DISCUSSION

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Papers 9659, 9660 and 9661

London's Docklands: engineering geology; ground conditions and tunnelling methods; a geological perspective of the highways

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Introduction to Paper 9659

Paper 9659 seeks to set the geological context of Docklands for Papers 9660 and 9661. It also argues that the engineering geological appreciation of the area and, as a consequence, the geotechnical awareness of the soil types within the area, are underpinned by an understanding of the fundamental stratigraphy. In this sense, engineering stratigraphy should be viewed as a variant or subdiscipline of engineering geology. However, it is rare that the opportunity exists, or that time is available to give such a study true justice. It has been the process of urban renewal, as pioneered by the LDDC, that has enabled the true value of a systematic appreciation of engineering stratigraphy to be demonstrated.

2. The revision of the geological setting which is described in the Paper has demonstrated that particular care should be exercised when limited data are interpreted within the context of a preconceived regional model. For example, in the past, the presence of the Greenwich Fault across the area has been used to justify the various anomalies during the interpretation of data from a number of individual site investigations. Without the fault, that justification disappears, leaving only the anomaly unexplained.

3. It is inevitable that the increase in available data collected during the development of the Docklands will have changed the understanding of its geology. It is only surprising that the review is as limited as it is and this really commends the quality of mapping and the skills of the early geologists who mapped the area for the Geological Survey. The new understanding is by no means complete and will evolve further as new data are made available.

Dr R. A. B. Bazley, *British Geological Survey*

Since the early part of the century, I think we have been remiss in the BGS in not paying more attention to the basic geology of London; perhaps the study contained in paper 9659 will give an added spark to the BGS to review all the data that have been accumulating over a period of fifty years.

5. The amount of borehole and site investigation data that are being produced in London are, frankly, daunting. This is the prime reason why they have not been systematically collected and analysed. Added to this is the cost in terms of staff effort which, in recessionary times, has proved a major barrier. Having said that, however, computer methods of data storage are now available, and it can be argued that the cost to the general public in terms of contracts that are delayed because of unforeseen geological conditions is unacceptable. So now the job can be done, and we have to grasp the nettle. The way in which Dr Howland has tackled this relatively small part of London is a lesson to us all.

6. The BGS has taken the lesson to heart and is currently producing new maps as well as developing a database to cover the whole of London within a period of about three years. As our work expands, we will be able to put data such as Dr Howland's into a broader context. We are very interested in the structures that he has found, but as we have not yet tackled this area ourselves, we reserve judgement on the reality of the Greenwich fault. He, of course, has the modern data and may well be right. In any case, his analysis of the different varieties of faults is a distinct step forward.

7. The BGS LOCUS project (*LO*ndon *C*omputerized *U*nderground and *S*urface mapping). At the moment, we are tackling the City areas. Our subsurface data are being reclassified and put on a computer database where they can be easily accessed. Our maps are being digitized and put on a modern topographic base. The various datasets will eventually be capable of interaction and it is hoped they will be useful for engineers in the future.

8. There are real geological problems under London and they have been stated clearly by Dr Howland and Mr Ferguson. In particular, the Woolwich and Reading Beds present lithologies whose variation is difficult to predict and the base of the superficial deposits is proving spectacularly uneven. These are difficult deposits and difficult surfaces. They need to be

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described more carefully in future, as Dr Howland and Mr Ferguson have pointed out, and the descriptions need to be available to future workers. The BGS is the obvious central depository for such data, be they shallow borehole data or temporary site information. I know Dr Howland is likely to make some of his records from Docklands available to us. Numbers of subsurface records in our London datasets are variable from place to place. For instance, we hold over 2000 for the City area but only 50–60 for the whole borough of Barnet. So I do make a plea to engineers to keep borehole records and, preferably, to deposit them with the BGS so that we can prevent today's mistakes from being repeated tomorrow.

The BGS LOCUS Team

As Dr Bazley has outlined, BGS under the aegis of the LOCUS project is currently modelling geological surfaces with computer-held borehole data for 1 : 10 000 sheet TQ38SW (The City sheet).

10. To date, our modelling has not extended as far as Docklands so we are not able to comment in detail on Dr Howland's results.

11. The BGS modelled surfaces—in particular, the top of the Chalk and the base of London Clay—illustrate the broad regional structure. We note with interest Dr Howland's reinterpretation of the Greenwich Fault and the north-east trend of his Greenwich Syncline. Our new interpretation of the area just to the west suggests a fault within the Chalk with a north-west trend.

12. We should welcome the opportunity to integrate Dr Howland's Docklands data with ours. This will allow a better appraisal of the regional setting for the Greenwich Syncline.

13. There is little doubt that these fresh, computer-generated analyses, bringing together large datasets of old and new information, will improve our understanding of the detail of buried structures below London.

I. E. Higginbottom, *Consultant, Wimpey Environmental*

Dr Howland has laid to rest the ghost of the Greenwich Fault which has haunted speculation into the geological structure of south-east England for well over a century, and has had engineering implications.

15. A minor fault trending south-west/north-east was found in 1850 during railway construction about 3 km to the south-east of Greenwich on the North Kent Railway as it was then called.[1] That has since become a spectacular example of the kind of over-interpretation of a fault that Dr Howland warned us about. The Geological Survey could trace it for only about 0·5 km during their large-scale mapping in the 1880s, and I have had private doubts about exaggerated later interpretations which now seem to be abundantly confirmed. I noticed it was absent from the Barking Creek Barrier investigation, where it had been predicted that it would be found; instead at both Barking Creek and the Thames Barrier site, minor faults and flexures were found which had a completely different trend, generally much more northerly or slightly east of north than the south-west/north-east trend of the Greenwich fault, which by a series of imaginative leaps, grew in scale, as perceived, over the course of a century. For example, the 1884 Colchester earthquake was speculatively associated with an extension of the Greenwich fault into the Colchester area. That event, and probably the interception in 1880 of a fault in a borehole at Wickham Bishops, between Colchester and Chelmsford, led Dalton[2] of the Geological Survey, in 1890, to postulate a south-west/north-east fault, 75 km in length. By 1923, in a further interpretation,[3] the fault had become about 100 km long. Moreover, it has not escaped notice that yet more arm-waving extrapolations could, for example, make it reach the coast in the neighbourhood of Sizewell. The assumed persistence of the south-west/north-east trend generated another cycle of speculation as recently as 1983.[4] This involved hypothetical faults in a young geological formation which, were they real, would have repercussions on the seismic hazard at Sizewell. These speculations have increased the complexity and cost of the Sizewell investigations.

16. The first person to suggest that the received south-west/north-east trend was not, in fact, present offshore of south-east Essex was Dr Brian D'Olier.[5] He ran a great deal of shallow seismic reflection data in association with the Maplin project, and this was subsumed into the Geological Survey's Thames Estuary map, which shows the pevailing trend in that part of the estuary is north-west/south-east and not south-west/north-east. I believe that there is, in fact, a great deal of minor structure within the Thames Valley, with a variety of trends, and the moral I think is carefully to make our own re-evaluation of the primary evidence before a line of fault shown on a geological map is accepted.

17. On another topic, I think of the boundary between the Thanet Beds and the chalk as being susceptible to the development of solution hollows in the chalk, into which the surface deposits collapse. That does not seem to have been a problem at Docklands. Is this because the chalk outcrop is peripheral to the development area, or was it indeed a problem?.

Dr B. D'Olier, *D'Olier Associates, Consultant Geologists*

I notice that there appear to be some flint gravel ridges within the Woolwich and Reading

Beds. Could Dr Howland say from which direction these ridges had migrated and perhaps, therefore, where the outcrops of Upper Chalk were situated from which this flint gravel had been originally derived?

P. L. Fagan, *G. Maunsell & Partners*
Dr Howland has a classification for the Woolwich and Reading Beds of facies A to H, but I am not sure if this is his own or some other recognized system.

20. I am pleased to hear that the BGS is going to revamp the geology map for London. I know that, from a practical engineer's point of view, there are now at least three classifications for the Woolwich and Reading Beds: firstly, facies A to H (Howland); secondly, a classification by Dr C. King (Palaeo Services Ltd); thirdly, a classification by Dr R. Ellison (BGS, Keyworth). If the area is going to be remapped, it would be helpful to have a unified approach to the Woolwich and Reading Beds, because correlation between boreholes classified on a different system is somewhat confusing when a cross-section is being drawn. I personally use the system by Ellison and, from a geotechnical point of view, this seems to be very successful. I do not know of other systems.

21. It would be interesting to know where the line is drawn between basal London Clay deposits and Blackheath Beds.

J. Buchanan, *Fellow*
With reference to Paper 9659, could Dr Howland comment on the extent to which he thinks he has sorted out the geology of the area or whether he thinks there is much more to be done to clarify the geology in this specific area and in the surrounding area. From the Paper, it seems that there may be more surprises.

23. Would the Authors of Paper 9660 consider that, of the many different proposals for the method of construction, there was one which would perhaps have served throughout with the occasional assistance, as turned out to be the case, of the use of compressed air. To one reading the Paper and analysing the data in the tables, it would seem likely that one or two of the methods used might well have succeeded throughout with some occasional help from an alternative. What do the Authors think about this? It is stated in the Paper that pipejacking was preferred to segmental lining when there were ground problems. Why should this be so, when the excavation method would be the same in each case?

24. The Authors of Paper 9661 have given excellent examples of the the solutions to the problems of changing foundation material. Would they consider adding another figure by including section C–C which is referred to in Fig. 11. This would help to illustrate the problems of adjacent structures.

D. D. Wilson, *Consultant Engineering Geologist*
Could Dr Howland outline some of the history of the site investigations which were carried out, relating especially to the time frame, the number of contracts, the scope of the SI and monitoring, and further SI during construction.

26. With regard to the sewer tunnels described in Paper 9660, how many pay items were there, and was there any breakdown of items for unforeseen conditions, groundwater problems, and for hand or machine excavated tunnels?

27. Regarding geology and tunnelling conditions, could the Authors of Papers 9660 and 9661 say whether the geological sections were presented in data for tenderers or the documents made available to the prospective contractors?

D. Pope, *London Transport*
I am the Engineering Manager for London Transport for the extension of the Docklands Light Railway which will go under the Thames from the southern end of the Isle of Dogs to Greenwich and Lewisham. We have recently commissioned an extensive geotechnical survey for that project, and have supplied survey information to both Dr Howland and the BGS. A geophysical survey was carried out in the Thames which showed some form of discontinuity slightly to the east of the line of our tunnel. I am not sure whether or not it is the Greenwich Fault but there is definitely a geological faultline there.

29. The tunnels being planned by London Transport, both for our railway and for the Jubilee Line, will cross this area, with tunnels much larger in diameter than the ones involved in the drainage projects. Could the Authors of Paper 9660 say to what extent their findings can be extrapolated and used by people planning these two railways.

A. S. Athanasiou, *Sir William Halcrow & Partners Ltd*
What monitoring has been installed for the embankments and how would this be done?

31. It was interesting to see in Paper 9661 that an effort has been made to match a graded change by using jet grouting columns. Has any monitoring been carried out that has verified this design approach?

Dr E. C. Hambly, *Vice-President, ICE*
With reference to Paper 9661, complicated earthworks have been used to bring the embankments up to the bridges. To what extent did the design of the bridges take account of the very difficult geotechnics? Were they designed to move or were they designed to be rigid on piles?

Q. Leiper, *Tarmac Construction*
With reference to Paper 9661, with whom did the financial risk lie for the ground column option? Obviously, it was a solution that enabled some money to be saved compared with the other alternatives. Was the risk with the Specialist Subcontractors and the Main Contractor, or had it really remained with the Author's company (as the Engineer) and the Client?

Dr Howland, *Paper 9659*
In reply to *Mr Wilson*, the site investigations from which the data in the Paper were drawn were commissioned by the London Docklands Development Corporation through a series of term contracts. These have been operated annually since 1982 to provide geotechnical information within the Docklands area. Since 1984, these have been supplemented by separate term contracts to provide environmental and chemical site investigation which, I believe, has been the first use of such contracts.

35. During this time the geotechnical term contracts have undertaken 275 separate investigations, providing some 4500 boreholes. As outlined in the Paper, the contracts were set up initially to provide a vehicle for data collection to aid the general development of the area. As the development has been taking place, the contracts have been used increasingly by consultants to the Corporation to provide project specific investigations to their design and under their general supervision.

36. The Corporation has maintained a continuing programme of data collation and appraisal to improve the understanding of the geotechnics of the area. Where possible, it has supplemented its own information with reports from other parties. Its general policy has been to make this knowledge base available to other interested parties on a reciprocal basis.

37. I should like to thank *Mr Higginbottom* for describing so lucidly the history of the awareness of the Greenwich Fault and showing how 'speculation' can so easily drift to become a 'fact'.

38. On the point of solution features in the Chalk, I have not come across any evidence for them in Docklands. Such features form where groundwater is actively flowing, notably during cold climatic phases. In Docklands, the Chalk is present as a subcrop below the Thames Ballast in the east of the area and outcrops only to the south of the Thames beyond the present study area. Over much of the remaining part of Docklands, it is at depth and found beneath a varying thickness of Tertiary deposits. Interestingly, before deposition of the Thames Gravels, more of the Chalk may have formed an outcrop in the present flood plain area. It is possible to speculate that if the marine base level were also reduced at the time and if positive groundwater flow were present, wthe chalk may have been subject to solution. This geomorphological situation would have similarities to that on chalk downlands today where swallow holes are found in chalk stream valleys. No such features have been found, and if they were present, it is possible that they, and any other weathered profile, were removed during the erosive phase which preceded the deposition of the Thames Gravels.

39. In reply to *Dr D'Olier*, unfortunately the study area is actually too small to allow much assessment of the wider regional basin during Woolwich and Reading Beds times. My feeling is that the gravel ridges have a north-east–south-west to north–south trend, with the transgressions coming from the east. I would anticipate that the gravels have been derived from long-shore drift.

40. In reply to *Mr Fagan*'s question, the system of facies classification A to H described in Paper 9659 has been devised for the Docklands data and is based on my own assessment of those data. I am aware of the other systems, but these are equally specific to certain areas or even to the scale of the study. The Woolwich and reading Beds formation has such an innate variability that any classification would be very sensitive to the area on which it is based. It would be a major task to unify the various classifications which have been developed, and from an engineering point of view, the final result might be too coarse to be of practical use.

41. This limitation can be seen to be true of Ellison's classification when applied to the Docklands data. Ellison's work considered much of the Woolwich and Reading Beds' outcrop. This offers a fundamental framework, but the smaller Docklands study area allowed a finer resolution of the various facies present than Ellison described. This was felt to be important since the consequential understanding of the facies development is important if the depositional environment is to be unravelled. It is only then that any logic that allows local predictions of variability on the scale of engineering requirement can be applied to the data. Without this finer understanding, such formations as the Woolwich and Reading beds can be treated only as a random mix of sands and clays at a local level.

42. In connection with the base of the London Clay and the Blackheath Beds, I do not believe that the Blackheath Beds, certainly as a formation, is present in Docklands. The material which tends to be described as such is my uppermost facies of the Woolwich and Reading beds. This is a sandy gravel, characteristically with some shell debris. It is usually less than 0·5 m in thickness and is often absent. I believe that it represents the final transgressive sequence of the Woolwich and Reading beds. Above this is found the London Clay, the

basal sequence of which is a series of silts and silty clay.

43. In reply to *Mr Buchanan*'s question, 'Is there any more to learn about the area?', I can only answer, yes, very much.

44. Every time a new borehole is put down it brings to light information which changes the ideas. The fun of geological interpretation is that it is a never-ending story. Fortunately, there comes a time when the changes can be viewed as refinements. However, the exercise has not been academic, there has been a very real and considered purpose to it. In order to maximize its understanding of the geotechnics of the area, the LDDC has followed a policy of collecting as much information as possible for the area, from whatever source. As mentioned earlier, this is on a reciprocal basis, as the improvement that this gives to the broader understanding of the area has benefits to all involved in it. We are therefore continuing with the interpretation as new data are collected. There are also other aspects of the study which have not been dealt with in detail here. For example, in the case of the Thames Gravels, we have mapped their basal surface and can now relate the depressions to the river terrace hierarchy of the area. This has led to an understanding of their formation and, consequently, to an appreciation of their engineering condition and relationship with the surrounding soils. We are also looking at the hydrogeology in great detail and have developed a computer simulated model of the Docklands area. This describes the relationship between the upper aquifer of the Thames Gravels and the lower aquifer of the Chalk and Lower London Tertiaries. In Docklands, the two interconnect and one interesting point has been the extent to which that interconnection is influenced by the engineering development which has, and will, take place.

Mr Ferguson, Mr Runacres and Mr Hill, *Paper 9600*

In reply to *Mr Buchanan*, we believe that, in the event, the TBM capable of operating in open or earth pressure balance mode would, with the occasional assistance of compressed air, have tackled all the ground conditions encountered, with the exception of the stretch in the Phase 2 contract where the Woolwich and Reading Beds lensed out between the Flood Plain Gravels and Thanet Sands at a buried channel. There, ground treatment was also necessary because of the very loose nature of the Flood Plain Gravels and the risk of a loss of compressed air.

46. Pipejacking was preferable to segmental lining when a mixed face of London Clay and Flood Plain Gravels was being tunnelled through, because time spent not mining in a cycle is less with the former. Hence, rates of progress are faster with pipejacking (see Table 10 of Paper 9660), thus reducing the time available for softening of the London Clay at the face, and the clogging and balling that ensues.

47. In reply to *Mr Wilson*, separate pay items were provided for each anticipated tunnel drive (i.e. between assumed launching and receiving shafts) and each of the strata to be tunnelled through on that drive. Mixed faces, where anticipated, were treated as separate strata and itemized separately. There was no breakdown of items for unforeseen conditions or groundwater problems. In the case of the latter, all of the drives were below the water-table, and information on groundwater levels and permeability tests was provided in the factual site investigation report made available to tenderers. The method of tunnelling was the responsibiltiy of the Contractor, and tenderers priced the tunnelling items for their chosen method. In no case did Contractors resort to hand-tunnelling methods as a result of difficulties encountered during tunnelling.

48. Tenderers were provided with factual site investigation information, but not with interpretative data such as geological sections. This is still the normal practice for contracts let under ICE 5 Conditions of Contract.

49. In reply to *Mr Pope*, we believe that although the tunnels planned for the Jubilee Line and the Docklands Light Railway extension to Lewisham are significantly larger in diameter than the drainage tunnels, the experiences gained on this project are relevant to those future projects where similar ground and groundwater conditions will be encountered. The most notable experiences were

(*a*) alignment control difficulties when in or entering mixed faces
(*b*) reduced rates of progress when in mixed faces
(*c*) damage to tunnelling machines as a result of hard materials.
(*d*) wear of cutters in Flood Plain Gravels
(*e*) potential for differential soil take when in mixed faces, leading to increased surface settlement
(*f*) Thanet Sand below the water-table can cause major problems, and tunnelling near, to or through this stratum must be carried out with the utmost care.

Mr Young and Mr Rutty, *Paper 9661*

In response to *Mr Leiper*'s question regarding the financial risk associated with the jet grouted column scheme, we should clarify that the scheme presented is entirely the Engineer's design. It is perhaps misleading to use the word 'option', as the jet grouted column scheme, and only that scheme, was presented in the tender documents. The financial risk therefore lies where it conventionally lies. The flexible nature of the Limmo embankment design, with its acceptance of long-term ground movements in areas of untreated ground and their potential maintenance implications, was well recognized at the design stage.

51. With regard to *Dr Hambly*'s enquiry about the interrelation between the bridge design and the geotechnics, the answer varied from project to project. All of the bridges were founded on piles. In some cases, the bridges were designed to resist the earth pressures in the conventional manner. An example of such a structure is the Canary Wharf eastern access bridge. In this case, the abutment is also a plant room, and provision for lateral forces on the structural box was straightforward. In other cases, it was found that provision for lateral forces had a major impact on the structural design of piles and bridge substructures, so that it was preferable that the earth pessures should be relieved. This was achieved by the provision of a 'buried' reinforced earth structure behind the bridge abutment. Detailed discussion of the bridge design concepts is, however, outside the scope of this Paper.

52. In reply to *Mr Athanasiou*'s question on monitoring, the extent of monitoring was determined to suit the individual designs. For the schemes at Canary Wharf eastern access and at Prestons Road, the performance of the design was insensitive to ground response. In both cases, albeit by different means, the embankment loads were transferred to a grid of piles. Monitoring of construction performance was confined to levelling of the retaining walls. On the Lower Lea project, the condition of the founding structure for the Leamouth embankment, including not only the new dock infill but also the old foundations and River Lea retaining wall, was investigated, but no specialist instrumentation was installed for monitoring purposes. On the other hand, the Limmo embankment was extensively instrumented.

53. The instrumentation of the Limmo site was installed to confirm two aspects of the design. One aspect was the stability of the bank of the River Lea under the surcharge of the new embankment. To confirm this, inclinometers and piezometers were installed towards the south of the embankment to measure movements and pore pressure responses in the alluvium.

54. The other aspect of monitoring, and one to which *Mr Athanasiou* makes particular reference, related to the performance of the jet grouted columns. The issue of particular interest in this case is the pattern of embankment settlement both within and outside the treated area. This was monitored by levelling of the reinforced earth wall along the north side of the embankment, and by the installation and observation of two profile gauges or horizontal inclinometers, laid at the base of the embankment and essentially perpendicular to the reinforced earth wall. One of the profile gauges was laid within the area of the jet grouted columns, and the other outside it.

55. The piezometers showed an immediate rise of head of typically 3·0 m below the centre of the embankment, reducing under the sideslopes. Dissipation is variable, but is typically 50% over the 12 months since substantial completion of earthworks. The inclinometers at the toe of the embankment on the bank of the River Lea show negligible lateral movement. The levelling of the reinforced earth wall shows smaller settlements adjacent to the bridge abutment, increasing away from the bridge. This pattern is repeated in the profile gauges. There are substantial variations in settlement, some of which can be associated with old foundations found during construction, and with the removal of those foundations. At completion of fill placing, the settlement of the reinforced earth facing panels at the rear face of the bridge abutment was 80 mm.

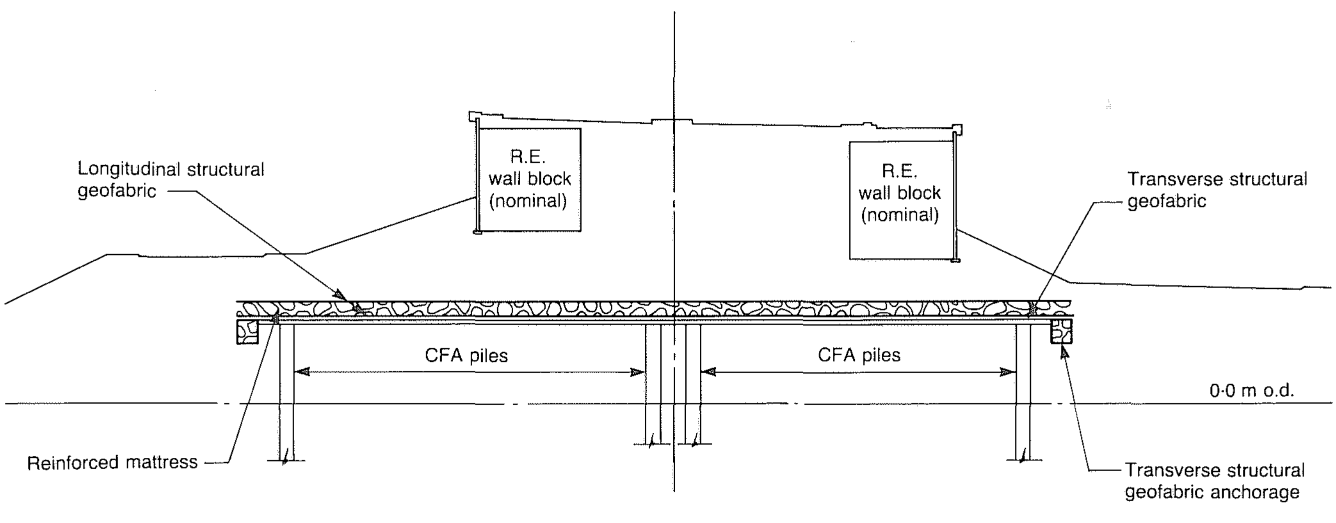

Fig. 13. Cross-section through Leamouth embankment towards its full height

56. Although this settlement was built out, there is some time-dependent movement. At the time of writing, the time-dependent settlement at the rear of the abutment has been about 20 mm. Under the untreated central part of the embankment, under approximately 60% of the height of new fill compared with the abutment, there has been about 50 mm settlement. Monitoring is continuing, and it is hoped that a suitable forum will be found for presentation of these results at a future time.

57. *Mr Wilson* equires about the presentation of geological sections. As is conventional practice for highway schemes, borehole logs were presented, but an interpretation such as a geological section was not.

58. *Mr Buchanan* questions the interaction with adjacent structures, and requests the presentation of an additional figure. That figure is presented as Fig. 13. It shows a cross-section through the Leamouth embankment towards its full height. The reference to section C–C was left in error on the notes to Fig. 11 of the Paper. However, in general, the problems posed by adjacent structures—other than those forming part of the schemes themselves—were few.

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