

## The bentonite tunnelling machine

J. V. BARTLETT, A. R. BIGGART &  
R. L. TRIGGS

### Mr J. V. Bartlett

The bentonite tunnelling machine was a complex example of 'systems engineering', however much one may dislike the term. The substitution of an industrial process for a skilled craft does not always meet with approval, but in this case the soft ground mining craft is not attracting recruits, and the new industrial process provides a far better environment for tunnellers.

65. Being a complex system assembled for the first time for the tunnel drive at New Cross, it is remarkable that it worked so well so soon after being launched into the ground. This reflects great credit on the mechanical and electrical engineering and on the site staff. There was much dedication and ingenuity and the right answers were found in a very short time.

66. As to the future, there are several prospective drives in Britain, and an important need to get one or two fully commercial contracts done using the system so that people here and abroad get full confidence in it. Britain's geology is very mixed, but there are many cities overseas founded on sand and gravel and it is to be hoped that they will benefit from the method in the fullness of time.

### Mr A. R. Biggart

There are two points I would like to draw attention to first of all concerning the machine. The first is the vital part that sealing has played in the successful operation of the machine. Fig. 2 shows five places where good sealing is important: the main bearing, the feedwheel, the tail seal, the main slurry pump and the telescopic pipes. In the case of the feedwheel, the tail seal and the telescopic pipes, the solutions were developed during the trials. The second point is related to the first, and this is the problem of wear. The particular places that are concerned are the cutting teeth, the feedwheel and the main gravel pump.

68. In any discussion of this method of tunnelling an important consideration is safety. Safety is improved on three fronts. First, the risk of subsidence at the surface and collapse underground has been virtually eliminated. Secondly, there is a marked reduction in the number of movements below ground, and thirdly, the replacement of compressed air has removed the medical risks associated with compressed air tunnelling.

69. Further experimental work has been done since the end of the main trials. This work shows that it will be possible to use the method for ground with a lower limit in particle size of 25 microns.

### Mr R. L. Triggs

Clearly the future lies with the tunnelling machine, but I am going to suggest that for the next few years a little less attention should be paid to the excavating machine on the face and a little more to what goes on behind it. Today the machines used in the soft ground and soft rocks which are encountered most of the time in Britain are reliable and capable of advancing the face a good deal faster than any lining can be built behind them, with the single exception of the unbolted ungrouted wedge-block lining.

71. At rates of advance of 1000 ft/week or more the transport of the muck is

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becoming a limiting factor both in the tunnel itself and particularly in a shaft more than, say, 150 ft deep. Of course, these transporting problems can be overcome: a larger diameter shaft can be sunk, the winding equipment can be doubled up, etc. but the bottleneck then becomes economic, that is to say, the saving of money on the face is more than balanced by the increased cost of the shaft and the head gear.

72. So here, I think, are the two main fields which deserve time and money spent on them in the future: linings which are simpler and faster to erect behind the machine, and methods of transporting the muck which will not hold up the machine in its advance.

73. With regard to the latter problem at New Cross the muck was moved from the face up to the tip on the surface 'untouched by human hand', and it seems to me that this is a path that should be followed for the future. It is not in many circumstances the cheapest way to move muck at the moment, but as the price of labour increases vis-a-vis the cost of machinery, it surely will be in due course. There is another benefit. The equipment—that is, the pipework necessary to move the muck—occupies no more than a couple of square feet of the tunnel and the shaft cross-section, and it is therefore possible to employ intermediate shafts for the removal of spoil which are in effect large boreholes rather than shafts proper.

**Mr T. A. Coombes**, National Research Development Corporation

The NRDC is a public corporation whose job is to secure the development of inventions if this appears to be in the public interest. Our colleagues persuaded London Transport to put up some of the money and to help in arranging for a potentially useful hole to be constructed at New Cross. Having borne most of the cost of building the first machine and of digging the first 140 m of tunnel, the NRDC's work is not finished. Recently its board has agreed with the licensees to pay jointly for a second and improved smaller diameter machine to be designed and built, and a number of interesting contracts are in the offing.

75. Civil engineers may be reluctant to risk local authorities not accepting a new method without some form of guarantee. The NRDC is prepared to discuss providing such a guarantee on reasonable terms and under appropriate circumstances. In due course naturally the new process must stand on its own feet commercially, but until then the NRDC believes that it is important enough to be encouraged.

76. Interest has been shown from many parts of the world, from Brussels to Bratislava, but I suspect that the world is waiting for Britain to take the first step.

77. The NRDC is confident that the bentonite shield will produce soundly constructed, cheaper tunnels built both quickly and in safety and with a minimum of disruption of the surface.

**Mr E. W. Cuthbert**, London Transport Executive

From an operational point of view, underground stations should be at the least practicable depth to minimize the time taken by passengers moving between the street and the platforms. The floor level of the ticket hall and subways connecting to it from the entrance ramps and stairways should be about 5–6 m below street level and platform level about 9 m below street level. Assuming London Transport tube trains in single track tunnels, it follows that the extrados of the 4 m dia. running tunnels where they leave the station will be about 7 m below street level. In order to minimize the running time between stations, to conserve energy and to provide for drainage, the running tunnels should be graded to a low point between stations, where the cover would be of the order of 12–15 m for stations 1.5 km apart.

79. It would almost certainly be impracticable to construct tube railway tunnels at such depths anywhere in Central London quite apart from considerations of strata because of the presence of existing tunnels. In this area tunnels of new lines will be at depths of the order of 30 m where they will almost certainly be constructed in

London Clay or the Woolwich and Reading beds which are not always water-bearing. In the outer area, however, as at New Cross, depths of cover of the order of 15 m are practicable, provided one has the means of tunnelling economically in Thames gravel. However, if on any route more favourable strata than water-bearing gravel were to exist at a greater depth, this would be preferred, even if it involved accepting the disadvantages of deeper stations, provided the overall cost of the railway could be reduced. Whilst there may be limited opportunities to use the bentonite shield for underground railway construction in London, there are undoubtedly large cities elsewhere in the world where one has to tunnel in water-bearing non-cohesive soil or not have an underground railway at all. There the bentonite shield should come into its own. Referring to the tests at New Cross, it would appear that the tunnel diameter might have to be increased if a bentonite shield were used.

80. Rebuilding tunnel lining erected out of tolerance in ground requiring the use of a bentonite shield might be dangerous, and I should be obliged if the Authors could give their views on the tolerances which could be worked to with this shield in Thames gravel, bearing in mind the tolerances which have been found to be attainable in London Clay during recent underground railway construction using conventional or drum digger shields. Any necessary increase in tunnel diameter must be taken into account when assessing the economics of the bentonite shield method.

81. From the limited field trial described in the Paper, I am left with some doubts on the reliability of the bentonite shield systems. Are the Authors satisfied that the 'down time' on the plant as a whole would be comparable to that with other soft tunnelling systems?

82. I would now like to refer to § 22 and Fig. 2. The text refers to a three-way split of the bentonite flow at the tunnel face. Fig. 2 clearly shows the flow to the plenum chamber through one mono pump and to the agitator in the sump, but seems to omit the second mono pump and the delivery to the feed wheel. Would the Authors please elucidate this?

83. In § 33 references are made to the absence of a cushion against the surge of an incompressible fluid and § 42 indicates how the pressure variation was reduced. Would there be any advantage in fitting a surge chamber between the plenum chamber and the pressure control valve?

84. The last sentence of § 49 states that tests suggest that no difficulty should be experienced with water levels up to 20 m above the tunnel. This represents a five-fold increase on the pressure experienced at New Cross, and I would appreciate information to justify this statement, with particular reference to the effect of this scaling-up of pressures on the various seals at the shield.

85. Referring to the Authors' remarks in § 57 about a universal tunnelling machine, would they please say whether they consider that the New Cross shield could cope with a face at which a water-bearing gravel/London Clay interface was at or near axis level?

86. The method of financing development work is of considerable interest. At New Cross the final cost was in excess of £500 000. This was shared in the proportion 56% to NRDC and 44% to the London Transport Executive. The total cost will be transferred to London Transport's Fleet Line account if and when the third stage between Fenchurch Street and Lewisham is authorized.

87. I have some doubts about the extent to which new techniques should be tried out in the course of normal projects. Of course every project is a one-off job and demands innovation, but I would question whether one should be committed to the full-scale use of an untried technique without field trials. Could one insure against the consequential losses if the opening of a new railway were seriously delayed by failure of a new technique? It seems to me that the aim should be to carry out field trials on new techniques as at New Cross where experience has been gained without delaying a large project, and where it was arranged that the work produced by the trials might eventually be incorporated in such a project.

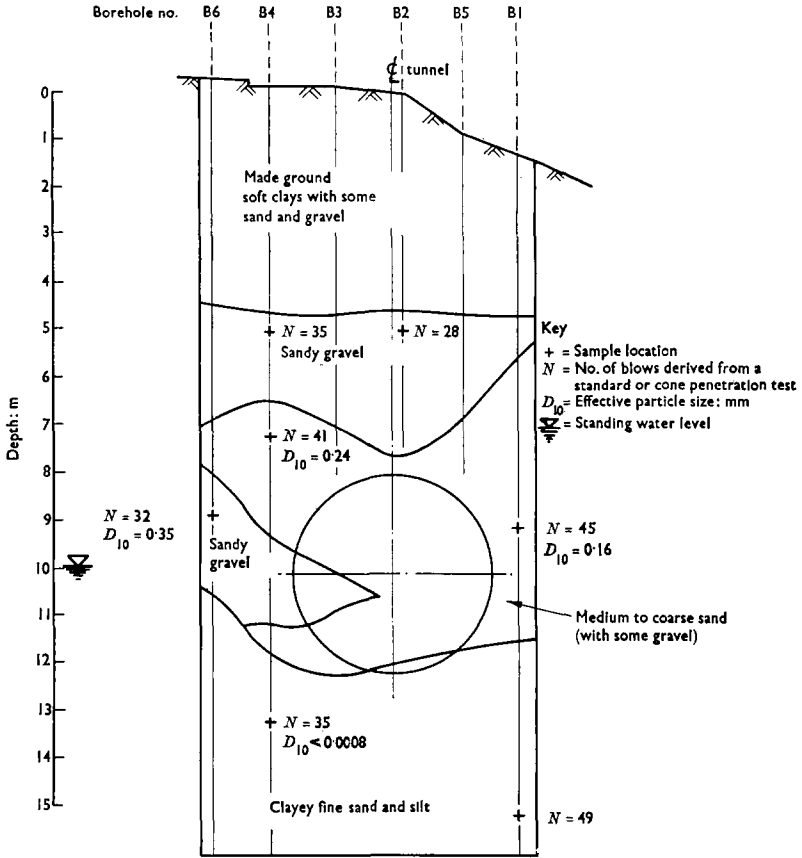


Fig. 12. Details of soil properties at section B-B

**Mr B. Boden,** Transport and Road Research Laboratory

We were fortunate in the Tunnels Division to be able to carry out a series of ground movement observations over the last 40 m of the drive.

89. Figure 12 is a considerably simplified soil profile at one of the TRRL instrumentation cross-sections. Below knee level the effective particle size would be of the order of 75 microns. The problems associated with separating these finer particles probably led to larger ground movements being recorded here than at other more favourable locations along the route. Nevertheless, the trends are very encouraging in the way that the ground responds to the influence of the bentonite pressure.

90. Figure 13 shows a series of vertical movements measured in a borehole located close to the centreline of the tunnel. The movements are plotted at levels corresponding to the appropriate magnetic rings shown on the cross-section, and lie on a

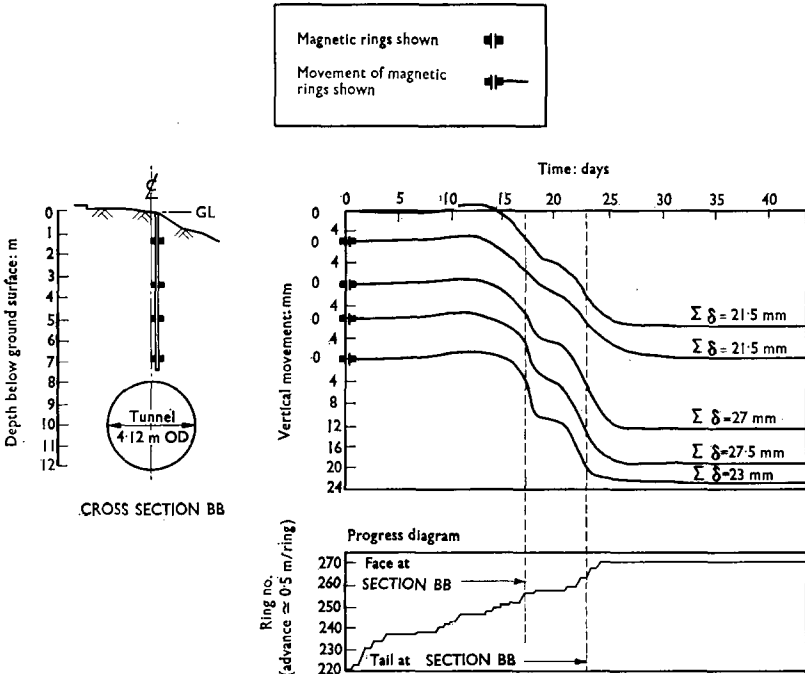


Fig. 13. Vertical ground movement at borehole B2

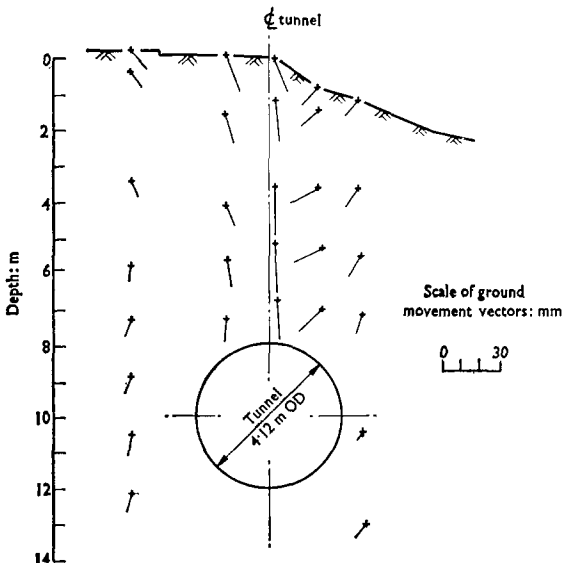


Fig. 14. Two-dimensional vectors of ground movement. Section B-B 20 days after passage of shield

## DISCUSSION

time base which is common to the underlying progress diagram. The settlement curves are clearly in phase with the progress curve. Particularly in the zone close to the tunnel, disturbance of both the face and the bentonite is necessary to create movement in the ground and equilibrium appears to be re-established when this disturbance ceases. This is, of course, what the inventors intended. In a non-bentonite supported tunnel face, the greatest amount of settlement would occur directly over the crown of the tunnel. In this case the greatest settlement occurs some 3 m above that level, demonstrating the restraint offered by the bentonite in the zone adjacent to the tunnel.

91. A comparison of a series of stations located along the tunnel centreline showed that the settlement/time gradients were approximately parallel despite variations in tunnelling performance. This implies that the settlement velocity tends towards a constant value and, if this is so, endorses the value of faster rates of tunnelling; the faster the rate of advance the smaller the amount of settlement ultimately obtained.

92. Lateral ground movement observations showed that the upper soil layers migrated towards the centre of the settlement trough during the passage of the shield in the normal way. The soil around the tunnel generally showed a reduced and, in some cases, reversed lateral movement, presumably due to the influence of the bentonite pressure. A similar pattern was observed in the longitudinal ground movement. This is summarized for the lateral and vertical movement in Fig. 14, which shows the vectors of ground movement at Section B-B 20 days after the passage of the shield.

### **Mr A. M. Muir Wood**, Sir William Halcrow and Partners

The bentonite shield is undoubtedly one of the important advances in soft ground tunnelling. Its first use is particularly opportune at a time when, to counter the medical risks, the conditions of working in compressed air have been made very much stricter and in consequence the economic benefits of an alternative are made that degree more viable.

94. I want to ask a rather fundamental question: why bentonite? For open textured ground and for the initial experiment I can well see why bentonite would be the first choice, but with finer material there could be considerable latitude in the substance that one would put into the water in the face of the machine in order to support the face. Elson<sup>2</sup> lists six factors which contribute to the stabilization of trenches by means of bentonite and he estimated the magnitude of the three principal contributory factors:

- (a) the hydrostatic pressure exerted by the slurry;
- (b) the passive resistance of bentonite in the trench against shear failure as it might be displaced plastically by a falling in of the side of the trench;
- (c) the effect on the shear strength of the ground, on account of its impregnation by slurry.

In fact, the contributions of these three factors he found to be, in very rough figures, 65–85% for (a), 3–30% for (b) and 3–20% for (c). For the bentonite shield one can immediately eliminate significant contribution from (b) in view of the very different geometry of the slurry in the face, coupled with its continuous agitation in operation. In consequence, I think that his figures would reduce themselves for a bentonite shield with a 7% concentration of bentonite to about 95% of the support being provided by the direct pressure and no more than, say, 5% by the increase of the shearing resistance of the ground by impregnation. With a 4% slurry concentration, which I believe was used for the bentonite shield, I think the support could be provided just as well by using a clay with insignificant thixotropic properties. Is there any reason why London Clay should not be used in London to achieve the same effect, particularly if one were using the machine in finer ground where otherwise the greater difficulty in separating bentonite for recycling would form a high fraction of the overall cost? A supply of clay, derived from another tunnel face for example, could be used

once through only. This raises wider questions of spoil disposal and would favour pumping to collection points and disposal at sea, but is by no means an impossible development.

95. Clearly there is a wide option in the pressure in the bentonite shield in relation to the overburden, and if one knew something about the packing, in relation to its densest state, of the granular material around the tunnel it might well be possible to adjust pressure in such a way as either to compensate for the effect of closer packing of the grains as the machine goes past or, possibly, of loosening of the ground in an extreme circumstance, and hence to control to a considerable degree the extent of consequential settlement.

96. Could some of the problems in the bearing seals be solved by making use of the expedient of glands, similar to those fed by water or steam for pumps and low pressure turbines? If the fresh bentonite were fed into these glands at a slightly higher pressure than the bentonite in the face of the machine, grit would be excluded from the bearings.

97. I continue to see the universal tunnelling machine as a chimera; what is much more likely is the development of a series of machines, each tolerant of a certain range of types of ground, with considerable overlap between the capabilities of each machine. It would then be practicable to choose a machine for a particular tunnel through variable ground with much reduced risk of reversion locally to traditional methods.

98. Finally, I should like to make a point about the financing of the experiment. Whilst I agree entirely with Mr Cuthbert, I think there is a particular difficulty and constraint upon experiments of this nature being carried out other than by foresighted authorities such as London Transport with a continuing interest in tunnelling economics. The constraint relates to time as much as to cost. Where it is possible to foresee that the success of some such experiment might have a significant effect upon the cost of a tunnelling project I believe that some latitude is needed in present day procedures, in authorization of the necessary expenditure before the full scheme was included in the construction programme.

#### **Mr R. P. Lewis, Edmund Nuttall Ltd**

The statement that ground conditions affect the cost and stability of any tunnelling operation is not only superfluous, but also a gross oversimplification of the situation. Nevertheless, it has been the dream of tunnellers throughout the ages to make a universal tunnelling machine, hopefully capable of combating any ground conditions which may occur. This dream of the future is still a long way off, but whilst past hopes have centred around adapting conventional techniques to suit more arduous conditions, the bentonite machine provides the opportunity of adapting a process designed for sand and gravel to conditions which are normally considered more tolerable.

100. Since the conclusion of the experiment most investigation has been concentrated on extending the range of ground conditions which the bentonite machine can handle downward from the gravels and sands through the silt range, ultimately to the clays. The problems in this exercise are not in machine design but in the efficiency of the separation in the bentonite cleaning plant on the surface. By starting from the assumption that only bentonite of sufficient quality to provide stability to the excavated ground must be pumped to the tunnel workings, the problem ceases to be one of capability of the machine and becomes one of economics of bentonite recovery. How much of the bentonite can be reclaimed from that already used and how much has to be provided fresh? With flows of 700 gal/min and slurry costs of £5/1000 gal, it does not take a computer to calculate that the economic savings of the process will soon disappear through bentonite consumption if reuse of bentonite is not kept up to about a level of 95%.

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101. Separation in the experiment was achieved by the use of 12 in. hydrocyclones, allowing particles down to an average size of 75 micron to be removed. Since then trials have been carried out using 3 in. cyclones, and this is considered to be the smallest size which it is practical to use without increasing the risk of continuous blocking beyond acceptable limits. The results of these trials have shown that average separations of between 15 and 30 micron are possible depending on the quantity of fine material in the ground and the quantity of bentonite one is prepared to lose in the separation process.

102. With a straightforward system of screen and 3 in. cyclones, grounds with a size distribution down to about 25 micron can be handled, but bentonite consumption may be up to 10%. By adding a 12 in. dia cyclone before the 3 in. cyclones designed only to discharge solids at a moisture content of 30% most of the solids are removed with only small quantities of slurry, and the 3 in. cyclones can be run to remove the remaining solids for limited periods of time only, resulting in a saving of bentonite.

103. The resulting underflows from cycloning can be disposed of as slurries using sludge gulping disposal tankers, or they can be further treated. The addition of water and further cycloning, as a washing operation, eases handling of the solids and reduces disposal costs for only modest capital investment, whilst the use of centrifuges would produce similar economies in disposal and enable more bentonite to be recovered but at the expense of greater capital investment. It will be seen that each individual situation, taking account of tunnel diameter, tunnel length, and ground conditions has to be examined to determine the most economical solution.

104. Further developments which it is hoped will start in the near future involve the use of chemical additives to the slurry, or even wholly artificial slurries which will enable fine silts and clays to be removed from the slurry economically. When this development comes to fruition the present range of ground conditions will have been enlarged even more, and a start will have been made to overcome the difficulties at present experienced by nearly all methods of tunnelling, including the bentonite machine, that is, the difficulties of mixed face.

**Mr N. D. Pirrie**, Sir Robert McAlpine & Sons Ltd

It is stated in § 51 that 'the estimated cost savings compared with conventional methods are up to 50%'. I would ask what rates of progress were assumed in each case when comparing compressed air working with the bentonite process? Was the cost of providing compressed air plant and the installation of air locks included in the bentonite case, because, of course, that is still necessary at full capacity for service and safety reasons, even though it may not be used?

106. In a drive of 140 m it is, of course, not necessary to move the reclamation and slurry processing plant from its initial installed position on the surface, but for a drive of several kilometres is it envisaged that it can remain in one place, as can the air compressor plant? If it has to be moved to a new site, then this cost has also to be taken into account when making a comparison. Was this done?

107. Looking at the dimensions of the reclamation plant involved on the surface, is it really practical to consider vibrating screens, cyclones and settling tanks being stored and operated inside the tunnel, as has been suggested?

108. Rates of driving of 2.5 m/10 h shift were achieved, peaking at a rate of 4 m/shift. What in fact was the longest sustained drive in continuous hours or shifts and what was the distance driven in that time?

109. The rate of progress would appear to be limited by the capacity of the helical feed wheel to deliver, or else the cutter head is absorbing two to three times as much power as a clay digging machine. Can the Authors please comment on the ease of digging experienced? Bearing in mind the understandable difficulties of sealing the helical feedwheel, how effective was the seal to the cutter head main bearing and its drive, from the slurry and sand in front of the pressure bulkhead. The life of this

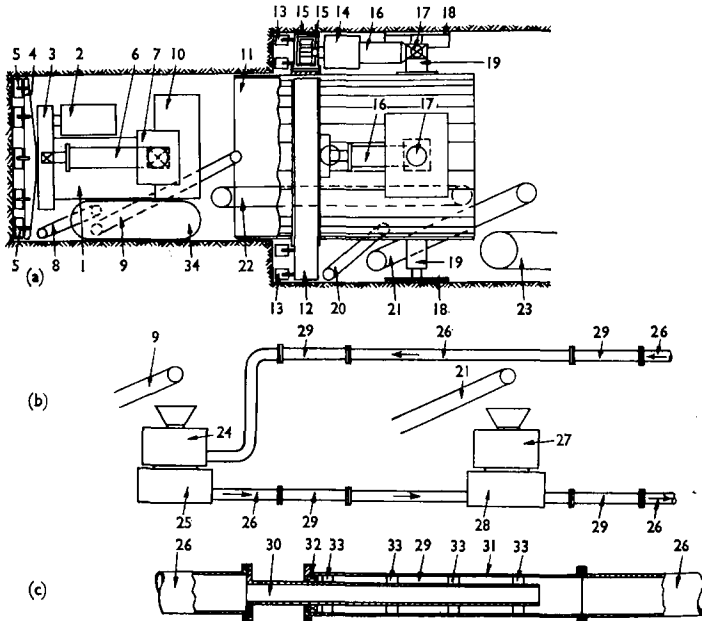


Fig. 15. Specification for tunnelling machine

main bearing and drive is critical. How many digging hours did the machine actually work?

110. Finally I would make the point that since the other machines can be adapted to use the process, the Paper might perhaps have been better titled 'The bentonite tunnelling process'.

**Dipl. Ing. W. M. Braun**, Consultant

Figure 15 is taken from the British Patent Specification No. 961295 describing a novel and interesting array of tunnelling machines. This invention deserves attention also because it incorporated spoil removal by hydraulic transportation of fragmented rock material in a pipe line system.

112. The detail of the drawing (b) shows the 'hydraulic conveyors', separately positioned where they would replace the conventional conveyors in (a). Material receiving hoppers, rock crushers and loading traps are indicated at positions 24, 25 and 27, 28. These are, incidentally, the points of the system where the fluid is charged with the solids, and hydraulic transportation commences. Arrows indicate the direction of the flow. There is some similarity to the bentonite shield slurry circuit diagram. It may also be worth mentioning the telescopic tube arrangement (c) which is necessary for adjusting the length of the pipe lines to suit the progress of the tunnel boring machines—obviously a common feature of both patents.

113. The drawing and the specification imply, furthermore, that this high capacity hydraulic spoil removal system would be necessary for the success of the principal invention, the ingenious combination of two (or more) tunnelling machines working

in sequence. While the first machine bores a pilot tunnel, this is enlarged almost simultaneously by a second device, a mechanical reamer. The follow-up operations for tunnels of very large diameters (accommodating motorways for instance) might even require multi-stage reamers. These tunnel boring refinements resemble those which were actually provided by the German firm, Wirth & Co., for major rock tunnelling ventures in Switzerland.

114. While the question of who may be infringing the other inventor's patent could only be answered by experts on international patent law, civil engineers may query why the fine gravel which the bentonite shield mined could not be instantaneously converted into an appropriate in situ concrete lining which would be—so to speak—extruded by the tunnelling machine. Current experience with solidified slurry in cut-off wall schemes seems to justify, in my opinion, the development of bentonite/cement/gravel concrete mixes.

115. Another point, incidentally, was raised earlier in this discussion by equipment designers and operators, apparently concerned with the difficulties of tunnel driving when the shield's rotor has to work partly in clay and partly in the overlying gravel and sand layers (not to mention groundwater on top of the clay or other impermeable formation). These ground conditions often occur at the depth of 20–50 m below the surface, just where the underground railway is wanted. The inventor of the shield shown in Fig. 15 introduced therefore a new rotor type having a frontal array of adjustable steel plates which can be tilted. As it performed much more efficiently than conventional boring head designs, particularly in alternating layers of clay and gravel, it might also offer advantages in combination with the bentonite slurry pressure chamber.

116. I conclude by saying that there is obviously much work to be done on tunnelling machines, and that the economics may have to be assessed and proven in each case for the particular tunnel project.

**Mr R. P. Burgess**, Robert L. Priestley Ltd

When we at Priestleys first saw the bentonite machine patent document, we thought the idea was an excellent one, but were apprehensive about the design and practical application of certain requirements of the process—designing and manufacturing a feed-out mechanism capable of dealing with particle size from approximately 70 micron to about 10 in., whilst maintaining a stable pressure of bentonite in the face of the machine. In addition producing a satisfactory tail seal appeared to present a fairly difficult problem, and in the event the difficulties were more severe than expected.

118. The first thing to decide was the type of machine that seemed to be most suitable for application of the process. The clear intention was to endeavour to make the bentonite process the experiment rather than the tunnelling machine. Two types of machine were available for conversion. The first was a drum digger which would entail sealing behind the rotating drum and maintaining a pressurized zone within it. It was considered that the drum might be shortened but the whole of this was rotating and it was considered necessary to have a stationary bulkhead to mount the feeder unit, which would have presented additional sealing problems. The alternative machine had a central shaft and the central area was, in our opinion, too restricted to enable satisfactory design for mounting the sump, feed-out unit, and valve equipment required within the body of the machine.

119. We therefore decided to design a tunnelling machine specifically for the bentonite experiment, based on our standard machine design, which seemed well suited for the process. The Priestley machine design has a sealed bearing arrangement in the head and a relatively clear stationary area within the body, so that a fixed bulkhead to maintain the pressure could easily be placed at the front diaphragm and the driving gear could be sealed as is normally done in our machines.

120. In reply to just two of the points that Mr Pirrie raised, the torque used in the

machine was very much less than one would normally expect for a 13 ft 6 in. machine. This was not surprising because the rate of advance specified was slow. The machine incidentally was designed for approximately three times the speed specified. The thrust also was low when one takes into account the pressure of the bentonite on the bulkhead of the machine. The main areas of difficulty were in connexion with the feed-out arrangement. Originally six different designs were considered and finally three of these were developed.

121. The helical feedwheel was the finally adopted unit. There was an entry zone on the pressurized side of the feeder and an exit zone on the atmospheric side. The unit was designed so that there was at no time a straight-through path between the inlet and outlet openings. Material was fed in on the pressure side of the bulkhead and as the helix rotated it was discharged at atmospheric pressure into a sump, on the exit side of the machine. The feed hopper was arranged so that it was not possible for large stones to jam the blades at the entry side of the feeder. The first helical feeder worked satisfactorily for only a short time, after which the sealing arrangement on the helix was improved, but again the potential life was insufficient.

122. Edmund Nuttall's engineers suggested experimenting with a double gate system, which was manufactured and after modification worked satisfactorily. During this time an improved helical feedwheel was developed which overcame the problems in the initial unit and gave a better output than the double gate feeder. This unit was the one finally used on the machine.

123. I have never previously been involved in a job in which there was so much enthusiasm and co-operation from the Contractors' Engineers and the Consulting Engineers. I am sure this is largely responsible for the success which was achieved on the experimental tunnel. It was our company's aim to produce a reliable machine and I think it is true to say that the down time of the machine itself was negligible. On the various bentonite arrangements, however, there were delays and much modification work had to be done. Several modifications were made to the tail seals, and

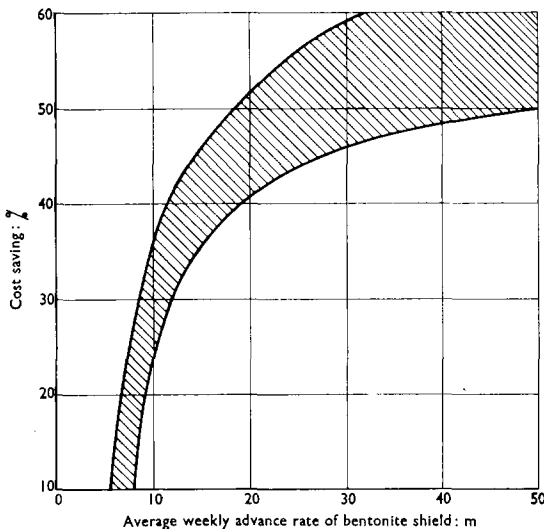


Fig. 16. Potential cost saving of bentonite shield over tunnelling with compressed air and ground treatment

## DISCUSSION

we are much more confident now about the prospects for a second machine than we were initially about the first machine working at all.

124. This is not a universal machine—nor will there be one for a long time—but I think that if the bentonite process is used with a shielded soft ground machine (and these machines are now made so that they can take hard ground cutters also) then if the machine as in the present design can readily be converted to a conventional machine very much more flexibility is available than was previously possible.

**Mr M. P. O'Reilly**, Transport and Road Research Laboratory

In addition to measurements of ground settlement and deformation taking place during the trial tunnelling at New Cross the Transport and Road Research Laboratory also carried out a study of the likely reductions in costs which might stem from the use of this new tunnelling method. In this exercise the bentonite shield system was compared with existing tunnelling methods using compressed air up to a pressure of two atmospheres and/or ground treatment; the proportion of time-dependent costs ranged from 30–50%. Fig. 16 shows the envelope of results obtained, and it is clear that when consistent advance rates of 15–20 m/week are obtained, the new method offers considerable potential savings in cost over traditional methods.

126. Of course, paper studies such as this can only indicate potential, and to be of benefit these hopes must be translated into reality. At the time the above studies were undertaken the bentonite shield method was capable of dealing with soils containing particles above 75 micron size and this range has now been extended down to soils with a particle size of 25 microns or larger. In addition tunnelling machines are still not as reliable mechanically as one would wish. I feel reasonably confident, however, that an industry which can conceive and produce the bentonite tunnelling machine is well fitted to solve the remaining technical problems needed to improve this system so that its full potential is realized.

**Mr K. F. Larkin**, Mott, Hay and Anderson

The settlements of 17 to 20 mm mentioned by Mr Bowden did in fact occur in the area where he was working. Earlier in the drive where there was a more steady rate of advance the ground was not as fine and silty as he found, and settlements were approximately 10 mm. It is considered that this settlement is due in part to a poor slurry condition in that it was not then possible to remove the fine sand and silt particles.

128. Obviously the condition of the slurry is of paramount importance, and investigation into means of controlling and improving the slurry in the circuit were conducted on site, there being certain properties which affected performance.

129. The first is viscosity. It is the most easily and readily measured property and gives an immediate indication of any variation in the slurry condition. The degree of penetration and pumping pressures are governed by any change in the viscosity. Secondly, there is the solids content. Excess solids adversely affect all other properties, especially above a concentration of 5%. Whilst tunnelling through the region of fine silty sands, solid contents rose to values in excess of 10% and on occasion 30%, and obviously resulted in severe control problems. Thirdly, there are the gel strengths. Extremely high gel strengths require very high pumping pressures and obviously lead to difficulty in control. With the penetration of bentonite into the surrounding ground, a loss does occur, estimated from measurements to be of the order of 60 kg of dry powder per metre of tunnel. Other losses occurred, as has been intimated, at the cleaning plant and in accidental spillage in the tunnel. The total losses for the experiment were estimated at about 600 kg/m of tunnel. Although the losses were lower than might have been expected for an experiment, it is considered that even with the spillage reduced these losses would aid the maintenance of the slurry by necessitating the addition of freshly mixed bentonite. Obviously the better the condition of the slurry the better the control.

**Mr J. Buchanan**, Sir Robert McAlpine & Sons Ltd

Will the Authors please state how and where the contaminated material was disposed of? The 105½ m of tunnel excavated after the sandwashing plant was installed represents 1400 m<sup>3</sup> of solid volume. What was the total volume of loose material, including bentonite slurry, disposed of and how much of it required special treatment? If these amounts were multiplied by 10 for approximately 1 km, what would be the problems of disposal?

131. In § 22 the Authors describe the three-way split of the flow of slurry. The circuit diagram, Fig. 2, only shows two ways, but nevertheless it would appear that the agitator takes one-third of the flow. How much does this affect the economics of the system? It would appear that a saving of half of the flows to the feedwheel and the agitator would save one of the hydrocyclone units. Will the proportion increase with a smaller diameter working face?

132. Reference is made in § 49 to the difficulty of removing particles finer than 75 micron, but Fig. 9 indicates that there was no such material encountered at New Cross, so that it would appear that all the slurry passing through the cyclones could be reused. Is this so? And was the only wastage that which adhered to extracted sand and gravel, or was slurry extracted from the circuit elsewhere and for other reasons?

133. How much slurry was used per m<sup>3</sup> of solid excavation and what was the type of bentonite used? Have there been any opportunities for experiment in order to select the suitable bentonite material, or was this based on earlier research?

134. The fact that there are so many questions to ask is no reflection on the Authors, and while the full report from the NRDC is eagerly awaited, they must be thanked for presenting so much information already so concisely.

### **Messrs Bartlett, Biggart and Triggs**

135. **Mr Cuthbert** has pointed out that the ideal depth for a Metro is fairly close to the surface, and the bentonite machine process demonstrated an ability to work at such shallow depths. He goes on to say that if more favourable tunnelling strata exist at greater depth, even if it means deeper stations, the deep system may cost less and be preferred. We agree, provided that the operational penalties of the deep system (such as increased journey times, escalators and all maintenance and running costs) are taken into account fully in the costing process. London's deep stations appear to satisfy 8 million acclimatized customers, but they do not encourage people to use the 'tube' for short journeys and architecturally cannot be made as attractive as shallow 'cut-and-cover' stations.

136. The selection of running tunnel diameter to give adequate clearances for a particular metro system is a complicated matter, but we do not feel that the bentonite machine requires a larger diameter than other methods of construction: the bentonite machine has excellent steering characteristics mainly because the presence of the pressurized slurry in the face ensures that any differential operation of the shove jacks produces an effective turning moment. Although the speed of construction is vastly greater than traditional methods, it does not approach the very high rates achieved in some clay tunnels which have on occasion led to machines getting so off line that some rebuilding of tunnel lining has been necessary.

137. **Mr Cuthbert** asks whether the 'down time' on the plant as a whole will be comparable with that in other soft ground tunnelling systems. The bentonite tunnelling process is designed to deal with the difficult problem of using a mechanical digger in non-cohesive conditions and, for this reason, the machinery involved requires a high degree of sophistication. It must, therefore, be true to say that the 'down time' will be greater than that on the simpler clay or rock digging machine. This higher than normal incidence of 'down time' is taken into account in the cost calculations mentioned in the Paper.

138. Figure 2 shows a simplified slurry circuit, and for the sake of clarity, items such as the flow line to the feedwheel were omitted from the diagram. At the design stage, a surge chamber was carefully considered in the circuit between the plenum chamber and the pressure control valve, but calculations showed that the chamber would have to be impractically large and it was, therefore, decided to achieve pressure control by the method described in the Paper. During the course of the New Cross trials, the pressure in the plenum chamber inadvertently reached a high point of 3 atm on more than one occasion. This excess pressure appeared to have no damaging effects on the various seals within the machine. We therefore believe that a 20 m head of water above the tunnel, representing a pressure in the plenum chamber of between 2 and  $2\frac{1}{2}$  atm would not be excessive.

139. The bentonite machine could, at present, deal with limited quantities of very fine material such as clay, but becomes less economical as the need to renovate the slurry becomes more frequent. It would be wrong to commit it to a face which was half gravel and half London Clay. Such a face would normally be a transition between gravel and clay and if the gravel were chemically consolidated over a transition length, it might be possible for the machine to operate as a bentonite machine in the untreated gravel and thereafter as an orthodox tunnelling machine.

140. **Mr Muir Wood** is, as usual, thinking ahead to the next stages of development, and indeed moves are afoot to try slurries other than bentonite. We would feel more sanguine had other slurries been tried successfully in trenches where, on occasions, with the groundwater well below surface level, the hydrostatic pressure in the slurry filled trench exceeded considerably the hydrostatic pressure in the surrounding ground. The initial trials of novel slurries might be carried out better in a trench than in a tunnel.

141. **Mr Pirrie** asks what rates of progress were assumed in calculating tunnelling costs using the bentonite machine? A progress of 4.5 m per shift was assumed for the bentonite tunnelling machine, and a progress of between 2 m and 3 m per shift for the comparative methods, using a standard hand shield, the upper and lower limits depending on whether or not compressed air, chemical consolidation or a combination of both techniques is used. The cost of the small compressed air installation was taken into account in the case of the bentonite tunnelling machine. Only a very simple compressed air set-up is required in order to provide safe working conditions for maintenance men within the plenum chamber when this has been evacuated of the bentonite slurry.

142. The cost exercise was based on a theoretical drive of 1 km. Over this length it is not considered necessary to move the reclamation and processing plant from its initial position. The only additional measure required is to install intermediate pumping stations between tunnel face and processing plant. These additional pumping stations were allowed for in the cost calculations.

143. We agree that a bulky separation plant is generally better kept out of the tunnel, especially as the pipe circuit offers such a convenient means of removing spoil from the tunnel. Nevertheless, we can envisage circumstances where some of the separation processes are best carried out in the tunnel: indeed the largest stones were removed behind the machine at New Cross.

144. **Mr Pirrie** also asks for figures for the longest sustained driving rate. We believe that to quote these figures would be misleading since, due to the experimental nature of this drive, the machine was frequently stopped for modifications, tests and measurements to be carried out.

145. The time taken to muck one ring of 0.5 m was approximately 30 min. This rate was limited more by the maximum shove rate of the main rams than by the performance of the helical feedwheel. In general, there was very little trouble in digging the material. On one or two occasions when the machine had to be stopped in the middle of a dig, there was some difficulty experienced in restarting the main cutter head due to the settling of the material already dug and still within the plenum

chamber. The normal solution to this problem was to allow the machine to ride back 10 mm or so in order to relieve the pressure on the head. Once the feedwheel had been redesigned with the same type of seals as the main bearing, there was no further trouble due to leakage. We agree with Mr Pirrie that the main bearing seal is essential to the correct functioning of the machine. Slight leakage was experienced during the drive, and because of this there will be some modifications on the next machine produced. The machine completed a total of approximately 300 digging hours.

146. Mr Buchanan expresses interest in the problem caused by the disposal of contaminated material. This was largely solved by installing the sand washing plant, which resulted in more than 90% of the excavated material produced by the process being clean. There was no appreciable quantity of silt in the ground encountered at New Cross. If, in future, this problem occurs, then the correct solution would be to extract the silt from the main circuit using small diameter hydrocyclones, and thereafter dilute the resulting underflow of rejected material and reclaim the silt by settling.

147. The main factor affecting the quantity of flow of slurry in the circuit is the size of pipe necessary to take the largest anticipated size of stone in the ground. A minimum velocity is required in this pipe to prevent settling and subsequent blockage. The total distance to be pumped also affects the pipe size, as too small a diameter of pipe would cause excessive loss due to friction. It must be stated that the flow to the feedwheel and the agitator is a necessary part of the system and cannot be dispensed with.

148. The ground excavated varied throughout the length of tunnel. There was some silt contained in the ground towards the end of the drive which resulted in wasted slurry. The sand removed by the 300 mm hydrocyclones contains approximately 30% of slurry by volume. In addition, small amounts of slurry adhered to the gravel. There is also some loss of slurry due to radial penetration into the ground around the tunnel. There was additional wastage at times due to cement contamination, but this problem was solved during the course of the contract by the use of chemical additives. The total use of bentonite was approximately 100 000 kg/130 m of tunnel, (57.8 kg/m<sup>3</sup> of solid excavation).

149. Fulbent 570, which is a naturally occurring calcium-based bentonite converted to a sodium base, was used throughout the Contract. The use of this particular material was based on the previous results of research carried out in slurry trench walls.

150. We would like to thank all those who took part in the discussion for providing additional information and valuable comment and indeed for answering the questions raised, other than those dealt with above.

## Reference

2. ELSON W. K. *An experimental investigation of the stability of slurry trenches. Geotechnique*, 1968, **18**, 1, 37-49.

## Corrigendum

§ 48 line 2: for 50 mm read 500 mm.