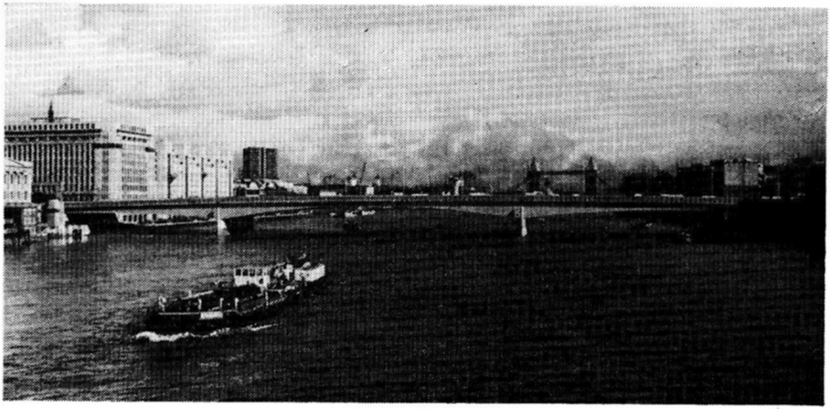

Courtesy John Mowlem & Co. Ltd.

7595 & 7597

DISCUSSION

London Bridge

CHARLES D. BROWN & P. F. MEAD

Mr Brown

It was interesting to examine Rennie's structure during demolition. Although the bridge was extensively cracked the workmanship was first-class. Telford's opinion of the safety of Rennie's bridge has clearly been vindicated but the clay beneath the foundations was grossly overloaded and the factor of safety at foundation level must have been very low throughout the life of the structure.

D2. Although there was just enough room for the new bridge structure between existing buildings most careful consideration had to be given to safety. I would like to pay tribute to the Contractor's skill and safety record during this work which has proceeded without a fatal accident to the public or to the workmen, and the bridge has been completed without any detrimental effect to adjacent structures.

D3. The most delicate operation during stressing of the superstructure was hanger rod adjustment since the gantry and new beam deflexions were varying by several inches as these operations proceeded. These movements were greater than the ultimate load extension of the temporary hanger rods and after some difficulties with the first box during which one or two of the hangers broke, continuous monitoring by electrical gauges was employed.

D4. As expected, creep strain of the superstructure and other small movements have not yet ceased and it will be necessary to re-set the main expansion joints about the end of the maintenance period by which time the youngest box member will be nearly two years old. There has been some minor internal hair line cracking in the box members, in particular at the lateral concrete diaphragms. During construction of the first box the diaphragms were generally cast in situ and shortly thereafter re-strained against shrinkage by post-stressing against the adjacent concrete box units. Minor shrinkage cracking ensued but this problem was greatly reduced by precasting diaphragms in subsequent boxes.

Papers published: *Proc. Instn Civ. Engrs*, Part 1, 1973, **54**, Feb., 25–69.

D5. The Corporation of London wished to have a fitting successor to Rennie's bridge and they could afford to pay for excellence. I hope that by joint efforts we have been able to achieve this.

Mr Mead

The congested site at this historical crossing has added to the Agent's normal administration and engineering duties the role of diplomat, and we are indebted to the police, river authorities and our neighbours for their patient forbearance and co-operation.

D7. Of the various construction techniques, illustrated by the Paper, I will give more details on two aspects.

D8. The curtain rail technique, devised to position the steel sheet piling under the arches of the old bridge and used to accelerate the works, consisted of a steel beam from the underside of the bridge, extended out sideways beyond the line of the bridge and supported by temporary works. Sheet piles were slotted into one another off the end of this beam and as each one was lowered to its level, it was moved sideways along the beam and fitted into a series of roller hangers, running on the bottom flange. In this way it was possible to assemble the complete number of piles necessary for the whole width of the bridge. Their length is limited by the height from the underside of the the beam to bed level. This assembly was then rolled into position and the piles lowered from their hangers between guide wailings on to the bed.

D9. A side-hung air hammer was then used to drive the heads to mean tide level. Subsequent curtains of piles were brought in on top, plated, welded and re-driven in a similar manner. Once head room permitted, heavier hammers were used, mounted on top of the piles to speed up driving. The junctioning to the existing piles was done outside the line of the bridge.

D10. Of the four old river piers, two were demolished inside their cofferdams by telescopic jib cranes working under the bridge and loading the stone into barges. The two piers without cofferdams were dealt with in the same way down to low water level. For the final demolition, a hydraulic breaker has been adapted for underwater use and mounted on a hydraulic excavator to break up the stones which will then be removed by a large tine grab. The numerous old timber piles surrounding the pier will be extracted by direct pull from a 40 ton short jibbed crawler crane mounted on a barge using a specially developed gripping device operating under water.

D11. Much thought and effort has gone into not only the conception, design and planning, but also the architectural appearance of the bridge. The result is something of which we hope London can be proud. The success of this project has been due in no small measure to the excellence of the relations and the co-operation we have enjoyed with all parties concerned.

Lord Holford, William Holford & Partners, Consulting Architects

The Papers are valuable because they are factual: they record achievements. I should like to pay a tribute to the solid work and to the imagination behind the design of the bridge, the gantry and the other plant needed for its construction, as well as the prodigious effort that went into its actual building and supervision.

D13. As Consulting Architects for the new London Bridge we were privileged in two ways. The Bridge House Estates Trust, the client committee, as advised by the City Engineer, could afford to allow us to specify first-class finishing materials and craftsmanship, provided that these contributed to good appearance and low maintenance costs.

D14. Also, as soon as it was decided in 1965 to accept the Consulting Engineers' recommendation to replace the existing bridge by a new bridge, I had the benefit of his early consultation on the effects that the preferred design and method of construction would have on an historic setting with changing patterns of use. This joint consultation at the planning stage laid the basis of collaboration on matters of detail, so that form followed function throughout and did not try to dictate to it.

D15. I should like to make two points dealing with the visible form of the bridge rather than with its inherent structural system, or with the process of its building. The first concerns pedestrians, and the second concerns granite.

D16. Many felt, when the design was under consideration in Parliament and with the Royal Fine Art Commission, that pedestrians should be protected on their way to and from London Bridge Station and their offices in the City. Many ideas were mooted, such as a lower deck below the traffic, which would have interfered with the river clearance, or a metal and glass shelter over the downstream pavement. Not only did these additions conflict with the clean lines of the bridge, but they would have done away with one of the clearest and most attractive views of the river up and downstream.

D17. Looking ahead, however, one had to admit that the existence of an auxiliary covered way, perhaps with moving pavements, was a possibility for which provision should be made. A model was constructed to show how this covered corridor on the centre line of the bridge could be supported on columns from the central island and raised about 16–18 ft above the main deck level. The haunches for these columns, if they are ever needed and if they can ever be afforded, have been incorporated in the design. Meanwhile, the downstream pavement has been widened to 21 ft. It has been protected by a screen from the vehicles on the carriageway, and it has been warmed, along with the carriageway, against ice.

D18. As to the granite, Mr F. Stower and Mr R. Gray were especially concerned with its selection, quarrying and surface treatment. Mr Gray has written fully on the subject.[D1]

D19. The new London Bridge relieves congestion over a small, but vital, length of the road system. It engenders no new traffic. Instead, it eases the movement from the north bank to the south, it anticipates future improvements at the approaches, it makes provision for an eventual covered walkway system, at least at the City end of the bridge, and by a future covered corridor to the railway station. It will also provide a means by which pedestrians can cross from east to west on the approaches to the bridge without encountering traffic.

Mr R. S. Anderson, Resident Engineer

In the early stages of the project I was asked to write out a list of firms from whom the client could invite tenders. From a plethora of firms which varied from the most distinguished to Joe Bloggs I determined the criteria by which I would choose such contractors, namely: first, that the firm chosen should have the financial stability to spend money to earn the money; second, that they should be able to dig hazardous holes in a 21 ft tideway in safety; third, that they should know their business in the prestressing game; fourth, administratively they should be sound since this was an administrative exercise above all; and finally, that in the end we would get 'the good London finish.'

D21. Out of some 24 we found six who had pretensions to three or four of these criteria and I, among others, was pleased that 'London John' won the contract.

D22. Reverting to the criteria, whether or not John Mowlem had the money to put forward, they put their whole endeavour forward which is the same thing. They dug the shafts quite brilliantly, and no one concerned was ever apprehensive about the very difficult ground conditions, nor about the safety of the workmen, because they brought the right kind of workmen with them.

D23. Although they did not appear to have done prestressing on this scale, they did their homework. Some difficulty was encountered, mainly due to uncertainties in connexion with the E-value of the 19-core strand, until a 400 ft length was used as a test piece instead of the 8 in. gauge length which is standard. Their assiduity and adherence to the agreed system relieved us of all concern.

D24. All the administration was done by engineers. We suffered from none of the outside forces which bedevil many contracts, and hence managed to meet the needs of the police, the Port of London Authority, London Transport, the fire brigade, the ambulance service, the 100 000 pedestrians a day and those concerned with the shipping, assisted to a great extent by the co-operation and good will of our neighbours. The police, both the City and Metropolitan, the Port of London Authority, in the persons of the Director of Marine Services and the Harbour Master, allowed us every scope provided they knew what the score was, and we made certain that they did know. The London Transport, GPO and London Electricity Board worked with us, despite many changes of programme, and adjusted their arrangements to meet ours with a co-operation which could hardly have been expected. Each of these organizations could well have taken the opposite line, and much of our success is due to the fact that they did not.

D25. We got 'the good London finish' which we hoped we would have and which London John prides himself on, and we had the assistance and persistence of the Architects, who were filled with understanding and, pleasingly, with energy!

D26. The gantry was most elegant and brilliantly conceived. It was found to be easier to traverse this large machine by hand rather than by mechanical means.

D27. Perhaps one of the most difficult problems was to follow a piece of high tensile steel through the shops to the gantry itself. Apparently the method is to ask the foreman. Drillings had to be taken to establish that we really had high tensile steel. The demolition of the gantry merits a paper on its own. It was a *tour de force*.

D28. The concrete in the casting yard was monitored by a German gentleman from Sandbergs, who had last seen the Surrey Docks through a bomb aiming sight in an aeroplane; but he did it with great Teutonic thoroughness, and John Mowlem's workmen tried to outdo him in skill, with such success that constant strengths of 10 000 lb/sq. in. $\pm$ 2% were achieved.

D29. The long term planning of the demolition by Mowlem's planning organization began to show the thought that they had put into the design of their temporary works at a very early stage, and eventually the mattresses which supported the arch could be hung without having to drill holes through the old arches. They were then stressed up to 110% of the arch load to jack out the keystones. Of all the hazardous activities undertaken, this must have been their greatest triumph.

D30. One of the most significant features in running the whole job was that the Agent and I seemed to be able to finish every day's work in harmony, and hammer

Schedule A. Box 1. Stressing procedure

Southern table span
1. Stress southern table span to 25%
2. Check hanger loads at units 67, 68, 69, 70 and 63, 64 and 65
3. Stress southern table span to 50%
4. Remove and relax hangers in order as listed in Table D1

Northern table span
5. Stress northern table span to 25%
6. Check hanger loads at units 20, 21, 22, 23 and 27, and 28
7. Stress northern table span to 50%
8. Remove and relax hangers in order as listed in Table D2

Suspended span
9. Stress suspended span to 50%: procedure as laid down in Table D3
10. Release and remove remaining hangers in all spans as Table D4
11. Stress suspended span to 100%

Final stressing
12. Stress southern and northern table spans to 100%
13. Lower suspended span to final position

each other with renewed and rethought vigour in the morning! Thus any decision took less than 24 hours; this maintained our excitement and, I am sure, contributed to the workmen's contentment; if the workmen are content, they give you a good job.

Dr S. K. Liszka, F

I wish to emphasize certain aspects of construction closely tied up with the design of the bridge, namely stressing procedure. Mr Brown states in Paper 7595 that the gantries were specified and designed by the Engineers at tender stage, and in § 39 he states that the Contractor adopted main lines of the Engineers' procedure and further developed the gantry design. I should like to amplify this. The gantry was completely redesigned because the Engineers' scheme presented a number of problems.

D32. The basic principle of overhead support for both the old and new structures was retained; however, the Contractor's design allowed the units to be transported along the gantry without interruption, and the gantry itself to be moved sideways across the bridge without hampering the flow of traffic. The gantry design for exactly known loads produced no problem, but having both the gantry and the reinforced concrete box girder during erection, with structural properties changing from loose weights of the elements to self-supporting structures, both connected by hangers,

Table D1. Proposed procedure for removal of hangers at 50% stress with no load on cantilevers

Southern table span

Sequence of removal, unit number	Relaxation required to hangers at unit numbers										
	60	61	62	63	64	65	66	67	71	72	73
51 52 53 54 55 56 57 58 59 69 70					None						
68								$\frac{3}{8}$			
67						$\frac{1}{8}$	$\frac{1}{8}$				
66			$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{3}{8}$			$\frac{1}{4}$		
65		$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$				$\frac{1}{4}$	$\frac{1}{4}$	
64		$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$					$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{8}$
63		$\frac{1}{4}$	$\frac{1}{4}$						$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{8}$
62									$\frac{1}{8}$	$\frac{1}{8}$	
61	$\frac{1}{8}$										
60											

Table D2. Proposed procedure for removal of hangers at 50% stress with no load on cantilevers

Northern table span

Sequence of removal, unit number	Relaxation required to hangers at unit numbers 18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
39																
38	None															
37																
36																
35				1/8												
34															1/4	1/8
20				1/8												
21	None															
22						1/8										
23	None															
24		1/8														
25	1/8	1/8														
26	None															
33															1/8	
32										1/4	1/4	1/4	3/8	1/2		
31										1/4	1/2	1/2	5/8			
30										1/4	1/4	5/8				
29										1/4	3/8					
28										1/8						
27																

together with the differential settlement of gantry supports and different points of supports for the reinforced concrete box girder and the gantry, produced a problem which had to be analysed in detail. This involved finding the influence of one on the other during stressing and releasing the box girder from the gantry.

D33. The detailed stressing procedure was worked out specifying four factors: first, which hangers had to have the load checked, adjusted or be removed at various stages of stressing (Schedule A); second, the sequence of hanger removal and adjustments required, as laid down in Table D1 for southern table span and in Table D2 for northern table span; third, stages of stressing the suspended span and

Table D3. Procedure for stressing the suspended span

Stage	Stress, %	Hanger number	Relaxation required, *in.*	Hanger to be removed	Reaction required, *tons*	
					North	South
1	5	40	$\frac{7}{16}$*	—	None	None
		48	$\frac{1}{8}$*	—	None	None
2	10	—	—	—	—	—
3	10	—	—	—	20	20
4	15	—	—	—	—	—
5	15	—	—	—	40	40
6	33	—	—	—	—	—
7	33	—	—	—	65	65
8	33	19	—	Rvd	—	—
		71	—	Rvd	—	—
9	33	18	—	Rvd	—	—
		72	—	Rvd	—	—
10	33	17	—	Rvd	—	—
		73	—	Rvd	—	—
11	33	16	—	Rvd	—	—
		15	$\frac{1}{4}$	—	—	—
		14	$\frac{1}{8}$	—	—	—
12	33	15	—	Rvd	—	—
		14	$\frac{3}{8}$	—	—	—
		13	$\frac{1}{8}$	—	—	—
13	33	14	—	Rvd	—	—
		13	$\frac{5}{8}$	—	—	—
14	33	13	—	Rvd	—	—
		12	$\frac{1}{4}$	—	—	—
15	50	—	—	—	—	—
16	50	—	—	—	122	122

* These operations to be applied uniformly
Rvd: hanger to be removed

rate of reaction transfer on to main beam cantilevers shown in Table D3; fourth, final removal of hangers, shown in Table D4.

Sir Harold Harding, Past President

I was happy to read of the speed with which the City Corporation was allowed to rebuild London Bridge. How different from the 'Battle of Waterloo'! There is much to be learned both from the Papers under discussion and the Papers by Buckton and Fereday[D2] on the demolition of Waterloo Bridge in April 1936, and by Buckton and Cuerel[D3] on the New Waterloo Bridge in June 1943.

D35. In 1923 Waterloo Bridge, which like London Bridge had been settling, started to settle in earnest. The Council of the Institution of Civil Engineers were asked for their opinion and they advised the London County Council (LCC) to accept that of their own consultants, Sir Basil Mott and Sir Maurice Fitzmaurice, which was to pull it down.

D36. Directly this crisis became known, Sir Harley Dalrymple-Hay devised a scheme for underpinning and asked my chief in John Mowlem and Co. to give him an estimate in which I was involved at a lowly level. Publicity led citizens who had never heard of Rennie, and who had hardly noticed the bridge, to leap to the defence

Table D4. Procedure for removal of hangers at 50% stress with full load of suspended span on cantilevers

Sequence of removal from unit number	Relaxation required to hangers at unit numbers 84	85	86	87	88	89
Southern table span						
74						
75						
76						
77						
78			None			
79						
80						
81						
82						
83	$\frac{1}{4}$					
84		$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$		
85			$\frac{1}{2}$	$\frac{3}{8}$	$\frac{1}{4}$	
86				$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$
87					$\frac{3}{8}$	$\frac{1}{4}$
88						$\frac{3}{8}$
89						
Northern table span						
12						
11						
10						
9						
8						
7						
6				None		
5						
4						
3						
2						
1						

of Rennie's masterpiece, and they held a conference of societies urging the preservation of Waterloo Bridge.

D37. The LCC saw that this was to be a close run thing, so they built a temporary bridge alongside the existing one. As London Bridge was not held up by such battles it was possible by ingenuity to use the new bridge as a temporary one. The Royal Commission on Cross River Traffic was formed in 1926, and the evidence still has value. The Commission recommended, however, that the bridge should be reconditioned and a new bridge built at Charing Cross. In 1932 the LCC ignored this and decided on a new bridge, but the battle still raged.

D38. In § 16 of Paper 7595 Mr Brown, quite rightly, mentions the possibility of injection work below the piers and its unsuitability. In 1932 I was starting to introduce the Joosten process into the UK, and it interested Sir Harley. It proved equally unsuitable in the conditions at Waterloo, but this did not deter him from making an even more ingenious scheme for underpinning. He suggested that I ask my directors for another estimate and they told me to do it myself. Sir Harley then briefed Sir William Davidson who told the House of Commons that John Mowlem and Co., one of the most experienced bridge building firms, had made an estimate for underpinning of £500 000. Members of Parliament then voted to retain the bridge. I knew that the railway bridge across the Thames from Victoria was the last one Mowlems had built—in the 1890s, but now they have revived their reputation as Thames bridge builders.

D39. The LCC, being instructed to underpin, sensibly called in Rendel, Palmer and Tritton who produced a sound scheme in which they emphasized that in each step a condition must be made safer before each step to relax was taken. Then Herbert Morrison, leader of the LCC, leapt on to the parapet and started to demolish the bridge with his own pick-axe! I was gratified. Eventually the Government provided money to build a fine reinforced concrete bridge, now matched by a fine post-stressed concrete bridge. Both of these would have given pleasure to the Rennies.

D40. In Buckton's Paper [D2] on the demolition of Waterloo Bridge he gives credit to Sir Basil Mott for using the steel gantry for holding up the arches. In the case of London Bridge, presumably the cost of demolition is inextricably mixed with the erection. Buckton's Paper states, 'Mr H. J. B. Harding observed that when the Royal Commission on Cross River Traffic was appointed in 1926 it issued a preliminary questionnaire to some of the principal witnesses. Question 3 read: If the present bridge should have to be removed and not rebuilt, (a) How long would the operation take? (b) How much would it cost? (c) To what extent would waterborne traffic be interfered with during progress of the work?' Two witnesses answered 24–30 months, costing £275 000 to £300 000 and no interference. These two witnesses wanted to pull it down. Two other witnesses, who were keen to keep the bridge, said $3\frac{1}{2}$–$4\frac{1}{2}$ years, costing £500 000 and interference to some extent. I went on to ask the Authors which estimate was nearer the result, but they did not reply. However, Sir Harley was rather cross. This proves that even among our great men, the wish can be father to the thought!

D41. At London Bridge the only bridge erection in the true sense might be the steel gantry, because the cofferdams are dock or maritime work, the shafts with grouted segments are tunnel work, the abutments are retaining walls, the units are precast concrete work, and the suspension and stressing is post-stressed concrete work. All these are matters in which Mowlems have vast experience. So it is a mere coincidence that the combination of all these difficult skills has resulted in the production of a beautiful bridge. From my own experience, there is no better example of a perfect piece of work, with a perfect relationship between the staffs appointed.

Mr D. W. Smith, University of Dundee and Mott, Hay and Anderson

This job looked, at the design stage, as if more than average knowledge was necessary for the Designers to foresee and allow for site difficulties. The designer of a bridge must always consider how it will be put up. It is no use just designing a complete structure and hoping that somebody will put it up. This becomes more important as site difficulties increase.

D43. It seemed that the site difficulties in this case were rather pronounced, in that there was virtually no working area at the site, road and river traffic had to be maintained throughout and the London clay was overloaded by the foundations of the existing bridge. These difficulties caused the Designers to spell out rather fully the erection procedure, even to the extent of making an attempt at a detailed design of a gantry. It proved only to be an attempt, as the Contractors made a complete redesign, and one has to admit that the gantry that was finally used was superior in that the crab could be moved from end to end of the bridge, and not merely end to end of one span.

D44. I hope there will continue to be vigorous debate about how far designers and consulting engineers should specify and be responsible for construction procedure. This particular job appeared to be an example in which considerable involvement was inescapable.

D45. With regard to the jointing between precast segments, some bridges have been made with precast segments joined end to end with very thin joints of adhesive. This neat arrangement would have been attractive here since there was no working area at the site, and site mixing of jointing concrete would have been unnecessary. The considerations which led to the decision to have concrete-filled joints were, first, that the precision of the ends of the precast pieces that would have been necessary if they were to meet in a paper-thin joint would have been extremely great, even greater than the fine tolerances which were in fact worked to. It would have been practicable to achieve this only by casting one segment end to end with another, and my firm thought this was an unreasonable constraint to put on the work in the precasting yard. Not only the manufacture of precast units, but also control of deflexion during erection, would have to be very precise, because when joints are made paper-thin with adhesive, they have to be made one by one as the segments are moved up. Therefore, weight is gradually being put on to the gantries, and deflexion continues to build up after some of the joints have been made. It is difficult to visualize how this could have been achieved without earlier joints being opened up by deflexion caused by the weight of later units. The problem of the relative deflexion of the new bridge, and the gantry supporting it, would thus have been even more difficult with paper-thin joints. The concrete joints called for great skill in making, but their final appearance is satisfying inasmuch as they break up just sufficiently the otherwise monotonous flat face of the concrete.

D46. It was thought that as precast concrete is designed to zero stress at the tension edge, then if there is no continuous longitudinal reinforcement, theoretically a very small overload begins to open up cracks. This probably does not matter as long as the longitudinal reinforcement is continuous; however, with discontinuous reinforcement, the opening up of cracks will be concentrated between segments. Accordingly, lapping of reinforcement in the tension part of the top slab was allowed for in joint design. There was some complaint from the site about the fact that too much overlap of reinforcement had been allowed and that unless some bars were cut away the concrete could not be poured in.

Professor J. K. T. L. Nash, King's College, University of London

I should like to say a little about the stability of the old bridge as I was concerned with looking at this point.

D48. The bridge which has been demolished was designed by John Rennie, senior, and the philosophy was basically that which he had used successfully in the adjoining Southwark and Waterloo bridges, all three of which have now been replaced. His son, Sir John Rennie, was the engineer and he describes the project in detail in his autobiography.[D4]

D49. Figure D1 shows a longitudinal section of the bridge and Fig. D2 is a typical cross-section at one of the piers. Fig. D3 shows that the clay is typical of the London clay in this region. In order to construct the foundations, cofferdams were built around each pier and the area inside was excavated down to the clay. Beech piles, each 20 ft long with an average diameter of 12 in. were then driven into the clay at a spacing of 4 ft in one direction and 4 ft 6 in. in the other so that each pier was founded on between 192 and 200 piles. Rennie observed that, on driving the piles, the surface of the clay rose by an amount equal to the solid content of the piles that had been driven in, and this implies extensive remoulding of the clay immediately below the piers.

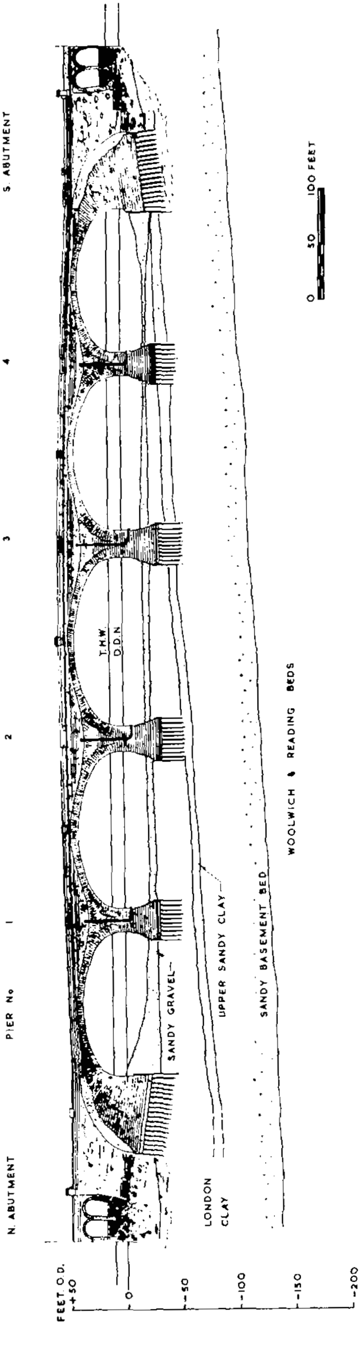

Fig. D1. London Bridge

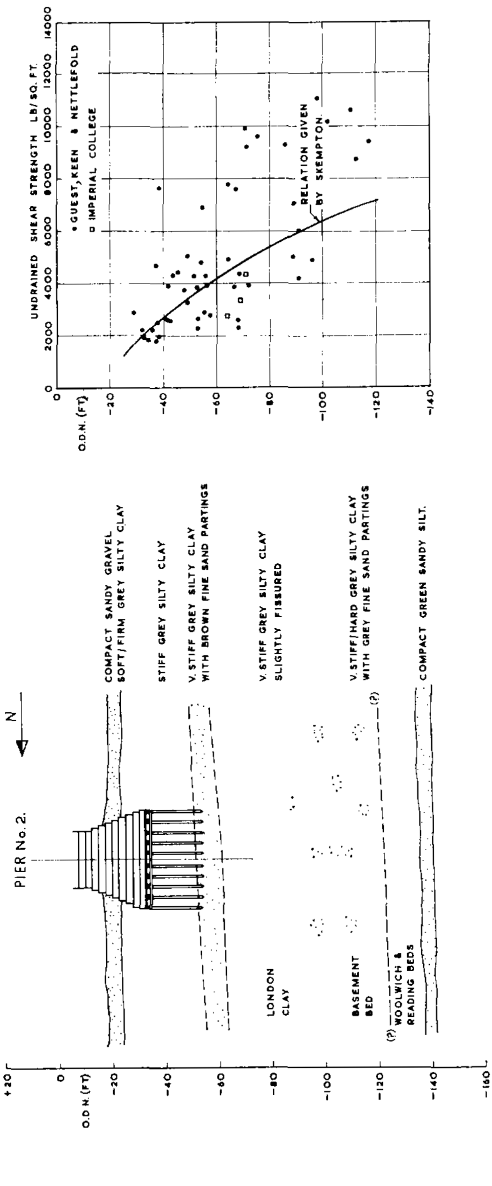
UNDRAINED SHEAR STRENGTH LB/SQ.FT.
0 2000 4000 6000 8000 10000 12000 14000
• GUEST, KEEN & NETTLEFOLD
□ IMPERIAL COLLEGE
RELATION GIVEN BY SKEMPTON
O.D.N. (FT)
0 -20 -40 -60 -80 -100 -120 -140
PIER No. 2.
N
COMPACT SANDY GRAVEL
SOFT/FIRM GREY SILTY CLAY
STIFF GREY SILTY CLAY
V. STIFF GREY SILTY CLAY
WITH BROWN FINE SAND PARTINGS
V. STIFF GREY SILTY CLAY
SLIGHTLY FISSURED
V. STIFF/HARD GREY SILTY CLAY
WITH GREY FINE SAND PARTINGS
COMPACT GREEN SANDY SILT.
LONDON CLAY
BASEMENT BED
WOOLWICH & READING BEDS
(?)
+20 0 -20 -40 -60 -80 -100 -120 -140 -160

Fig. D2

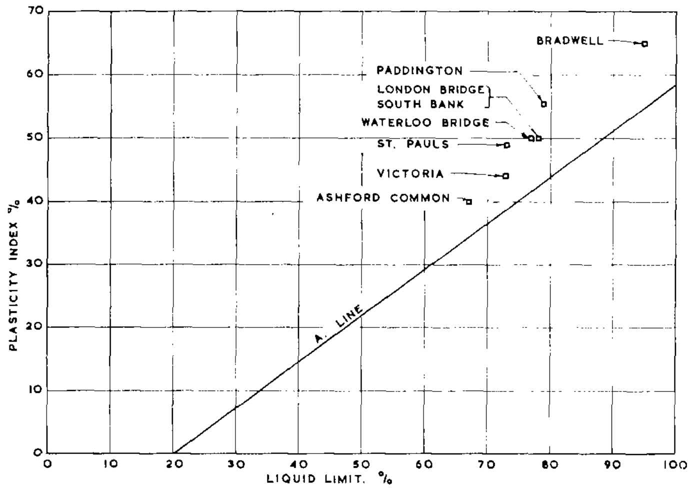

Fig. D3. Comparison with index properties from sites elsewhere in the London Basin

D50. The loose clay between the heads was then removed to a depth of 9 in. and the space was filled with ragstone bedded in lime mortar. The tops of the piles were connected with 14 in. square timber sills and the space between them was filled with brickwork in lime mortar. This was repeated in the other direction with close jointed 6 in. planking bedded in mortar laid on top. All the timber was spiked in position, and on this platform the masonry was built. Two samples of the wood were retrieved from the site investigation boreholes: one was beech which parted readily along the grain and the other was pine which was extremely strong. On this evidence the timber might well have deteriorated considerably.

D51. Rennie's original bridge weighed 120 000 tons and the 1904 modifications increased this to 130 000 tons so that each pier was finally carrying about 21 000 tons, the live portion of which was negligible compared with the dead load. Each pile therefore carried about 110 tons which is excessive. From the driving records Wellington's formula gives a safe load of about 25 tons/pile, and this makes no allowance for group or block effect. If the piles are ignored then the pressure on the surface of the clay is about $5\frac{3}{4}$ ton/sq. ft.

D52. This pressure implies a factor of safety against shear far lower than would be adopted today. In 1861, Hunter remarked that similar piles under the new Westminster Bridge carried only 15 tons each or an overall pressure of 2 ton/sq. ft on the foundations. On loading the piers Rennie recorded a vertical settlement of approximately 3 in. when the 12 000 tons from the arch were transferred to them. In addition, all the piers tilted downwards from west to east, due possibly to the tops of the piles being above the clay on the east side.

D53. A few days after the opening of the bridge in 1831 one Peter Jeffery, a cheesemonger of Cheapside, petitioned Parliament that an enquiry be made into the stability of the new bridge for, as he put it, 'there is too much reason to apprehend that a calamity similar to the one which befell the New Custom House may speedily happen to the new London Bridge'! Jeffery had observed the considerable tilting, for it was simple to do this when the tide was at the turn and the water still. Rennie suggested that Jeffery was concerned with the loss of trade he was to suffer due to the new approaches to the river crossing, but Parliament took the petition seriously, and three

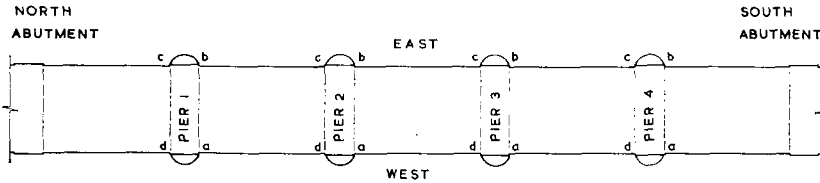

Fig. D4

Table D5

Pier number	Points around pier	ODN levels of bottom of string course		
		Intended	Sept. 1831	June 1965
1	a	9·80	8·55	8·25
	b	9·80	8·21	7·77
	c	9·80	8·05	7·51
	d	9·80	8·38	8·10
2	a	9·80	8·48	8·11
	b	9·80	7·98	7·42
	c	9·80	7·71	7·15
	d	9·80	8·23	7·83
3	a	9·80	8·90	8·70
	b	9·80	8·30	7·79
	c	9·80	8·13	7·72
	d	9·80	8·75	8·57
4	a	9·80	9·05	8·77
	b	9·80	8·48	8·06
	c	9·80	8·34	7·95
	d	9·80	8·94	8·63

eminent civil engineers, Thomas Telford, then President of the Institution, James Walker, his successor to that office, and William Tierney Clark, famous for his bridges over the Danube, were appointed to examine the new structure.

D54. The House of Commons ordered their report to be printed on 20 January, 1832 and they confirmed that the bridge was perfectly safe. Having discovered the existence of this report, I looked for any papers in connexion with it, and was excited when I found much of the verbatim evidence given to the Commission not only by Rennie, but also by the contractors and by individual workmen. It was clear from reading these alone that immense care had been taken with the structure.

D55. The Commission arranged for numerous levels to be taken over the new bridge, and it was therefore possible for Mr R. Anderson to go over the same points 134 years later and to see what further movement had taken place. These are shown in Fig. D4 and Table D5 and, relating these readings to those which have been taken regularly since 1904, it became evident that the differential settlement was continuing. This was confirmed by a crack survey in the structure itself. Finding this level book was also exciting, although relating the levels to an absolute datum today is not easy, for the benchmarks on the churches on either side of the river from which they were measured move with time and tide; however, the relative readings are fully valid.

D56. It now appears that the 3 in. immediate settlement of the piers would have been due in part to elastic compression, but in greater part to a failure of the whole

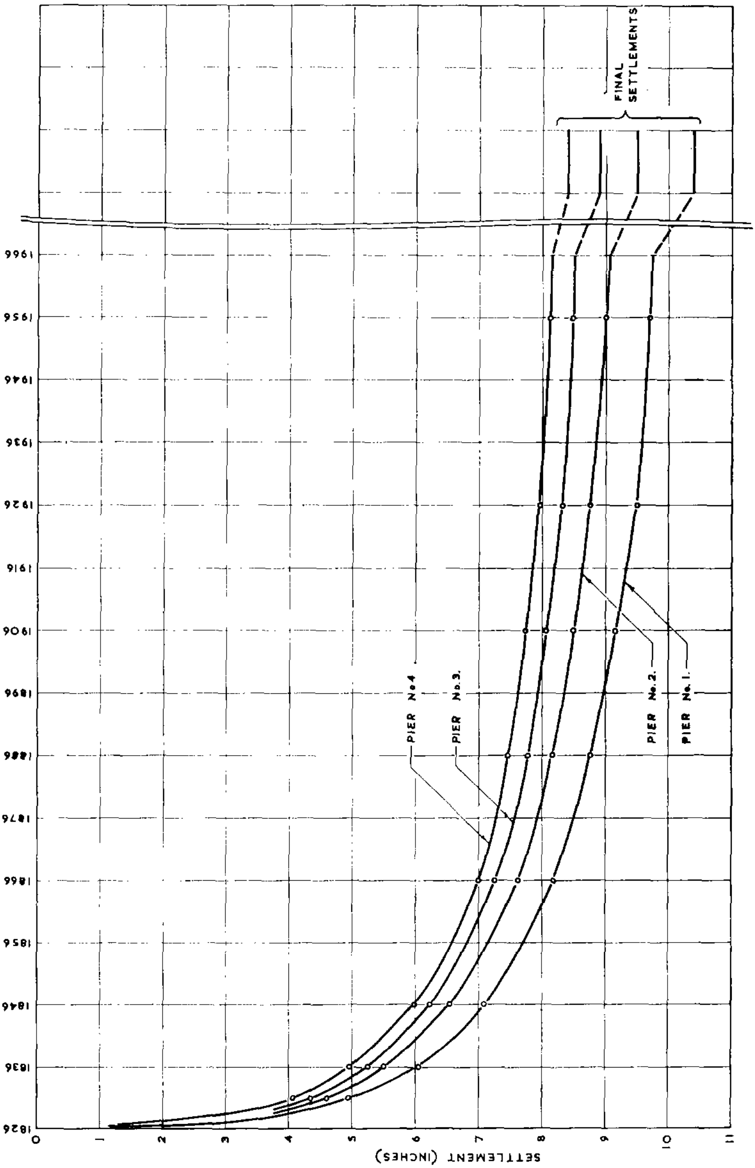

Fig. D5. Calculated settlement of London Bridge piers

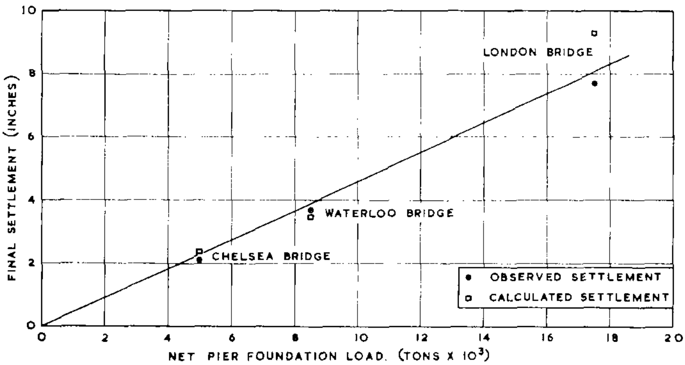

Fig. D6

pile group when a tilting of up to 10 in. occurred. Then the factor of safety cannot have been greatly above about 1·4, based on the remoulded strength and ignoring the ring of sheet piling which remained around each pier and the intact and sound clay which surrounded it and existed below the piles. Fig. D5 shows calculated settlements for each of the piers made by Professor R. E. Gibson, and Fig. D6 makes a comparison with the new Waterloo Bridge and Chelsea Bridge.

Mr R. Beresford, Mott, Hay and Anderson, Resident Engineer in Arizona

Many people from both sides of the Atlantic wrote to me giving their views on the morality of what I was doing. The expressions used varied between 'wonderful gesture' and 'an act of international cultural piracy'! Whether this project was a waste of human resources depends on one's point of view. However, the facts are that Rennie's old bridge is preserved, the City of London has benefited financially, a new desert city has a fine centre-piece on which to focus its community spirit, a wealthy American has become wealthier and many tourists are enjoying looking at 140 years of London soot, which, alas, is steadily falling off under the combined assault of sunshine and oxygen!

D58. Figure D7 shows the bridge connecting the new island to Arizona. Initially, in the absence of a river to span, my firm thought very carefully about casting the arches directly on to gigantic sand mounds. We were apprehensive of restricting free movement of the bridge against passive resistance of the sand, particularly when seasonal temperature vatiations were of the order of 100°F.

D59. Trouble was avoided by carefully timing the closure of each arch and relieving the passive pressures against the steeper parts of the arch by blowing through with air and water, so effectively loosening the sand at the arch springing points.

D60. This initial cavity was later extended until all the arches stood free with a clear 5 ft gap between the soffit and the sand. This technique contrasts strikingly with the methods that Rennie was forced to use by the presence of the Thames. The stonework, amounting to some 10 000 assorted pieces varying between a few pounds and 8½ tons, was assembled well in the circumstances. The erection of the granite facing presented a problem in so far as the Union of Masons' three year working agreement terminated at precisely the point of laying the first stone. Unusual measures were called for while the protracted negotiations continued, and in fact the contract with M. M. Sundt of Tucson was terminated, and the stonework completed under direct labour. Masons were hard to find, but eventually we gained the services

Fig. D7

of an expert stonemason from the Forest Lawn Cemetery in California who trained five teams of masons from local bricklayers!

D61. With the completion of the granite face work, the remaining sand, used as a working platform for the masons, was removed and using a combination of suction dredge and scrapers, some $2\frac{1}{2}$ million cu. yd of sand were excavated to form the new river and beaches along the lake front.

Mr R. B. Hill, Cementation Civil and Structural Holdings Ltd

After a lifetime concerned with structural concrete I now find myself running a structural steel firm. This has caused me to consider the structural medium chosen for this scheme, particularly in the light of Mr Brown's statement in § 27 where he rather briefly dismisses the point by saying that there was little to choose in price between steel and concrete designs. Although the unit weight of steel is three times that of concrete, relative working stresses are ten to fifteen times as great, giving a factor of 5 in strength/weight ratio in favour of steel. I am aware that that does not take cost into account, but the point I should make is that the range of prices submitted was considerable. The price accepted, as stated in § 115, was about £4 million. This compares with the published estimate of £3 million not long before bids were invited. The price my firm quoted was £5 million, and that was not the highest. With such a large range, the standard deviation of the prices was too large to be calculable. It is unlikely that a similar situation would have occurred if the bridge had been in steel and it would be helpful therefore if the Authors could enlarge on the statement that there was nothing to choose in price between steel and concrete. How did they arrive at that conclusion?

D63. With disarming candour Mr Brown states in § 116 that the bridge which was bid for at about £4 million finished up at about £5 million. It would be interesting to know where the difference arises.

Professor A. L. L. Baker, Imperial College of Science and Technology

I was delighted to see the bridge in its final form, because it provides a tremendous argument against those environmentalists who make a target of concrete as a nuisance and a pollution.

D65. I have found that one of the most difficult parts of a bridge with suspended spans is dealing with the shear where the suspended span depends on a projecting nib. That, in many cases, has led to failures and I would be pleased if Mr Brown would say how the load from a suspended span is taken up by sloping 90 strands which must be well anchored right at the end in order to take up that load. There must be a fairly high level bearing stress on the concrete where that load is transferred to the sloping cables. I am sure it is done perfectly, but it would be interesting to have a detail because it is a difficult detail to design. There have been many failures through bad detail design for that kind of scarf joint.

D66. In Fig. 7 of Paper 7595 some of the strand cables are external to the box section, and they are in the corners. How are those bonded to the concrete? I ask this because at Imperial College prestressed box girder bridges are being tested to scale, and great difficulty is found in scaling down the ducts and cables within thin flanges. Putting the cables outside was considered, but the conclusion was reached that one could not be sure of the cables being bonded properly throughout their length to the concrete in the box section.

Mr J. R. J. King, John Mowlem & Co. Ltd

One of the most daunting aspects of the job from the Contractor's point of view was the extent of the planning and design of the temporary works and method concentrated in the first few months of the Contract. I do not know of a project of this magnitude where so much of the method had to be decided so quickly, and which predetermined what was done for the next three or five years. Many of the temporary works' designs and methods were interdependent so that every modification and improvement advanced had repercussions on everything already decided on.

D68. The basic tool in the Contract was the gantry and this, together with the precast units, was to be ready for assembly of the first box 15 months after commencement, which was a sizeable undertaking. The gantry differed from that proposed by the Engineer, and my firm planned and designed over 1800 tons of steel bridge from the start to meet the requirements of BS 153 to suit the dual purpose of suspending new bridge units and also of suspending the existing bridge arches during demolition. It had also to be suitable for rapid transfer from one box position to another. To give but three examples of the degree of interdependence, the height of the gantry depended on the space needed to assemble and stress and then lower the suspended spans. That operation was carried out two years after the commencement of the Contract, but it had to be worked out in sufficient detail in the first month to decide the height of the gantry above the new bridge deck level.

D69. The planning of the sequence of casting units had to be decided quickly, because once they had been cast and moved into the storage area, they could not easily be moved into a different sequence. The method of suspension of the units was required not to leave any marks or blemishes on the exposed faces, and after a considerable amount of research, positions were found among the reinforcement and stressing ducts in which anchor bolts could be placed. On this depended the layout of the bottom boom of the gantry trusses.

D70. Much credit was due to our planning and design engineers in Constructional Services Ltd, the design team of Mott, Hay and Anderson, who were checking our design day by day, and to Redpath Dorman Long's engineers who built the gantry for us.

Mr A. D. Barrett, John Mowlem & Co. Ltd

I can speak at first hand only of the problems which occurred during the last two years of the London Bridge work. I should like to draw attention to four points arising from the Papers and from my experience, from which perhaps lessons can be learnt in principle.

D72. Mr Brown states in § 11 of his Paper that the foundation pressure under the old bridge piers, ignoring the piles, was about 5·75 ton/sq. ft. When the mixed granite and sandstone pier 3 of the old bridge was demolished in the cofferdam, the close timber sheeting surrounding the lower part of the foundation was exposed. Site dimensions now recorded on drawings show that the centre line of the lower part of the foundation was some 4 ft 6 in. upstream of the centre line of the old London Bridge. I believe this was caused by a decision taken during construction to widen Rennie's bridge on the downstream side only, and therefore to move the centre line downstream. The eccentricity of loading on these old foundations increased the pressure on the London clay from 5·75 to about 7 ton/sq. ft under the downstream toe. It is small wonder therefore that not only did the massive old London Bridge settle on its foundations, but that it settled downstream.

D73. I have always felt, perhaps in my ignorance of prestressed concrete design, that the use of prestressing techniques would somehow reduce the quantity of ordinary reinforcement used per cubic yard of concrete. I appreciate that in all bridge work reduction of deadweight is desirable, but it would appear that the quantity of high tensile steel reinforcement in the in situ concrete in diaphragms and between the boxes was of the order of 1 ton/5 cu. yd of concrete. This concentration of reinforcement can have considerable effects on construction time and overall economy, both of which could be reduced if a little more concrete were provided, especially in the region of in situ joints, to leave more room for the reinforcement.

D74. As Mr Mead stated, the decision to build the new London Bridge on the same centre line as the old, while keeping it fully operational during the construction period, involved the Contractor in severe restrictions which generally precluded adjustment to suit any snags which inevitably occur on a project of this nature. Access to site mainly by river was alleviated to some extent by the co-operation of adjacent property owners who allowed us walking, and sometimes machine, access to the works at low level. There was a further limitation on the amount of noise we could make at certain times in the evenings when the use of piling or concrete breaking equipment was precluded. The river had completely changed in character during this long Contract, in that what had been busy wharves and warehouses became disused, awaiting redevelopment. River activity changed to many more large vessels and pleasure craft in the summer. Tugs previously available at short notice were available only by special arrangement.

D75. The Contract, lasting $5\frac{1}{2}$ years, is being finished in turbulent times with seemingly little cost relationship to 1967. The Contract was framed with a modified variation of price clause and in 1973, $5\frac{1}{2}$ years later, the Department of the Environment indices indicate that overall costs have escalated from the date of tender to mid-August 1972 by 42%. When the indices become available for the first and second quarters of 1973, I feel sure that they will indicate an escalation of total costs of 50–60% of those applicable in 1967.

Mr S. H. Studinski, Surrey County Council

It would appear from Fig. 7, Paper 7595, that the concrete boxes were cast in two lifts with construction joints at the junction between webs and the top slab.

D77. Could the Authors explain how the bottom slab and the webs were cast in one lift, and also whether the effect of differential shrinkage was allowed for in the design, as the top slab was probably cast a few days after casting the webs and the bottom slab?

DISCUSSION

Mr J. F. Davies, Berkshire County Council

In 1969, I was resident engineer on a large segmentally constructed bridge in Lancashire. The bridge has both internal and external prestressing cables, and the Papers bring to mind one or two familiar problems.

D79. I am particularly interested in the grouting details and would be pleased if the Authors could enlarge on the reasons for the duct interconnexion and the nature of the care taken during grouting. Was any radiography testing specified to check the success or otherwise of this operation? Would the Authors also detail the method of placing and compacting the pea-shingle concrete encasement to the external cables at the top of the boxes?

D80. I note that the anchorages to the internal prestressing cables over the piers are situated on the under side of the top flange, and as strand feeding and stressing probably would have been easier had they been placed in recesses on the top of the boxes, what were the main reasons for their location as detailed?

Mr H. V. Colley, Greater London Council, formerly Agent of John Mowlem & Co. Ltd

Mr V. H. Collingridge was Contract's Director from the inception of construction and acknowledgement must be made of his energy, expertise and discipline which established the foundation on which the engineering success of the Contract was built. Mr Collingridge's enforced retirement from the Contract, owing to ill health, was a serious blow to the Contractor.

D82. There is an error in § 1, Paper 7595; the accepted construction period for the first stone bridge is 33 years and not 30. The priest, Peter de Colechurch, in 1163 rebuilt, in elm, a bridge at London. In 1176 the pious architect began building his stone bridge, which was completed in 1209 by the worthy London merchants, Serle, Botewrite and Almaine. Welch[D5] provides this information. The priest, besides designing and carrying out the work until his death in 1197, is also said to have built the Bridge Chapel from crypt to roof at his own cost and charges. Whether Peter de Colechurch's health was failing or King John was dissatisfied with the progress I cannot say, but he wrote to the Mayor and citizens of London recommending Isenbert Xainctes as a new architect to finish the work. Although the present works have so far considerably exceeded the original Contract period, it does not appear to have been necessary for the Queen to intervene.

D83. In § 2, Paper 7595, there is an incorrect statement; the Client received the benefit of Government Investment Grant, which was substantial in relation to the profit a Contractor may hope to earn on such a Contract.

D84. Referring to Paper 7595, § 4, press headlines speak of 'six lanes to nowhere' and it is understood that the bridge has been designed for eight lanes of traffic ultimately. Will the Author provide a summary of traffic statistics and networks used to justify the decision to widen the bridge?

D85. Mr Brown incorrectly referred to the five year Contract; Paper 7597, § 6, refers to 64 months as the extended Contract, and § 65 of Paper 7597 incorrectly reports all pier demolition complete. The original Contract period was 54 months and at the reading of the Papers approximately 65 months had elapsed yet two bridge piers remained visible at low water. What is the extension of the Contract period and the estimated duration of Contract up to final removal of old bridge piers down to $-24{\cdot}00$ OD?

D86. Paragraph 11, Paper 7597, is incorrect; during my four years as Contractor's Agent the programme was updated manually at site since it was quicker and inevitably there was no Tender allowance for the luxury of a computer.

D87. Paper 7597, § 59, dismisses in 16 words the toil of the demolition Subcontractor's contribution to bridge demolition. Messrs Goodman Price Ltd were employed for the demolition of balustrading, all brick work and masonry in spandrel walls and carriageways. Contract drawings showed the full width of the bridge demolished following erection of boxes 1 and 2. However, the Contractor elected to demolish the bridge in two longitudinal strips of equal width. By demolishing the arches in this way and erecting boxes of new bridge after each strip had been demolished, the gantry moves were kept to the minimum of three compared with an original proposal of seven, thus saving time and money. Demolition of spandrel walls and carriageway was undertaken in two stages. For the upstream half of bridge the surfacing was chopped up with an 'Arrow Thumper' with a 1500 lb hammer and the massive York stone slabs spanning between spandrel walls were peeled off with an NCK 466—1 cu. yd hydraulic Backacter which afterwards ripped out the brick work spandrel walls approximately 2 ft 9 in. thick.

D88. The timber facing to the demolition mattress was lined with sheets of expanded polystyrene to fill voids between mattress and intrados when bringing the mattress up tight to the arch. Five-ton and ten-ton Demag hoists suspended from gantry runway beams were the principal handling equipment for stone during demolition.

D89. The extent to which the waterway could be obstructed by cofferdams was a matter of great concern to the Port Authority, lest an increase in the deposition of silt upstream of the bridge ensued. Would the Authors place on record the percentage of waterway cross-section, measured below Trinity high water, obstructed by pier and abutment cofferdams and say whether additional siltation actually occurred?

D90. Paper 7597, § 65, incorrectly states that the two river piers without cofferdams have been removed. It is a pity that this operation which has considerably taxed the Contractor's ingenuity, since the piers are still clearly visible at low water, has been dismissed in a single sentence. Would the Authors please describe these operations and say what plant has been used, or will be used?

D91. Paper 7597, § 25, refers to the driving of 24 × 12 in. universal beams as piles. These piles were driven with a BSP DE 30 hammer; two piles were test loaded and working piles were subsequently rated as 80 or 100 ton piles. It is understood that it has not been possible to extract these piles; could the Authors give details of equipment and pulls applied to extract these piles?

D92. Mr Brown referred to hard driving of sheet piling, a statement which is inconsistent with the ability to drive 60 ft Larssen 3B piles with a McKiernan Terry No. 6 side slung hammer. Obstructions were encountered on river cofferdams causing declutching and the problems referred to in § 29, Paper 7597. When driving cofferdams to the north abutment, a single shaft cofferdam was obstructed by a close

Table D6

Pile hammer	Energy per blow, *ft lb*	Max. pile length, *ft*	Penetration, *ft*	Location and remarks
BSP DE 40	32 000			Too heavy for sheet piles
SP DE 30	22 400	70	36	Larssen 3B Driven in pairs
Delmag D 5	9 040	70	36	Larssen 3B Driven singly
McKiernan Terry No. 7	4 150	42	42	Larssen 3B. Driven singly in circular work
McKiernan Terry No. 6	2 500	60	24	Larssen 3B. Driven singly with hammer side slung in cradle

cluster of 12 in. dia. timber piles occurring across some 30% of the area. Table D6 shows pile hammers used in relation to the lengths of piling driven.

D93. The Contractor elected to design his own more versatile gantry which constituted approximately one fifth of the Contract sum; it is therefore incredible that so little should have been written in the Papers about this major item of plant.

D94. Reference is made in Paper 7597, § 12, to a yard with enough space to store $2\frac{1}{4}$ boxes at any one time—this statement is incorrect. The Contractor was given 150 000 sq. ft at the southern end of the casting yard shown in Fig. 3. This yard could barely accommodate three-quarters of a box after space had been allocated for storage of old bridge masonry, a casting area and general storage and loading area for all bridge materials. An additional area of about 150 000 sq. ft was acquired by the Contractor to accommodate up to $2\frac{1}{4}$ boxes of bridge rather than shut down the casting yard through lack of storage space.

D95. Although Paper 7597, § 15, refers to black streaks appearing on segments, in fact the manifestation was generally circular patches.

D96. Referring to Paper 7597, § 16, the later supplies of duct were formed from helically seamed strip steel, stronger transversely but unfortunately flexible longitudinally and requiring a considerable amount of extra steel fixing to secure against movement during concreting. The ducts provided (4 × 1 in.) gave insufficient tolerance for the accommodation of five 0·7 in. tendons, alignment of segments and casting errors. Consequently the drawing of tendons, after units had been lined and levelled, was a painful operation.

D97. With regard to Paper 7595, § 90, what measures were taken to overcome heat stress problems when welding the typical fifty $1\frac{1}{2}$ in. dia. bar reinforcement in diaphragms, and what welding tests were carried out?

D98. Would Mr Mead provide the accident frequency figures for each year of construction, together with an analysis of the accidents under each standard classification?

D99. Approximately one quarter of the Contract value, less contingencies etc., was billed by the Engineer in temporary works for gantry, cofferdams and temporary decking. Would Mr Brown say whether, if re-billing the works, he would adopt a wholly 'method related' system of bills of quantities?

D100. The success of the project may be adjudged differently by the Engineer, Client and Contractor. The Engineer's criteria could be as follows.

(*a*) Was the Tender in accord with my original estimate?
(*b*) Was the final cost within the estimate?
(*c*) Was the site survey adequate and accurate?
(*d*) Was the site investigation adequate?
(*e*) Did the fundamental design remain unchanged?
(*f*) Did the Contract documents protect the Client and lead to a quick and fair settlement?
(*g*) Was the Contract period quoted in the documents, correctly assessed?
(*h*) Was it right to specify so many temporary works?
(*i*) Did I need to issue many additional drawings?

I should like to hear Mr Brown's assessment against these criteria. Referring to item (*c*), failure to survey the true position of existing piers adversely affected clearances for shafts and cofferdams. Referring to item (*d*), insufficient data were available for gantry foundations at the abutment, giving rise to increased costs for difficult foundations. Referring to item (*e*), the fundamental design was unchanged. Referring to item (*f*), settlement has not been easy or quick. Referring to Paper 7595, § 115, the cost seems likely to exceed the Tender sum by 37% when the fundamental design and details have hardly altered at all. Referring to item (*g*), 54 months were specified and the final period is likely to be 68–71 months. Programme rearrangements have been made to save time, additional piling plant was brought to work on downstream cofferdam cells and gantry moves were reduced to a minimum.

D101. If programme modifications leading to savings are offset against the Contractor's share in the delay, then the 17 months overrun must be apportioned between extra works and errors in the Contract period specified. The completed bridge is virtually unchanged from the Contract drawings and the Engineer's Tender programme allowed insufficient time to carry out the works.

D102. The Contractor has a briefer set of criteria: (*j*) Did I make the profit I sought? (*k*) Will I be invited to undertake further work? (*l*) Did the profit justify the heavy demand on the Company's resources?

D103. Mr Mead's views will be of interest. Shareholders have not had much encouragement to date! Mr King commented on the very heavy demand upon the Contractor's resources and it seems that unless the ultimate profit is proportionately better than usual, or the order book was empty at the time of Tender, the answer to item (*l*) must be 'it was not worth it'.

D104. The Client's criteria will be simple: (*m*) Did the job cost more than I expected? (*n*) Was delivery on time? (*o*) Did I suffer undue inconvenience during construction? Against these criteria, the Client could be unhappy.

Mr A. C. E. Sandberg, Messrs Sandberg

The mean concrete strength of the order of 10 000 lb/sq. in. with a standard deviation of 410 lb/sq. in. probably makes this the finest structural concrete ever produced in London. The achievement of this, however, was not without effort. In 1966, in the design stage, Mott, Hay and Anderson approached us in connexion with a reasonable design strength which would be achievable in several years' time using locally available aggregates, and considerable thought was given to this aspect and that of the specification generally.

D106. It was subsequently decided that an exposed aggregate finish would be required; visits were made throughout the UK and many samples were examined and tested. The Institute of Geological Science also helped considerably in the search. None of the initial 40 odd samples was selected, for various reasons. A fresh quarry was found, which appeared promising, but after various trials it was rejected partly because of possible colour inconsistencies. Finally, Creetown granite and Hunnable sand were approved after a number of trial panels had been cast.

D107. While pursuing this perfection in aggregates we had feared that the concreting might be subjected to the black staining effect which can arise somewhat unpredictably and, unfortunately, this developed. This peculiar staining which is currently the subject of further research is attributed generally to the reorientation of cement crystals under certain conditions. We did some investigations on different types of cement and an incidental change of cement due to closing of a works improved the condition. Changes were also made in the shuttering. Fortunately, in this instance, the discoloration was of a relatively shallow nature and could be removed in the course of grit blasting, and in special cases the use of acetic acid and a needle gun. It was fortunate that the Architect required an exposed aggregate finish, or we might still be submitting sample panels.

D108. With regard to the export of the old bridge to Arizona, we were approached by the Americans, who were concerned about the durability of the stone. The fact that it had survived for 140 years in London's somewhat unpleasant conditions was not considered sufficient evidence, and we were asked to subject this stone to accelerated tests, reproducing conditions in Arizona covering changes in temperature, moisture, sandstorms, attacks from Indians, etc. In point of fact we did specific gravity tests, modulus of rupture, compressive strength, moisture movement, thermal expansion, soundness tests and cycles of temperature changes, all of which proved to be satisfactory.

D109. With regard to the gantry considerable attention was paid to the important and to some extent unresolved problem of identification of high yield steel and mild steel. In addition to check tests at the Works, all material arriving at the stockyard was identified against works test certificates and HYS stamping. If any plates or sections were to be cut the stamping was transferred to the new portions. After grit blasting which removed the original blue marking, all members including mild steel were given an overall coat of blue primer, and immediately for the HYS a streak of red because the conventional blue marking might have caused confusion. Any members scheduled to be HYS whose identity could not be proven were checked by chemical analysis.

Mr R. Bowdler, Mott, Hay and Anderson

In connexion with the reconstruction of London Bridge, there are some references concerning the settlement of Rennie's bridge that might well be placed on record.

D111. Measurements of the pier movement of the structure were started in 1946 to establish the adequacy of the foundations. A quinquennial levelling survey was carried out at points on the pier and the centre line of the arches at parapet level. The interpretation of these records was made difficult by the variation in bench mark levels which had themselves subsided by approximately 1 in. during the 20 year survey. These general ground movements are caused by two main factors, a tilting of South East England, and a reduction in the pore water pressure in the chalk and overlying strata, brought about by increased water extraction from this aquifer.

D112. Figure D8 shows the bridge settlements relative to the surrounding ground; these are assumed to be due to foundations settlement. The relative settlements across any one pier are up to 20% of the total movement. (The uplift that occurred during the demolition of the piers was up to $\frac{3}{4}$ in.) The differential settlement recorded contrasts with the evidence discussed where the variations between the water level and masonry courses on any pier (up to 9 in.) was assumed to be due to differential settlement.

D113. Further information concerning settlements was published in *Engineering*, 1869.[D6]

D114. Information given in a letter written by Mr E. W. Morris, who made the drawings of the bridge for Sir John Rennie, to Mr H. Carr in 1869 ties up with data collected from the site before demolition and with information recorded in a report by Telford in 1831. This is summarized in Table D7 and indicates first, that the difference between the levels on the upstream and downstream sides of a pier are much greater at the level of the pier springing than at the arch soffit level or the parapet level and second, that downstream ends have settled more than the upstream ends of the piers during the 140 year life of the bridge.

D115. Undoubtedly, some differential settlement has taken place but it would be a mistake to assume that this is as much as that indicated by the incline of the masonry courses.

Mr Brown

Dr Liszka rightly comments that the gantry was redesigned by the Contractor who produced a better gantry, albeit considerably more expensive than the gantry design included in the tender. The main reason why a gantry was designed and specified for tender purposes was because it was unreasonable to expect tenderers to design and price such major temporary works, weighing nearly 2000 tons, within the limited tender period.

D117. **Professor Nash** has enlarged on the valuable contribution which he and Dr Gibson made in providing a second opinion concerning the stability of Rennie's bridge. After an exhaustive investigation of old papers they produced a comprehensive report which agreed closely with our findings. I am not quite sure, however, that they were able to relate the original levels to an absolute datum with which present levels could be compared and therefore the suggested total final settlement figures for the old bridge should be treated with caution.

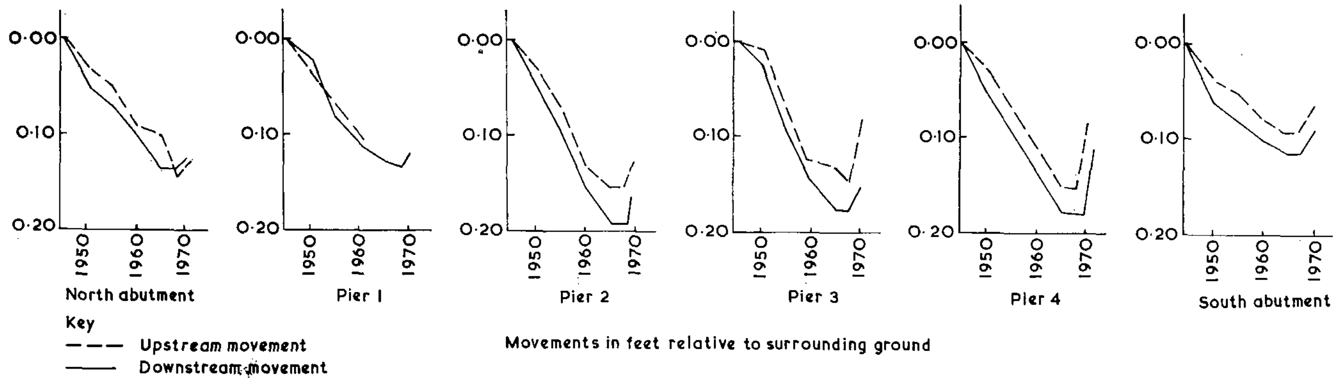

Fig. D8. Pier movements upstream and downstream of piers between 1946 and demolition

Table D7. Level differences between upstream and downstream ends. (Dimensions in feet over 56 ft width)

Position of level	North abut-ment	Span centre line	Pier 1	Span centre line	Pier 2	Span centre line	Pier 3	Span centre line	Pier 4	Span centre line	South abut-ment
Springing of pier, 1831	—	—	0·33	—	0·50	—	0·60	—	0·57	—	—
Springing of pier, 1968	0·42	—	0·46	—	0·57	—	0·79	—	0·72	—	0·02
Soffit of arch, 1967	—	—	—	0·41	—	0·41	—	0·57	—	—	—
Parapet, 1968	0·27	0·29	0·35	0·51	0·46	0·41	0·64	0·60	0·35	0·12	0·12

D118. **Mr Hill** raises the question of steel as a structural medium instead of concrete. At the time the bridge was designed a steel design would have been of steel box girder construction, which no doubt would have required strengthening to accord with the new design rules for this form of construction, and therefore we have had a merciful escape. However, for a bridge of this span there should still be little difference in price between steel plate girder construction and the concrete design which has been adopted.

D119. In order to clarify **Professor Baker**'s query, a simplified sketch of a typical end block unit is shown in Fig. D9. Each of the three bearings carries a maximum reaction of 210 tons and the inclined strands resist 50 tons of this. The principal stress at the junction with the box proper amounts to approximately half of the allowable stress for the particular concrete used.

D120. The external cables are surrounded by fine aggregate concrete on completion of stressing, and bond to the main box was ensured by ½ in. links at 6 in. centres which were cast into the box and left projecting until the cables were threaded. The links were then bent round the cables and encased in the surround concrete.

D121. The point which **Mr Barrett** raises about eccentric pressures under the old bridge piers was discovered by Professors Nash and Gibson in their investigation during 1965. Apparently in 1825 during construction of Rennie's bridge a decision was taken to increase the width of the structure by 6 ft. Unfortunately, one pier was already constructed but alterations were made to the other piers to correct eccentric foundation pressures. There must have been small eccentric pressures on the first pier but the effect on the bridge as a whole would be much less than suggested by Mr Barrett and an increase in pressure to about 7 ton/sq. ft at the downstream toe (based on beam bending theory) seems unlikely.

D122. I have a great deal of sympathy with Mr Barrett's comments on the effect of the variation in price clauses on this Contract. The DOE indices show that the cost of new construction has risen by more than 50% during the construction period of approximately five years, whereas the Contractor's recovery of cost increases under

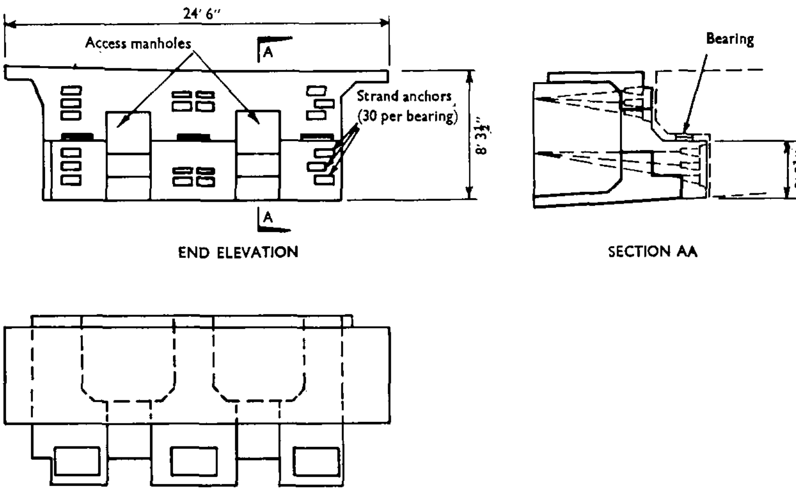

Fig. D9. London Bridge: suspended span joint the price variation clauses in the Contract have only amounted to about 5% over the same period. The cost variation clauses have operated unfairly in a period of high inflation and I do not think it would be possible today to let a five year contract for such major works except by incorporation of more equitable price variation clauses linked to official cost indices.

D123. In reply to **Mr Studinski**, Fig. 7 is misleading in cross-section detail in that the sections have been drawn towards the end of individual box units at a point where the top flange has been curtailed behind the webs to allow for longitudinal continuity of deck reinforcement. Apart from end anchorages units the boxes were generally cast on end which facilitated construction without temporary joints between webs and flanges.

D124. In reply to **Mr Davies**, difficulty was experienced in sealing ducts across the in situ joints between segments and it was decided that, in order to avoid the risk of grout from one duct bleeding into an adjacent one and forming a blockage, each group of the internal ducts should be grouted simultaneously.

D125. No radiography was specified as it was considered impossible to make meaningful checks on three superimposed layers of cables. Reliance was placed on careful control of grouting materials and procedures and provision of temporary stand pipes at key positions. The pea-shingle concrete protection was hand placed and poker vibrated.

D126. The reason for placing the anchors on the under side of the flange was that it was impossible to obtain sufficient angular deflexion of the cable within the thickness of the flange. This deflexion was needed in order to obtain clearance around the jack and was obtained by locally thickening the flange on the under side.

D127. Several of the points referred to by **Mr Colley** have changed since he was associated with the Contract. His reference to Government Investment Grant presumably refers to the cost of contractor's plant and equipment as reflected in the original tender. However, the final amount of grant is still not known but it is expected to be less than 3% of the cost of the works.

D128. Traffic statistics which justify the project are given in the Parliamentary proceedings and **Lord Holford** has dealt with the planning and environmental conditions in these Parliamentary proceedings and in his contribution.

D129. The original Contract period was 54 months and this was insufficient to allow for difficulties which arose, particularly in the river in dealing with river bed obstructions. A fair extension of time is at least six months to which must be added a further three months for the National strike in the industry in 1972.

D130. The maximum percentage of waterway obstructed during construction of the works was about 18% which should be compared with an obstruction of about 12% provided by the piers of Rennie's bridge. No increase in siltation has been reported as a result of the construction of the works.

D131. The diaphragm detail was altered and the amount of welding of reinforcement was greatly reduced. The difficulty of diaphragm reinforcement has also been referred to by Mr Barrett and it would have been simpler to post-stress the diaphragms. However, end anchorages might have marred the appearance of the bridge elevation and the decision was taken to provide ordinary reinforcement to these members in the knowledge that formidable quantities of reinforcement would be required.

D132. The bridge was opened on time to suit the Client's arrangements for the Royal opening ceremony, but the outstanding demolition works at bed level have been a little prolonged due to the Client's wish to clear cofferdams and all visible obstructions in order that the works should present a pleasing appearance on the opening day.

D133. Several speakers have queried the increased cost of the Works. Although the basic design of the new bridge has not altered, agreed cost and work variations have amounted to about £1 million. These included additional architectural treatment (granite and special aggregates, etc.) and pavement heating added to the permanent works, temporary works additions mainly in the form of massive protective buttresses at the piers, additional works for statutory undertakers and accelerated demolition of the old structure to suit the requirements of the Arizona re-erection programme. The final cost of the Works is not yet known, but there is no reason to suppose that an equitable final settlement will not be reached.

D134. Mr Colley gives many criteria for judging the success of the project to which he contributed so much but he takes too short a view. Surely the main criterion for a new London bridge is the judgement by future generations of this generation's best endeavours.

Mr Mead

I was interested in **Mr Anderson**'s basis for selection of firms to tender for this Contract. I am pleased to say that Mowlems were financially stable in those days as well as today!

D136. **Sir Harold Harding** raised a point about the cost of demolition and supposed it was mixed up with the cost of construction elsewhere. The tender price in fact gives one version, and I prefer Sir Harold Harding's version.

D137. **Mr Smith** made mention of the thin joints. We looked at these as a possible alternative, and agree with him on his decision about the 4 in. joint.

D138. He also referred to some complaint from the site that, owing to too much reinforcement overlap at the joints, the concrete could not be poured. The site's first concern was that with the added congestion of hooked ends, if the reinforcement was to be kept within the outlines of the concrete, the stressing cables and their ducts could not be positioned.

D139. I understand **Mr Beresford**'s problems. Had we had these instead of the problems we did have, the job would have been far simpler but less interesting.

D140. Some support for **Mr Barrett**'s comments on eccentric loading of the piers can be gained from the fact that vertical cracks were discovered during demolition across the piers under the downstream edge of the old bridge.

D141. Enlarging on Mr Brown's reply to **Mr Davies** on the question of duct grouting, lack of space precluded the fitting of grout-tight duct couplers at the joints and to ensure no blockage of adjacent cables or incomplete grouting, the following additional precautions were adopted. Ducts were prefilled with water and those found to be interconnected were grouted simultaneously. At intervals and at all high spots, $\frac{3}{4}$ in. dia. clear plastic pipes fitted with clamps were inserted. The ducts were thus vented and grout rise observed during grouting.

D142. In order to make a sound job of concreting the external cables, much thought, time and careful supervision by the Contractor was needed, particularly where the cables were at the top of the box. The space between individual cables was only 0·42 in., maximum aggregate size was therefore limited to $\frac{3}{16}$ in. and the concrete poured through 4 in. holes formed at every joint in the top slab. Compaction was by means of small immersion vibrators through these holes. Special pipes were inserted as the concrete came up to level and these were subsequently used for pressure grouting to overcome any shrinkage or to fill any voids that may have formed.

D143. **Mr Colley** has contributed much useful additional information overcoming some of the Authors' space and time problems. However, I can assure him that computer updating of the programme was done for the first $1\frac{1}{2}$ years of the Contract. Thereafter it was discontinued as it was found cheaper and quicker to do it by old-fashioned methods. The details and methods of pier demolition have been given in the discussion.

D144. With regard to Mr Colley's criteria for success, while the final financial outcome is still awaited, I am pleased to inform him that the City of London has awarded the Contractor several more contracts which have been accepted. I disagree with a number of his conclusions.

D145. With regard to the extraction of the 24 in. × 12 in. UB steel piles, various methods were tried including a direct pull of 110 tons and an HD15 extractor operating on air at 150 lb/sq. in. with a 40 ton pull. Some piles were broken but all failed to extract. Finally, they were cut off up to 12 ft below bed level by suitable sized divers using oxy-arc mainly working inside protective 1 m dia. steel tubes, the excavation being done by pre-grabbing and air-lifting.

D146. The problems of expansion and contraction with consequential stress variation due to the welding of the $1\frac{1}{2}$ in. dia. reinforcement in the in situ diaphragms between the prestressed boxes were recognized early by the Contractor. In the end, the problem was designed out and most of the bars were lapped.

D147. Initially, 20% of the welds were radiographed but as the results showed that the quality of welding was satisfactory, this was stopped, subsequent inspection being visual.

D148. It would be appropriate for a separate paper to be written on the gantry design and its use.

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