*Discussion on Paper No. 6591**

Applications of soil mechanics in the design of stabilizing works for embankments, cuttings and track formations

by

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and

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Mr. A. H. Cantrell (Chief Civil Engineer, British Railways, Southern Region) said the Paper was an interesting one and contained a considerable amount of material for discussion. There was not time for him to comment on everything that he would like to speak on, but he would like to say that he considered that a good deal of progress had been made in the study and application of soil mechanics during the last twenty years or so. The Authors mentioned one of the first major blanketing jobs carried out on a railway in this country, at Hildenborough on the main line to Tonbridge. That had been done in his young days and he happened to be the technical assistant who organized the job. He well remembered that during the first week-end the Chief Engineer came to see how the work was getting on and considered that they were wasting money by going too deep. He therefore arranged that at future week-ends they should go 6 in. less deep, which was duly carried out. In § 116 of the Paper it was stated that after 11 years failure occurred and eventually the whole job had to be done again, but the failure of the original week-end's work had not occurred until several years later. In other words, the depth to which the blanket went was most important. Mr Cantrell was sure that if in those days they had known as much about soil mechanics as they did now that job would have been successful straight away, instead of having to be done again about 20 years later.

126. For some civil engineering jobs experience could still often decide suitable foundations, but he thought it was far more difficult in blanketing work or in any other work of that nature simply to go by experience and a soil mechanics analysis was most necessary if an effective job was to be done straight away.

127. To apply suitable remedial measures for slips was, of course, very important indeed for railways. A sudden blockage of the line was most disruptive to traffic. To get the track back into use as soon as possible was therefore important. It had been asked why the railways did not have a soil mechanics analysis made the whole way along their banks and cuttings. That was a lovely idea and he was sure that the Authors would like to organize the undertaking of works of that sort in selected places —not everywhere—but, of course, the money and the staff were not available. It was most important, therefore, that when a slip took place, although the maintenance engineers had to undertake first aid repairs at once, the soil mechanics experts should also come in at once, obtain what information they wanted or could get, and then advise on final remedial measures before the engineers had gone too far. In the case of an embankment the soil mechanics experts could often say what size of berm should

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* *Proc. Instn civ. Engrs*, vol. 21 (April 1962), pp. 705–732

be put in or, if it was difficult with surrounding property to have a big berm, what sort of sheet-piling should be put in; but that information must be available quickly. It was on those occasions that the soil mechanics section had to move quickly to get the information they wanted and work out what had to be done.

128. Sheet-piling, he felt, must be used with a great deal of caution. The piling, unless great care was exercised, would gradually give way, and unless present-day engineers were very careful in their design their successors in 20 to 40 years would criticise them for not having done a permanent job. If sufficient care was taken, however, it could be done. When sheet-piling was driven the greatest supporting pressure was obviously at ground level on the outside of the sheeting. This ground normally would have very little resistance power and could therefore be more or less discounted in the calculations. The piling, therefore, must go deep. He was sure that that was one of the prime considerations in putting in piling to stop any movement of a slip. It must also be realized that as time went on the fill behind the piling would consolidate, not only in the ordinary way but by the natural vibration of passing trains. It was no good, therefore, working with the pressures which might be obtained from reasonably new fill. Vibration was a dreadful enemy of a lot of excavation and foundation work and must be taken into consideration.

129. There was no doubt, of course, that in cuttings, where it was necessary to have support quickly, sheet-piling could be very valuable. There had been a case where the sheet piling would not have sufficed unless strutted back, and so they had strutted right across the railway line to sheet piling on the other side.

130. In § 39 the Authors recommended cut-off drains along the top of cutting slopes to prevent surface water flowing from adjacent property, especially if the cutting was in a side-long slope. He agreed that it was most important. Just a ditch cut in the clay was worse than useless; it must be a concrete channel, so that the water would not enter the back of the slope. He would not have thought, however, that the depth need be as great as 5 ft, and perhaps the Authors would give their reasons for quoting 5 ft.

131. In § 71 Mr Toms referred to Fig. 16 but had not done himself justice; he had not explained exactly what had happened there. The land was marshy and the bank of chalk had been built in order to keep the high tide out. The high tide after the sea wall had collapsed used to come up twice a day, go over the railway bank and flood very valuable agricultural and pastoral land, so that the River Board had wanted to build this bank as the quickest temporary remedy. The height of the bank had originally been fixed so as to be quite sure that the highest tides would not spill over, but Mr Toms and his colleagues said that 20 ft would be too much, the reason being that the weight of that bank on the soft ground would allow the middle of it to sink and there would be a crack right up the middle. The Board took no notice, and the result was as foretold. Mr Cantrell well remembered Mr Toms taking a photograph from inside the crack showing how at the bottom it was quite wide and gradually got narrower towards the top, giving a perfect illustration of what could happen to a heavy bank on soft ground.

132. With regard to what was said in § 56, he did not altogether agree that failures on soft ground formation would happen in the early days of construction. That was certainly generally true, but he recalled a slip which had occurred some time ago on a bank which was between 80 and 100 years old. Following a very long wet spell the ground underneath the bank softened and a slip occurred. He was sure that it was due to softening of the ground, but he accepted the Authors' statement that normally the ground would gradually consolidate and it was only during construction that there was likely to be this difficulty.

133. It was most important to continue with research on soil mechanics. Mr Bartlett had explained what he was trying to do but had admitted that the research people did not know nearly enough about some of the things they talked about and therefore must go on and on. The point was, of course, that by successful research on

soil mechanics a considerable amount of expenditure could be saved not only on new works but on maintenance. Successful soil mechanics research, whatever it cost, could amply pay for itself in time by the saving on maintenance. It was, of course, important that soil mechanics experience and engineering knowledge and experience should go hand in hand. The Paper provided good evidence that they were doing so.

Mr M. G. R. Smith (Chief Civil Engineer, British Railways, Western Region) observed that the Paper contained a great deal of interesting information and was unusual in at least one respect, in that the Authors disagreed on certain points. They had had the kindness to explain, however, exactly where they disagreed and where they agreed with each other. On one matter on which they seemed to agree, in §§ 89–91, they referred to unstable track formations and divided them into three types. As in the past immense sums of money had been spent on drainage, and very large sums were still being spent on drainage, he wanted to ask a few questions about drains.

135. In the Type 2 formation failure, the slurry penetration failure, a drainage system was clearly indicated. Presumably the Authors would agree that also in strength failure cases, Type 1, there was a case for drainage and it would be considered to be necessary in addition to blanketing; but did they foresee a time when blanketing might be sufficient and no money need be spent on drainage at all? They knew the trouble given by drains put in in the past, which were the root cause of some of the troubles experienced instead of the cure.

136. What did the Authors consider should be the standard policy on drain design? Should there be separate carrier and collector systems? What should be the maximum depth of a collector drain? What should be the fall for those drains? Should there be or should there not be foundations, concrete or otherwise, under the drain? What should be the diameter of the pipes? Should they be porous or not? Should they be perforated or not? Both types were available; should they be provided or not? Perhaps the most important point of all was what should be the back fill of the drainage trench. Many types had been tried. Most people seemed to favour ordinary gravel as the best back fill for a trench. Should that back fill of gravel (if it was the best material) be provided only for the collector drain, and should the carrier drain, presumably below that, be sealed? Was stone dust a good material as a filter material for the sides of drainage trenches? Would water continue to flow through it after a number of years? He was beginning to be a little doubtful about that in some places. What was the best blanketing material to use in normal cases?

Dr C. P. Wroth (Lecturer, Engineering Department, Cambridge University) said that it was pleasing to see the success which British Railways had had in locating actual slip surfaces by means of inserting expendable liners and polythene tubing in boreholes. He had known that such work was going on, but this was the first time he had seen detailed results published. It was very satisfactory to have in Fig. 2 examples of slip surfaces defined so accurately by this method; and such evidence provided valuable confirmation of assumptions made in embankment design about the shape of the likely slip surface.

138. He wished to take issue with the Authors over §§ 28–35 regarding the behaviour of over-consolidated clay. The behaviour of a saturated clay sample during consolidation and subsequent shear was best illustrated by two diagrams closely inter-related. In Fig. 41, the moisture content w of the sample was plotted against the effective normal stress σ' $(=\sigma-u)$. Directly above, in Fig. 40, the shear stress τ was plotted against σ'.

139. He wished to consider a normally consolidated sample, represented by the point P (in both diagrams). If an undrained shear test were carried out on this sample, its condition throughout the test must be represented by a point on the line APB in Fig. 41 since the moisture content would be kept constant. As the test progressed a positive pore pressure would be developed, while the effective normal stress σ' would be correspondingly reduced; and the sample would take the path PQ, in both diagrams.

At the point Q failure would occur and the sample could then undergo unlimited deformation without further change of any of the three variables w, σ' and τ.

140. If instead the sample underwent a fully drained test from P, no pore pressure could develop and σ' would remain constant so the sample's condition would be limited to the line CPD in Fig. 41. As the test progressed the sample would expel water, contract in volume and follow the path PR, reaching failure at R where no further change of w, σ' or τ would occur.

141. On the other hand an overconsolidated sample starting from the point S would behave in an opposite manner. In an undrained test, with w constant, it would develop

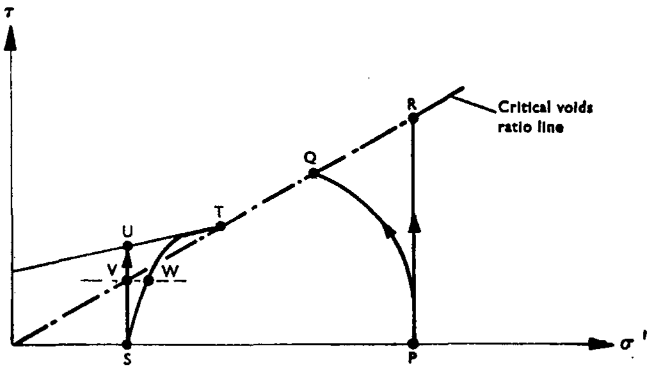
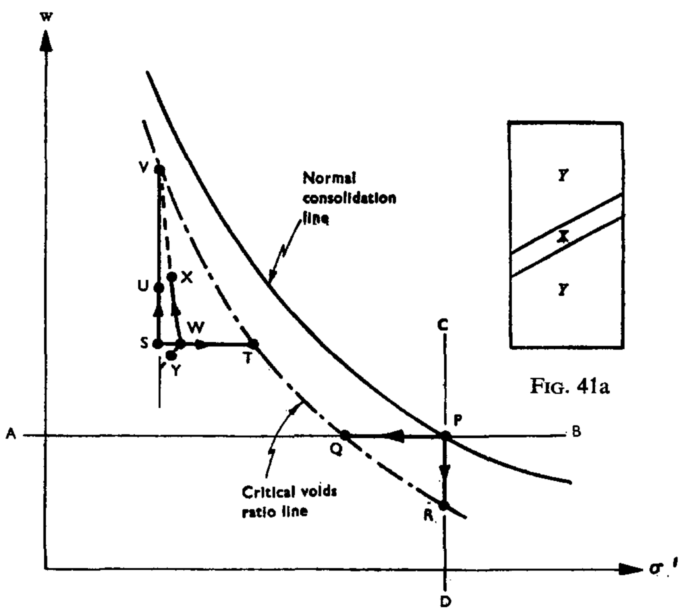


FIG. 40



FIGS 40 AND 41: TYPICAL SHEAR TEST RESULTS ON SATURATED CLAY SAMPLES

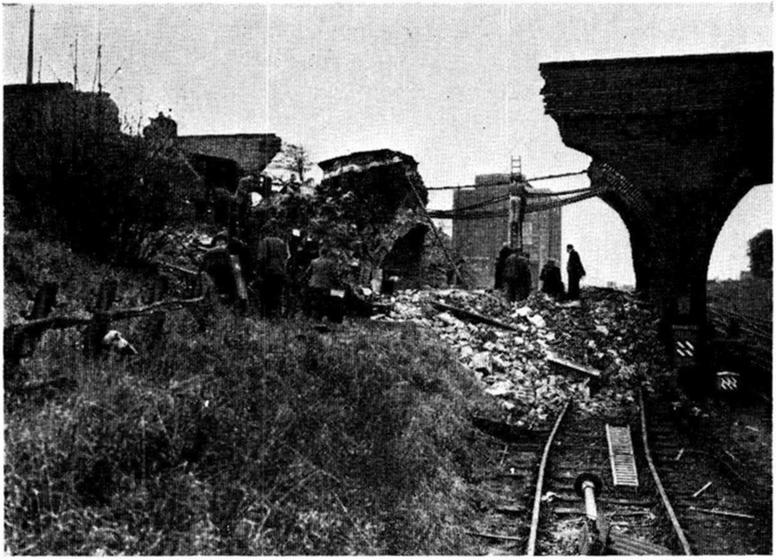


FIG. 45: ASPINAL ROAD BRIDGE—COLLAPSE OF TWO ARCHES DUE TO SUDDEN SLIP

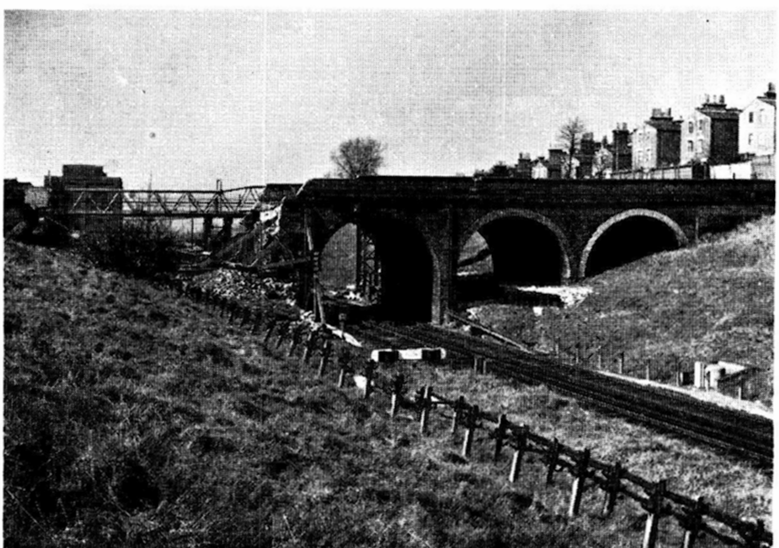


FIG. 46: ASPINAL ROAD BRIDGE—PILING AND STRUTTING, TEMPORARY FOOTBRIDGE IN BACKGROUND

FIG. 47: HONOR OAK PARK STATION—REMEDIAL PILING

FIG. 48: TOP OF SLIP AT HONOR OAK PARK STATION

FIG. 49: COLLAPSE OF CIRCULAR WING WALL CAUSED BY EARTH PRESSURE DUE TO SLIP

FIG. 50: EMERGENCY MEASURES TAKEN DURING SUNDAY TO OPEN LINE TO TRAFFIC AFTER COLLAPSE OF CIRCULAR WING WALL

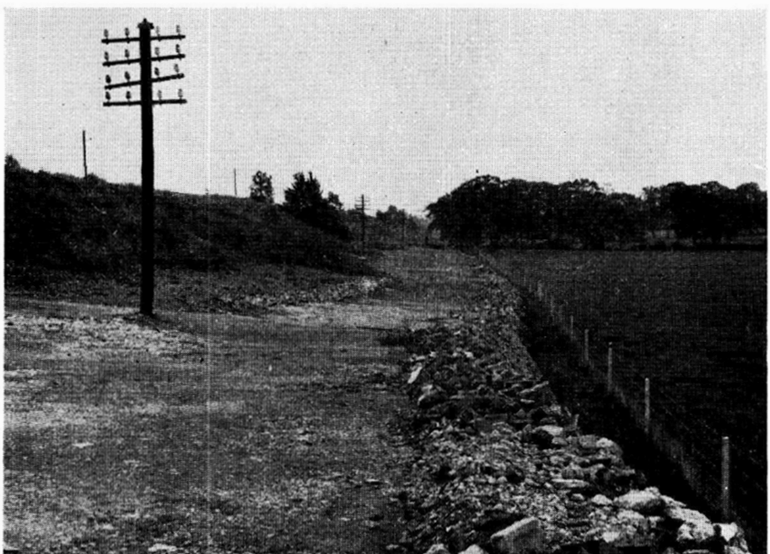


FIG. 51: ADVANCE MEASURES TO PREVENT SLIPS OF SOFT EMBANKMENT—HILDENBOROUGH, KENT

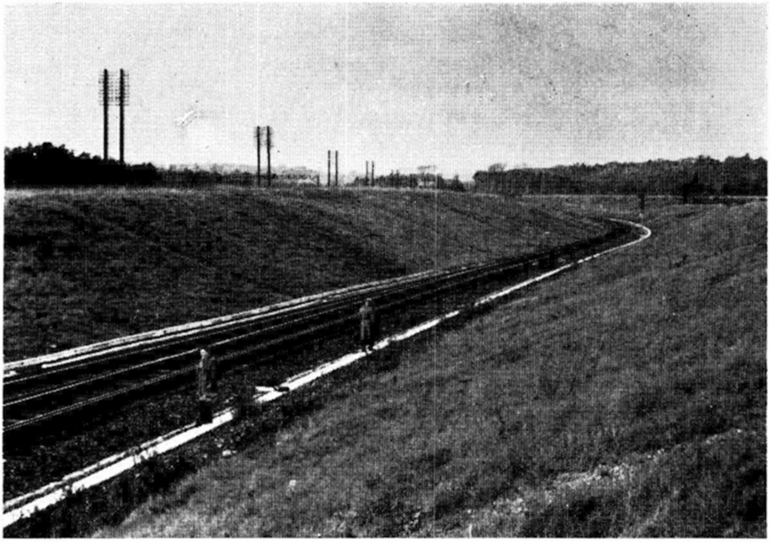


FIG. 52: SHOWING $2\frac{1}{2}$ TO 1 SLOPES CONSTRUCTED IN LONDON CLAY FOR NEW LOOP LINES, CHISLEHURST. NOTE GRAVEL DRAINS

FIG. 53: 1938 FORMATION BLANKETING OF WEALD CLAY USING SMALL SLABS—FAILED AFTER 22 YEARS

FIG. 54: FORMATION BLANKETING OF LONDON CLAY AT CLAPHAM JUNCTION USING "ONE-PIECE" SLABS—STILL FUNCTIONING WELL

FIG. 55: GENERAL VIEW OF "ONE-PIECE" FORMATION BLANKETING AT CLAPHAM JUNCTION

FIG. 56: SEVENOAKS TUNNEL SOUTH FACE—EARTH SLIP IN CUTTING 5 SEPTEMBER, 1958

FIG. 57: SEVENOAKS TUNNEL SOUTH FACE—CLEARING "PORRIDGE"

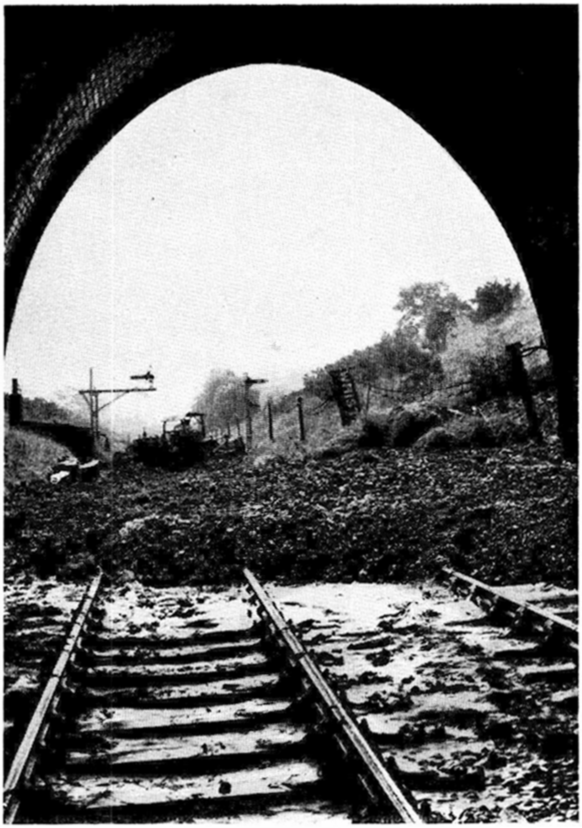


FIG. 58: SEVENOAKS TUNNEL SOUTH FACE LOOKING OUT FROM TUNNEL—CLEARING IN PROGRESS

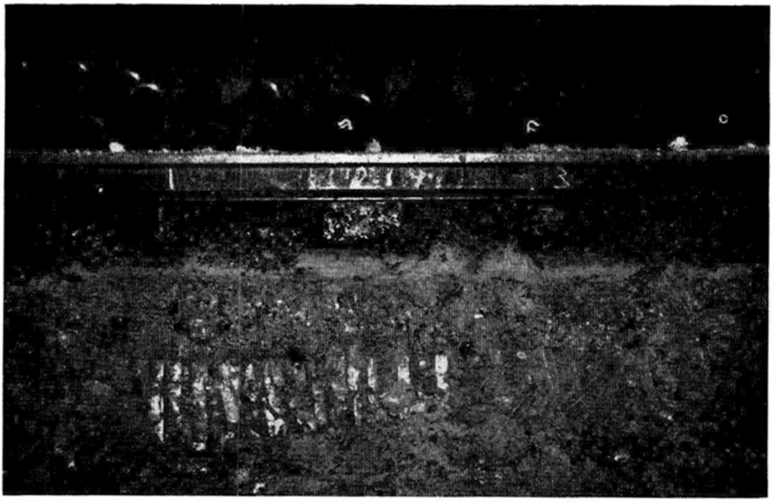


FIG. 59: EXCAVATION SHOWING CLEAN SAND OVER SLURRIED BALLAST ON HARD FORMATION

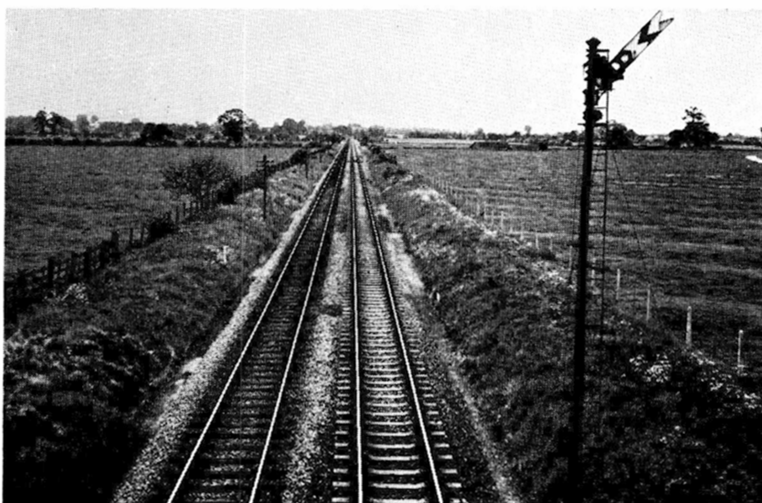


FIG. 60: LONG SHALLOW CUTTING OF WEATHERED CLAY WITH NO DRAINAGE WHERE STRENGTH FAILURE WAS CURED BY GROUTING

FIG. 61: SLIP AT HOOK, SOUTHERN REGION 27 DECEMBER 1960. FIRST STAGE—UP LOCAL UNDERMINED

negative pore pressure causing an increase of σ' (as τ increases) until failure occurred at T. Further deformation would cause no further change of w, σ' or τ.

142. In a fully drained test, σ' would be constant, and the sample would expand until failure was reached at U. On further deformation the sample would continue to *expand* under *decreasing* shear stress until an ultimate condition (allowing unlimited deformation) was reached at V.

143. It had been shown by Roscoe, Schofield and Wroth[4] that the points R, Q, T and V defined one unique line which had been termed the critical voids ratio (or critical state) line. It was important to realise that R, Q and T represented both the failure and ultimate conditions of their respective samples, whereas for the last case the two conditions gave markedly different points U and V.

144. This critical line was of great importance as it divided the sheep from the goats. On the one side were the well-behaved samples, the sheep, which work-hardened whatever was done to them and which gained in strength with time. On the other side, lay the goats which either developed negative pore pressure or dilated and softened, thereby losing strength with time.

145. When slope failures were analysed by the effective stress method the strengths used would be those corresponding to R, Q, T and U. The point that he wished to make was that for the last case (i.e. a failure of a cutting in an overconsolidated clay) the long term strength which should be used was the ultimate value *V* and *not* the peak value given by *U*. The ratio of these values would depend on the degree of overconsolidation, but would probably be in the range 0·5 to 0·8. He presumed that the peak strengths had been used to obtain the high, but evidently false, factors of safety quoted in § 35, for two slopes in limiting equilibrium.

146. The Authors might ask how the lower and ultimate shear strength could be obtained without passing through the peak strength first. He believed that the sample could do this by what he termed "dodging round the corner". Fig. 41a represented an overconsolidated (triaxial) sample which was to be kept without overall change of moisture content, and subjected over a long period to a fixed value of shear stress corresponding to the ultimate value *V*. As soon as this loading were applied a negative pore pressure would develop and the (stable) condition of the sample would be represented by the point W.

147. If for any reason (such as non-uniformity of loading or of the sample itself) the zone X was subjected to a marginally higher shear stress than the neighbouring zones Y, there would be a pore pressure gradient down the sample with a maximum within X. Water would be sucked into X at the expense of Y, without change of overall moisture content or of applied shear stress, and the states of the respective zones would be represented by the points X and Y in Fig. 41. This gradual process would continue until zone X had softened sufficiently to fail by reaching the state at V, *without* passing through U.

148. He believed that this was the explanation of the ultimate failure of "creep" tests mentioned in § 30. In this context he would like to ask the Authors to supply details of these tests:—

(i) How was the load applied?
(ii) What precautions had been taken to ensure that the sample had been at *constant* overall moisture content throughout the ten years?
(iii) What was the consolidation history of the samples? and
(iv) After failure, had any measurements been made to discover whether there was a gradient of moisture content within the sample?

149. Moreover, he believed that this behaviour also occurred in actual slope failures of cuttings in overconsolidated clay. The Authors had stated in § 29 that "clay from above or below the shear zone is considerably stronger", i.e. it had lost moisture content to the gain of the failure zone as the latter softened. This was to be expected, since

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[4] The references are given on p. 163.

there must have been marginally worse stress conditions in the slip surface itself, for otherwise the soil would have chosen a different slip surface on which to fail. Therefore he was bound to disagree with the second half of § 31.

150. He wished to ask the Authors whether or not they agreed that this was a possible explanation. If they took the lower value of ultimate strength given by V in place of the peak strength U, would it lead to more acceptable factors of safety for the two slopes quoted in § 35?

Mr F. J. J. Prior (District Engineer (London, Eastern), Southern Region, British Railways) said that as a District Engineer he might claim to represent the practical side, very largely at any rate. The District Engineers were most grateful to the research engineers for the investigations which they made and the advice which they gave them for design purposes, but it often happened in the inner London area that when trouble occurred the necessary remedial action had to be taken without the backing of the research engineers until later. They tried to do the work so that it would fit in economically with any scheme which the research people put before them later.

152. Another thing found in the inner London area was that slips usually took structures with them. In the country one was usually more fortunate and had a straight problem to deal with. Fig. 45* showed a bridge, a 5-arch structure, 2 of which had collapsed very suddenly due to an earth slip. Heave could be seen under the siding which passed through the second arch. The running lines, on the right, had not been affected. The failure had taken place suddenly. At 4 o'clock one afternoon a member of the public had seen the parapet courses slightly dipping and had reported it to some railwaymen; at 6 o'clock the supervisor was there, by 8 o'clock the D.E. had arrived and at 8.15 it was flat on the ground. That showed how quickly these things could occur.

153. Fig. 46 showed the collapse and the strutting carried out to hold the other piers apart and sheet piling. The failure was due to shallow foundations on London clay; the clay softened up and, it was suspected, developed a slip circle (see Fig. 42) similar to that which the research people discovered on the other side. It had been possible to design sheet piling to stop collapse there. The D.E. had been fortunate to have in stock the temporary bridge shown, which had been put up the following weekend.

154. Another slip was illustrated in Fig. 47. It carried the station canopy and the back screen wall forward to foul the track. It was in London clay which had very slow creep, barely perceptible over many years. It had been loaded on top outside the Commission's property, causing a sudden movement with the disastrous results shown. Fig. 48 showed the top of the slip. The overloading had not been very large, about 7 ft, but it had been enough to make the toe go. The soil mechanics investigation into it was shown in Fig. 43.

155. Fig. 49 showed another sudden slip which had occurred on a Sunday morning and affected the Up main line from Dover to Victoria. A woman in a house opposite heard a loud bang and called the police, and they called the station to stop traffic. A circular wing wall had collapsed with no warning whatever. It was suspected that it was due to earth pressure and a slip behind. In these days the section of the wall would probably not be considered strong enough anyway, but 3 ft had been left standing. The immediate remedial measure that was adopted was a line of sheet-piling in a circle and then the wall was rebuilt adequately. Another view was shown in Fig. 50. Fortunately or unfortunately there had been a motor cycle shop below which had acted as a prop to the slip when the masonry fell on it.

156. Fig. 51 was an example of action taken in advance, before trouble occurred, by constructing a berm about 350 ft long. The embankment had given rise to difficulties over a number of years. About 2,500 tons of rubble from demolitions in London, which had been obtained quite cheaply, had been rolled in with a 10-ton roller, and it stopped all movement.

* Figs 45–61 are photographs and are placed between pp. 144–145

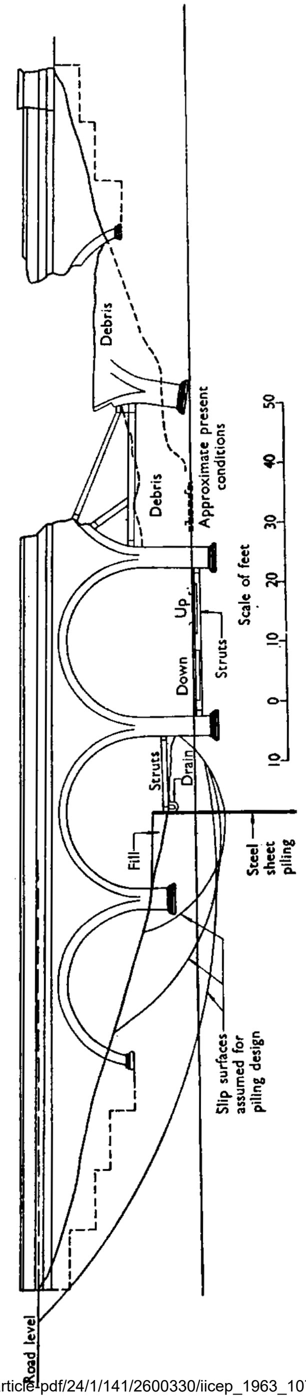

FIG. 42: ASPINALL ROAD BRIDGE—SLIP ANALYSIS

157. Fig. 52 was an example of the consideration given by Mr Toms to design and showed the design of new cuttings and formations for fast loops at Chislehurst. It had been coupled with soil investigations and considerable research into statistics of past types of cuttings of this nature. The two together had produced the design shown. The formation, in view of the trouble experienced previously on the old loops, was blanketed to 2 ft 3 in. thickness of quarry dust with 12 in. of ballast on top, and he hoped that clay would not be seen again for many years.

158. He had not known that other speakers were going to refer to the site at Hildenborough, but it had been mentioned by Mr Toms and Mr Cantrell. Fig. 53 showed the blanketing there, put in in 1938. It could be said that it had done its job. It had lasted for 22 years. Mr Cantrell had commented on one reason for its final failure, its shallowness. Another reason, which Mr Prior had found when he took it up, was the fact that the slabs had tilted in different directions and produced gaps of up to 10 in. The ash underneath them failed and the clay eventually flowed through the gaps straight up into the tracks. That work had now been taken out and the present normal type of blanketing put in, but he did not consider that the earlier work had been a complete failure as it had done its job for 22 years on a fast main line.

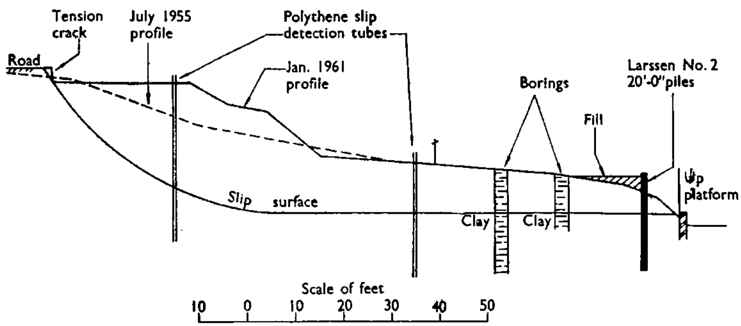

FIG. 43: HONOR OAK PARK STATION—SLIP ANALYSIS

159. Fig. 54 showed another site mentioned by Mr Toms with a one-piece slab going in. That was probably the reason for there being no sign of failure yet. Fig. 55 was a general view of the work at Clapham Junction.

160. On 5 September, 1958, there had been a cloudburst in the evening. There had been 80 landslides in Mr Prior's district and 40 in an adjoining district. They were surface slides. Fig. 56 showed the result in the face of Sevenoaks tunnel on the Dover main line. The depth was about 9 ft and water had been ponded back in the tunnel. Fig. 57 showed the scene on the following morning. The material resembled porridge. Fig. 58 was the view looking out from the tunnel. The trouble had occurred on a Friday night and the line was opened to traffic at 4 a.m. on the Monday morning. The permanent remedial measures took the form of a concrete toe wall and improved drainage.

Mr D. J. Ayres (Development Assistant, Civil Engineering Laboratory, British Railways, Western Region) said that the application of soil mechanics in investigation and analysis of a failing slope was of little use in itself as the Factor of Safety is already known to be less than 1. The real object must be to use soil mechanics if possible to reduce the cost of remedial works and to keep the trains running with the minimum disruption of traffic.

162. As a general approach to earthwork problems it was more economic to drain out water which was causing high stresses which led to failure than to construct to resist

those stresses, but it was still more economic to intercept the water in the first place. The impermeability concept was especially economic for clays.

163. The most successful method for treating embankment slips used very little soil mechanics theory. This was grouting and from the successful treatment of over 160 slips on Western Region he knew where to inject the grout and in what quantities with a good statistical idea of the costs beforehand. The system was cheap (from £5 to £7 per ft run of bank), with a swift result. There was one essential rule that a site, once started, must be grouted to completion without any delays of several days waiting for supplies of cement or sand.

164. The grout found its way into the slip plane or planes as it were without the aid of theory.

165. An interesting development was the grouting of slips in cuttings which had been successful on selected sites. There was water coming from behind the slip plane in these cases[5] but no further movement occurred either along the slip plane grouted or in the soil beneath. A slope at Hullavington had given trouble for many years[6] on the up *Bristolian* route and eventually the up track began to lift. Other measures having proved ineffective grouting was tried and movement ceased. The track had not moved from then up to the time of speaking although subsequent superficial movements on the slope well clear of the track had been dealt with by keying them to the main mass of previously slipped ground. Other cutting slopes such as the well documented Wood Green movement[7] and a larger slip in marl near Paris had also been successfully treated.

166. Regarding track formations, he disagreed with many statements in the Paper. When he had propounded the three types of failure (§ 89–91) many years previously, he had always insisted that the type of track movement indicated whether a strength or pumping failure was occurring as noted in § 104. Fig. 59 showed a hard formation on which a keyed pitching stone had been laid, when the track was constructed about 60 years previously. Above the pitching stone had been normal ballast supporting the sleepers. The track had failed by pumping and a 6 in. layer of fine uniform sand had been placed on the pitching stone and then 5 in. of ballast supporting the sleeper, in 1943. The figure showed this sand layer in position. The track now stood very well. The important fact of the previous pumping was that as a filter the ballast and not the formation had failed. Regarding § 90, Type 2 failure occurred independently of the strength of the formation, therefore application of the S.R. Design Curve Fig. 18 was irrelevant to this type of failure, as were the tests[2] described by King and Pitt in which failure of the Meldon dust by penetration was taken as a criterion. The latter tests merely proved that Meldon dust could fail as a filter, which was known, but a correctly graded filter would not fail[8]. Terzaghi's filter rule (§ 101) did not apply to cohesive subgrades. There was little need for the D_{15} size of the filter to be much less than 0·1 mm. An economic conclusion, applied to sites like Fig. 59, was that it was not necessary to excavate to the formation to treat pumping failure although on this and many pumping sites the S.R. design system § 96–100, and § 107, and Fig. 18 would suggest that deep excavation was necessary. Overstressing was obviously not a criterion of failure from an examination of the site. Track movement and the associated time-lag with rainfall were the only definite criteria of the type of failure. His design curve (Fig. 19) had only meant to be applied to sites where Type 1 failure had been established.

167. The soil movement was towards greater equilibrium, strength failure only occurring while the total system of distributing forces was greater than the restoring forces. Dead loading of the heaves § 121 confirmed this.

168. The trouble expended, § 102, in taking 4 in. samples was unnecessary for strength failure as the drained strength parameters of the clay were the controlling factor, i.e. it was an effective stress failure.

169. The weather strength cycle indicated that the clay was in the critical voids ratio condition, i.e. of continuous disturbance, and the Road Research Laboratory had produced data on most soils concerning the problem[9]. The values of ϕ' were mostly

in the range of $21° \pm 2°$ so that sites could be considered to have the same stability for the same water equilibria. He was thus now prepared to jettison his own design curve Fig. 19, along with the S.R. curve Fig. 18, and concentrate on the suction conditions upon which strength depended, for a more progressive approach. Measurements of stresses and strengths in the ballast and formation indicated in the Paper of the S.R., W.R., and British Railways Research Department work programme seemed to be irrelevant to the real problem in that they would only indicate the depths of excavation, i.e. a costly investigation into refinements of the most expensive remedial measure, viz. deep excavation with track occupations, speed restrictions and drainage schemes. This was not necessary, as excavation methods including a waterproof layer in the replaced ballast or subbase would only involve a depth of 2 feet whilst track grouting achieved waterproofing without track occupations etc. at a sixth of the cost.

170. This was a more practical approach in view of the many factors other than strength parameters affecting failure which he had tabulated[10]. The site in Fig. 60 showed a long shallow cutting without any drainage system, and where water lay in the cesses. Experimental sections of cementitious and bituminous track grouting had stood well since 1958 and seemed to preclude the necessity of drains. This method, shown in Fig. 33, was favoured where track occupations were undesirable.

Mr W. A. Lewis (Principal Scientific Officer, Road Research Laboratory), remarked that he had not intended to speak, regarding the proceedings as a railway engineers' benefit night, but the persuasive charm of the Chairman in appealing for non-railway speakers had made him feel that he should put in a plea from the point of view of the road engineer. He wished first to congratulate the Authors on their Paper. It was delightful to have a Paper which one could read and understand without having to spend many hours trying to comprehend the finer points of soil mechanics. Having said that, he wished to raise a number of points on the Paper which had occurred to him as he listened to the earlier speakers.

172. In § 33 the Authors referred to the fact that the Southern Region had carried out a statistical analysis of the stability of various slopes. When he read that he thought that this would be just what the Road Research Laboratory wanted, a Table showing for all the different soil types and depths of cut precisely what slope had been found to be stable; but, alas; there was no further mention of it in the Paper. He hoped that the Authors in their written reply would include some of this information. They must have a vast amount of very valuable information available.

173. Following on from there, he would like to know what was the type of slip that proved troublesome. The Paper gave the impression that many of them were the traditional deep-seated circular slips, and from reading soil mechanics Papers one would gain the impression that that was the only type that anyone worried about. On the roads it was very rare to find one of these slips which were so amenable to mathematical treatment; most of the slips were irregular surface slides and many occurred part way up the slope. Often the slips did not occur in the deepest part of the cutting as would be expected from theoretical considerations. To what extent was that the case with railways? To what extent did the railways get these deep slips? Was the real problem this surface instability, which was annoying from the point of view of maintenance but did not really lead to serious failure of the cutting in the case of railways or roads?

174. He was surprised that the Authors did not include as a possible remedial measure the use of vegetation, though they did mention grassing slopes. Many years ago Mr Toms had been part-Author of a Paper at a conference at which there had been a series of Papers on the use of vegetation in the stabilizing of artificial slopes. He suggested that the Authors should complete the present Paper by expressing their views on the use of vegetation to promote long-term stability. For long-term stability the planting of poplars and other fast-growing trees might be the answer. He would value the Authors' views on that matter.

175. The Authors described a large number of different types of remedial measure,

but he was left a little confused about the economics of them and in fact about the economics of the whole problem. Was it more economical to design a slope in terms of laboratory tests and get a slope for some soils of 4 to 1 which would be stable for the next 500 years or was it more economic to have a very much steeper slope which might last for only 20 years, and then remedy any slip if and when it occurred? To what extent but the economics of these various measures considered? A great deal had been said about grouting, but how economic was it? How economic was sheet-piling?

176. In § 56, dealing with the stability of underlying soil, the Authors briefly referred to the use of vertical sand drains and said that the long-term consolidation under bank loading could be accelerated by vertical sand drains, and they left it at that. He thought that that gave rather a wrong impression. A great deal had been said and written over the years about vertical sand drains. They had to be treated with caution. If the soils were very organic the vertical sand drains would not be very effective in accelerating settlement. Even with non organic soils there was little clear evidence to suggest that vertical sand drains accelerated the consolidation. They might, however, increase the stability by acting as sand piles, but the theoretical ideas on the subject did not necessarily work out in practice. In fact the work of installation of vertical sand drains might cause increased pore pressures and re-moulding of the soil and the cure might be more severe than the disease. A word of caution was required therefore in regard to the Authors' rather sweeping statement. He hoped the Authors would not be hurt by his saying that; they had written a very useful Paper.

Mr R. A. Hamnett (District Engineer, Woking, British Railways) showed a number of slides.

178. Fig. 61 showed the initial stage of a big slip at Hook at the end of 1960. The length was about 180 ft and within a couple of days had extended to 250 ft. The line shown suspended in the air was the Up Local and later the Up Main also went. The bank itself was composed of a core of rather silty clay overlain with an average of about 8 ft of clayey-sand. The natural ground on which the bank was founded consisted of 2 ft of topsoil over a shallow band of gravel about 2 ft deep, this being on top of stiff blue clay. This might be the slip which Mr Cantrell had in mind in referring to the long-term failure of natural ground. It was considered that the cause of this slip was abnormal saturation and the weakness of the natural ground.

179. Fig. 44 was a cross-section of the initial stage of the slip. The slip spread laterally in the London direction and in so doing broke a culvert and blocked a stream. The boreholes were of interest in that they were continued down into the ballast level and acted as drains to drain the pocket between the slip surface and the clay.

180. Calculations showed that the use of sheet-piling was not likely to be successful and it had therefore been necessary to have a berm. Unfortunately no road access had been available and so the berm had to be brought in wagons. That had meant that it was necessary to use a larger berm than would otherwise have been required because the weight of the berm material had first of all to go into the wrong place and tended to aggravate the slip. Other slides showed the sheet-piling by the damaged culvert, the sideways spread of the toe of the slip, the berm in course of construction, and the completed berm. The horizontal distance from the nearest rail to the toe of the completed berm was 190 ft. That was the distance over which the berm material had to be shifted, and there was over 20 000 tons of material.

181. Fig. 21 of the Paper was shown and indicated in more detail how the Down Local line had been heaved upwards. The treatment had been to move the fill from the top and form a berm and put in drainage. Afterwards the Down Local formation had been excavated and the track re-laid.

182. Another slide depicted a crushed 9-in. earthenware pipe at Horsley, and was of some interest because of the remarks of the Authors and Mr Cantrell on ditches at the top of cuttings. There was a ditch at the top of the cutting in this case and it had been felt that that was the real cause of the trouble. They had diverted the water from it but

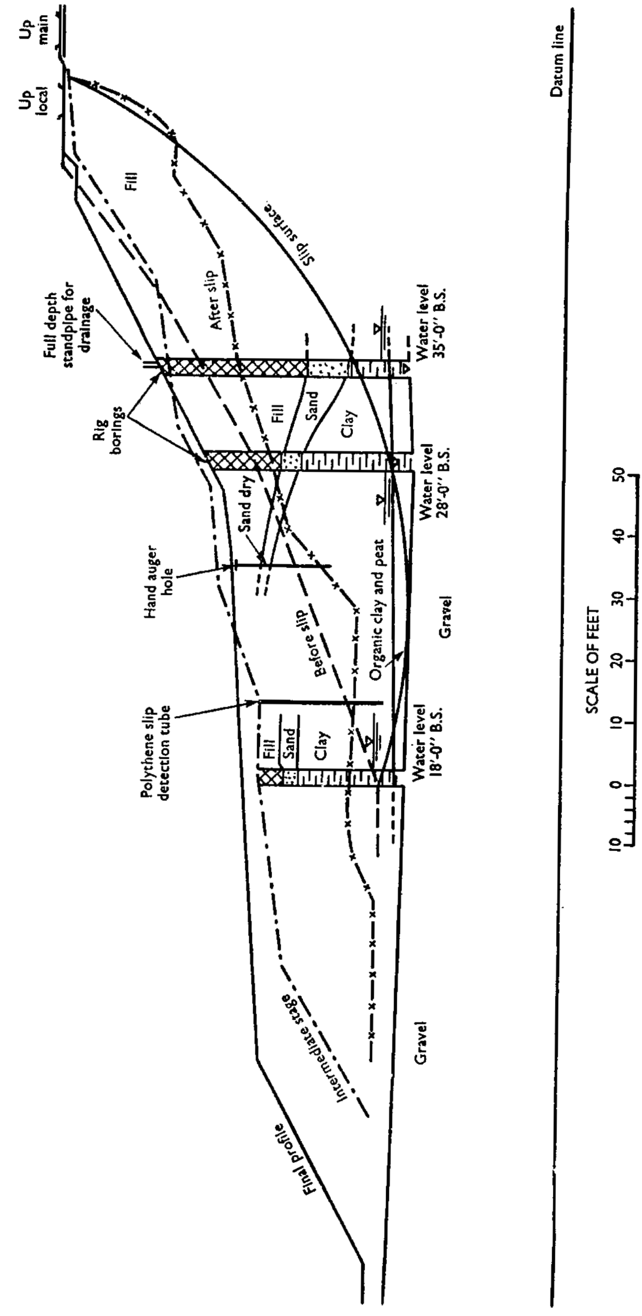

FIG. 44: SLIP AT HOOK, SOUTHERN REGION, 27 DECEMBER, 1960, SHOWING STAGES OF SLIP AND FINAL BERM

found that the slip still continued, and they had therefore decided to put in drainage with counterforts and an excavation had been made. Whilst that was being done the slip worsened and it was found that underneath the ditch at the top, about 18 in. below it, there was an agricultural drain and that had been the real cause of the trouble. The diversion of the water flowing into that had steadied up the slip appreciably. They had made excavations about 20 ft deep for the stop-blocks and these were converted into combined catch-pits and piles by putting concrete tubes inside them, placing old rail reinforcement outside the concrete tubes and concreting the space between the tubes and the edge of the excavation.

183. A sheet-piling wall which replaced a shallow mass-concrete wall which had been failing owing to the cutting slip and distorting the Portsmouth main line was described and illustrated. Mr Toms's investigation had shown that the soil was not sufficiently good to take a mass-concrete wall again and resort had therefore been had to sheet piling.

184. Another slide showed a similar job to one which Colonel Prior had described, undertaken soon after the last war, using rubble from bomb-damaged buildings in London. It was a berm at Witley, on the Portsmouth main line, and was over ¼ mile in length. There had been practically no trouble since that work had been carried out.

185. Mr Hamnett described and illustrated a cutting at St Helier, in S.W. London, where the cutting slopes were in London clay. They had originally been designed at a slope of 1 in 2, which was quite inadequate. On one side of the cutting, stabilization had been carried out by sheet-piling. That had been successful in keeping the slip away from the track, but there had been a number of minor slips over the top of it. On the other side, plain and arched brick buttresses had been constructed to support adjacent property and these had attained their purpose.

Mr R. J. Collins (Assistant District Engineer, Bristol, British Railways) said he wished, like Colonel Prior, to deal not with the theoretical background to the stabilization of slips but more particularly with the considerations in the mind of the District Engineer when deciding what type of remedial measures should be undertaken. The primary considerations were, he thought, the speed with which the slip could be stabilized, the cost of the operation, and the interference with traffic during the course of the work. Many of the older methods used did not fulfil any or some of those considerations. Counterforts were expensive, mainly because manual excavation was often necessary; machines could not be used because their weight would aggravate the slip, or the vibration of the machines would do so. Added to that was the hand packing of the stone, which he thought was necessary to get the maximum effect. Occupations were needed to unload the stone at the site and the method was slow in stabilizing the slip.

187. In § 41 the Authors mentioned that counterforts acted as drains and seemed to imply that they acted solely as drains. He had been under the impression that a counterfort acted inherently to stabilize the slope and that though the drainage function was important the strength of the counterfort itself was also important.

188. To toe walls the same objections applied. If it was necessary to remove the spoil from the toe of the slip and replace it with the toe wall, often at great expense and inconvenience, not much was achieved in the end, because the weight of the toe wall was only fractionally greater than that of the spoil removed.

189. Gabions had been used but similar disadvantages existed. They did, however, provide a tidy toe to the embankment and prevent soil spilling over into the cess. On the River Avon, where there was tidal erosion and a slip developed affecting the rail track above, gabions had provided useful protection to the river bank.

190. Coming to methods favoured more recently, they had done a good deal of rail piling. Scrap rails were available easily and cheaply and the rails could be handled easily. They had devised a light frame with an engine and dolly which could be manhandled on the site. On a large slip last summer they had used an earth-boring auger

on a caterpillar tractor to bore a hole 12-in. in diameter. A rail had been inserted into this, ballast added and the whole grouted to form a pile, which presented a broader face than the rail itself would have given.

191. He regarded grouting as one of the best methods to adopt, but its use was limited to embankments. He was interested in the reference made by Mr Ayres to grouting in cuttings. Mr Collins had had experience of only one cutting being grouted that which Mr Ayres mentioned, 15 miles west of Swindon on the South Wales route, and he did not agree that it had been particularly effective. He had seen the site within the last week and there were signs of movement in the cutting. It had been grouted early in 1958, and 12 months later they had carried out an investigation and found that two out of the three grouting sites had failed. He would like information on why grouting should be effective on embankments and apparently not so effective in cuttings. They had used it for very many slips on embankments but not in cuttings.

192. Bincombe Cutting, mentioned above, was about 40 ft in depth in blue lias clay and must be a happy hunting ground for soil mechanics engineers, because almost every type of remedial measure had been tried there. There were counterforts going back 25 years, toe walls, gabions and grouting, and he thought that in the end they would have to trim the slope to a more natural angle in order to stabilize it.

193. The mention of grouting recalled that the Wiltshire County Council were doing a job near Box on a county road where they had grouted a large part of the hill-side. They had been grouting for over two years. One wondered how much that would cost and how effective it would be as ground conditions might be similar to those encountered in cuttings.

194. In § 78 reference was made to pulverized fuel ash and the difficulty of handling it. They had used it at Bristol for injecting into the filling in a viaduct and into the adjacent embankment and he could confirm that, when dry, it was awkward to handle. They had used Dumbo hoppers for storage and pressurized vehicles to bring it to the site but the men suffered severe discomfort from flying dust. He would be interested in any method for improving the handling of fly ash. It was extremely good for tipping where there was a slip on an embankment and the track had to be restored quickly. Locomotive depots were closing and they were getting far less locomotive ash than before, but power station ash was available and seemed to be a much better material than locomotive ash. It was very light, it compacted well and did not then absorb water so readily as normal locomotive ash.

195. He hesitated to give figures for costs because sites varied so much and travelling time and other overheads varied a great deal. A rough guide, however, might be of interest. He had selected eight sites at random where grouting of embankments had been carried out and found that the gross cost varied between £350 and £700 per chain of track. Counterforts were far more expensive and a single counterfort could cost anything between £500 and £2000. At the normal spacing of 25–30 ft apart that meant £1000 to £4000 per chain. He had no reliable figures for rail piling, because so often it was done in conjunction with something else, but he thought that if used with a gabion toe wall, a total figure of £700 to £800 per chain might not be very wide of the mark.

The following contributions were received in writing:

Mr E. Zolkov (Head of Soils and Roads Laboratory, The Standards Institution of Israel), wrote that although he did not wish to enter into the consideration of why the grouting of the slips with cement grout was effective, he would like to dispute the Authors' rather absolute rejection of a reaction between the soil and the mortar.

197. The fact that most of the clays encountered were calcareous clays and presumably that their cation exchange complex was largely calcium saturated did not preclude an action between the cement and the clay.

198. Clare and Cruchley[11] had demonstrated the influence of lime on a number of British clays whose predominant exchangeable cation in most cases was calcium.

199. Zeitlen and Zolkov[12] had shown that the stabilizing agent in the clay—$Ca(OH)_2$ reaction was the hydroxyl anion and not the calcium cation. It might be anticipated that many clays were sensitive to high pH. The pH of the mortar was certainly in the region of 12 and more and one might expect a reaction as long as the pH remained sufficiently high.

Mr P. Lumb (Lecturer in Civil Engineering, University of Hong Kong) wrote to ask if the Authors could give a description of the methods used in dealing with the flow sides mentioned in § 8?

201. In Hong Kong, shallow flow slides occurred frequently on steep natural slopes and in cuttings in areas of decomposed volcanic rock, where the soils ranged in grading from sandy silt to clayey silt. When in a dry state the strength of these soils was high, the unconfined compression strength being normally greater than 50 lb per sq. in., but when fully saturated all cohesion was lost and the soils were purely frictional. It could be shown[13] that, for unprotected surfaces, there was a danger of instability of a slope steeper than the angle of internal friction when the rainfall intensity exceeded the saturated permeability k of the soil, and that the depth to which a saturated, or nearly saturated zone could develop during a rainstorm of duration t was approximately $k.t/n(1-S)$, where n was the porosity and S the initial degree of saturation of the soil. For Hong Kong this calculated depth agreed fairly well with recorded values of 10 to 15 ft in actual slides.

202. The drop in cohesion was not as severe if the actual infiltration rate of rain water could be kept below the potential rate, and in Hong Kong this was achieved by constructing interceptor channels above the slope to take away the run-off water, and by providing a less permeable surfacing to the cutting face. Grassing the face by turfing or hand planting was rarely successful when the slopes were steeper than about 40°, and the usual practice for steep slopes was to cover the face with "chunam", a weak soil-cement mortar, which although effective and cheap, was very unsightly. The successful establishment of grass as shown in Fig. 25 appeared to be a very attractive alternative to chunam plaster and he would be grateful if the Authors could give further details of their experiences in grassing steep slopes.

Mr J. Dowling (Materials Branch, Ministry of Works, Nairobi, Kenya) wrote that he had read with particular interest the section dealing with unstable track formations because about 4 years ago he had the opportunity of analyzing a "type 1" failure on behalf of East African Railways and Harbours Administration.

204. The line was a single track metre gauge which crossed the Athi Plain en route from Nairobi to Mombasa in Kenya. The subgrade consisted of 2 to 3 ft of black cotton clay overlying rock. The track ran on an embankment of black cotton about 2 to 3 ft high having a top width of 18 ft. The rails were carried on trough section steel sleepers bearing on a 12 in. thickness of ballast.

205. The track had given trouble for a number of years and following the heavy long rains of 1958 (April to June) the difficulties became acute. Samples of the subgrade were tested in the Materials Branch laboratories of the Kenya Ministry of Works, and water contents of 50% were found. The liquid limit was 99% and the plastic limit 30%.

206. In the analysis it was assumed that 30 in. of the embankment below the bottoms of the rails had been or would be replaced by frictional material.

207. Subgrade shear strengths as low as 3 lb per sq. in. were measured and this value was used to analyse the failure by two methods, which gave safety factors of 0·8 and 1·3 respectively. In the first analysis the track was treated as a continuous strip footing with a width equal to the sleeper length. The semi-circular bulb of maximum shear stress (due to live load) based on a sleeper as diameter passed into the black cotton clay below the embankment (Glossop and Golder's method).

208. In the second analysis the live load was replaced by an equivalent trapezoidal

surcharge whose base was located at the base of the embankment. The black cotton clay layer between the base of the embankment and the rock surface was then treated as a fully plastic layer in Jurgensen's Plastic Theory.

209. It became clear subsequently that failure was mainly due to the black cotton clay in the embankment itself squeezing sideways and upwards. Remedial measures consisted of complete replacement of the ballast by stone dust, plus drainage works to prevent softening of the subgrade. Track levels were maintained by adding stone dust as the black cotton became displaced, resulting in a gradual increase in "ballast" thickness. A skin of true ballast had been placed to stop wind erosion of the stone dust.

A. J. McNeill (Retired Civil Engineer) wrote that early in his career he had to carry out a cutting on a hillside for a trunk road widening in very wet ground. The nature of the soil was known from a small cutting taken out in the same strata in the vicinity, it was variable in character, but consisted mostly of soft sand laid down by glacial action, slips took place and the slope was stabilized with difficulty by stone packing.

211. In the case of the larger cutting, which extended to several hundred yards, the hillside rose at a steep angle and it was not possible to have a slope flatter than $1\frac{1}{2}$ to 1. After considering the construction of a toe wall, and even a full depth retaining wall, it was decided to excavate it out to the cross section as planned, taking every precaution with drainage.

212. There were three separate systems of drains, the trap drain on the hillside above the cutting consisted of 4-in.-dia. agricultural pipes 3-ft deep, a drain at the bottom of the slope 9-in.-dia. open jointed pipes 2-ft 6-in. deep, another longitudinal drain at the opposite side of the road 6-in.-dia. agricultural pipes 3-ft deep, acting as leader for the 4-in.-dia. drains 2-ft 6-in. deep laid at 30-ft spacing below the carriageway to drain the formation. All pipes were surrounded with broken stone except those under the carriageway, which were filled with fine clinker to prevent damage from rolling. The benefit from the trap drain far exceeded expectation, providing a dry cutting almost down to formation, except at one point where water came through below it. Here the slope width was about 50 ft and the water though only a rather elusive trickle caused considerable damage, as excavation proceeded and support was removed, in spite of the provision of drains a slip took place over a width of about 20 yd followed soon by a second one, owing to the steepness of the hill a heavy landslide even appeared a possibility. A toe wall was built with some difficulty, the drainage made good in to the heart of the slip, which was then covered with rough hill turf from the vicinity, providing a growth of natural grasses and native plants, no further trouble was experienced. Over the remainder of the cutting it was dry down to formation but as water began to show the 9-in. drain was laid at the bottom of the slope following closely on excavation, small slips occurred occasionally and were made good with stone packing, and excavation was completed. When the formation was shaped, on trying to roll it, water again worked up through the sand and the drainage of the road foundation proceeded. The results of this were entirely successful, road foundation construction was then possible including full rolling.

213. Some further measures were adopted to improve the stability of the slope, packed stone herringbone drains were constructed and it was soiled and seeded. Looking back after a lapse of 36 years he felt it was, on the whole an example of successful drainage, one detail, however, could have been better, a 4-in. depth of soil sown with a mixture of rye-grass and clover on ground 500 ft above sea level, was rather inadequate, an increase in the depth of the soiling and a choice of a suitable mixture of natural grasses would have developed a stronger protective covering on the slopes.

214. Turning now to maintenance trouble from water in road foundations, he had experienced this where the softer limestones had been used in the broken stone regulating coat which was often required under tarmacadam surfacing. If crushed under rolling, when wet this powder became soft and pliable and, with additional water formed a

slurry which was pumped up by the pounding of heavy industrial traffic. He therefore felt justified in exercising caution in the use of quarry dust for blanketing.

215. He recommended this Paper to road engineers, many of whom might never have had to deal with unstable conditions in earthworks but, with the increase in road building, might now have to face this difficult task.

Mr A. H. Toms, in reply, said that from the work which had been done on the Southern Region, and from the consideration of work done on other Regions, such as the Western, it appeared that the most significant issues facing railway engineers were these. First, the study of the rheological problem of the clay, and the behaviour of clay under long-sustained stress. When, earlier, they had started this work on the Southern Region they seemed to be the only people to have done any, but at the London Conference of the International Society of Soil Mechanics in 1957 a small number of people had been interested. Unfortunately the 1961 Conference in Paris had been disappointing in this respect.

217. The study of the swelling effects in clays, of which he had shown examples, was equally as important as the study of slips, particularly in relation to tunnel failures, which the Authors did not have time to touch on.

218. The idea of waterproofing embankments was important though not easy to put into practice on existing ones. Mr Ayres thought that his grouting might be a waterproofing of the top of the embankment and, in so far as that might be so, Mr Toms was in favour of it. Consideration ought to be given to means of surface waterproofing embankments but he had yet to find an answer.

219. With regard to the strengthening of clays by the addition of chemicals, Mr Toms had spent a good deal of time in investigating the properties of Krilium, a garden soil conditioner. It did have an effect, but not at the moisture contents of clays in slips in which they were interested.

220. The physical and chemical bonds in virgin sands seemed to be important. Very deep excavations in sand quarries alongside the railway existed with near-vertical sides. The bonds were but weak and yet had a major effect.

221. In an article in the March 1962 issue of *Géotechnique* R. B. Peck, Professor of Foundation Engineering at the University of Illinois, wrote about engineering vis-a-vis soil mechanics and went on to deal with engineering education in the United States and said that a knowledge of precedents, familiarity with soil mechanics and a working knowledge of geology were requisites for the successful practice of subsurface engineering, and of these a knowledge of precedents was by far the most important. Mr Toms could not agree more. He had been investigating engineering problems for 35 years, and the longer he lived the more convinced he became that it was essential to have a harmonious relationship between theory and practice. One without the other was no good; and that applied as much to practice as to theory. He commended Professor Peck's article to all engineers.

222. The depth to which cut-off drains at the tops of slips should be laid was a matter of economics. So far as his own experience went, the deeper they were the better: it depended on the depth at which there was water in any quantity flowing in the ground. While 3 ft might be satisfactory at one site it would be necessary to go to say 5 ft at another. In the case of the Sevenoaks slip they had gone to 5 ft because there was a fair amount of water percolating to that depth, and it had not appeared economic to go much deeper.

223. Could drains be omitted from track blanketings? S.R. design was on the basis that the formation would be wet in winter in spite of drains but, for other reasons, it was better to put them in. In any case they were required for disposal of storm water. Where the outfalls were such that one could not get a drain to the requisite depth one should put the drain as deep as practicable and the blanketing the full depth required, regardless of the depth of the drain.

224. Mr Wroth considered the slipping of a slope as due to preferential migration

of pore water into the zone of critical stress, apparently assuming that this zone could be very narrow. Calculation and experience showed that shear stress did not vary very rapidly over quite a wide range of depth.

225. As Colonel Prior had said emergency action often had to be taken, in the case of slips, before the soil mechanics investigation could be made, but the soil mechanics engineers were usually called in as soon as possible, in order to collaborate in determining the best final answer. In many cases they had been able to put in polythene tubes or do borings, which had given vital information on depth of slipping, etc., before the chance had been lost.

226. Mr Ayres spoke of keeping the water out of embankment slips and that was certainly an ideal. He also said that it was better to adopt a method which should not work but did than a method which should work and did not. Mr Toms considered it was best of all to adopt a method in which it was possible to have faith because it should and did work!

227. The arguments about filter gradings for blanketings and drain backfill really called for a detailed answer, but the short answer was that they could prove the required grading of a filter blanket for any particular soil by testing with the pulsator, which showed up incorrect grading immediately.

228. Mr Cantrell had answered the question of whether or not blanketing was necessary in cases of track formation deep failure.

229. Mr Lewis asked questions which obviously required answering in writing. An objective analysis of the Papers presented at the Biology & Civil Engineering Conference would show a quite wide divergence of view, but also a general impression that vegetation such as one normally got on embankments often went insufficiently deep to arrest a slip. There had been cases of 100-year-old trees with deep roots sliding bodily down with bank slips, a typical case having been at Botley embankment in 1947.

230. It was very interesting to hear what had been said about rail piling, and he would like to know in due course how it performed. On a number of banks on the Southern Region, which had had timber piles put in many years ago, after a time the clay flowed round the piles. The width of the piles in relation to spacing was obviously important.

Mr D. L. Bartlett, referring to Mr Smith's point about drainage systems, hoped that he did not expect a specification from the platform but said the Authors would try to provide something in writing. Regarding Dr Wroth's questions Mr Bartlett would say that if he were forced to do an analysis on a bank in over-consolidated clay he would use the results of drained tests and effective stress analysis. He had never complained about the factors of safety associated with this form of analysis.

232. Mr Bartlett was very interested in the examples quoted by Colonel Prior and Mr Hamnett and had exactly the same thought in mind as Mr Lewis when listening to them, namely what a wealth of information was hidden away and ought to be available. It was surprising how many slips were of the more or less classical circular nature and could be analysed using conventional means.

233. Mr Ayres had justified the empirical approach to grouting. Mr Bartlett fully agreed; for want of something better at the present time they could not do anything else. He was, like Mr Collins, interested to hear Mr Ayres say that a cutting slope had been grouted successfully. It had been his impression that this was not possible and he would like to have more information about it, though from what Mr Collins had said the one case of which he knew had not been altogether successful. The reason probably lay in the fact that with a cutting there was a supply of water available from behind whereas with an embankment there was not. That was only a guess, but it was linked up with the theories he had put forward for an embankment.

234. Mr Lewis referred to vegetation on slopes. The Authors had not said much about it because it was an accepted practice. Mr Bartlett did not think that anyone would claim that it was a method of stabilizing unstable slopes, but it was a method of

rendering their instability less likely in the future. It was applied generally. In the case mentioned in the Paper, sewage sludge had been used to promote growth of grass.

235. The economics of remedial measures had been touched on, and no doubt the Authors could provide more information. He did not think that to design for a shorter life than was currently customary would be a practical proposition, because whenever there was a slip there was a tremendous disruption of traffic. It was not merely a question of the remedial measures which had to be applied to the slip itself.

236. It was interesting to hear of the refinements associated with rail piles mentioned by Mr Collins, by grouting them to make a more effective pile.

237. With regard to the functions of counterforts, while counterforts might lend some physical strength to a bank Mr Bartlett still subscribed to the view their main effect was in reducing the pore pressure to zero in their immediate vicinity and that they added little to strength except where they replaced the soil itself.

The Authors, in a joint reply, wrote that regarding Mr Smith's questions as stated in Mr Toms's verbal reply, on the S.R. drains were usually installed as deeply as practicable in blanketings to minimize flooding and buoyancy problems in the blanket. It was, however, believed that the formation, when properly blanketed would remain stable without any drains.

239. Undoubtedly too coarse a backfill material to track drains had caused much damage to track by allowing plastic flow of clay and washing of other materials into the voids and thus into the drains.

240. Whether or not a sealed carrier drain separate from the collector drains was economic depended on the grades and outfall levels and discharges to be provided for. In general it was found satisfactory to have collector drains only and to use them as carriers also.

241. Concrete bedding and haunching to drains was conventional but it had been found on the S.R. to be perfectly satisfactory to lay the drains direct in the backfill material provided that the backfill round the open joints was coarse enough not to flow into them. This generally implied a coarser fill round the pipes than the blanketing material itself, but there were places where the pipes had been buried in Meldon dust alone and, so far, without causing significant silting up of the drains.

242. Graded gravel was undoubtedly a good backfill for drains but finer material such as Meldon dust would need to be interposed between it and the clay where the latter was subjected to live loading of any great intensity. Meldon dust had been used as part of or the only backfill to drains for twelve years or more and there had been no reports of track flooding due to inadequate permeability. Of course, where there could be very large short-duration run off the concrete wall-block and channel-type drain developed on the S.R. and described in the paper by Toms and Beatty[1] would, naturally, be more immediately effective than rock dust backfill alone.

243. So far as the blanketing material itself was concerned it had been proved at five sites on the S.R. by opening up, five years or more after blanketing on London and Weald Clays, that in spite of the fact that Meldon dust was on the coarse side as a "Terzaghi" filter for these clays pumping up into it had not occurred. Mr Ayres had contested the legitimacy of applying the Terzaghi rule to cohesive materials but pulsator tests indicated that surface breakdown of the clay was encouraged by a coarser material and, in practice, Meldon dust was effective at the proper thickness, even though there might be a germ of truth in Mr Ayres' suggestion!

Dr Wroth

244. In §§ 137 to 141 Dr Wroth confirmed, in different form, what had been outlined in the Paper but the unlimited expansion of a sample at constant effective stress mentioned in § 142 seemed an unreasonable concept. On the other hand, a critical voids ratio during shear at constant effective stress was a logical one.

245. Paragraph 144 was surely only another way of expressing the well-known difference in behaviour of overconsolidated clays and the rest.

246. Dr Wroth's suggestion that it could be possible to cause shear failure in clay without stressing it to the peak of the stress-strain curve seemed illogical. It was much more likely that in an actual slope, in which self weight shear stresses on any potential slip surface were not uniform in the pre-slip elastic state, there could be progressive failure due to peak stress being reached at, say, top and bottom only in the first place. The subsequent drop in shear resistance at these points as strain occurred would transfer the points of peak stressing progressively further and further towards the middle of the slip arc. Thus general failure might occur at an average shear stress well below the peak value. Practical experience suggested that this might be a fact.

247. If the theories put forward by Dr Wroth were the whole answer there would be no phenomena of very slow creep since the moisture content migrations which he suggested as being the explanation could take place relatively rapidly and, in laboratory specimens, would be complete in a few hours. It must, however, be emphasized that in the S.R. soils laboratory specimens had sustained static loads for months (not ten years as mis-stated by Dr Wroth), at overall constant moisture content and had then collapsed. This indicated that there must be some other major factor at work which was thought to be slow plastic breakdown of the clay skeleton bonds under sustained shear stress.

248. The answers to § 148 were that load on the "creep" specimens was simple dead weight loading; the moisture content of the 1½-in.-dia. specimens was kept virtually constant by means of double rubber sleeves with silicone grease in between; the London clay samples were "undisturbed" brown clay in the overconsolidated state but no oedometer tests were done to determine the "history".

249. No tests had yet been done on moisture migration in the creep test specimens.

250. Paragraph 149 was an incorrect interpretation. What had been said in the Paper was that samples of remoulded clay from the slip zone were frequently found to be at a higher moisture content than the clay generally above or below that zone. This did not mean that water had migrated from that clay to the slip zone. It could have been present as freely available water in fissures and have been absorbed by initially stiff clay on its fissure surfaces.

Mr Prior

251. In § 159 Mr Prior stated that there was no failure yet where the large one-piece slabs had been used in blanketing. In fact, trouble had been experienced and on opening up one site it had been found that for some, as yet inexplicable, reason there had been very considerable and irregular settlement of the slabs and dispersal of the rock dust on which they were bedded.

252. Fig. 56 showed the washout, by cloudburst in 1956, of the surface of the classic Sevenoaks slip of 1939. It was very satisfying to find that the 1939 stabilizing work had been so effective that the slip as such did not move at all during the cloudburst.

Mr Ayres

253. Mr Ayres was apparently of the view that no soil mechanics analysis of a slip was of much use and yet he rightly urged its use to reduce the cost of remedial works and to minimize disruption of rail traffic. This was clearly a self-contradiction. Obviously, as Mr Cantrell had implied, a proper soil mechanics assessment of any situation was highly desirable to ensure that the best information was available in deciding on remedial works.

254. In § 163 Mr Ayres suggested that grouting of slips was the most successful method of stabilizing them. Until the mechanism was understood the factor of safety provided by grouting was speculative and might be but marginal and of relatively short duration. By contrast the factor of safety provided by berms, sheet piling and regrading could be estimated and it was reasonable to expect permanent benefit. It was, therefore,

presumption to say that grouting was the "most successful" method, even though it was, in many cases, the cheapest and simplest.

255. The grouting of cuttings must suffer from the disadvantage that it would tend to impound groundwater and raise the groundwater pressures tending to displace the cutting slopes.

256. Regarding § 166 the different types of track formation failure had been clearly recognized for very many years and experience had shown repeatedly that it was useless to carry out shallow treatments on a site where there was deep shear or plastic failure resulting in heaving and corresponding deep pocketing.

257. On the contrary pocketing could, apparently, result from progressive pumping up of material eroded from the surface of the soil formation or, sometimes, from the early "blankets" themselves. In such cases shallow blankets and drainage might suffice.

258. Mr Ayres's scathing remarks about the "irrelevance" of the S.R. pulsator tests described by King and Pitt were unfortunate because it so happened that the indications given by this machine as to critical blanket depths and the behaviour of the soil in contact with the blanket, had closely paralleled site experience. Moreover, Mr Ayres's views as to the possible value of sub-track stress research were certainly not supported by those who had been charged with the job of recommending what research was essential to a better understanding of track formation failures. Even road and air-field engineers were now beginning to express views indicative of a dissatisfaction with the largely empirical approach to road and runway design as exemplified by the present methods which ignore any considerations of shear stresses in the soil.

259. In regard to the influence of rainfall on the period during which a track was troublesome this might well apply to pumping due to temporary saturation, but there were many deep shear or plastic failure sites in cuttings where natural groundwater was nearly always present and the conditions did not vary to the same extent between periods of wet and dry weather: § 168 was therefore in error. Stabilization of heaves by dead loading or screw anchors was logical and it would be interesting to learn the long-term economics.

260. Paragraph 169 was insufficiently explicit to be commented on and the Authors would attempt to secure clarification later.

261. Paragraph 170 recorded an experiment the outcome of which would be awaited with great interest. Presumably this was a site where heaving or other symptoms of deep plastic failure were not in evidence.

Mr Lewis

262. The Authors very much welcomed Mr Lewis's comments, particularly on account of his record of extremely valuable research on road and earthwork compaction problems.

263. Certainly, it would be very convenient if the statistics collected for modernization earthworks design along particular lengths of railway could be codified into a simple document. This was far from being the first request that this should be done. Unfortunately, and as, no doubt, Mr Lewis would readily appreciate on reflexion, there were large variations in type in any given geological stratum such as, for instance, the London Clay and, also, local groundwater and other variables had marked effects on slope behaviour. Rough guides emerged such as, for instance, that it was inadvisable to excavate to a steeper slope than 1 in 3 for a vertical depth of more than 20 ft in London Clay where there was a normal watershed behind. But to draw up anything like a code was inviting the omission of consideration of all the factors affecting any particular case.

264. The answer to § 173 was that most of the slips which caused the greatest trouble on British Railways were deep or relatively deep ones. There were many "flow" slides of a shallower type, such as the one at Whitstable illustrated in Fig. 1.

265. In reply to § 174 vegetation such as grass was very necessary to ensure surface

bonding and erosion prevention on a slope but it did not appear to have much if any effect on stability at a depth, except insofar as a turf layer minimized surface cracking and also acted to some extent as a penetration barrier in times of short heavy downpour.

266. Mr Moran of the L.T.E. was enthusiastic about trees, of the right kind, on slopes but main line experience did not encourage their planting.

267. In reply to § 175 the Authors' view was that, in most cases anyway, slopes and stabilizing works should be designed for permanence. Slips were potentially so hazardous that to design for only a short life would be wholly unwise.

268. Regarding § 176, so far as the Authors were aware there were but few examples of the use of vertical sand drains on B.R. for accelerating settlement. All Mr Toms could say was that the ones under the approach embankments to Kingsferry Bridge were working almost exactly as planned by the consultants.

269. The warning given by Mr Lewis would certainly be borne in mind in the case of sensitive soils, since it appeared quite logical.

270. Mr Hamett's contribution to the discussion was welcomed but required no comment.

Mr Collins

271. Mr R. J. Collins stated that counterforts were expensive because mechanical plant could not be used on the slip. A demonstration had shown that a modern small hydraulic excavator on a County Crawler tractor could excavate narrow 12 ft deep trenches, up a slope of 1 in 2, in very short progressive lengths, and that it was possible to lay drains in them without men having to go down into them. It seemed reasonable to expect that this procedure could be adopted for the construction of drainage trenches in slips provided that the work was done in dry weather.

272. Hand packing of stone as a counterfort backfill was not necessary since it had been shown that a material such as washed ballast was adequate. Certainly, if block stone was to be used as a matter of economy then the sides of the counterforts would have to be closely hand-packed to reduce to a minimum the voids into which clay could squeeze or flow. Sevenoaks slip (see Prior, Fig. 56, § 160) had demonstrated that closely hand-packed brickbat sides with random brickbat fill could be entirely successful in stiff fissured clay.

273. In reply to § 187 experience on the S.R. in brown London Clay indicated that even where a rock-filled "counterfort" drain remained standing as a stone wall up a slope, and might therefore be expected to give some mechanical support to the clay on each side of it, there had often been slipping of the clay down between the counterforts. This could have been due to softening and flowing of the clay into the excessively large voids in the random-packed coarse rock or hardcore.

274. Paragraph 192 referred to Bincombe Cutting slip. This was considerably deeper (75 ft) than the 40 ft quoted and it had been handed over in 1950 to the S.R. by the W.R. Investigations commenced by the W.R. had been extended by the S.R. who had shown that this slow slip could probably be stabilized only by exceptionally costly very deep drainage or heavy sheet piling both sides of the tracks with struts under them, as had been done at Botley. Fortunately, the movement had never become sufficiently troublesome to justify these elaborate measures.

275. The Authors were particularly interested in Mr Zolkov's opinion that the stabilization of slips by cement grout might be due to reaction between it and the clay, and they would look further into the matter.

276. The answer to Mr Lumb's question on flow slides was that the one in London Clay at Whitstable was, at present, being dealt with by installing a deep cut-off drain along the top of the cutting and a system of drainage "legs" running down the cutting slope, to discharge, through a mass concrete toe wall, into a track drain. The "legs" were being taken down into unslipped clay, the depth of slipping having been proved by the shearing of boreholes and polythene tubes.

277. The grassing of slopes of new earthworks or regraded slopes of slips was

standard practice and the customary specification, based on the recommendation of Mr Moran of the L.T.E., was a minimum of 4 inches of top-spit soil or matured sewage sludge sown with Red Fescue grass at $\frac{1}{3}$ oz. per square yard. Naturally in another country it might be necessary to choose different grass.

278. Though it seemed possible to establish grass on very steep slopes there appeared to be a real problem in how to maintain it there. There was no doubt that, on chalk slopes steeper than about 45° unattended grass tends to be gradually dislodged by frost action. If the loam soil layer itself is very thick it tends to slip off the chalk taking the grass with it. The experiments at present in progress on a steep chalk slope on the Western Region and on steep Bunter sandstone cuttings on certain Eastern Region Colliery lines should prove of considerable interest in due course.

279. Mr Dowling's experience of lateral plastic flow of the notorious black cotton soil beneath a railway embankment was interesting and akin to troubles in Sweden and Holland. In the former, the raising of a low embankment by only a few feet had caused lateral flow over a distance of, it was believed, about 30 metres or more.

280. Mr McNeill's treatment of a troublesome cutting by ample drainage followed by turfing was evidently sound and certainly of interest. The Authors were glad to have this contribution in writing and also the supporting evidence that 4 inches of soil in the conditions mentioned, was rather inadequate. They would consider 4 in. the absolute minimum in the British Isles.

281. On the matter of the behaviour of soft limestones in road carpets the Authors had shown, with the pulsators, similar deficiencies in soft limestones as railway track ballast and sub ballast. Even apparently hard rock was not free from significant breakdown by crushing and attrition when tested in the pulsator under conditions akin to those even at some inches depth below the sleepers.

282. The Authors appreciated the recommendation that their paper should be studied by highway engineers. Actually there was a very close liaison between the Building and Road Research Laboratories and the various British Railways soil mechanics engineers and the help given by the former was freely acknowledged.

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