Soft ground tunnelling for the Toronto Subway

by

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Mr F. A. Haxton (Charles Brand & Son Ltd) complimented the Authors on having contributed so much useful information so concisely. He was very impressed with the overall tunnelling progress figures which were given, especially when it was remembered that the compressed air tunnelling was carried on with the split shift system which he would be hesitant to try in this country.

98. Figures for the McAlpine digger shield progress were not comparable with the Victoria Line drives mainly because the Victoria Line was only 12 ft 6 in. diameter. It had, in addition, a concrete expanded lining instead of a grouted lining as in Toronto. However, it might be of interest to refer to the progress over the last three weeks with the McAlpine digger shield on the Victoria Line.

99. During those three weeks of 45 8-hour shifts, 1380 ft of tunnel were driven, an overall average of 3.8 ft/h. The best 24-hour period produced 110 ft, and on two occasions 48 ft were driven in one 8-hour shift, that is, one 2-ft wide ring every 20 minutes.

100. The use of the higher grade cast iron for the tunnel lining and the figures for breakage of segments given in § 27 were interesting. Segment breakage had always been troublesome in this country, not because of the intrinsic loss of the castings, but because of the high cost of replacing them once they had been built into the tunnel.

101. With regard to the linings, perhaps the Authors could state what method of packing or adjustment was used in the machined circumferential joints to maintain correct line and level. As to the question of the use of grummets, on recent contracts in this country polythene grummets, which he noted had been adopted in Toronto where leakage was difficult to stop, had unquestionably proved their superiority over the now old-fashioned hemp variety.

102. With reference to the split shift system and the extreme stringency of the American and Canadian compressed air regulations emphasized in the Paper, an international conference on decompression in civil engineering work was at that time taking place in London, and it was hoped that this would go some way towards establishing international standards.

Mr N. D. Pirrie (Sir Robert McAlpine & Sons Ltd) said he wished to highlight and enlarge on one or two aspects of the Paper. The first was in regard to the compressor installation for Contract U.2 and the second was in regard to the digging shield on Contract D.2.

104. It was useful that the Authors had illustrated the compressor house, because it was important to point out that in addition to the need for quiet compressors, due to adjacent hospitals, it was also necessary to have a very compact set-up, because the area allotted for the compressor plant was very restricted and contained on the central

reservation of a dual carriageway road. These two factors together led the contractor finally to adopt single-stage rotaries for the low pressure air. In fact, rotaries were also used for high-pressure air, resulting in a low roof line and very little space being taken up. There were no heavy reciprocating compressors requiring large foundations, a necessary consideration with hospitals nearby. The saving in the size of the compressor house was considerable and of the order of 30% over the more orthodox type of plant.

105. With regard to the digger shield, the published tables gave a chance to compare the cost of digging by hand shields and digger shields in the same conditions of free air. If in Tables 6 and 9 one substituted 78 for 12 for the tunnel shields in the column 'Cost per lineal foot of tunnel' of Table 6, it then offered a direct comparison of costs—the figure 12 covered only erection, dismantling and provision of skin plates, the shield already having been paid for in the previous contract (Table 5). The new total then became \$645 as against \$513 for the machine-driven tunnel, that is, a saving in cost per linear foot of 19% by the use of the digger shield. It should also be noted that the cost of tunnel construction was halved. This was due largely to the reduction in labour which was less than half that required by the hand shield.

106. These were significant gains and when it was borne in mind that they included a two-month stoppage in a nine-month period they were even more significant. It would also have been noticed from the comparisons of progress between hand and digger shield that when each was making its best progress the digger shield was about twice as fast. In London this had already become outdated and the digger shields on the Victoria Line made a progress of about four or five times that of a hand shield. This was due not only to further development with the digging shields themselves, but also to the absence of grouting and quicker ring building which was now possible with the new designs of expanded segments.

107. In general, to take advantage of a digger shield a minimum length of drive should be half a mile. The savings were progressively greater beyond that distance.

108. To anticipate the question of what was the structural failure that caused a two-month delay, it could be stated that it was simple but costly. There was a horizontal beam across the diameter of the shield, and it was bolted at its extremities to base plates within the cylinder section of the shield. The digging began with no overcut, and as had been stated, there was no bead to ease progress. The shield became tight as it progressed, and a squeeze at the crown caused the weld retaining the baseplate to the horizontal beam to fracture. It then became necessary to form a shield chamber so that the cutting edge could be jacked back to circular and the joint made good.

109. To prevent such a squeeze occurring again, a 1-in. thick sole plate was put under the shield for the bottom quadrant and an edge tooth cutter was mounted on the digging wheel, which was allowed to enlarge the tunnel about $\frac{1}{4}$ inch beyond the cutting edge, but because of the sole plate at the bottom no undercut of the shield could occur. Consequently, the shield did not 'drive'. The result of that was to reduce considerably the thrust necessary for the forward progress of the shield and cause a reduction of shield forces generally. The reduced thrust also significantly reduced the number of fractured segments and it would be noticed that only two were damaged out of 20 000.

110. Mr Pirrie suggested that it was no longer necessary to construct chambers of about twice the diameter of the shield in order to erect this. It was possible to design skin plates and cylinder sections of shields in such a fashion that only about 3 ft of headroom was necessary above the crown, the shield design being such that its erection could be carried out from within the skin plate. A big saving in time and money could thus be achieved.

111. He was interested in the fact that consideration had been given to the use of S.G. iron for the tunnel segments, but noted that this had been considered impracticable. It would be interesting to know whether the reasons were technical or financial.

112. Since tunnelling with segmental linings was a cyclical operation of mucking and building, any reduction in the number of cycles in any given length of tunnel would save both time and money. With that in mind, there appeared to be no strong reason why segments should not be 3 ft wide instead of 2 ft wide, and it would be interesting to have the Authors' views.

Mr H. J. Donovan (Sir William Halcrow & Partners) said he found a number of the figures, particularly those on progress, fascinating. He always viewed progress by relating production to cu. ft/man hour. The number of men in a tunnel gang could be large, they could work all the shifts in a week and do a record length of tunnel but when reduced to completion of cu. ft/man hour the result would not be great. He had taken some figures from the Paper and compared them with those obtained on the Victoria Line, and it had to be admitted that the Toronto Subway had the edge on the Victoria Line. Using a hand shield and bolted cast iron lining, the figure for the Victoria Line was 14 cu. ft/man hour whereas on similar work at Toronto the figure was 16½ cu. ft/man hour. Going back over the years, between 1926 and 1936 on the London Underground the best progress with a hand shield and bolted cast iron lining was 9 cu. ft/man hour.

114. The next change came with the Metropolitan Water Board Thames to Lee Valley tunnel where hand shields with expanded concrete lining were used and the progress rate went up to 22 cu. ft/man hour. The Potters Bar tunnel with hand shield and expanded concrete lining produced a figure of 26 cu. ft/man hour. For the Metropolitan Water Board tunnel a digger shield was designed and used with expanding concrete lining. This gave a progress of 48 cu. ft/man hour, just over the figure with the hand shield. On the Victoria Line some fantastic progress had been made with digger shields and expanded linings, the best figure to date being some 120 cu. ft/man hour. This was some 13 times the rate in pre-war years and demonstrated the great improvements in tunnelling methods following mechanization.

115. With regard to the quantity of compressed air used in tunnels driven in air, a formula $Q = N \times D$ was quoted, where N was a constant of 3. In the 16-ft diameter tunnel with six men in the face, and allowing for a total of some 10 men in the tunnel, the formula allowed some 90 cu. ft/min. per man. This appeared low as the usual figure was at least 100 to 200 cu. ft/min. per man.³ Had the Authors any comment on this?

116. It was interesting to compare the cost of the digger shield and the hand shield drives. The cost per week with the former was greater but the overall cost worked out cheaper. This illustrated the virtue of using the digger shield.

Mr R. G. Cole (Director, John Howard & Co. Ltd, previously Project Engineer for the Contractor), in amplifying certain points in the Paper, said that all the tunnelling was carried out from the two main shafts, Nos 4 and 7, and two subsidiary shafts, Nos 3 and 5. Four horizontal airlocks were constructed at the bottom of each of shafts 3 and 5, thus allowing the pilot tunnel iron, when dismantled, to be taken forward and used in the running tunnel, without having to be taken above ground. Also, during the driving of the tunnels for Queens Park Station, the majority of the muck was taken out forward from the shield in order to reduce the traffic congestion at the bottom of shaft 7, which at that time was servicing two station tunnels and passages, and the two running tunnels in drive 3. All the horizontal airlocks were constructed with reinforced concrete walls across the tunnel.

118. The shields were a great success. There were certain teething troubles with the rams, but once the necessary alterations were made the shields went ahead without any breakdowns of consequence. The fact that they were self-contained, giving unrestricted working room, was a great advantage. Behind the shield the muck was loaded by conveyors into standard tunnel skips.

119. The cast iron was first class, both from the point of view of accuracy of machining and the strength of the iron. As mentioned by the Authors, the iron received very rough treatment in the dismantling of the pilot tunnels and the breaking out of the air decks, with very few breakages.

120. The air pressures on the job varied from 3 to 22 lb/sq. in. In drives 1 and 2 where there was ample cover, the pressure could normally be kept below 18 lb/sq. in. and was only raised above that when local pockets of water or buried water courses were encountered. Drive 3 was, however, more critical in that the cover was reduced to 10 ft of loose ground, and there were a number of very small blows in the parkland. Air pressures were therefore kept down to a minimum, resulting in a very wet invert which created problems, while the sinking of the shield necessitated certain regrading of the vertical curves.

121. The caulking was carried out with Philplug Caulking Compound. The grummets were hemp dipped in red lead. Most of the persistent leaks were at grummets and the hemp was replaced by polythene. On hindsight it would have been more economical to use polythene grummets from the start as the labour cost in replacing grummets was very high.

122. On progress, the contract was completed just within the contract time, in spite of 4 to 6 weeks lost by strikes. They were all inter-union disputes and outside the control of the contractor. All the leading miners were brought over from the United Kingdom, as the local labour had virtually no experience in handling shields or building cast iron segments, and their success in training local labour was an important contribution to the completion of the contract on time, particularly as 80% of the labour was of European origin, with little knowledge of English and still less of Irish!

Mr K. Wynne Brown (British Inspecting Engineers Ltd) said that, having been charged with the design of the hydraulic equipment and circuits for the six Toronto shields, his firm had laid down five parameters to overcome those troubles experienced during the reconditioning and operation of the Dartford Tunnel Shields.

124. The first was that the shields had to be self contained to avoid the need for surface pump houses, accumulators, long lines of mains, and so on, and also so that the areas behind the shields would not be congested with pumps, tanks, etc.

125. The second was that all hydraulic equipment had to have its swept surfaces protected from dirt and grout, i.e. the shove rams were reversed with the jack rods anchored and the cylinders moving inside outer protective cases.

126. The third requirement was that the main rams must have maximum stiffness to resist unknown side loads (the moving cylinder ram here gave considerably increased stiffness) and all auxiliary equipment had to be sufficiently robust to resist that possibly most destructive form of mankind, the tunnel miner.

127. In Dartford he had seen 7-in. diameter solid medium carbon steel rams badly bent as a result of side forces and in Toronto a valve handle nearly 1 in. in diameter bent over 90° but with the valve still operable.

128. In order to avoid down time therefore, the equipment had to be easily isolated and any power supplies duplicated so that if one pump failed, it would be possible, by suitable valving, to run all the equipment at half speed from the remaining pump.

129. The final parameter was the ease of replacement of the main shove rams should this be necessary. In order that the ram could clear the last ring of tunnel iron, the rear location of the jack was eccentrically mounted in the shield. This enabled the jack to be tilted towards the tunnel centre line during removal (Fig. 9).

Mr G. S. Dodds (Messrs Mott, Hay & Anderson) referred to § 40 in which reference was made to pea gravel. This implied that American engineers had used pea gravel since construction of the Lincoln tunnel out of habit and to suit the unions. Mr Dodds did not believe that this was so. He had been employed on the construction

FIG. 9: DIAGRAM OF RAM SHOWING MOVING CYLINDER (A), OUTER CASE (B), ECCENTRIC MOUNTING AND RAMPS (C), SHIELD STRUCTURE (D), AND TUNNEL IRON (E)

of the Callahan Vehicular Tunnel under Boston Harbour which was shield driven, building outside diameter steel rings of 30 ft 8 in. diameter. Pea gravel was blown through the front ring grout holes using a high air pan, and it was necessary to use burlap bags to seal the gap between the tailskin of the shield and the last ring built. Grouting was kept ten rings back from the front ring, i.e. roughly a tunnel diameter, giving a slope of approximately 45° between the top of the grout and the invert of the shield. This was effective in keeping grout away from the shield.

131. There were, however, limitations to the use of pea gravel. Mr Dodds had not used it in running ballast, where excessive air losses might be expected over back rings not grouted. Also, a large tunnel diameter was helpful in accommodating the air pan and storing materials. However, he considered the use of pea gravel and grouting as an excellent method of filling behind tunnel rings in the right conditions and thought that British contractors might well take it up to their advantage.

132. With reference to § 61, factors influencing air losses were: (1) tunnel pressure relative to pore water pressure in the ground; (2) permeability of the face and strata above; (3) area of ground open both at the face and over the tailskin and rings behind the shield. It was surprising how little was known of compressed air losses in tunnels and how little research had been carried out on this aspect. On the Blackwall Vehicular Tunnel duplication under the River Thames in London, fairly high air losses occurred and Mr Dodds had tried to sketch flow nets for conditions both at the face and the tail of the shield. If the tunnel were filled with an incompressible fluid, such a flow net would be valid, but research was needed into the flow net pattern obtained when air passed through open ground. This might be done using a transparent tank filled with beads and he had tried to get some research started at Blackwall. Flow nets would give some indication of the pressures existing in the ground and of the 'quick' condition which could occur at ground or river bed level when blow holes appeared.

133. Finally, with regard to § 57, the Authors stated that pairs of shields were driven together. How close were they, and did the Authors feel that pairs of shields should be driven in parallel?

Mr T. M. Megaw (Partner, Messrs Mott, Hay & Anderson) said that it might be of interest to Members to know that the late Mr Vernon Bartlett, whose son had presented the Paper, had played a large part in 1956 in the preparation of the original report for the Toronto Transit Commission on which the tunnelling scheme was based. The scheme followed very closely the lines of the report and was very successful.

135. As the scheme virtually introduced what one might call 'London tunnelling' into the North American continent, a cautious approach by orthodox methods, including the use of bolted and grouted cast iron linings, was recommended. This was adopted for the first contract where compressed air working was clearly necessary, and where important buildings were affected, in particular the Parliament Buildings

directly under which the tunnel was driven. It was interesting to see how quickly progress to mechanical methods was made by the introduction of a digger shield on the second contract, and how experience on the shield had found its way back into London tunnelling methods for the Victoria Line.

136. It was always clear that the ground for the second contract was much better than that for the first, which had called for compressed air. Where a digger shield was used with orthodox bolted cast iron lining, problems of grouting inevitably arose, as had already been made clear in the discussion.

137. It was interesting to hear the argument concerning the use of pea gravel filling as a preliminary to grouting, though in his view this was not the answer. The answer was found in the expanded linings which had been developed. More generally, it was difficult to see how pea gravel could really provide the immediate seal against swelling desirable in material such as London Clay. Behind a shield which could cut a true circle in cohesive clay, flexible linings offered great advantages in providing immediate support, and in eliminating delays.

Mr J. R. J. King (John Mowlem & Co. Ltd) said he had one or two questions to ask about the comments on alignment of the tunnel and control of the shield. One imagined that the shield in question with its diameter of 17 ft 6 in. was shorter in length in proportion to the diameter than the shields being used on the Victoria Line, and this would make it easier to change direction and control alignment. He was a little puzzled as to how the shield was controlled without a bead, but gathered that the ground was overcut, and the problem of stopping the shield diving due to over-cutting the invert was overcome by thickening the underside.

139. Contractors trying to drive the shields on the Victoria Line, which had an external diameter of 13 ft 1 in., had encountered serious problems with alignment and control of the shields, and he felt certain that without a bead a situation could arise in which it was not possible to change the direction in which the shield was going; however much selected rams were used, the shield would continue on that line. It would be interesting if the Authors could say a little more about this.

140. The Authors had said that the tunnel was handed over within tolerance, but mentioned that some rings had been changed. How many were changed, and, when the shield did go off line, what action was taken to get it back on line? Was it once per ring or once per shift, and was it varied in accordance with progress or with the type of ground being driven through?

141. Finally, did the comparison of driving speeds between the hand shield and the digger shield include the time and cost of erecting and dismantling the digger shield?

The following contributions were received in writing:

Mr K. W. Torpey (Messrs Mott, Hay & Anderson) thought that one aspect of the construction worth mentioning was the effort made by all concerned to make working conditions on the project as safe as possible.

143. Safety Inspectors from the Ontario Department of Labour visited the site regularly. In addition, the Construction Safety Association of Ontario, a body subsidized by the contractors of the province, provided their own inspectors, who suggested precautions and supplied safety literature. The contractor employed a Safety Engineer to act as liaison between these two bodies, and his full-time duties were wholly related to the safety of personnel employed upon the work.

144. Monthly meetings were held, at which compressed air working was reviewed. Any unsafe practices which might have arisen during the month were discussed, and the utmost was done to ensure that these did not recur.

145. As an illustration of what was achieved, every miner wore a safety helmet, contrary to the custom on many soft ground tunnelling sites. The men were also well acquainted with accident hazards by means of instruction and propaganda posters, etc.

146. The contractor was at all times amenable to suggestions for improving safety, which helped to create the harmonious atmosphere in which these safety efforts were conducted.

Mr A. W. Shilston (Consulting Engineer) wrote that he wished to develop the theme in the last sentence of the Synopsis to the Paper that 'emphasis is placed on differences in practice in North America'.

148. Little had been said in the Paper about the formulation and administration of the contracts undertaken. So far as Mr Shilston was aware, no general reference had been made in the *Proceedings* of the Institution to differences in contract procedure between North America and the United Kingdom.

149. It was generally understood that in North America civil engineering and building contracts were placed on a lump sum basis, the contractor being responsible for taking off his own quantities. The design was generally 'frozen' before the tender stage, and for tendering purposes contractors received a very full set of tendering drawings and a highly detailed specification. Variations were strongly discouraged but when introduced proved very expensive and reflected the interruption in the production programme.

150. At a recent Informal Discussion at the Institution,⁴ disenchantment was expressed with the present Civil Engineering Bill of Quantities procedure and the advantages of the American system emphasized. Yet the impression formed in Mr Shilston's mind from reading technical journals through the years, without any direct experience of North American practice, was of the existence of a gradual move both in North America and elsewhere, towards the inclusion of Bills of Quantities in tendering documents. Admittedly, the trend seemed to be linked primarily with building as distinct from civil engineering work; another variable was perhaps the lack of uniform procedure within the North American continent itself. Also Bills of Quantities were not necessarily of very great assistance to civil engineering estimators as they had to build up their price on an assumed construction programme which could vary markedly between contractors, and Bills of Quantities could never be a provider of all things to all men.

151. Dealing more specifically with tunnelling contracts, in Great Britain a procedure had developed in which the engineer closely identified himself with the construction phase. Before the introduction of the I.C.E. *Conditions of Contract*, the speculative aspect inherent in civil engineering contracting was very considerable, and at its highest in tunnelling work. Yet this identification of the engineer with construction—normally minimal—even under the old forms of contract allowed a certain shouldering of the risks by implementing variation order procedure.

152. To Mr Shilston's mind there seemed a subtle link between the I.C.E. *Conditions* and the Civil Engineering Bill of Quantities in applying the measure and value system to tunnelling work, allowing the engineer a fair degree of flexibility in exercising his various responsibilities.

153. He suggested that in Britain the lump sum form of contract applied to tunnelling work was unsuitable and he invited the Authors to discuss its application to tunnelling works in North America. Was it generally accepted there that the engineer's responsibilities required him to intrude into the realm of construction and temporary works in that particular context? If so, would the innate characteristics of the lump sum contract tend to inhibit the engineers in fulfilling those responsibilities, as against the more adaptable risk-sharing and value form of British contract? In their reply, it would be helpful if the Authors could highlight any apparent differences in the legal position of the engineer in North America when compared with the United Kingdom.

154. Dealing more specifically with the actual works, could some information be given about the bid procedure adopted and the division of risk therein as between employer and contractor? To what extent was the question of constructional

procedure a matter for direct specification and payment as against the alternative procedure of giving tendering contractors complete freedom and placing reliance on subsequent negotiation to choose the most technically and financially attractive offer. The latter procedure of course mitigated against equitable bidding. Was the invitation to bid on an open or selective basis?

155. It was usually considered necessary, in Britain, to man a tunnel face continuously, except for the weekends when it was effectively boxed-up. This did not appear to be the case at Toronto. Had this not given grounds for concern, particularly when tunnelling under property? It was understood that insurance companies in North America were more active than was usually the case in Britain to satisfy themselves that all was being done to reduce risks during tunnel driving. Was this premise correct?

156. Mr Shilston assumed that only steel boards were used but he would welcome comment on that point. Was the grout blown through pans or pumped, and were any special procedures adopted, particularly in built-up areas, to test the solidity of the grouting behind the iron segments?

Mr R. F. D. Ritchie (Chief Power Engineer, New Zealand Ministry of Works) wrote that he found the Paper of great interest because he had been concerned with the design and construction of the only shield-driven tunnel in New Zealand and the shield (Fig. 10) had included a feature that was still noteworthy twenty years later: it, too, was self-contained except for electric power supply.

158. Until the construction of the Tekapo Hydro-Electric Station large tunnels in New Zealand had been in rock, but the Tekapo scheme had required a tunnel through a mile of glacial moraine containing particles of all sizes from clay to small boulders. The Ministry's staff and workmen had possessed no firsthand knowledge of shield tunnelling but the disadvantages of using heavy skin-tight timbering had been so great that the use of a shield had been decided upon. As no account of the work had been published the contributor thought that some details might be of interest.

159. Although the shield had been designed before the war, construction had to be postponed until 1945. As this was a time of serious shortages the shield had had to be fabricated by welding from available rolled sections and skin plating from the wreck of the steamer *Port Bowen*. The only high pressure pumps available had been of the fuel injection type. It had been found that banks of these could easily be accommodated within the 23-ft diameter shield, together with an oil reservoir and two pumps from a tractor for operating the erector arm at 100 lb/sq. in., retracting the jacks, and feeding the high pressure pumps, thereby improving their operation.

160. The 100-ton jacks had been designed for the same pressure as those at Toronto but had worked satisfactorily at 7000 lb/sq. in. when a slightly projecting boulder had had to be passed without bringing it into the shield. The casting of the cylinders in steel had been a more exacting task than had previously been set for the small foundries in New Zealand, and porosity had given some trouble; a few cylinders had finally been replaced by bored-out lengths of ship's propeller shaft. Due to the tendency of the shield to dive, the upper jacks had seldom been required to exert their designed push; for considerable periods they had been used mainly for tightening the lining. The 'inside out' working of the Toronto jacks appeared to be a valuable innovation, but at Tekapo no grouting had been done close to the shield and bending in the rams had been reduced by the provision of ball and socket joints between rams and feet.

161. As cast iron had been out of the question the lining had been designed in reinforced concrete. The desired segment width of 3 ft had required a jack stroke of 3 ft 2 in., and this, plus the cast construction, had made the jacks heavy to handle when cup leathers required replacement. The very long stroke would have had no disadvantages had modern hydraulic packings been available. Despite the 'home

Fig. 10: LAKE TEKAPO: TUNNEL SHIELD

made' nature of much of the equipment the shield, designed for an advance of 3 ft per 8-hour shift, had proved capable of much better performance once initial problems had been overcome. That such performance had seldom been required had been due mainly to the difficulty of assembling true rings of lining.

162. Not only had the required accuracy of the cast iron moulds for the concrete segments not been realized, but the moulds had warped in service, so that cumulative inaccuracies in a ring had necessitated extensive packing at joints to limit cracking due to bolt tightening and jacking forces. By the time the worst moulds had been replaced by accurate steel ones the tunnelling had been well advanced.

163. Although pneumatic tools had been available the workmen had generally preferred to loosen material from the face with light hand picks. From the two working platforms this material had passed down chutes, but two men in the bottom of the shield had been required to shovel their spoil onto the conveyor belt. Boulders larger than 18 in. $\times$ 9 in. had been broken on the platforms or manhandled out to the muck trucks. One attempt to shoot a large boulder in the face had had such a disastrous effect on electrical and hydraulic fittings that the few others met with had been disposed of by excavating holes at the end of a working platform and pushing them aside.

164. The long tail on the shield would have made possible the replacing of a segment broken near the end of its first shove. As a segment weighed a ton it was fortunate that this had not been required, and it was doubtful whether the extra length had helped or hindered the steering of the shield.

165. A trailing platform had provided storage and handling facilities for lining, accommodation for equipment for placing pea gravel, and access to the upper bolts which had required re-tightening; it had in no way obstructed the work.

166. Mr Ritchie considered pea gravel packing well worth while in reducing grouting and keeping that dirty operation well away from the shield, even though it was difficult to have it done conscientiously. The lining had been designed with inconvenient temporary horizontal tie-rods which had been dispensed with once gravel packing had been mastered. Grouting had been done not only to make good deficiencies in the packing but to prevent deterioration of reinforcement and bolts in cracked segments which were obviously carrying bending stress.

167. It had been intended to fill the recesses in the lining segments flush with pneumatically applied mortar, but a trial had shown this to be so difficult overhead that an inner concrete lining, with a minimum thickness of 9 in., had been placed using travelling steel forms from another tunnel. This had had the advantage of sealing any cracked segments on the water face, and the surface had been so good that it was doubtful whether the head loss had been increased. The tunnel had been dewatered several times since it had been completed in 1950 and appeared to be in excellent condition.

The Authors, in reply, said that both Mr Haxton and Mr Donovan had been impressed by the Toronto tunnelling progress. That the output per man hour was higher than in London was the more surprising when it was remembered that the first contract, in compressed air, had entailed a substantial amount of face timbering with inexperienced labour. The answer must be partly that the high cost of labour in Canada encouraged the use of labour-saving devices such as spoil conveyors in conditions where they might still not be considered economical in this country. The enterprise of the men in a country where it was common to drive a thousand miles in search of a good job must also be a factor. However the balance was to some extent redressed by recent Victoria Line progress where outputs of 19 and 20 cu. ft/man hour had been achieved with Greathead shields and bolted cast iron lining in London Clay. These figures, like Mr Donovan's, referred to the best full week on each job.

169. In reply to Mr Haxton, curves and corrections to line and level in the running tunnels were made with machined tapered rings, with 1 in. taper on the 17-ft external

diameter. These special rings had been surprisingly cheap. A small number of steel shims had been used in circumferential joints to correct cumulative errors in the plane of the circumferential flange of the leading ring. The station tunnels were all straight.

170. The Authors agreed that plastic grummets should now be specified on almost every occasion, but the Paper described work started in 1959. In fact, the Contractor was free to use them and confirmed their superiority over hemp grummets towards the close of the work, as described by Mr Cole.

171. Mr Pirrie had discussed the costs of hand versus machine tunnelling. Whilst agreeing that digger shields offered very substantial savings when conditions were right, it should be made clear that the tables of costs in the Paper represented the costs to the client, based on the tender rates. There was no evidence that they were the true costs and that the total saving shown would recur on future work. Machine tunnelling was at present subject to numerous minor mechanical delays and all too often to major setbacks when unsuitable ground was encountered. However, it was clear that society would view with less and less favour the working conditions which often obtained in hand-driven tunnels, and the future undoubtedly lay in the development of sophisticated and reliable machine methods.

172. On the question of shield erection chamber diameters it was notable that two of the 17 ft 6 in. shields had been built in 18 ft internal diameter chambers. It had not been comfortable, but it had enabled one of the standard sizes to be used and had minimized the difficulties of constructing the chambers themselves in particularly bad ground.

173. The use of S.G. iron for tunnel segments needed further investigation. It was an attractive material, combining tensile strength with resistance to corrosion. It was understood that substantial special foundry melting equipment was required to make the material economically. There was now an increasing tendency to make spun pipes of S.G. iron and that might facilitate further developments.

174. As to the width of ring, whilst agreeing with Mr Pirrie that wider rings would be cheaper to supply and build, this had to be balanced against the need to avoid settlement by keeping to a minimum both the ungrouted ring width behind the shield and the length of excavation at the front of the shield. In the event there had been places under the Parliament Building where it had almost been necessary to shove the shield twice for each ring, and that was an operation which would soon neutralize any economy in the supply of segments. Economies might have been made by having wider rings for use in good conditions. This had been done at Dartford, where it was clear that a known length of tunnel would be in sound chalk, but in the variable ground of Toronto the problems of supply outweighed the possible economies.

175. Mr Donovan had raised the controversial subject of ventilation at the tunnel face. He had suggested that the amount of low-pressure air provided might have been sufficient to support the face, but not the men. The question might be partly answered by pointing out how much more pleasant it was to work in compressed air than in some of the long unventilated free air drives. Sampling of air in the Toronto tunnels had shown that the air had never been seriously vitiated. The Authors felt that no ventilation standard in terms of quantities of air could be applicable to the wide variations in temperature, humidity, dust, and other factors which occurred in different tunnels.

176. The Authors thanked Mr Cole and Mr Wynne Brown for providing their special knowledge of the projects. It was most satisfactory that the former as contractor should congratulate the latter on his part in the shield design which was carried out in advance of the contract. The hydraulic equipment had been supplied by Messrs Tangye and Messrs Andrew Fraser, and had given excellent service.

177. Mr Dodds had given further information on the use of pea gravel for filling behind tunnel rings, and Mr Megaw had pointed out some of its limitations. It seemed to be the case that almost all American tunnellers used pea gravel and all

British tunnellers, neat or adulterated cement grout. Surely these two different types of filling must have different uses.

178. Research into the flow of compressed air through ground would indeed be interesting but of strictly limited use in constantly varying ground conditions such as were met on this project.

179. With regard to Mr Dodd's last point, it had been specified that the longitudinal distance between two working faces should not be less than 30 ft. On the same theme of proximity of tunnels, the 18-ft concourse at Queen's Park Station had been built before the last station shield drive. The behaviour of the boulder clay in the pilot drives encouraged this course of action which reduced the time required for construction. The station shield was only 3 ft from the concourse tunnel, which was given no temporary support. The horizontal diameter of the concourse tunnel had decreased by $\frac{1}{8}$ in. as the cutting edge of the shield passed and then increased by $\frac{1}{4}$ in. at the tail of the shield, leaving its final diameter increased by $\frac{1}{8}$ in.

180. The Authors agreed with Mr King's comments on digger shield guidance. In Toronto control had been provided by slight overcut and the sole plate described by Mr Pirrie. In London the sole plate would not be acceptable with expanded linings as it would leave a considerable imperfection in the cylindrical surface against which the rings were expanded. The McAlpine machines in London had been controlled with a bead and about 3 in. undercut. None of the shields in Toronto had been seriously off line, and reconstruction had been limited to six occasions when a few rings had been rebuilt at weekends.

181. The comparison of driving speeds had not included shield erection and dismantling times.

182. Mr Torpey had described the arrangements to minimize accidents. There was certainly a greater 'safety consciousness' in Canada, and even the least scrupulous took account of the storm of publicity which was liable to follow malpractices.

183. Some of Mr Shilston's remarks about contractual arrangements in the United Kingdom and North America were supplementary to a recent discussion at the Institution.⁴ In the Authors' experience, the differences were less marked than was often supposed.

184. Lump sum and cost plus contracts were perhaps slightly more prevalent in North America but there was the same tendency for them to be used on commercial and industrial projects. Bills of Quantities were generally used for public works such as the Paper described. The bills were often less detailed and the items more comprehensive than in the United Kingdom and paradoxically this tended to involve the engineer more closely with the construction phase, because his design and specifications had to be all-embracing for tendering, and on the Toronto Subway projects included full details of such items as utility diversions and many temporary works such as the decking of streets. The contracts gave him full powers during construction. The engineer's position had been in all important respects the same as in the United Kingdom.

185. Mr Shilston had mentioned that variations were strongly discouraged. In Toronto the client was certainly to be congratulated on not making any substantial alteration to requirements in the course of the contracts, and the work had been finished on time and within the tender sums in spite of there being no contingency items.

186. It was unrealistic to suppose that changes in design which disorganized construction need not be expensive, whatever rates might be referred to in a detailed Bill of Quantities, and if there was one good lesson to be emphasized by the best North American practice, it was that unessential variations should be avoided at all costs.

187. Bidding was unrestricted and tenderers were invited to give alternative proposals provided they also quoted for the work as specified. There was no rise and fall clause.

188. In the absence of Clause 12 of the Conditions of Contract it might appear that contractors continued to take the full speculative risk inherent in tunnelling work, and that was still often the case in North America; but in Toronto the client had recognized the disadvantages of that procedure, and the specifications allowed certain 'special measures' to be paid for if required.

189. In further reply to Mr Shilston, all faces were manned continuously and boxed up at weekends except for the digger shield which was only used in very good conditions and was convertible to a Greathead shield.

190. Temporary supports left in had all been of steel where essential, but pressure-creosoted timber had been left in elsewhere. The advantages of timber from the miner's point of view were great, and in difficult conditions it was sometimes necessary to leave in more of the supports than anticipated. Orthodox pneumatic grout pans had been used and careful 'pricking through', inspection and regrouting were carried out.

191. Mr Ritchie's description of the Tekapo tunnel was the more valuable for discussing the various difficulties which arose in the course of the work. Mr Ritchie would doubtless agree that some of the methods used would have required modification had there been valuable property above the tunnel. Many engineers would envy and admire the ingenuity which improvised hydraulics to work at 7000 lb/sq. in. and built a shield from the wreck of a steamer.

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