CHALLENGES & SUCCESSES IN MICRO-TUNNELLING ON THE CHELSEA RIVER CROSSING

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Abstract

The 300 meter long Chelsea River Crossing in Boston, Massachusetts, was an example of a unique micro-tunnelling excavation project that pushed the limits of micro-tunnelling in terms of design, machine features, the geotechnical conditions that had to be traversed, and the contractor's perseverance against some seemingly insurmountable odds. The contract specifications required rock disk cutters, an ability to deal with boulders, and the ability to change cutters under compressed air pressure at any point under the river crossing. Of two qualified MTBM manufacturers, only Soltau provided a full and complete design at the time of machine selection, addressing all of the anticipated geological conditions with appropriate design solutions. This, and the service reputation of Soltau USA was the basis of Modern-Continental Construction Company's selection of one of the most innovative and powerful MTBM's built to date.

Initial difficulties with the slurry wall supported shaft excavation put the start of micro-tunnelling behind schedule. The unanticipated conditions in the shaft and consequently in the tunnel caused a number of difficulties making the project very challenging. The harder than anticipated till actually helped excavation, however, the unanticipated excess boulders resulted in slower excavation and considerable wear damage to the machine. Mechanical failures, difficulties associated with pumping of large sized materials, and the weather conditions exacerbated the excavation process.

Nevertheless, the project was completed successfully, albeit behind schedule. In retrospect, all of those involved in the project wonder that with so many adverse conditions, particularly geological in nature, the project was completed without major disasters.

1. Introduction

The project was designed for the relocation of the Massachusetts Water Resources Authority water main Section 8 which crosses the Chelsea River, to a lower elevation to allow dredging of the Chelsea River to an elevation of approximately –11.4 Boston City Base. The new pipeline will be approximately 396 m long from connection to connection and will be approximately 1.2 m in diameter, inside an approximately 1.8 m tunnel liner extending from East Boston to Chelsea. The project details are provided in **Table 1.**

2. Anticipated Geological Conditions

Boston is located in the New England Physiographic Province of the Appalachian Highlands; an area characterized by complexly folded and faulted bedrock that has been worn down by surface erosion and glaciation. The majority of the surficial materials found in the Boston Basin are Pleistocene and include glacial till, glacial outwash, and marine clays.

Table 1: Project Details

Project	Chelsea River Crossing
Owner	Massachusetts Water Resources Authority
Geotechnical Investigation & Design	Parsons-Brinckerhoff
CM Manager	Judith Nitsch
Contractor	Modern-Continental Construction Company & Westcon Micro-Tunnelling
Shaft Diameter (Launch/Recovery), m	10.4/7.3 (12 sided)
Shaft Depth, m	26.8/26.2
Carrier Pipe Type	Steel with Permalok Joints
Carrier Pipe Diameter (OD), m	1.88
Utility Pipe Type/Diameter (ID), m	1.2
Tunnel Length, m	304
Micro-tunnelling Consultant to MCCC	Dr. Peter J. Tarkoy, GeoConSol, Inc.
Slurry Consultant to MCCC	Gilbert Tallard, Liquid Earth

2.1. Launch Shaft

Geological conditions for the launch shaft excavation are summarized in **Table 2.** The soils indicated in the shaft were described as "heterogeneous fills, sands and gravel, interbedded organic silts, peats and sands, marine clays, glacial outwash sands and gravel, and till" in the geotechnical baseline report (GBR) prepared by Parsons-Brinckerhoff. The till was to include clay, silt, sand, gravel, cobbles, and occasional boulders as indicated in the boring logs and the contract specifications.

It is generally known in the area, and often pointed out in geotechnical reports, that for till the SPT = 60 - 100. However, higher blow counts are often sustained when encountering coarse materials (sand, gravel, cobbles, and boulders), sometime in excess of SPT > 300.

The GBR called for:

"Concrete diaphragm walls, constructed using slurry, are an appropriate means of excavation based on the subsurface conditions anticipated and this procedure is specified."

"Contractor must take into account the difficult excavation conditions, potential panel deviations, obstructions including boulders, rubble, and the like"

"Cobbles and boulders up to a size of three feet in any one dimension will be encountered during diaphragm panel and shaft interior bulk excavation."

TABLE 2: ANTICIPATED GEOLOGICAL CONDITIONS IN THE LAUNCH SHAFT

Elevation, m	Description	SPT N Values	Depth, m
4.6	Surface		0
	FILL	27	
0.6			4.0
	SILT and clayey SILT, tr f gravel, tr wood, stiff, moist, brown. (Petroleum odor); SILT and clayey SILT, med stiff, wet, gray.	10	
-2.4			7.0
	SILT and CLAY, some f sand, little gravel, slightly plastic, stiff, moist, green -gray.	16	
-5.3			9.9
	Silty SAND, f-m sand, little sitl, tr clay f-m gravel in upper section, med. Dense, wet, brown. 11.3 m Losing water; COBBLES or **BOULDER**; 12.2 to 13.4 m Lost approximately 300 liters of water.	53	
-11.6			16.1
	f-m SAND and f GRAVEL, tr silt, tr m-c gravel, very dense, wet, brown.	68	
-13.1			17.6
	Hole caved in at 59' No casing from 14.9 m to 18 m silty f SAND, tr m-c sand, little silt, little m-f gravel, very dense, moist, green-gray. (TILL);	248	Tunnel Grade
-22.8			27.4

Reasonable optimism would allow a contractor to anticipate no difficulties with boulders while anticipating one or two boulders at the most, since only one was specifically indicated in the boring at the shaft location in **Table 2.**

2.2. Receiving Shaft

The receiving shaft across the Chelsea River was expected to encounter conditions similar to those anticipated in the launch shaft.

2.3. Tunnel Conditions

Geological conditions for the tunnel horizon are summarized in **Table 3.** The indicated materials consist of clay, silt, sand, gravel, cobbles, and boulders to be encountered in glacial till. Of all of the materials anticipated, the cobbles and boulders will have the most effective impact on excavation. However, the GBR indicates:

> *"In places where the till is absent, glacial outwash in the form of sand and gravel directly overlie the bedrock"*

> *"The anticipated presence of numerous boulder and cobbles both singly and in groups throughout the tunnel envelope is consistent with general nature of the subsurface conditions."*

> *"While no boulders greater than approximately twelve inches in size or larger erratic where found in the subsurface exploration program for this project, they have been uncovered in open excavations to depth in many projects throughout the Boston area."*

> *"four areas of tunneling through boulders in the tunnel horizon greater than three feet along the length of the tunnel will be encountered within the limits of the tunnel excavation"*

TABLE 3: ANTICIPATED GEOLOGICAL CONDITIONS AT TUNNEL GRADE

Boring	Chainage, m	Material at Tunnel Level	Primary Material	Other Significant Material	SPT
97-101	Not drilled to tunnel depth;				
	0				
97-102		Silt and Clay	65%	Cobbles or boulders 12 m above tunnel horizon	240
	15				
98-202		Sandy Silty Clay	85%	Boulder 15 m above tunnel horizon	183
	36				
97-103		Silty Clay	85%	Cobbles 8 m above tunnel horizon	133
	73				
98-203		Sand and Gravel	95%	Cobbles above and below tunnel horizon	339
	116				
97-104		Silty Sand	45%	Cobbles outside tunnel horizon; 63/6 inches in tunnel horizon;	124
	146				
98-204		Silty Sand	85%		147
	170				
98-201		Sand	75%	Gravel and cobbles outside tunnel horizon;	186
	210				
97-105		Sand	90%	Cobbles outside tunnel horizon;	88
	268				
97-106		Sand & Clayey Silt	78%	Cobbles outside tunnel horizon; Boulder 15 m above tunnel horizon;	185
	307				
97-107	Not drilled to tunnel depth;				

The use of a GBR made it mandatory for the geotechnical investigators to arrive at a quantitative estimate of boulders in the bill of quantities. The contractor was required to give a unit price for tunnel in boulders for a total tunnel length of 5 meters only.

3. Micro-Tunnelling Machine Design & Specifications

Soltau was selected to build the micro-tunnelling machine for Modern-Continental because they had a full and complete design proposed to deal with conditions as indicated in the specifications and the geotechnical baseline report (GBR). Furthermore, their reputation for unparalleled service in the USA was also essential to the contractor's choice.

The MTBM is illustrated in **Figure 1, Figure 2** and specifications provided in **Table 4.**

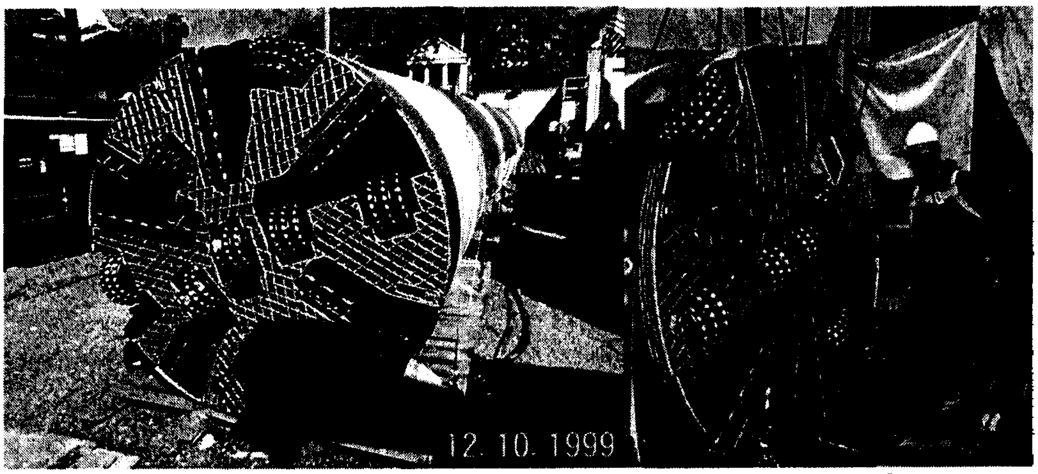

Figure 1: Soltau MTBM Utilized for the Chelsea River Crossing

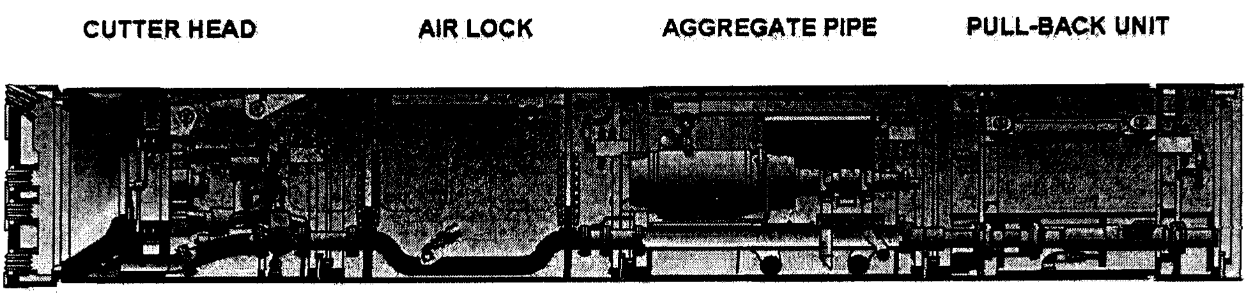

Figure 2: Soltau MTBM Schematic for the Chelsea River Crossing

The design of a micro-tunnelling system can only be the "best compromise" for the conditions anticipated. It is an attempt to design a knife, fork, and spoon all into one piece of equipment. Departures from the anticipated conditions always affect the "best compromise" adversely, especially when exceeding the range of practical and efficient performance of the micro-tunnelling system. The "best compromise" involves design and detailed specification and utilization of:

- Cutting tools,
- Cutterhead openings,
- Crushing chamber,
- Crushing chamber intake ports, and
- Slurry system geometry and capacity.

In the case of the Soltau RSV 600, the cutterhead openings were designed to keep out boulder-sized materials to be broken by the carbide insert disk cutters. Smaller materials were allowed to pass into the crushing chamber to be broken by the crusher. The resulting material would pass through the 50 mm intake ports to be transported through the slurry system with an intermediate pump in the tunnel, and up the 27 m deep shaft to the Schauenburg Separation Plant.

TABLE 4: SOLTAU MTBM SPECIFICATIONS

Machine Manufacturer	Soltau-Wirth
Machine Type	RVS600
Cutter Types	• Multiple kerf carbide insert disks • Carbide tipped picks (ahead of disks) • Carbide edged spades (recessed behind disks)
Cutterhead Gauge Diameter, mm	1960
Shield Diameter, mm	1930
High Pressure Water Jets	4 Rotated with cutterhead
Casing Pipe diameter, mm	1880
Machine Length, m	12
Torque	350,000 NM @ 4rpm 191,000 NM @ 8 rpm
Thrust	800,000 MT
Pullback Jacks	300,000 T 150,000 T pullback 750 mm jacks
Airlock Length, m	3
Pipe Type	Steel with Permalok
Pipe Diameter (OD), m	1.88
Pipe Diameter (ID), m	1.829

Although the required compressed air chamber (**Figure 2**) was part of the machine, no one really wanted to use or test it, especially in the sand, gravel, and cobble, material encountered, for fear of losing air to the river bed.

4. ENCOUNTERED CONDITIONS

4.1. Launch Shaft Excavation

The shaft as excavated, consisted of twelve slurry wall panels with a bucket clam excavator. Difficulties encountered <u>during panel excavation</u> consisted of:

- Maintaining alignment of the panels with a 25 m long bucket in radically changing consistency material from fill, sand, soft clay, to dense till (25 Mpa), and boulders and
- Removing boulders that penetrated outside the panel excavation limits.

During the excavation of the interior of the slurry panel supported shaft the manifestations of difficulties included:

- Misalignment of slurry wall panel and associated leakage and loss of ground,

- Boulders sticking out of the interior of the slurry wall,
- Hard boulders sticking out of the back of the slurry wall as indicated by drilling for jet grouting holes outside the shaft and encountering obstructions,
- Underground water leak with chlorinated water (from old water line), and
- Difficult excavation of till.

The problems associated with misaligned slurry wall panels were remedied with internal ring beams, spilling into the soil, jet grouting, and meticulous excavation.

As excavation approached the bottom of the shaft in till, excavation became very difficult and the teeth of the backhoe had to be changed several times for excavating only 2 meters. The testing of the material encountered revealed unconfined compressive strengths as much as 25 times what was anticipated as summarized in **Figure 3.**

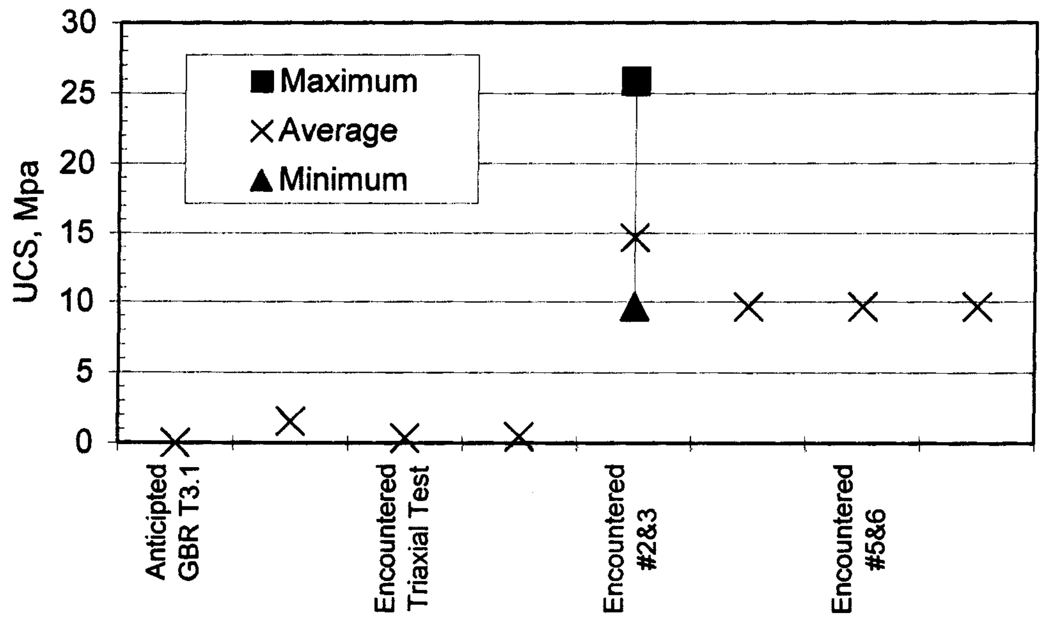

FIGURE 3: ANTICIPATED / ENCOUNTERED TILL CHARACTER IN SHAFT

The total delay sustained during shaft excavation was about 5 months, shifting micro-tunnelling excavation into the winter months.

4.2. Tunnel Excavation

Micro-tunnelling was begun 11 Nov 99 and completed 23 Feb 00. This period included downtime for failures of 2 sets of pinions and freezing and thawing of the separation plant.

4.2.1. Geotechnical Challenges

The encountered geotechnical difficulties were the result of materials that were not indicated, exceeded indicated quantities, or behaved differently than anticipated. They consisted of the following:

- Hard till (25 Mpa),
- Gravel (fine to coarse),
- Excess Cobbles,
- Excess boulders, and
- 5 m vs. 140 m of tunnel length in boulders.

The till at the bottom of the shaft excavation and the start of micro-tunnelling was so hard that a till face at a depth of 28 m stood unsupported for nearly 48 hours as illustrated in **Figure 4.**

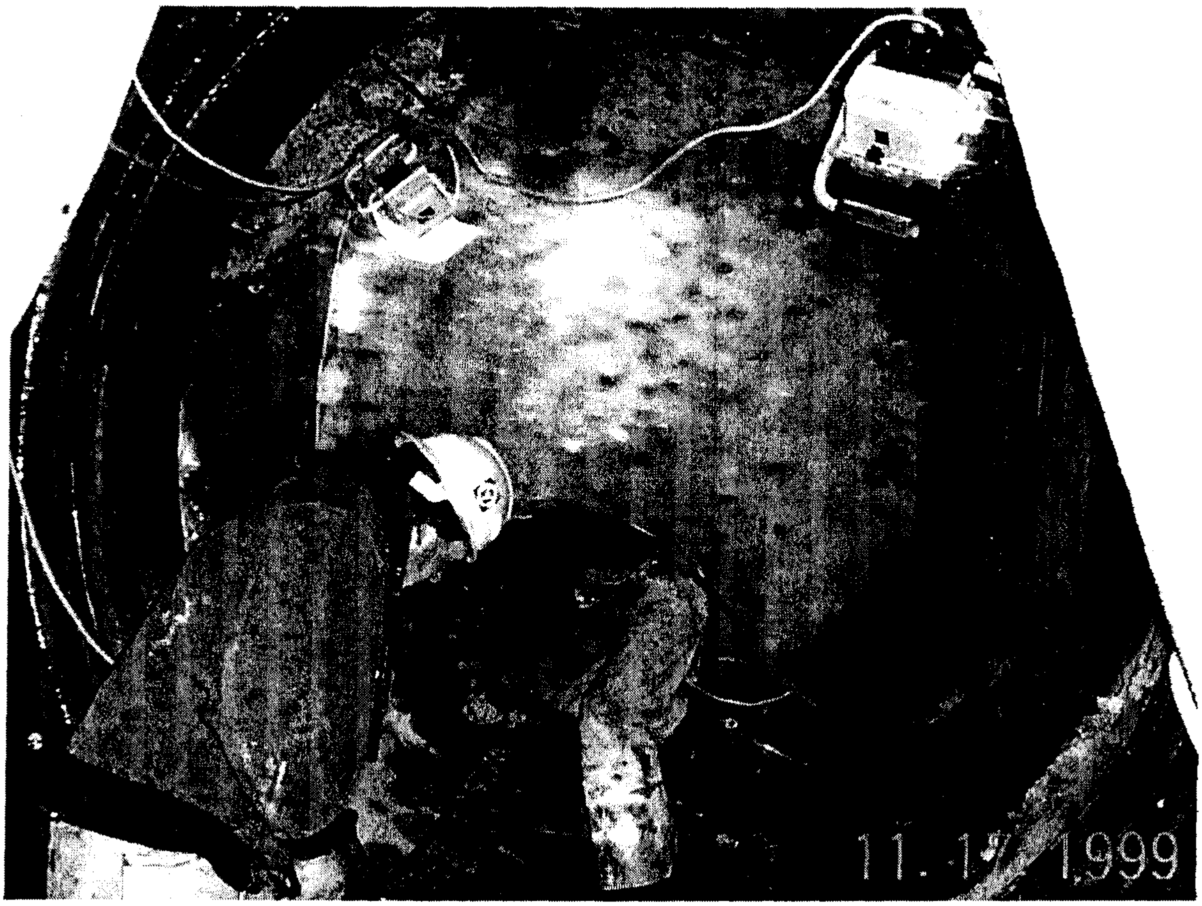

FIGURE 4: SOIL FACE OF MICRO-TUNNELLING LAUNCH

Boulders (in a sand, gravel, and cobble matrix) were encountered approximately 60 m into the drive.

The bill of quantities specified and required pricing of tunnel length bored in boulders as a unit price. The bid price was fair and equitable, however, no method of measure was provided by the design engineer to establish actual excavation in boulders. The failure to specify means of measurement for payment that departed from original quantities led to substantial and unnecessary conflict between the owner and contractor regarding payment. It was necessary to develop a reliable measure of when the MTBM was boring in boulders. This was rather difficult since there is no absolute way to "see" what the machine was actually excavating. Nevertheless, we were able to develop a multi-variable method utilizing machine parameters that could be confirmed by samples collected from the separation plant. The results are illustrated in **Figure 5**.

The determination of the presence of boulders was based on:

- Sound from the heading,
- MTBM Operator's experience with machine behavior,
- Need to limit rpm and maintain available torque in response to material behavior, and
- Material recovered from the separation plant.

The material illustrated in **Figure 6** came from an excavated length of 8 m and was thought to represent an 8 m boulder. However, it is probable that a large hard granite boulder (less than 8 m in length) was pushed ahead of the machine for a total of 8 meters until all of it was chipped by the disk cutters and it became small enough to enter the cutterhead.

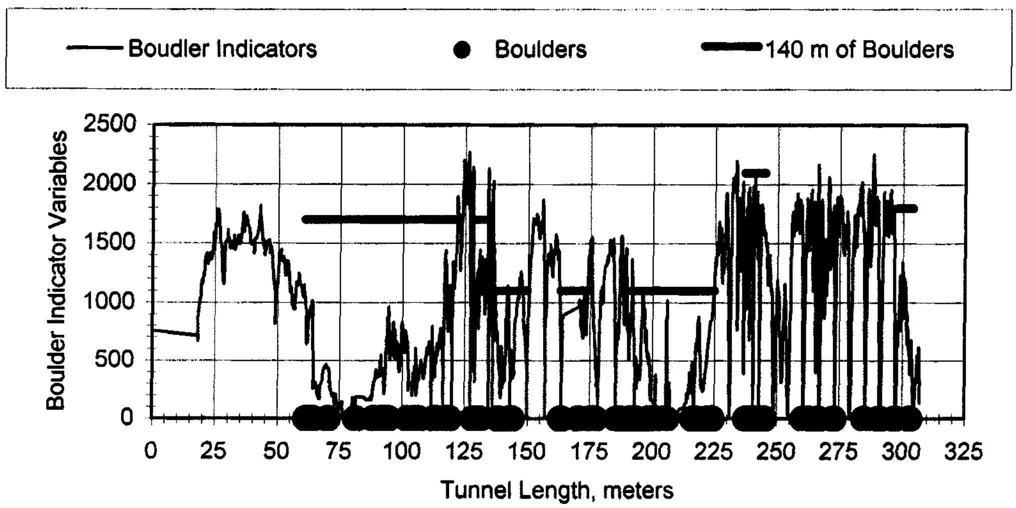

FIGURE 5: EVIDENCE OF BOULDERS THROUGHOUT DRIVE

In the second photo of **Figure 6,** some of the larger pieces (up to 40 mm) are also illustrated. The larger pieces on the right hand part of **Figure 6** are fragments of boulders.

FIGURE 6: GRANITE CHIPS FOR 8 M TUNNEL LENGTH & BOULDER FRAGMENTS

The unanticipated conditions encountered during micro-tunnelling excavation consisted of an unanticipated excess of tunnel length in boulders as illustrated in **Figure 7**. The anticipated length in boulders was 5 m and ~140 m was encountered. The difference was ultimately resolved by a global project settlement.

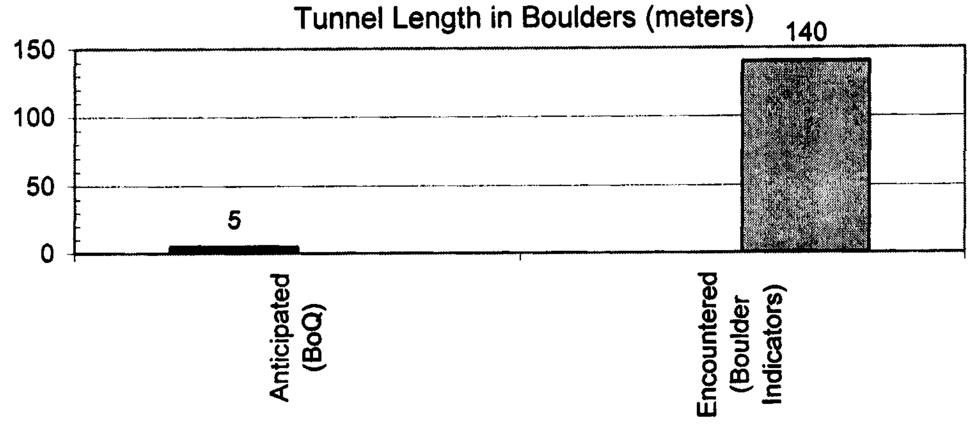

FIGURE 7: DIFFERENCE BETWEEN ANTICIPATED & ENCOUNTERED BOULDERS

4.2.2. Mechanical Challenges

On 22 Dec 99, the cutterhead failed to turn and it was discovered that the **drive pinions** had failed. Upon investigation, it was determined that the pinions failed because of:

- Inadequate amount of grease in the bearing chamber as a result a typographical error in the service manual and
- An inadequate hardening of the pinion gears by the sub-supplier to the manufacturer.

Unfortunately the failure came at an inopportune time when European factories were closed for the Christmas and New Year's holidays and during an extremely cold period in New England. The manufacturer replaced the pinions, however, micro-tunnelling could not resume because the unseasonable cold had frozen the separation plant during the repairs.

A second failure of **pinion gears** was not unexpected because the spare pinions (same batch) were also hardened below specifications. They were used nevertheless, because it was decided that it was more desirable to keep tunnelling and for the pinions to fail rather than the bull-gear to fail. After the first failure, Wirth-Soltau immediately undertook to manufacture a set of pinions in house and these were available when the under-hardened second set had to be replaced. The third set of pinions lasted until the end of the project.

During excavation in coarse materials, cuttings as large as 5 x 13cm often jammed the intermediate tunnel pump and the shaft **slurry pump**. To solve this problem, the impellers of the Denver Orion pumps were changed from closed impellers (passing 75 mm material) to open faced impellers with simple vanes (passing 100 mm material). The latter impellers resulted in reduced flow rates, however, the high ratings of the pumps allowed them to compensate.

Failure of hoses was more common than expected because of the abrasive cuttings of cobbles and boulders. Hoses were changed to a higher pressure rating with wound steel hose in the tunnel and to solid steel in the shaft.

There was great deal of concern regarding **tool wear** on the cutterhead. When the drive was completed, it was discovered that the spades and picks had been completely destroyed by the excessive coarse materials while the disk cutters were still in good condition as illustrated in **Figure 8**. Only the body of the cutter surrounding the tungsten carbide inserts was worn. Some of the carbides were also found to have been rotated.

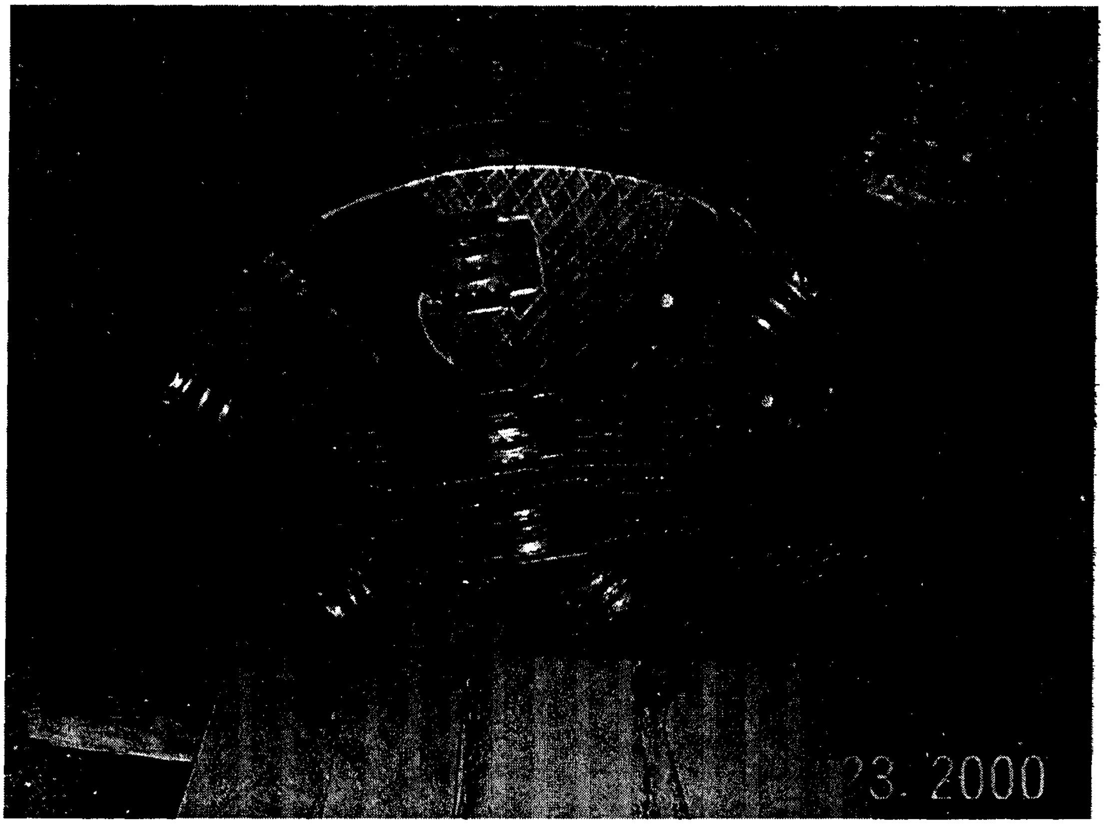

FIGURE 8: CONDITION OF TOOLS AT COMPLETION OF DRIVE

5. LESSONS LEARNED

Experience without learning is tragic. What have we learned on this project?

5.1. Quality Control

The failure of the pinions suggests two improvements to be necessary. First, the hardening by the sub-supplier was not according to specification, therefore our recommendation is that testing of critical components and treatments be measured and checked. Normal editing should catch the typographical error. However, to eliminate such fundamental problems, a more rigorous editorial process may need to be established.

5.2. Machine Design

The most important lesson we have learned was how lucky we were to select a micro-tunnelling machine whose original design was without any reservations, perfect for the anticipated conditions and also for the unanticipated and more adverse conditions.

Micro-tunnelling machine design is the "best compromise" based on anticipated conditions. If the designer can produce a design to cover a wider range of materials than indicated, the contractor starts with an advantage. However, if the conditions vary from those indicated and are beyond those for which the machine was designed, performance suffers and the machine may even fail. Consequently, a thorough knowledge of the full range of geotechnical conditions must be available for the appropriate design over the full range of conditions.

5.2.1. Cutterhead

The cutterhead, as designed, was very effective in keeping out large boulders while they were still large enough to cut by the disk cutters. For example, a granite boulder that was being cut for 8.5 m may have been pushed for that length, yet it was not ingested until it was small enough to crush (**Figure 6**).

5.2.2. Intake ports

We have found (Tarkoy, 2000a, b, c) that the size of intake ports in the crushing chamber are crucial to the success of the micro-tunnelling operation when having to deal with coarse materials (cobbles, boulders, rock cuttings). Rock cuttings tend to consist of small chips, < 1 x 2 cm (**Figure 6**), whereas cuttings from boulders and cobbles may be as large as 5 x 13 cm.

The original intake ports were 50 – 60 mm in diameter and were enlarged by the abrasive rock chips to about 70 mm. The size of the intake ports were ideal to pass all the material produced at the face, once the pump impellers were changed and the jamming of impellers eliminated.

Subsequent reductions of the intake ports (on the next project) have resulted in equi-dimensional coarse gravel commonly seating in the intake ports and blocking movement of excavated material (Tarkoy, 2000c). Other experience (Tarkoy, 2000b) confirmed that maximum intake port size is crucial when excavating coarse materials.

5.2.3. Torque

Very high torque is required for cutting and crushing gravel, cobbles, and boulders. We were lucky that the Soltau RVS 600 was one of the most powerful machines available at the time. There were no difficulties with the adequacy of torque to turn the cutterhead in, and crush the coarse material at the same time.

5.2.4. Hoses

It is essential that hoses be abrasion resistant and have the proper pressure rating.

5.2.5. Impellers

It is essential to take into account the anticipated large size cuttings in the selection of pump impellers. Open impellers have worked much better when there is a large coarse fraction in the excavated material.

5.3. Unknown Conditions and Unanticipated Geology

Micro-tunnelling demands three fundamentals, as follows:

- A superior exploration that defines the quantitative range of anticipated conditions,
- A machine design with a level of flexibility and over design for unknowns that prevent failure when unanticipated conditions are encountered, and
- Superior service and problem resolution from the manufacturer.

Soltau's thorough and conservative design that addressed the anticipated geological conditions, was crucial in the contractor's successful excavation of the 300 m long Chelsea River Crossing under unanticipated and very difficult conditions. Their service resolved problems when they were encountered.

6. CONCLUSIONS

All is well that ends well, as indicated by the celebration of my in-house micro-operator in **Figure 9**. Modern-Continental owes their success to a superior machine, incontrovertible manufacturer service, project management, and personnel committed to completing even the most difficult project without compromise.

FIGURE 9: MICRO-OPERATOR CELEBRATING COMPLETION

7. References

Tarkoy, P. J. (2000a). Analysis of Encountered Length of Tunnel Excavated in Boulders, In association with the **Chelsea River Crossing**, Prepared on behalf of Modern-Continental Construction Co. and Westcon Micro-tunneling, 20pp, 1 Mar 00.

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