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Mechanised Rock Tunneling in Adverse Conditions

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SYNOPSIS Several case histories are presented in order to highlight the way in which unexpected adverse geological conditions promote large delays in rock tunneling. These are selected from tunnels which have been excavated by drill and blast, roadheader and fullface tunnel boring machines. In each case the important properties of rock affecting the progress rates obtained are identified together with the nature of the tunneling problems encountered.

1. INTRODUCTION

In order to minimise costs and maximise progress rates in rock tunneling it is essential that a comprehensive geotechnical appraisal is prepared for each underground project. This provides basic data for the design and planning stages. It is equally important that it is made available to tendering contractors as the appraisal supplies essential information for the costing of the project and for the selection of the most appropriate methods of excavation.

Rock tunneling machines in particular offer considerable scope for achieving high advance rates in favourable ground conditions. The adoption of a planned and systematic approach allows steady progress to be gained in adverse conditions, as illustrated in this work.

By these means Engineers and Contractors can work together to allow rock machine excavation to compete on equal terms with conventional techniques and hence provide a highly economic alternative method of tunneling.

2. CASE HISTORY, ROADHEADER TUNNELLING MACHINE

2.1 Tunnelling Performance

The following case history is taken from a tunnel in England where a high capacity roadheader was used to excavate a 150m long, 4m diameter tunnel through a varied sequence of sedimentary rocks. A geological section of the tunnel and accompanying progress chart are illustrated on Figure 1. The materials encountered consisted principally of siltstones and sandstones however several thin beds of extremely strong limestone and siliceous sandstone (220 MPa) were present within the sequence.

As indicated on the delay chart the roadheader was installed at chainage 594m and used to excavate the tunnel to 620m during an initial training period. Excavation of the 1m thick bed of limestone in the tunnel invert gave machine cutting problems and high tool consumption rates resulted. From chainage 620 to 724m more accurate records of the roadheaders performance were maintained and a period of 6.6 weeks was required to excavate this 104m long section of tunnel.

In the first 1.6 weeks an average 13m/week was achieved as delays resulted from difficulties in cutting the limestone bed. In the following week a maximum 27m advance was achieved in the mixed beds present. This fell in the following two weeks to 16m/week as the proportion of sandstone in the face increased. In the preceding week an extremely strong and highly abrasive band of siliceous sandstone was encountered in the top section of the sandstone bed inducing severe cutting conditions and tool wear problems. Only 7m advance was achieved in this week. In the final week of the machine drive the roadheader excavated through a minor fault zone as shown on the section. On reaching chainage 724m the Contractor, realising that the hard bands would have to be excavated again, decided to withdraw the machine from the tunnel and recommence tunneling by drill and blast techniques. During the following six weeks similar strata was excavated by blasting as shown on the geological section and an average excavation rate of 27m/week was achieved.

2.2 Analysis of Roadheader Cutting Performance

The cuttability of the rock types of the stratas excavated can be accurately defined in terms of parameters obtained from a laboratory cutting test. This simulates the cutting action of a drag pick tool providing a measure of rock cuttability in terms of specific energy and a measure of tool wear. The use of these parameters to predict roadheader cutting performance has been discussed by McFeat-Smith and Powell (1979). Table 1 shows the test results obtained from samples of the various stratas excavated together with data obtained from the roadheaders performance during excavation.
TABLE I. Comparison of cutting test data and roadheader performance

<table>
<thead>
<tr>
<th>Strata</th>
<th>Laboratory Test</th>
<th>Roadheader Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specific Energy</td>
<td>Cutting Wear</td>
</tr>
<tr>
<td></td>
<td>MJ/m³</td>
<td>mg/m</td>
</tr>
<tr>
<td>Limestone</td>
<td>29.1</td>
<td>0.88</td>
</tr>
<tr>
<td>Siliceous Sandstone</td>
<td>26.4</td>
<td>4.61</td>
</tr>
<tr>
<td>Sandstone</td>
<td>13.9</td>
<td>1.84</td>
</tr>
<tr>
<td>Mixed Beds</td>
<td>7.9</td>
<td>0.30</td>
</tr>
<tr>
<td>Mudstones</td>
<td>5.3</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Comparison between the specific energy test values and the roadheaders cutting rates and general performance gives a logical correlation illustrating the value of this procedure for prediction purposes.

For both sandstones, mixed beds and mudstones the laboratory cutting wear parameter accurately reflects the rate of cutting tools consumed by the roadheader. For the sandstone bed the rate of tool consumption is very high and, depending upon tool costs, could place this rock close to the limit of economic application of the roadheader. In comparison, the tool consumption rates for the siliceous sandstones band clearly places this rock type well out with the range of rocks than can be economically excavated by roadheaders. This applies equally to the limestone bed which generated very high tool wear primarily due to...
impact damage (as opposed to abrasive wear) on the roadheaders point attack picks. This arose due to the combination of a high rock hardness and a difficult cutting situation.

### 2.3 Comparison of Roadheader and Drill and Blast Methods

It is clear that the roadheaders performance was severely handicapped by the occurrence of the extremely hard bands of siliceous sandstone and limestone in the tunnel. Indeed it is a credit to the designers of the roadheader that its cutting system was capable of maintaining progress when cutting rocks of hardness far in excess of those for which it was designed to function in. This aspect, namely the limitations of the roadheader cutting system relative to rock hardness and abrasivity, is a topic which is frequently given inadequate consideration, in some cases with disastrous results. Potential users of such equipment are well advised to seek the appropriate advice before installing roadheader machines in tunnels.

Several advantages that are to be gained by the use of roadheader tunnelling machines are well illustrated by this case history. As the roadheader cutting technique induces only minimal disturbance to the rock in the tunnel crown, in comparison with drill and blast methods, temporary support requirements are significantly reduced. In the present case the steel arch ribs and lagging support used throughout the tunnel and blast sections was no longer necessary and full advantage could be taken of the lower cost rockbolts, mesh and shotcrete support system which require less time for installation. In addition, overbreak is significantly reduced by the use of roadheaders. In this case an average 2.9m$^3$/m of overbreak measured in sandstone sections excavated by the drill and blast methods was reduced to 1.4m$^3$/m in the roadheader excavated section. Clearly where long tunnels are to be excavated the roadheader system can offer savings in quantities of concrete required to fill overbreak voids, and this may amount to a large proportion of the cost of the works. In addition significantly faster rates of advance are frequently realised by the selection of roadheader tunnelling machines as opposed to drill and blast techniques as illustrated by McFeat-Smith and Powell (1979).

### 3. CASE HISTORY, FULL FACE MACHINE (TBM)

#### 3.1 Tunnelling Conditions

This case describes tunnelling conditions encountered in a 3.5m diameter tunnel for the Kielder Water Scheme where a Demag TVM 34-48 tunnel boring machine excavated through sequence of sedimentary rocks. An 18m thick dolerite sill with a compressive strength in the order of 350 MPa was known to intrude the sequence but was expected to lie well below tunnel level. Figure 2 illustrates both the predicted position of the dolerite sill and the strata actually encountered at tunnel level. The TBM used is shown on Figure 3. The TBM cutting head included 14 bearings each housing a triple disc cutter. The advantages and disadvantages of this TBM and, in particular, the cutting tool arrangement have been discussed previously by McFeat-Smith and Tarkoy (1979 & 1980).

#### 3.2 Tunnelling Performance Ch. 2000-2691m

The progress chart on Figure 2 shows the advance rate of the face in metres per 100 working hour week relative to the geological section. Essentially the mudstones encountered in the initial 200m long section gave support problems and advance rates in the order of 42m/week were achieved. As the tunnel advanced from 2200 to 2600m the strata became progressively harder and more competent due to what was later realised to be thermal metamorphism from the nearby sill. As the TBM advanced cutting (penetration) rates fell from about 2.0m/hr in the mixed beds to 1.2m/hr in the silicified sandstone. Correspondingly weekly advance rates dropped as illustrated on the progress chart. Cutter wear problems became evident.

At chaineage 2690m a set of 14 new triple discs were inserted on the cutter head and used to advance the face by 1.6m. At the start of the shift a penetration rate of only 0.36m/hr was achieved. This fell further to 0.14m/hr by the end of the shift as all discs became worn and rendered unusable. This gave a phenomenal disc consumption rate of 25 discs/metre of advance. On inspection of the tunnel face (Figure 4) it was discovered that the TBM had progressed through a contact zone and was now excavating a full face of dolerite.

#### 3.3 Tunnelling Conditions Ch. 2691-3055m

At an early stage it was clear that geological conditions were significantly different from those expected and that the Contractor could expect to be reimbursed for costs incurred. It was also evident that whilst it would be expensive to excavate the extremely hard dolerite by TBM, the potential delays and costs of removing the machine and proceeding with drill and blast excavation were equally uninviting. The economics of this situation depended upon the length of dolerite that would be encountered.

Little was known about the nature and lateral extent of the intrusion at tunnel level other than that at a location 1500m ahead of the face the sill was located in its predicted position some 22m below tunnel invert level. The Contractor adopted the view that tunnelling would continue by his elected method of excavation. All discs on the cutter head were changed to button (tungsten carbide) impregnated discs and excavation was recommenced.

Penetration rates achieved in the dolerite were extremely low varying from 0.4m/hr were the dolerite was competent to 0.8m/hr where it was highly fractured. An average 3.6 button discs/metre were consumed throughout the sill which persisted in the tunnel for 365m. This extreme cutting condition had a major effect on the machine components, and rewelding was constantly carried out during planned maintenance periods. In addition, 111 of the shift time was normally required for inspection and replacement of the cutters. As illustrated on the progress chart an average advance rate of 35m/week was achieved.
3.4 Tunnelling Conditions Ch. 3055-3500m

At 3055m the dolerite fell below tunnel level and excavation continued using button cutters in mixed beds. The button cutters achieved only limited indentation and penetration rates of only 1.2 m/hr were achieved. At 3100m a 15m thick fault gouge zone was encountered that trended oblique to the tunnel. The performance of the TBM in this zone has been described previously by McFeat-Smith and Tarkoy (1980). A total delay time of 313 hours over and above normal tunnelling time was experienced here, part of this being due to various aspects of the machine's design. Beyond this zone excavation continued in extremely strong silicified sandstone (250 MPa). The use of button cutters again restricted penetration giving an average rate of 1.15m/hr. When the tunnel progressed beyond the sandstone into mixed beds the button cutters were replaced by disc cutters and high advance rates in the order of 85-95m/week were again achieved.

3.5 Analysis of TBM Cutting Performance

As with the previous case history, it is clear that the rock tunnelling machine had to cut rocks of hardness significantly higher than that for which it had been designed to function in. It is again to the credit of the manufacturer and Contractor that the TBM remained operational for the length of the sill, albeit at a high cost. It is however emphasised that TBM can be purpose designed for such situations, although rocks with strengths in excess of 300 MPa generally form the limit of economic application for TBM excavation.

The limiting penetration of button cutters is well illustrated by this example. Also evident was the advantages of reducing the number of cutting discs on the TBM cutterhead. This was highlighted by comparisons with the performance of a Robbins TBM using only single disc cutters in the same strata in the same project. The Robbins achieved penetration rates up to 100% greater than those gained here illustrating the disadvantages of cluttering the cutter head with too many tools. An equivalent study of tool consumption rates gave the same trend.

3.6 Comparison of TBM and Drill & Blast Methods

Overbreak in the dolerite and sandstone sections were generally negligible, even when closely jointed, whilst in the mixed beds and silty mudstone this was in the order of 0.1 - 0.3 m²/m, i.e. very low. Correspondingly temporary support requirements were nil for the dolerite and sandstone whilst sections of the mixed beds and mudstones were effectively supported by combinations of rockbolts and mesh at minimum cost.
Experience gained on other parts of the project generally was that overbreak values in the order of 2-3m³/m could be expected by drill and blasting in strong rock types such as sandstones and massive limestones and for mudstones. Temporary support requirements were likewise significantly increased by drill and blast methods, this being highest in the mudstones and in highly fractured rocks where steel arch supports and lagging were generally needed.

4. CONCLUSIONS

The principal advantage of favouring the selection of rock tunnelling machines is that the significantly higher average advance rates that can be gained result in large savings in labour and plant costs. Additional benefits are obtained from the minimal ground disturbance giving reduced overbreak and support costs which in some cases will be substantial. These benefits must be balanced against the increased capital cost of machines for the particular projects concerned.

As illustrated in this work, the key to ensure the successful application of rock tunnelling machines lies in obtaining the following:-

a. Realistic appraisals of the geological conditions that will be encountered.

b. Accurate predictions of machine advance rates and subsidiary costs.

c. Accurate estimating of the overall costs.

d. Adopting a planned and systematic approach on site, and

e. Having a foreknowledge of the various courses of action required when unforeseen adverse conditions are encountered.

It is hoped that this paper provides an insight into some of these factors.