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8058 DISCUSSION

Pipe-jacking applied to large structures

T. E. CLARKSON & J. W. T. ROPKINS

Messrs Clarkson and Ropkins

The topic of this Paper is a particular form of engineering which has evolved as a result of close dialogue between the clients' organizations and Cementation Ltd as designers and contractors, and it is truly a case of necessity being the mother of invention. Almost every new development has come about as a result of a client asking whether it is possible to adapt the existing technology to meet some new problem with which he was faced. Much of the development work really goes back to Mr J. C. Thomson, whose paper[1] covered the start of pipe jacking in the UK.

87. Several articles have appeared in the technical press in recent years describing individual large-scale pipe-jacked projects. The Authors felt it would be useful to summarize the development of these techniques and to give a brief account of the engineering principles involved. The resulting Paper is, therefore, of a general nature and we hope it will clarify the subject for those engineers who are not familiar with the possible applications of the techniques, and also provide a useful reference for those who are.

88. Much attention has been given to the Brent Cross tunnels project, for at the time of its execution it represented, in our view, the most enterprising application of our engineering resources in this field. This was particularly true of the North Tunnel where great care was necessary to provide a solution which would enable a tunnel of large cross-section to be installed at shallow cover without disturbing the A41 carriageways.

89. As mentioned in the Paper, we think it would be quite possible to install a tunnel in the same manner as was done at Brent Cross, but wide enough to accommodate three lanes of traffic. This would perhaps serve as one carriageway of a dual carriageway or motorway, because in providing such a box we think that the technical problems are directly related to the increase in the width. If the width of the unit is increased, so is the width of the jacking base, and the additional jacking force which would be needed for the wider unit can therefore be provided. As far as the length of such a tunnel is concerned, again it is a function of ground conditions primarily, but it is reasonable to suppose that tunnels considerably longer than Brent Cross could be constructed by the use of adequate numbers of intermediate jacking stations should the need arise.

90. We are also of the opinion that in the right physical circumstances there may be some merit in utilizing a jacked tunnel technique as part of an underpass scheme through an existing busy intersection between a dual carriageway trunk road and probably a single carriageway road at right angles (Fig. 14).

91. Such a scheme could possibly reduce the amount of land which is normally required for diverting traffic while construction is carried out, and again in the right circumstances it is quite possible that the tunnel section could be constructed with less need to divert services than if one uses an open cut section.

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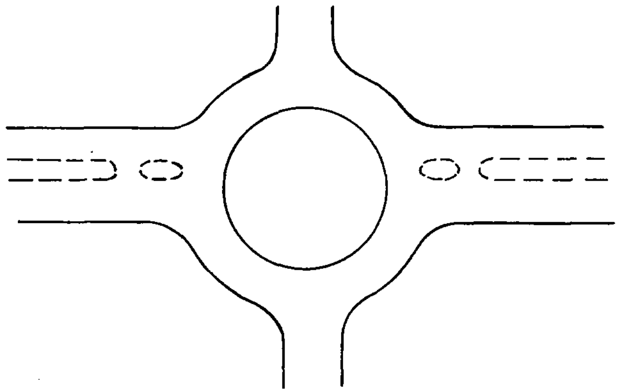

Fig. 14

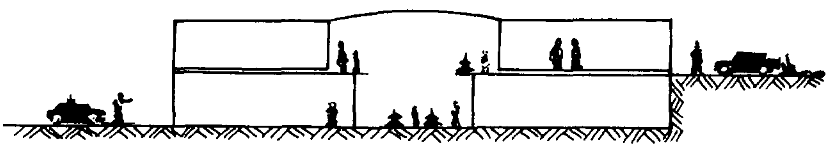

Fig. 15

Mr M. Skudder, Chief Surveyor, the Hammerson Group of Companies

As Surveyor for the client for Britain's first regional shopping centre, perhaps I could explain why we chose the particular site, how we came to require the tunnels, and other general aspects of the shopping centre.

93. The seed was sown in 1959 when visits to North America and studies of the shopping centres over there made it of interest to the Hammerson Group to develop the first major British regional shopping centre. Architect Bernard Engle and estate agent Trevor Donaldson were instructed to search for a suitable site.

94. Research on shopping areas with turnovers of more than £15 million/year showed that there was a gap in NW London, and this helped to narrow our search. A regional shopping centre depends greatly on the shopping motorist, and obviously on its proximity to major roads. At Brent Cross there is the Hendon Way (A41) to the east, the North Circular Road (A406) to the south and the extension to the M1 to the west.

95. Another essential is the close proximity to potential customers. Within 10 mins drive of this particular site there is a population of 400 000, and if this is extended to 20 mins drive the population increases to over 1·25 million.

96. Having established that this was an ideal location, we approached the owners of the site, the largest area of which was the former sewage works owned by London Borough of Barnet, and started planning the actual centre.

97. An outline planning application was made in 1964. In 1966 the then Ministry of Housing called in our application so that the Minister could hold an inquiry. By this time objections were coming in, mainly from other local authorities, chambers of commerce and other organizations who clearly felt that if consent was granted for such a sizeable project their own shopping areas would suffer. In fact, this centre has now been open for over 18 months and the effect on those centres has been minimal. The most problematical objection was lodged by the then Ministry of Transport who considered

proposals both for access and egress to be unsatisfactory. Public inquiries take considerable time to set up. But at least this delay enabled my company and our Consultants to get together with the Ministry of Transport to seek a solution to their objection. This was solved by the proposal to construct a vehicular bridge across the North Circular Road and two tunnels through the embankment of the A41.

98. Having resolved these objections, after the public inquiry we were granted outline town planning consent in 1970. In 1972 we obtained a full town planning consent for a shopping centre containing a lettable floor area of 800 000 sq. ft on two levels, taking advantage of the N–S slope so that at each level there is access from natural ground level (Fig. 15). This area was split between two departmental stores, four other stores, a supermarket and 82 other shop units of varying sizes.

99. Construction started in 1972, and after a contract period of $3\frac{1}{4}$ years the centre finally opened for trading on 2 March, 1976, by which time it was surrounded by 3500 car spaces, free to the customers. This has been found to be inadequate, and is being increased to 5000 free spaces. From conception to opening has taken 17 years.

100. After the pre-contract problems, the actual construction of the centre proved to be comparatively straightforward. Much, I feel, can be said on similar lines about the civil engineering works, which not only included the bridge across the North Circular Road and the two tunnels but three bridges across the River Brent, each of which spanned over 60 ft, and over a mile of carriageway which was subsequently handed over to the London Borough of Barnet as public highway.

101. The matter which gave concern at one stage was the tunnels. This was mainly due to the Consultant having advised us that the right technique for tunnels in this location was probably thrust boring or pipe-jacking, but that they would also be the largest tunnels ever attempted by this technique. Our fear proved groundless. Despite many stringent conditions laid down by the Department of the Environment (DoE), the thrust boring was carried out in advance of the programme set by Cementation Projects.

102. As Clients, the Hammerson Group perhaps learned little new, but there was certainly confirmation of one or two issues. First, anyone considering carrying out a project of this type not only needs to have a great deal of determination and stamina, but if he wishes to see it through from conception to completion, needs to be under 40 years of age. Secondly we found that while government departments, local authorities and even statutory undertakings, as they felt fit, bent rules, public companies were expected very much to stick to the book. The fact that we were able to do just that and achieve our objective is a credit to Cementation Projects Ltd.

Mr K. P. Elton, J. H. Coombs and Partners

As Consultants, we had realized for at least 3 years that these tunnels were essential, and considered various systems of construction. The first was to put an umbrella over the site, cut through and put a deck over the top. There were ideas of occupying one lane at a time and putting down contiguous bored piled walls, again with a roof over the top. A system like that at Wandsworth, with boxes in tiers was also considered.

104. The crunch came when the DoE insisted that in no circumstances would the road surface be affected. However, after inspecting the work at Bletchley where long boxes were being used for a subway passing 18 in. under the railway track, with the railway kept running, we decided that this was a viable solution.

Mr K. J. Flemons, Sir Frederick Snow & Partners

I should like to refer to the culvert which was thrust under the main London–Cambridge railway line at Tottenham Hale Station, since this was rather a complex project.

106. At the location of the thrust there was a turn-out from the main-line into a siding and immediately beneath this the twin tunnels of the Victoria tube line crossed the site diagonally. Clearance between the rail and the top of the culvert was 989 mm, whilst beneath the culvert there was a clearance of 1525 mm to the crown of the tube tunnels. Way-beams were initially considered for carrying the track, but it soon

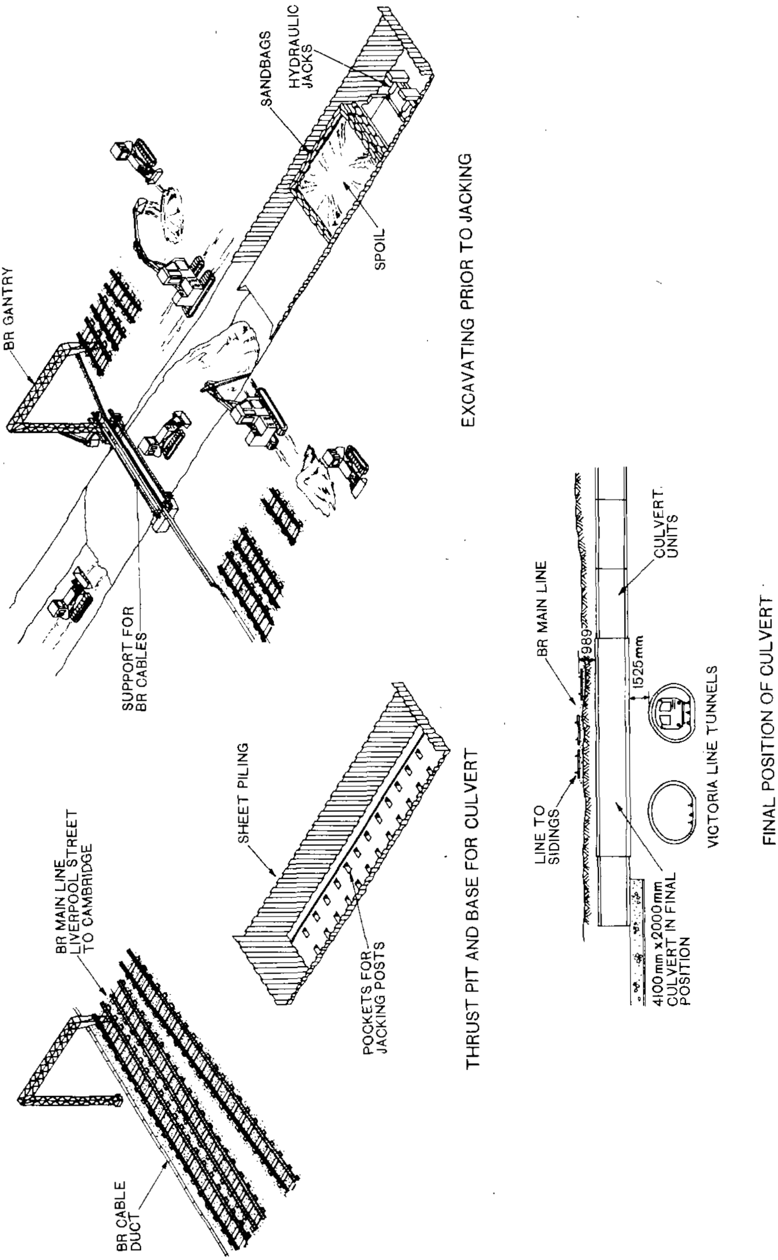

Fig. 16. Old Moselle northern improvement railway crossing

became apparent that there would not be sufficient space for foundations, so the possibility of thrusting a length of culvert beneath the railway was examined. Principles were agreed with British Rail and prices obtained from organizations specializing in thrusting work. Cementation Projects Ltd were appointed at an early stage and were connected with us on the design and were present at the various discussions which were held with British Rail and London Transport. The outcome was that a 20 m length of culvert was constructed inside a sheet pile cofferdam on the west side of the main-line and tube tunnels, and subsequently thrust across the railway.

107. One of the problems of this particular area was the very high water table, and during construction of the Victoria Line, the ground had been consolidated using the Joosten process of hard grout. The tube tunnels were only just within the clay and the grouting consolidated the overlying gravel. In order to contain the water during the thrusting operation, curtain walling of hard grout was formed on either side of the thrust line, with a soft gel infill. In addition, well points were put down outside the curtain walling. The system worked very successfully, and no water was encountered during the excavation and subsequent thrusting operation.

108. The original intention had been to retain the track and thrust the culvert beneath it, but British Rail were not keen about leaving the track in position because of the very small clearance above the top of the culvert.

109. Figure 16 shows the thrust pit and base and also the situation immediately before jacking. The track was removed prior to the commencement of the operation and the culvert thrust forward. Kentledge was placed on the back of the unit in the form of sandbags and ballast, to prevent it dipping once it left the base. There was a drop of 41 mm in the vertical plane, but the horizontal alignment remained true throughout the operation. The distortion of the underground tunnels was measured as the thrusting progressed, and though difficult to assess exactly, was approximately 1 mm. There were no significant problems with the joints in the tunnels and only a slight seepage of water was recorded, which did not affect the running of the tube trains. The actual operation was completed roughly 6 h ahead of schedule and British Rail had backfilled and relaid their track some 4–5 h before the scheduled time.

110. The internal dimensions of the culvert were roughly 4 m × 2 m, and its weight, plus that of the kentledge, approximated to 230 t. Jacking capacity of 900 t was available, but in fact the maximum required was 300 t, and then only for a limited period. The culvert was constructed in 1971 and I wonder whether the same techniques would be used again. Thrusting under railways has been carried out in South Africa with the running of the main line being maintained. On a similar project could this be done with a 989 mm clearance as shown or would it still need to be an open cut operation?

Mr P. T. Pearce, Cementation Projects Ltd

I would like to comment briefly on the need to overcome the procedural and commercial problems of applying these techniques. One of the essential features of this technique is that the specialized contractor must be involved in the early stages so that the design can be undertaken with the construction process in mind. There are two separate reasons. The permanent structure has to be designed as a section or sections which are capable of being put in place by the techniques involved. Secondly the temporary works, jacking pits, thrust walls and bases, and preparations to receive the front end of the structure, form an expensive part of the activity and should be designed in conjunction with the permanent works.

112. At Cementation Ltd we have found it is very desirable that the contractor should be involved early, normally by a design and construct contract or management contract. Most of our work has been undertaken under management contracts where the specialist work is done by the specialist contractor and more general work can be undertaken as sub-contracts placed in competition under the general control of the specialist contractor.

DISCUSSION

Mr M. K. Czechowski, Donovan H. Lee and Partners

It would perhaps add to the interest and value of the Paper if the Authors would, from their experience, comment on the type of joints used in multi-prefabricated units, the load transfer, alignment of the units during installation, watertightness, joint packing materials (resilient versus soft) and casting tolerances for the bearing surfaces of the joints, with or without packing.

114. Would the Authors commit themselves, from their experience, on how the jacking effort can be related to the soil properties obtained from laboratory tests and also how other factors mentioned in the Paper, such as distortion, lateral bending and shear, can be evaluated to make the necessary provision for them in the design stage?

115. As regards soil investigation, do the Authors not consider that a pilot heading prior to the main drive, or at least horizontal borings on the line of the thrust should be an essential part of the site investigation, especially when the drive is carried out in urban areas where vertical boreholes may interfere with the traffic? The pilot heading may also help to discover uncharted services which could disrupt the continuity of the drive, and may also provide a reference for the checking of the alignment of installation at the reception pit unaffected by ground movement which can be present at the jacking pit.

116. The Authors state that the thrust has to be applied below the centroid of ground resistance to prevent the units from diving. It is not clear why this should happen. Should not the thrust be applied to the units to coincide with the centroid of ground resistance, or even a fraction above it, to counteract any tendency for the units to rise? The units are supported and slide at the bottom of the drive and should be encouraged to stay there rather than to rise. The application of the thrust below the centre of resistance produces a tendency for the units to travel crabwise on the line of the thrust. Also in a long drive there would be a tendency for the units to twist due to the unbalanced lateral forces along the line of the thrust. Can the Authors suggest any method for correcting this twist?

Mr J. K. Bucknall, Bridge Engineer, British Rail Southern Region

The need to carry out all construction activities in such a way that the passage of railway traffic can continue unhindered is almost a guiding principle of the working lives of railway engineers.

118. In Southern Region we have not had occasion to use the fabricated in situ system of pipe jacking, except for a relatively small stream culvert of 4·8 m span which consisted of two box units. Although the cover was only 800 mm to the underside of the sleepers there were no unforeseen problems. The track was tied laterally.

119. The MPU system is well illustrated by the work involved in the construction of the bridge at Wandsworth which was completed in 1971. While this was some time ago, the recently completed bridge at Old Ford is virtually identical in cross-section to that at Wandsworth.

120. The abutments and pier were of three tier construction and unexpected settlement of the track and embankment top of some 2 ft 6 in. during the installation of the bottom tier only, caused reconsideration of our ideas about railway embankments. It had been assumed that embankments that had been in service for over 100 years would have been uniformly well consolidated. The mining was carried out carefully and there was no evidence to suggest over-excavation or runs at the face. The settlement was almost certainly caused by redistribution of large clay lumps that must have caused very considerable voiding above the bottom tier level. It was, of course, problems like this that led to the development of the drag sheet.

121. It was somewhat ironical that grouting of the embankment had been programmed, but at a high level to consolidate the bank for the passage of the top tier, which gave little trouble. I am not sure whether this illustrates that the grout was effective or unnecessary.

122. A feature of the MPU system that must not be forgotten is that jacking must be

continuous. On a long drive, in spite of intermediate jacking stations, if operations cease for a lengthy period there is a real danger that in certain ground conditions the frictional build-up will be too great for the jacking forces to overcome. With this in mind it is clearly prudent to have available resources on stand-by to ensure that any earth movements, vertical or lateral, do not cause interruption to vital services. On each job carried out on Southern Region these resources were provided and utilized.

123. I should like to ask the Authors to comment on suitable waterproofing methods for the MPU system. Although individual units can be treated, the usual tanking is clearly out of the question.

124. As a satisfied client I would not wish in any way to decry the ingenuity and high standard of enterprise shown in these projects, but they can eventually prove to be more expensive than expected.

Mr P. M. Deason, T. H. Engineering Services Ltd

My company now considers that drag sheets are essential to the successful jacking of large units beneath roads and rail tracks if the overhead services are to continue without disruption. At Wandsworth settlements of up to 750 mm occurred, the maximum settlement being on the drive pit side and reducing to zero on the reception side. The bottom tier units which were the cause of this settlement were thrust through silty sands and gravels of varying compaction, and this stratum was overlain by firm silty clay, the interface between the two strata being a short distance above the roof of the unit. The settlements which resulted were attributed to compaction of the unconsolidated granular soils immediately over the roof of the unit due to the forward movement of the unit and the high friction at the soil/unit interface. The solution evolved to prevent a repetition in the future of such an event was to interpose a membrane between the soil and the roof of the unit, this membrane being termed a drag sheet.

126. The drag sheet is fed out from the shield at the front of the unit between the soil and the top of the unit, and anchored off in the thrust pit against the head wall walings. By introducing lubrication between the roof of the unit and the drag sheet, the sliding is induced between the drag sheet and the unit rather than between the soil and the drag sheet. This prevents to a very large extent the disturbance of the soil which results in settlement like that at Wandsworth.

127. While the drag sheet was evolved for granular soil conditions, it is equally effective in firm to stiff clays where there is a tendency for the clay in contact with the roof of the unit to adhere to the unit and advance with it, thereby scouring out a void into which the overburden can settle. Also, when the units are deep there is little risk of pushing out the prism of soil overlying the unit, which is a real possibility where the cover is small. Here again the drag sheet comes to the rescue since the frictional force tending to displace the soil prism is very much reduced by the presence of the drag sheet. If friction is to be minimized, of course, the roof of the unit must be finished to very close tolerances; bentonite lubrication also reduces the friction still further.

128. The standard drag sheets are manufactured from reinforced rubber or plastic conveyor belting, but for long pushes with very shallow cover, as for example at Brent Cross and also the job in Durban, there is a risk of some movement of the overlying soil prism due to the extensive elastic extension of the drag sheet before slip occurs. In these circumstances, a multi-layer steel drag sheet which gives maximum strength with minimum extension has been successfully used.

129. As the techniques of thrust boring become more widespread, the problems to be tackled by the techniques become more and more complex. If these are to be successfully overcome, the technical and construction expertise must develop in step. The invention of drag sheets was a response to just such a situation, and similarly it has been necessary to develop other new techniques to deal with projects in the last few years, in particular the multi-tiered bridge abutments such as Old Ford and Wandsworth. Such structures require very close tolerances in driving if the slide path for the sliding in of the deck is to be installed quickly and accurately, and very careful jacking techniques and

guidance techniques are essential, especially where multi-precast unit systems are adopted for all three tiers.

130. The temporary works associated with multi-tier construction also require very careful design, since they have to be modified as each tier is installed. Over the last few years a number of techniques have been developed to deal with a wide variety of different site and ground conditions. The great advantage of the technique is its flexibility to meet these different conditions.

Mr W. W. Milton, Engineering and Power Development Consultants

Having read the Paper, one is only too well aware that this is a very specialist technique. Do the Authors see in the foreseeable future that pipe-jacking techniques of this size will become a commonplace method of civil engineering?

132. Mr Pearce stated that this is a specialist contractor's work where it is desirable that the contractor be brought into discussion with the engineer at an early stage. On large projects this could make the overall contractual position untidy. Do the Authors consider that this type of work will be carried out on a nominated sub-contract basis—in competition, I am sure—or do they see that major contractors in the near future may well develop the technique themselves? There is a danger that as this work becomes a little more commonplace, engineers may get ideas of how they believe the techniques can be used, and I shudder to think what may happen.

Mr H. E. Eilenberg, Consultant

The Authors and contributors have described a number of successful thrust bores with shallow cover. I should like to point out a potential source of trouble when wide span rectangular box culverts are thrust through cohesive soils with appreciable cover. Unless the shield is stiff, the leading edge of the shield roof may be deflected downwards on entering the bore. If this is not detected and rectified, the lead unit behind the shield will be thrust into a tapering hole of diminishing height, and the shield will be deflected further. This process will continue until, at some distance from the entrance to the bore, the lead unit will have been squeezed sufficiently for it to break, since it is unlikely to have been designed to overcome the potential passive resistance of the overburden soil.

134. At this stage it will have become clear that something has gone wrong; the lead unit will probably be propped and the height of the face excavation monitored. But if thrusting continues it is likely that subsequent units will break as they pass the place where the lead unit was broken.

135. A stiff shield, propped against deflexion, together with careful monitoring of deflexions, would help prevent the difficulties described above.

Mr K. Sriskandan, Department of Transport

The Authors have, in their introduction, suggested that there may be a case for thrust bored underpasses at an existing intersection of a dual carriageway and single carriageway at a roundabout. In urban areas, underpass solutions have been adopted, but all have been of the cut and cover type. In most cases there would be a large number of services to divert and this would militate against the use of thrust bored underpasses.

137. In semi-urban and rural areas the flyover solution is by far the more economical and there are many examples of 'temporary flyovers' which have been adopted on the outskirts of London.

138. I would say therefore that in the general case whether it be urban or rural, the economics, even taking account of the costs of disruption to traffic, would lead to solutions other than thrust boring.

The Chairman, Mr R. B. Hill

The abutment thrusts are very interesting and I wonder whether the technique could be taken further. Clearly in the Wandsworth case and at Old Ford, although the abutments were thrust, the bridge beams did involve line possession and therefore traffic disruption, although this was only a small proportion of the construction time.

140. Could this in certain circumstances be avoided, particularly if the site characteristics demanded it? For example, if there were some ancient building or place of beauty to be preserved, and conventional tunnelling techniques were, for some reason, not practicable, would it be possible to thrust the longitudinal construction members themselves, and stress them in position. This would probably be an expensive process but in thrusting rectangular boxes it really does not make any difference whether they are thrust laterally as abutments or longitudinally as beams. Perhaps the Authors will comment on whether that is a practicable proposition.

Mr R. C. Owen, W. S. Atkins & Partners

I was interested to read of the study with the DoE on the use of three lane boxes for motorways. I have in mind a project which would involve between $\frac{1}{4}$ and $\frac{1}{2}$ mile of such tunnel. What additional problems would be faced with a tunnel of that length, bearing in mind the maintenance of horizontal and vertical curvatures that are necessary for high speed roads?

Mr A. M. J. Wood, Resident Engineer, British Rail Eastern Region

I have been closely connected with three large rectangular thrust bored contracts, one the Old Ford job, the others a large rectangular subway at Romford and a multi-tier installation under construction at Brentwood for the M25 motorway.

143. Mr Bucknall referred to the brief of engineers working for British Rail, which is to ensure the absolute minimum of disruption to services, and several of the installations mentioned in the Paper involved eventually cut and cover in order to complete the job. The three projects I mention were all done with speed restrictions.

144. At Old Ford there was a restriction to between 20 and 10 mile/h which lasted for 12 weeks. The closest the top tier came to the underside of the sleepers was 8 ft. This was subsequent to the job at Wandsworth so the engineers had the benefit of the knowledge of potential track settlement which occurred there. There was considerable track settlement in line with that occurring at Wandsworth basically with the installation of the base drives. One abutment was adjacent to a canal. The subsoil was granular and there was considerable track settlement arising because of this granular fill. As on all jobs on Eastern Region, permanent way gangs were kept standing by day and night while the job was in progress, continually topping up.

145. At Romford the subway was 15 ft wide by 12 ft deep. Speed restriction was 20 mile/h for 4 weeks with 14 ft below the underside of the sleepers. There were 26 precast concrete units 4 ft long, and the job was completed 2 weeks ahead of the 4 week speed restriction with virtually no problems and minimal track disturbance.

146. The job at Brentwood is again a multi-tier construction. There are to be 12 weeks of 10 mile/h speed restriction. The minimum level is 12 ft from sleeper bottom. The base units are all in very good clay and there has been minimal disturbance to the track. At the centre tier units there were some problems with voids and water courses. At the top tiers, there is a slip plain area which has been treated with a bentonite and cement PFA grout mixture in the hope that the ballast, which is used to back-fill the slip plain, will have the consistency of London clay when it is mined.

147. All these jobs on the Eastern Region have been reasonably successful, but from the supervision point of view it has been very worrying while the job was in progress. At the time, the costs are frightening. I find that trains had to be stopped over sections of the tracks for only 5 h on one of the jobs and the same time on the current Brentwood job when there was an inrush of water.

148. The Paper refers to the dimensions of the jobs but there is no mention of costs. It would be of interest if the Authors could make some reference to costs per metre run, or just the contract value of some of their jobs.

Mr R. V. Watts, Rendel, Palmer & Tritton

The Authors refer to underline railway bridge 47A at Old Ford and, as one who was closely associated with it, I should like to make a few observations. The construction of this bridge, as the Paper mentions, was particularly complex for the reasons given and, with a multiple track layout together with points and crossings and the overhead system of electrification, was considered ideal for the pipe-jacked system of substructure.

150. Mr Bucknall has commented on the track subsidence at a somewhat similar bridge site at Wandsworth, which contract was undertaken before the advent of drag sheets. Drag sheets were developed, as described in the Paper, to counteract ground disturbance caused by forward movement of the units and were used at Old Ford. The reduced ground disturbance obtained with the use of drag sheets did not eliminate track settlement but reduced the rate of settlement such that track levels were able to be maintained by a permanent way gang packing ballast beneath the sleepers when necessary. At Wandsworth I understand the settlement was quite sudden, whereas at Old Ford it took place gradually.

151. A point which should be mentioned is that at Old Ford and at Wandsworth the tracks are on an embankment. The age of the embankments is such that the specification for materials and also methods of construction were possibly not as rigorous as present day standards would demand. Also, over the years some of the fines in the embankment construction might have been washed out, leaving the remaining material to become unstable when disturbed.

152. Notwithstanding the problems of settlement that have arisen in the past I feel there is much to commend the pipe-jacking system for installing bridge substructures at multi-tracked sites, particularly those with overhead electrification, as there is less disturbance to the railway. I do not, however, think that for single or double plain tracked routes, even those which are electrified, the system is economical as the costs involved in constructing drive and reception pits, installing jacks and setting up site etc., are relevant to all references, whatever the length of drive involved.

153. An instance I would cite in this respect is that of a 15 m span bridge carrying two plain tracks electrified on the overhead system. There was an existing small span brick arch bridge at the site and it was proposed to construct one of the new abutments beneath the existing arch, the second abutment being of pipe-jacked construction through the embankment. However, the cost of the pipe-jacked abutment was found to be sufficiently expensive to warrant inspection of an alternative scheme. This alternative, although requiring a much larger span of 30 m and with transverse sill beams supported on piled foundations, was considerably cheaper and proved very satisfactory.

154. The Authors mention that close control on alignment is imperative. I most certainly agree with this, particularly with regard to vertical alignment in order to facilitate the sliding or rolling-in of the bridge superstructure. In the case of the bridge at Old Ford a survey was carried out on the soffit of each of the upper thrusts to establish prior to the sliding-in of the superstructure the degree of inaccuracy between units, in order that an approximation could be made of the packing and shimming necessary for each point of support of the sliding-in tracks. Ideally it is preferable for the upper thrust units to be of the type incorporating removable lids so that sliding tracks can be assembled in position to correct line and level prior to the possession for bridge sliding, but where multi-span structures are involved this would necessitate wider piers and these are unlikely to be favoured by highway authorities.

155. Finally, a further aspect that I feel requires more research is that of providing for drainage at the backs of abutments as it is my belief that none of the various methods adopted with pipe-jacked abutments are as effective as the usual continuous rubble filter provided for abutments built in situ.

Mr J. S. Boothman (Member)

In 1969–71 I was involved with the construction of the Watford car park access tunnel and of the Derby ring road bridge as an employee at that time of British Railways,

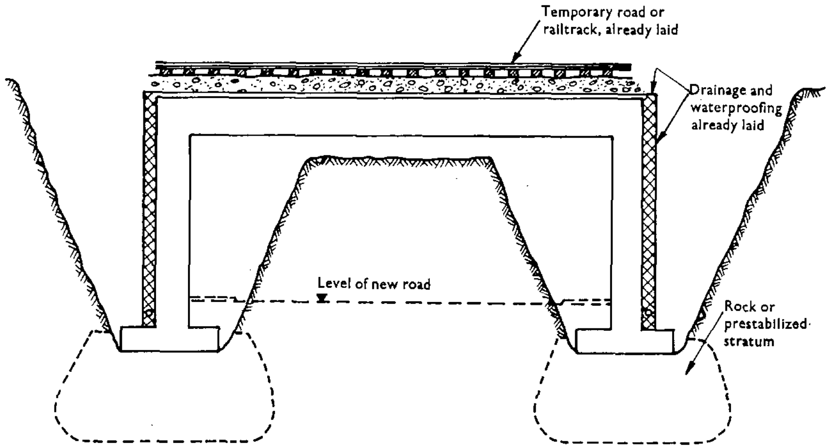

Fig. 17. Scheme for thrust installation of portal bridge

Midland Region; consequently I have already some limited knowledge of the processes described in the Paper. I should like to put forward some questions and suggestions.

157. It was explained that the use of drag sheets would have prevented or reduced the ground settlement caused by the installation of the bottom tier of units at Wandsworth. However it seems to me that subsequent thrusting of the upper tiers would then cause the sheets to ruckle up in front and so cause worse consequential problems. There would appear to be potential difficulties in restoring the frictional resistance to forward sliding at this interface due to earth pressure after removal of the dumpling. How has this been overcome?

158. Mr Wood referred to the installing of multi-tier abutments for a bridge to carry the Eastern Region railway line over the M25 motorway at Brentwood; from my recollection of the site the railway is here on quite a high embankment so that the upper tiers must be well above the thrust pits, and in addition the pits are comparatively long. Thus there appears to be no convenient strongback against which the upper thrusting jacks can react. The problem might be overcome by installing two half units simultaneously from opposite directions by means of pulling on cables tying between them through the bank, but an explanation of the method to be used will be welcome.

159. The solid grouting of the bearing strata for the Wandsworth Bridge and others and the rock foundations for the Milton Keynes headings must have involved some difficulty in excavation compared with softer ground. In such conditions it seems to me that it is not particularly necessary to have a complete floor on the bottom units. Since also the amount of dumpling to be excavated and the amount of accurate trimming to level in front of the shield would be consequently reduced, omission of the middle part of the floor should lead potentially to faster installation (Fig. 17).

160. I suggest that this arrangement would be most appropriate for large open cut drives where mucking out is external rather than through the structure. In fact these units could then be merely portal frames with slab strip feet, and the ground friction contact area will be minimized. If necessary the drive path beneath the feet could be pregrouted to ensure its bearing capacity during the drive, and also bentonite lubricated.

161. Under these conditions it should be possible to install a complete single-span portal bridge of any required span in only the time necessary to excavate a path for its legs and then to backfill behind them to restore the track or roadway, e.g. perhaps a long weekend such as was later required for the main bridge portal at Derby. This may be a solution to the hopes, raised by other contributors, of the possibility also of installing

bridge decks by the systems described in the Paper, although I should think that this application may be economic only in singular conditions.

Mr N. W. W. Cockroft, formerly Sir Bruce White, Wolfe Barry and Partners

As Chief Bridge Engineer to Sir Bruce White, Wolfe Barry and Partners I was responsible for the design and construction of Brent Cross flyover. Naturally, it was not foreseen that some 10 years later large tunnels would be driven between and beneath the foundations, and the risk of damage to the flyover gave rise to concern. The DoE therefore required that the design of the tunnels and the construction methods should be approved by us, and that we should monitor the movements of the retaining walls, piers and road surfaces in order to ensure that damages should be minimized.

163. When constructing the flyover we found in some areas, including part of the site of the north tunnel, made ground consisting of rubble apparently arising from the Hendon sewage works which formerly occupied the site. This rubble, being some 30 years old and reasonably well consolidated, was left in place, and when the proposal to drive tunnels through the embankment was submitted to us, we warned the engineer of the suspected presence of large pieces of brickwork and concrete in the rubble. In the course of transmitting this warning to the contractor it appears to have become distorted into an erroneous statement (§ 57) that large pieces of material were used in constructing the embankment.

164. At the North Tunnel, levels were taken on the road surfaces throughout the work, and settlement of the main carriageways did not exceed 20 mm, requiring no remedial action. Settlement of the order of 50 mm in the west sliproad was corrected on completion of the tunnel by relaying the kerbs, verge and footway and applying a hot-rolled asphalt carpet to the carriageway. At the east sliproad, the tunnel is so close to the carriageway surface that complete breaking-up of the carriageway was unvoidable, but two lanes were kept open to traffic at all times as described in § 72.

165. The major problem arose from the combination of additional horizontal forces on the east retaining wall during the approach of the shield with the need to cut out most of the wall's foundation over the width of the tunnel. Struts could only be placed below sliproad level and, to prevent overturning, ties near the top of the wall were needed in addition, and the upper part of the wall had to be strengthened. The ties were anchored to a bearing wall, constructed immediately behind the west retaining wall, not to the west retaining wall itself.

166. Replacement of the footings of the east retaining wall by a sand/PFA/cement concrete in a preliminary underpinning operation enabled the roof overbreak to be minimized—a few millimetres only. Vertical movement of the wall was less than 10 mm and the final departure of the top of the wall from true gradient is imperceptible. Calculations of the shield pressure indicated an extension of the tie bars of 10–12 mm, and the horizontal movement of the top of the wall was actually measured to be 12 mm. On completion, the tie bars were left in, although the wall is stable without their assistance. Some vertical and diagonal cracks occurred in the wall and existing cracks had extended, but the amount of cracking was small and of no structural significance. In order to prevent future staining of the concrete by water seepage, the cracks were sealed with an epoxy resin compound.

167. At the South Tunnel the two end sections were installed without difficulty, well within the permitted periods of sliproad closure, and this part of the work calls for no comment as regards protection of the existing works from damage. The centre section, however, passes so close to the foundations of the south approach viaduct of the flyover that Cementation Projects Ltd were unable to guarantee that pipe-jacking would not in this case cause excessive settlement. This part of the work is therefore not strictly within the subject of the Paper; nevertheless the problems involved are of great interest and merit description.

168. The viaduct consists of four 15·24 m simple spans of prestressed concrete pseudo-slab construction on reinforced concrete piers (piers 7–9). Each pier consists of

two independent portals comprising a lintel beam and two columns with reinforced concrete footings 2·75 m square, and rests on a mass concrete slab approximately $20 \times 4 \times 0{\cdot}75$ m (wrongly shown as PFA in Section AA of Fig. 13). The pier loads are transmitted to the London clay by a layer of consolidated hoggin.

169. Thermal movement of the deck is accommodated at piers 7 and 9 by hinges at the bottom of the columns, the deck being dowelled to the lintels, and at pier 8 by an expansion joint and rubber bearings. The columns of pier 8 are monolithic with their footings, but as horizontal forces on the pier due to thermal movement of the two halves (N and S) of the viaduct are opposite in direction and approximately equal in magnitude, only nominal reinforcement is provided in the columns.

170. As the deck is statically determinate, uniform vertical settlement of a pier induces only small stresses. A limit is imposed by consideration of the road profile and of the appearance of the viaduct, and settlement of up to 25 mm would be imperceptible.

171. Differential settlement between the two sides of a footing, however, causes movement of the pier relative to the deck. At pier 7, on the north side of the tunnel, this is absorbed by the hinge, and a footing rotation of at least 5 milliradians additional to the thermal movement can be permitted, but at pier 8 it produces shear forces in the rubber bearings which in this case are all in the same direction. It was found that a footing rotation of more than 2·5 mrad would give rise to a risk of overstressing the column reinforcement.

172. As differential settlement is sensitive to local variations of soil properties, calculations in advance of the work can only give a rough guide to the probable amount. Therefore although the calculations did not suggest a great risk of excessive differential settlement, we considered it necessary to make provision for correcting any excessive movement. Preliminary tests showed that the mass concrete foundation, after 10 years ageing, had achieved a strength equivalent to grade 30, and that the pullout strength of Macalloy bars grouted into the mass concrete with epoxy mortar was at least equal to their tensile strength. Each column was therefore supported by a group of Macalloy bars grouted into holes bored through the footing into the mass concrete and prestressed to a total load of 100 tons, approximately half of the maximum load on the column. The intention was that in the event of settlement approaching the permissible limit, the foundation would be jacked up to eliminate the settlement and possibly to produce a small rotation (about 1 mrad) in the opposite direction. The resulting small cavity below the foundation would be grouted up before releasing the uplift force. All concerned were very relieved that the necessity for this very delicate operation did not arise.

173. The stresses actually arising in the columns were estimated by measuring the deflexion of the columns relative to a line perpendicular to the plane of the footing. A plumb line attached near the top of the column was read against a bracket fixed near the bottom, and levels were taken on four reference points near the corners of the footing. The permissible deflexion being 10 mm it was specified that the plumb line must be read to an accuracy of 1 mm, to give an accuracy of 10% of the permissible maximum. Plumb lines were enclosed in PVC pipes to shelter them from wind and the plumb bobs were immersed in oil, and even in high winds were sufficiently steady to be read to the nearest 0·5 mm. As the gauge length for levels was only half of the length of the plumb line, the levels were required to be read to an accuracy of 0·5 mm, which proved unexpectedly difficult. Finally a Wild N3 level and Invar staff were obtained and proved capable of higher accuracy than was required; closing errors rarely exceeded 0·05 mm except in extremely bad conditions of poor light and severe vibration.

174. Movements of pier 8 corresponded closely to the expected pattern but were generally smaller than expected, the maximum column deflexion being only 2 mm. The calculated minimum compressive stress in the column was zero, subject to an error of ± 1 N/mm^2. Footing movements at pier 7 also corresponded to the progress of the work and were smaller than expected, while column movements corresponded as expected to temperature changes.

175. Throughout the work we have received the fullest co-operation and assistance from the Engineer, J. H. Coombs and Partners, from Cementation Projects Ltd and from the other companies of the Cementation Group who were involved. The successful installation of the tunnels with so little interference with traffic, and no permanent damage to the flyover, reflects great credit on them all.

Mr J. C. Thomson, Development International Trade Co Ltd

It is nearly twenty years ago, that as a Contractor, laying a sewer in the Peterborough area, I was faced with the problem of a difficult crossing under the main railway line. Based on information gleaned from an American engineering handbook I fabricated some equipment, bought some jacks and a hand pump and started pushing a corrugated steel pipe. That was the beginning of what today has become a substantial and sophisticated business. The Paper clearly illustrates the advances made in a relatively short period.

177. Being directly involved in the development of all the techniques and work described in the Paper I will confine my comment to the Acknowledgements. Frequently these are little more than a formal courtesy but in this case I believe that the assistance, encouragement and co-operation given by clients and their engineers has been very material in the development of these techniques.

178. The nature of the problems involved in the construction of a large underground structure by jacking methods necessitate first an involvement of the contractor from the earliest stages, second a close liaison between all the parties throughout the work, third a mutual understanding by all concerned of each others' problems in order to reach economic and viable solutions. Finally it is usual for there to be a number of key dates, such as rail possessions, that have to be met and which impose an overriding time discipline on the work.

179. Within such a framework the traditional barriers and demarcations of client, engineer and contractor tend to be blurred resulting in a combined contribution by all towards a successful end result.

Messrs Clarkson and Ropkins

The Authors would like to thank the contributors for the valuable comments on the Paper. It was interesting to hear **Mr Skudder**'s description of the Brent Cross project and the major difficulties involved, which placed the particular problems associated with tunnel construction in perspective.

181. **Mr Flemons** asked whether the techniques used at Old Moselle would be used now. There are now two alternative systems available which would be suitable on the basis of retaining the rail tracks in position. We could use a steel drag sheet which would be relatively inextensible to enable the unit to be thrust forward under the ballast with appropriate maintenance of track level by a permanent way gang. Alternatively the type of operation used at Durban could be adopted, where the rails were supported on skates as the sleepers there were only 300 mm above the culvert roof. The method used at Old Moselle would still be a viable approach if a short term closure of the line was acceptable, as this almost invariably provides the cheapest solution.

182. In response to **Mr Czechowski**'s questions, joint packing materials of a resilient nature are used in order to assist with distribution of load across the contact faces. Usually a joggle joint is formed in the abutting faces of the units in order to provide lateral restraint between adjacent units. Casting tolerances in the manufacture of units are necessarily tight in order to ensure good fit between units so as to achieve a uniform distribution of jacking thrust across the interface and to minimize lateral movement between adjacent units.

183. As mentioned in the Paper, additional reinforcement is normally provided in the units to withstand bending, torsion and shear forces due to lack of dead fit between units. This is achieved by assuming a non-uniform distribution of jacking thrust

through the unit: the degree of non-uniformity is a matter of judgement based on past experience of unit behaviour under installation conditions.

184. It is difficult to provide effective watertight seals within the wall thickness of rectangular units. This problem is probably best tackled by proprietary sealing systems placed subsequent to installation of the units. Rolling-ring type rubber seals have been used with some success in pedestrian subways of circular cross-section.

185. Determination of jacking loads is very much a matter of accumulated experience. Frictional and adhesive forces on the pipeline can be calculated from a knowledge of the ground properties as determined by the sub-soil investigation. The assessment of load required to provide the necessary face support and steerage capability is more a matter of judgement based on considerations of ground conditions and unit configuration in the light of past experience of similar jobs.

186. Provision of jacking reaction is usually an expensive part of the temporary works and experienced judgement is necessary to minimize construction costs, whilst at the same time avoiding the pitfall which many pipe-jacking contractors have fallen into of having the thrust reaction structure fail. On the Brent Cross North Tunnel for instance, we designed for 3000 t of jacking thrust at the rear unit and at the IJSs and in practice a thrust of the order of 2600 t was required.

187. With regard to the point of application of jacking thrust in MPU drives, we have found that if the centroid of applied thrust is located somewhat below the centroid of ground resistance we are better able to maintain a horizontal alignment of the drive. Twisting of units is avoided by careful control of the mining process within the shield and by inclining the shield with the steering jacks provided. The horizontal pilot heading suggested by Mr Czechowski would be regarded as essential where vertical boreholes along the line of the proposed drive are not possible.

188. **Mr Bucknall** and **Mr Wood** both deal with railway engineering problems. It may be fair to say that we have had a love–hate relationship with the railway engineers throughout the development work, and we have had our problems. One could infer from the fact that we are still on speaking terms that these were solved.

189. We are a little disturbed at the implications that jacking is an expensive solution and would refer to our comments on this point in the Paper. It is only when one takes into account in the equation the costs of disruption to road, rail or other services that in many cases the total cost falls clearly in favour of a pipe-jacked solution. We are hesitant to quote typical costs as requested by Mr Wood because they are so dependent on the particular ground conditions and locations that it can be misleading to generalize.

190. Mr Bucknall raised the question of waterproofing methods for the MPU system in the context of multiple tier abutments. Our approach is to cater for any water seepage through the abutment structure by forming drainage paths through the units, connected into a collector drain formed within or on the front face of the abutment structure. In the latter case the drainage system would be concealed by the architectural fascia.

191. **Mr Milton** questioned the possible future scope of this type of work. The Authors' view is that there will only be limited demand for solutions of this nature to meet particular problems and they will continue to be most economically solved by the early involvement of a specialist contractor.

192. We would agree with **Mr Eilneberg** that the shields must have sufficient rigidity to avoid distortion and account is taken of this in their design.

193. Turning to **Mr Sriskandan**'s comments on the use of such techniques for road works, we should generally agree that the first choice would probably be a flyover for a road intersection, and equally this would apply where it is necessary to cross a railway with a trunk road. However, in the urban situation there is always the problem of the impact of high level roads on the adjoining environment and in these circumstances there may well be some extra money available for putting the intersection below ground rather than at window level. One of the Cementation Group of Companies was recently involved in the construction of an underpass of the type referred to in the Paper. This

was constructed using what one might term conventional techniques. Having studied the solution adopted and considered the amount of land acquired for temporary works and traffic diversion, and the impact on traffic for the duration of the works, we think an alternative on the lines suggested could have been viable.

194. In reply to **Mr Owen,** the installation of a quarter mile long tunnel by pipe-jacking methods would be a major problem to examine. Certainly we can envisage a situation in which portions of this work could be carried out by jacking, and if there were sufficient access positions from which one could drive there is no reason to think that a total length of a quarter of a mile could not be built up by this method. The tunnels in Durban were in all over 160 m long and indicate that one can form quite long sections of tunnel by these methods.

195. In response to **Mr Boothman**'s question on the use of drag sheets for multi-tier structures, we would explain that the drag sheet used for the lower tier is removed from within the upper tier shield as the upper tier is progressively installed. The resistance to forward sliding of the upper units in the completed abutment is provided by the shear generated on the interface between the infill concrete and unit roof and by steel shear connectors placed through holes in the unit roof where appropriate. Many multi-tier abutments have incorporated vertical prestressing to form the integrated abutment unit.

196. Referring to the comment on the possibility of omitting the floor of the shield and unit, we think that this would only be worth considering in very hard ground or rock, in which circumstances jacking is seldom likely to be the economic solution.

197. The Authors acknowledge the interesting contribution by **Mr Cockroft** on the Brent Cross tunnels, and finally would thank **Mr Thomson** for his comments and assistance in preparing the Paper.

Reference

1. THOMSON J. C. Horizontal earth boring. *Proc. Instn Civ. Engrs*, 1967, **36**, Apr., 819–835.