief on test samples.

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