Correspondence.

Mr. Bruce. Mr. A. FAIRLIE BRUCE desired to know whether the Author had considered the advisability of substituting concrete for brickwork in the cut-and-cover work, as it appeared to Mr. Bruce that this might have been done with advantage as regarded both strength and economy. Ballast could apparently have been obtained from the excavations, and a mixture in the proportion of 1 of cement to 2 of sand and 5 of screened ballast would have been quite water-tight, and much stronger than ordinary brickwork. It was mentioned in the Paper that the river-wall was constructed of 8-to-1 concrete, and that the tubing was lined with 4-to-1 concrete, but the Author did not state what ratio the sand bore to the ballast. It would be useful, too, if the Author could give the approximate relative costs of caulking the lead joints with pneumatic hammers, and by hand.

Mr. Goodrich. Mr. E. P. GOODRICH, of New York, observed that the construction of tunnels had made very rapid strides in the United States during the past decade, owing at first largely to English practice being followed and to the employment of British engineers and contractors. But conditions within and in the vicinity of New York harbour, for example, were not conducive to tunnel-building, by reason of the widely varying nature of the materials encountered. This variation comprised, on the one hand, silt so soft that in one instance the shield was pushed bodily through it, displacing and probably compressing the material as it moved, so that no excavated material was removed through the tunnel for long distances; while in other instances, ledge rock had been encountered, much harder than, but otherwise similar to, that found in the Rotherhithe tunnel. At only a few places in the United States had there been encountered material comparable with London clay. The St. Clair River tunnel was driven through material which worked like cheese, and some of the material now being removed for the Detroit River tunnel was of the same nature, easily cut by enlarged "shave-hooks." While for all deep work, and even through rock, a shield was employed, a new method had been resorted to in several cases, notably those of the Harlem River and Detroit River tunnels now under construction. In these works a modified "cut-and-cover" method was employed, caissons of the same size as the tunnel-lining being constructed at the surface on shore, then launched, hauled into position, and sunk in

Mr. Goodrich. place in a dredged trench. The adjacent ends having been made tight by divers, the caissons were covered with concrete and rip-rap stone to prevent flotation, and were finally pumped out. For a tunnel at a comparatively small depth below the river-bed that method had been found cheap and expeditious. Some caissons of reinforced concrete had been constructed for tunnel purposes, but the majority so far had been of timber and steel. For shaft caissons, the methods employed were very similar to those described by the Author, except that reinforced concrete had been advantageously employed in many works. In that way no metal skins were required, the concrete which would be placed between them acting as the caisson-wall without other covering. At first, trouble was experienced in securing air-tight work, but that was overcome by making use of air-tight air-shafts. Reinforced-concrete linings sunk in that way were less expensive than steel lining, and they obviated the necessity for leaving in the work relatively large masses of metal which might suffer corrosion. The Author's conclusion as to the inefficacy of a rust-joint was of great importance. It would be of considerable interest to know the range of temperature experienced by the tunnel-lining. It seemed to Mr. Goodrich very doubtful if, solely from the effect of the monthly atmospheric fluctuation, it could be so great as to do any damage, and he suggested that the real trouble arose from the range between a high temperature produced by the setting of the grout, and the final and permanently cooler one. He had no information as to the setting-temperature attained by the lias lime employed for the Rotherhithe tunnel grouting, but laboratory observations on Portland-cement concrete had disclosed setting temperatures as high as 180° F. The Paper contained reference to the difficulty experienced in making a water-tight juncture between the old and new walls in the vicinity of Rotherhithe Station. It would be of interest to learn the special methods there employed—whether grout was again successfully used or whether other means were employed. Referring to the statement that the ground apparently settled towards the trench on a 1-to-1 slope from the bottom of the excavation, it would appear from the composition of the strata shown in Fig. 2, Plate 3, that the settling material was probably composed largely of clay with some sand and ballast. It would be interesting to know whether the character of the soil appeared to influence the amount of settlement observed; and any notes as to crushed or buckled braces and their size and arrangement would be most interesting. Particulars of the size and design of the river-wall, close to which one shaft was so successfully sunk, would also be of interest. The

Mr. Goodrich. value of a pilot-tunnel was regarded as an open question by many engineers, and it was not evident why information as to the character of the strata to be encountered could not have been obtained almost as accurately and much more economically from numerous borings. That was especially true when it was noted that the large shield was being erected during the driving of the pilot tube, so that none of the accurate information obtained by means of the latter could apparently be employed in modifying in any manner the design of the shield, even had it been possible to do so if the pilot-tunnel had been entirely completed before the shield was commenced. It was obvious how the excellent condition discovered in the pilot tube could support the material at the face of the main working, but Mr. Goodrich was not satisfied that actual economy had resulted from its employment.

Mr. Haigh. Mr. A. H. Haigh, in allusion to the design of the tunnel, was of opinion that its cross section presented an abnormally strong invert, disproportionate in every way to the duty it had to perform. Constituting one-third part of the whole periphery of the tunnel, and its sharp curvature being due to the particular method of tube-tunnelling adopted, it had been made as strong as the soffit of the tunnel, with its 2-inch metal, and numerous heavy $1\frac{1}{2}$-inch bolts buried under 15 inches of 4-to-1 Portland-cement concrete. It could scarcely be contested that special iron segments, weighing at most one-half of the soffit portion, might have been advantageously applied throughout the 1,230 yards of iron tunnel, which would have effected a saving of nearly £50,000. Ten years later than the Blackwall tunnel, lighter bolts might have been used throughout the work, saving nearly £10,000. On considerable portions of the London tube railway-tunnels, little more than one-half of the circumferential bolts originally provided for had been applied. Looking at the lining of the Rotherhithe tunnel and the section of the roadway and footways the concrete inside the iron flanges seemed excessive. Large shields were driven easily with accuracy, more so than the quicker-moving small shields, and lining-allowance inside the flanges, beyond a bed for tiling, was unnecessary. With that modification the diameter of the tunnel could have been reduced somewhat. The reduction of diameter would have diminished considerably the expenditure on excavation, concrete lining, and iron, on the 1,230 yards of iron tunnelling, and more on the cut-and-cover portion. The above-mentioned considerations would indicate a possible saving of £60,000 on the cost of 1,230 yards of iron tunnel alone, or, say, 13 per cent. of the cost, exclusive of the lining and roadway. The pilot-shield seemed to have been the most risky part of the procedure. Mr. Haigh. Concluding from the Paper that borings across the river were not made to determine the strata, the speed of the Price excavator involved imminent risk of very sudden immersion in water, when the shield trap might have filled with sand, and the whole machinery and face cutters have been completely buried, with little or no room to work in to secure the face and rescue the shield. In driving two tunnels beneath the Thames, as described in an earlier Paper [1] discussed at The Institution, the preliminary borings determined accurately within a few inches the actual stratification, as afterwards proved. In addition to that precaution, borings with a carpenter's auger were made, during the tunnelling, at the face, to prospect continuously just ahead of, and outside, the fresh positions to be taken by the cutting edge as it was driven forward. These auger-borings were continued until entry was made into the strata expected.

Mr. H. J. Howe, of New York, observed that the locality Mr. Howe. of the work was historic and inspiring, and that American engineers who used Rankine as a text-book might well dispute the title of possession of Brunel and his contributions to engineering science with the engineers who had so lately constructed this other Rotherhithe tunnel. The only suggestion which Mr. Howe desired to make with reference to the convenience of passenger movement at the shafts of the tunnel, was that a travelling staircase should be installed. Moving staircases had been designed for such purposes and were entirely practicable. In New York they were becoming more and more popular and the demand for their provision by carrying-companies more insistent.

Mr. A. Woodroffe Manton wished to know if the caulking Mr Manton. recesses of the lining-joints were machined, so as to present metallic uncoated surfaces of exact width, independent of contraction of the casting. Was the lead- and rust-caulking carried out in compressed air, when its efficiency could not be ascertained? If so, on removing the pressure, leaky caulking could only be put right by cutting-out, and it seemed difficult to ascertain the actual point of leakage, as water would first pass at the worst place. As the concrete lining heated up the cast-iron lining, the combined caulking would probably be disturbed, and the rust in front much reduce the value of the lead behind, which, with a little further caulking, even with leakage occurring at the same time, could easily be made

[1] A. H. Haigh, "Subaqueous Tunnelling through the Thames Gravel: Baker Street and Waterloo Railway." Minutes of Proceedings Inst. C.E., vol. cl, p. 25.

Mr. Manton. water-tight. There should not be any objection to caulking the lead under compressed air, to avoid air-leakage with slightly varying widths of segments and to stop water, and, just before concreting, to recaulk the lead where necessary, filling up the remainder of the recess with some elastic cement or mortar, so that it would set with the concrete and cool with it. The lead grummets seemed excellent, but Mr. Manton would suggest cutting off all water, except perhaps in the case of the three back bolts of the cross joint, before it could get inward to the bolts, by placing a machined recess behind the bolts; these would be removed, if lead caulking were used; the thread might be $\frac{1}{16}$ inch less in diameter than the shank in order to avoid damage. The machined recess, say, $1\frac{1}{4}$ inch deep, might be slightly dovetailed in the boring-mill, the rest of the recess, i.e., to the front of the flange, being set back, say, $\frac{1}{4}$ inch, unmachined, but uncoated, to clear the caulking tool and allow of good mortar contact. With regard to the shield, had the absence of skin throughout been a disadvantage? Had any broken segments been found, and if so, were they broken by bolt- or joggle-stresses? As he suggested this "hung-on" skin, with joggled segment-joints, in a communication to The Institution in 1901, the behaviour of this shield under such high stresses was of interest to him. It was not quite clear why the jacks were set so far back as to increase the "overhang" of the tail; if that were necessary, he would suggest a cantilever reinforcing-plate inside the skin, projecting, say, 2 feet from the jack-boxes, backwards to about 6 inches from the ring being erected; or, perhaps better still, rearward cantilever gusseted extensions, between the jack-heads only, of the jack-box castings. The whole cast-steel portion of the shield appeared to be $\frac{1}{2}$ inch larger in diameter than the tail, instead of the cutting edge only. Was the inch bead at the bottom only found better than the $\frac{1}{2}$ inch bead all round? With the progress attainable, it would be interesting to know why single-ended erectors had been considered better than a double-ended one? Also had there been sufficient play, both sideways and up and down, in the attachment to the segment, so that the latter needed only to be placed roughly with the sling-chain? Unless the pilot-lining were available for further use elsewhere, Mr. Manton would suggest using standard main-tunnel segments in a suitable polygonal pilot-shield for the lower three-fourths of the circumference, with two light top plates for easy erection; the taper space between the heavy segments being "made up" with hard pine, and smaller bolts being used for cross-joint holes not in line. Only the top plates, if not required elsewhere, would be scrapped, the remainder of the ring being hauled into the main shield for use again. It did not seem clear why the emergency-lock was so short; it could hardly contain two shifts if a serious "blow" occurred at changing-time. In the light of recent experience with concrete bulkheads, the metal bulkhead seemed to have achieved great success; how much radial tunnel-lining error had been allowed for and how? Had there been any sign of distortion or damage at the attachments to the lining? Had the outer ends of the locks shown much movement with air-pressure variations, and was any fixed "alignment-lock" provided to get over such difficulty? Would not it be well to have a steel movable screen in case of fire on the safety-gangway? With such a large output of excavation per ring, would not electric locomotives have been preferable and more adaptable in the way of recovering time-losses caused by congestion at the shields or locks? If necessary, they could be run through the locks in case of breakdown. Mr. Manton.

Mr. J. C. Meem, of New York, had been especially impressed by the very large size of the shield and the varying quality of the material encountered, and its general behaviour under the operation of a shield of such size. While the material appeared to have varied and to have allowed a very appreciable loss of air at times, the river-bottom seemed to have been underlaid with a stratum of mottled clay, which blanketed the escape of air so successfully that full pressure corresponding with the hydrostatic head was not required, apparently, at any time. He believed that material similar to that encountered in the work described was not found in the vicinity of New York, and that the driving of a shield exceeding 30 feet in diameter would be attended with greater difficulty there. Under the North, or Hudson, River probably fewer of these difficulties would be encountered, as it had been found possible to advance the shields used in the existing tunnels under the Hudson River as much as 70 feet in 24 hours without opening the doors for the admission of material. The shield simply compressed the material and drove it aside in a manner corresponding with the driving of a pile. On the other hand, the larger portion of the material underlying the East River was fine sand with just enough clay to make it a good air-resisting medium, and through this a shield of larger size than those used heretofore might be driven with some small increase in the difficulties. Mr. Meem did not believe, however, that a shield of large size could have been driven under Joralemon Street, in Brooklyn, where it approached the East River, as the sand was so granular that it was with the greatest difficulty that pressure could be maintained in a shield of approximately only 18 feet diameter, sufficient to keep water out during the construction of the Rapid-Transit tunnel. He Mr. Meem.

Mr. Meem. questioned whether it would be possible to drive a shield of that size through coarse sand and gravel without virtually waterproofing the upper part of the face before the lower part could be excavated sufficiently to put in the bottom rings. His experience had lain more in land and river approaches than in subaqueous tunnel-work; and the following accounts of work, with the execution of which he had been associated as engineer, might be of some interest. In connection with the tunnel-approach work in upper Joralemon Street, joining the present Rapid-Transit tunnel with the Brooklyn Subway, the tunnel emerged from the subway into a two-track, flat-arched tunnel, with reinforced-concrete sides and roof—the latter being approximately 4 feet in thickness. That ran into a two-track, flat-roofed reinforced-concrete tunnel, with a division-wall, which again merged into two brick tubes, each 15 feet 9 inches in diameter, built of four rings of brickwork without haunch-walls: this last connected with a cast-iron concrete-lined tunnel, driven under the East River, between that point and the Battery in Lower New York, by the ordinary shield method. The brick and concrete tunnels mentioned were entirely above tide-level, and were built by a sectional roof-shield and timber method, which had been previously used to some advantage on a large sewer-tunnel in Brooklyn. The shield consisted of ten special sections built of 10-inch I-beams, cover-boards and cover-plates, with a tail protruding 3 feet 6 inches behind, each section being approximately 3 feet wide by 17 inches high and 15 feet over all. These sections, called "jills," were actuated by hydraulic jacks of 60 tons capacity, connected with a hand-pump by copper tubing. At the junction of the brick tunnels the ten "jills" separated into two sets of five each, shaping the roof of the brick tunnel. Under the tail of each "jill," as it was advanced, lagging of 2-inch pine boards was set in and blocked up from roof-bars resting on the caps in the heading, being eventually transferred to five-segment arch timbers of 12-inch square section (each segment being about 5 feet long), springing from wall-plates laid along the sides at the springing-line of the arch. These arch-timber sets were 5 feet apart, intermediate between the caps, which latter were dug out and dropped as soon as the arch-timbers were set in place and properly blocked. The middle portion of the bottom, called "the dish," was built in a sheeted trench wide enough to admit a muck-wagon. From this "dish," blocking was sprung to carry the arch-timbers while the sides or "wings" were excavated. Double rows of longitudinal ties, in the shape of heavy channels bolted back to back, served as an additional precaution in tying the timbering together at the level of the springing-line. This bracing was used to carry

Mr. Meem.

the arch-timbers while the sides or "wings" were excavated. As soon as the invert was finished, the ribs were set and the loading was transferred to them, so that the arch-timbers could be removed. The roof arch was then finished in the ordinary way, all longitudinal roof-bars and other blocking being removed, leaving only the lagging. Progress on each of the brick tubes varied between 5 and 7 feet per day of two 10-hour shifts. Before the completion of the entire Rapid-Transit tunnel across the East River, it was decided to construct an emergency- and ventilating-shaft at a point on Joralemon Street where the normal level of tide-water was 4 feet above the top of the tunnel. In order to avoid interruption of the passage of men, material and supplies through the tubes, the shaft was sunk thus:—The cast-iron tubes at the place in question had been finished but not lined. They were 25 feet apart between centres, and approximately 18 feet over all, an extra foot having been added on the bottom during the reconstruction of a portion of the work. The internal dimensions of the main body of the shaft were 54 feet wide, 19 feet long and approximately 65 feet deep, extending about 3 feet 6 inches below the outside of the tubes. The shaft was sunk by the ordinary methods of digging, the hoisting being done by an ordinary hoisting-engine and derrick. The sides of the shaft were sheeted with 2-inch planking, set horizontally and braced with light vertical and heavy horizontal rangers and bracing down to the level of the water. At this point interlocking steel sheet-piling was driven across the ends of the shaft and between the tubes, extending to a depth of about 12 feet below water. To this sheet-piling a roof of 12-inch square timbers was affixed, which, after being internally braced and fitted with vertical locks, was loaded with spoil to a depth sufficient to counterbalance any expected air-pressure. This roof was fixed at an elevation of about 4 feet above the water-level, the spaces between the sheet-piling directly over the tubes being filled in with wooden sheeting. The whole was then air-proofed on the inside and air was introduced under pressure. As the excavation advanced, air-proofed sheeting was introduced around the sides of the tube, and below the bottoms of the sheet-piling when that depth was reached. As soon as the bottom was reached, it was waterproofed in the regular way with asphaltic mastic, and the structure, as designed by the Rapid Transit Commission, was built in the shaft and around the tubes; the connection around the tubes was waterproofed by a special method designed by the contractors. As soon as the shaft had been completed to the normal level of the water, the tubes were cut out flush with the inner face of the shaft.

In this latter work two interesting facts were observed. The

Mr. Meem. first was in connection with the difficulty of holding the air. In spite of taking the greatest care in air-proofing the sides and roof, it was found very difficult to hold the water down to the level required for safe excavation for the last 2 or 3 feet; the air required to do that was estimated to have been in excess of 6,000 cubic feet per minute for the last few days of the work. Although this quantity of air was pumped continuously into the shaft, no place of escape was seen, except the area required for the insertion of each new plank around the bottom, as soon as the water could be lowered enough to admit of its being put in. Of course, if short sheet-piling could have been driven internally, much of this air-loss would have been prevented, but the presence of the tubes interfered materially with that method of work. It was this experience particularly which caused Mr. Meem to doubt the practicability of driving a shield of the dimensions noted in the Paper through ground of this character. The second interesting fact was that as the shaft progressed vertically, the pressure at the top, and especially on the longer sides, continued to increase greatly, requiring the bracing and struts near the top of the shaft to be constantly strengthened. This observation accorded with the phenomena of earth-pressures often observed by contractors and their engineers, and recently interpreted by Mr. Meem,[1] namely, that the pressure of earth against a sheeted face or wall was not due to the sliding effect and therefore greatest at the toe, but was due rather to the wedging or arching effect of the earth against the face, and was therefore greater near the top, with the centre of pressure about one-third of the way down. The Author might possibly find in this law some explanation of the fact observed at the Rotherhithe tunnel that in the open-cut work the movement was observed to be outward rather than downward; that is, the outward movement, while coincident with the downward movement, was much more appreciable. Mr. Meem believed that the nature of the material caused variation in the frictional resistance experienced at the Rotherhithe shafts; also that the irregularities and the "binding" of caissons would increase it greatly, and that it would vary in an increasing ratio with the size of the caisson, due to the fact that earthy material, even in water, had a horizontal as well as a vertical arching tendency. That seemed to be confirmed in a small measure by the fact that 14-inch hollow steel piles recently driven in sand, cleaned out to the bottom and tested under his supervision, were found to show

[1] Transactions of the American Society of Civil Engineers, vol. lx, p. 1.

an actual skin-frictional resistance of less than 100 lbs. per square foot. Mr. Meem.

He was greatly interested in the Author's description of the rotary tunnelling device, and also in the description of the steel bulkheads, both of which improvements seem to be in the line of much-needed progress.

Mr. EUGENE W. STERN, of New York, asked if any precautions had been taken to prevent damage to buildings from the excavation of the cut-and-cover work. In New York where a great deal of that kind of work had been done in the past few years, it had been found expedient to take measures to prevent damage to buildings adjoining such excavations, by underpinning their foundations. There were several methods in common use. The one most frequently adopted was to "pick up," on needles of timber or of steel girders, such piers or foundation-walls of the buildings as were within the danger-zone. By the use of screw-jacks under these needles it was possible to hold the building up to its right level, while the piers of the building were being carried down to a proper depth; such depth depending on the nature of the soil, and the position of the piers with reference to the line of excavation, etc. Mr. Stern's experience was that the foundations near the work should be carried down to the level of the excavation for the tunnel, while those further back might be stepped up. That method was satisfactory for moderate depths where but little water was encountered. Where the depths were great, and there was quicksand and water to contend with at some depth below the old foundation, steel pipes about 12 inches in diameter were used for underpinning, in short sections with screw-joints. They were forced down under the wall or piers by hydraulic jacks, the sand inside the pipes being taken out by means of a water-jet and pumping. When one length of pipe was forced down far enough, another was screwed on. Finally the pipe was filled with concrete, and a tight bearing for the wall above was secured by means of two granite blocks with steel wedges between them. Where the building to be supported was a high and important one and the foundations were deep, small pneumatic caissons, about 36 inches in diameter, had been substituted for the 12-inch pipes referred to; and that was undoubtedly the safest and best method. In the lower part of Manhattan Island the soil overlying the bed-rock, ranging in depth from 40 feet to 125 feet below the street-level, was mostly sand, sometimes quite coarse, to about tide-level, and below that level it gradually became finer and was in many cases quicksand or silt. The soil being permeable, the level of the ground-water responded readily to Mr. Stern.

Mr. Stern. the rise and fall of the tide, and any excavation adjoining buildings in the water-bearing strata had to be most skilfully handled. He knew of a fifteen-story building which was pulled 8 inches out of plumb, and another building of twelve stories as much as 15 inches out of plumb, by neglect of proper precautions.

Mr. Thomson. Mr. T. KENNARD THOMSON, of New York, found a very interesting feature of the work in the bed of rock 3 feet to 5 feet in thickness which extended across the river, with sand, loam and pebbles below it. He would be glad to know the nature of that rock, whether it was of the same material as the real bed-rock, and how far it was above the latter. In New York, bed-rock meant the New York gneiss on which the island rested, which was entirely different from anything above it. There were plenty of hard boulders in the glacial drift, which was termed "hard pan," above the bed-rock, but scarcely anything but rock was found below. Had the layer of rock been found at other points under the Thames? It was very interesting to know that it was possible to tunnel under the Thames with only 7 feet of covering. A similar attempt under the East or North (Hudson) River at New York City would result in "blow outs," which, as was no doubt known, had occurred frequently and on one occasion had carried a man from the front of the shield to the surface of the water—without doing him any serious damage, however, for, declining to exhibit himself in a circus, he soon resumed his old place in the Battery (East River) tunnel and then went to work in the Pennsylvania Railroad tunnel. The fact that the sides of the caisson were parallel, was undoubtedly of much assistance in keeping the caissons level. Tapering the caissons from the bottom up, as many proposed to do under the impression that it would reduce the friction, was liable to produce one of two very different results. First, as actually happened in the deep piers of the Hawkesbury Bridge, in Australia, the material traversed, being firm and compact, did not flow back into the cavity left above the cutting-edge, and it was difficult to keep the caisson level. That caused so much trouble at the Hawkesbury Bridge that the material was dumped around the cylindrical "open" caisson, and was allowed to settle for about a year before sinking was resumed. The second effect had been experienced in America, where the surrounding material did flow into the cavity, to the extent of binding or jamming the caisson and greatly increasing the friction. The friction stated by the Author, $3\frac{1}{2}$ cwt. to 6 cwt. per square foot, seemed quite high for such a large caisson. Was it not possible that this would have been reduced if the side plates had been made truly vertical with butt joints instead of battering outwards to make a lap joint? The sinking of such a small caisson only 67 feet in 63 days seemed rather slow practice. It was interesting to note the precaution taken of only lowering the air-pressure a few pounds when the men were out for meals, for in New York it was very common to lower the pressure from 25 lbs. per square inch or even occasionally from 35 lbs. per square inch to almost atmospheric pressure while the whole gang was in the air-chamber. Mr. Thomson had frequently been in the air-chamber when the pressure was thus lowered, allowing the caisson to sink 1 or 2 feet. Of course the pressure was instantly raised again, to prevent the water from flowing in. Would not a 7-foot or 8-foot pilot-tunnel have been more economical and equally efficient? The engineers were to be congratulated on the completion of such a fine piece of work so successfully. Considering the layer of rock encountered, it was very doubtful if any more economical method than that used could have been adopted for the Rotherhithe tunnel. But in localities where similar materials, clay, etc., were encountered without the strata of rock, there were two methods which would be cheaper and much more expeditious. The first was a method invented by Mr. D. D. McBean and successfully used for the construction of the Rapid-Transit tunnel under the Harlem River, New York City.[1] Briefly, it was to dredge a tunnel and then drive a line of sheet-piling—forming a continuous line on each side of the tunnel. In the first section these sheet-piles were cut off above the level of the top of the permanent tunnel, and then a temporary timber-roof was sunk on the top of these sides. Then this temporary roof was weighted and compressed air was pumped into the working-chamber formed by the sheet-piling and roof, so as to complete the excavation and place the tunnel lining. On the second section the sheet-piling was cut off at a point half-way between the bottom and the roof of the tunnel, and the permanent roof was sunk directly on to these sides at a great saving of time and expense. As enough weight to hold down the entire air-pressure required to keep the water below the bottom of the tunnel could not be imposed easily, only half the theoretical air-pressure, 10 lbs. instead of 20 lbs. per square inch, was employed and the balance of the water was dealt with by pumping, which was successfully accomplished, and very economical. The other method, which was more economical of time and money than the foregoing, was to build the tunnel in sections on the surface—complete—and after sinking two sections in place to sink a

Mr. Thomson.

[1] Minutes of Proceedings Inst. C.E., vol. clxxiii, p. 101.

Mr. Thomson. pneumatic caisson over the joint, so that every bit of concreting, waterproofing, lining, etc., was done in air—compressed or atmospheric—a method patented in America but not in England. The engineers were very fortunate to be able to build a tunnel in which the lining was nowhere more than 2 inches out of place. That was largely due to the good judgment shown in using substantial cast-iron lining, and the care with which the work had been performed. Some of the tunnels in America had been designed much too small, and with much too little metal in the lining, with the result that a good deal of expensive reconstruction had been required.

The Author. The AUTHOR, in reply to the Correspondence, disagreed with reference to the construction of the cut-and-cover criticized by Mr. Fairlie Bruce, his view being that concrete would not have been stronger than, or even as strong as, brickwork in the cut-and-cover portion of the work; and he was confident that it would not have proved watertight. The Thames ballast commonly used for concrete in London generally contained a suitable amount of sand and was not screened unless the amount was excessive. In reply to Mr. Goodrich's observations, the iron tunnel-lining probably sustained a fall of temperature of 30° F. after the caulking was executed, but the subsequent variation was, of course, much less. There was, however, a slight increase in the leakage, during cold weather, in this and in other iron-lined tunnels with which the Author was acquainted. The rise of temperature due to grouting, which was considerable, was limited to a few rings nearest the face, which had ample time to cool before any caulking was done. The difficulty of making a watertight junction between the old and new walls at the crossing of the East London Railway, was due to the fact that, as stated in the Paper, the old walls had a clay backing, while the new walls were waterproofed with asphalt. The lap joint between the asphalt and the clay was serrated with deep V-grooves, forming a barrier to the water somewhat akin to "puddle plates." The caulking recesses in the iron lining were not machined, and the caulking was all done under compressed air, the work being thus more efficient, in the Author's opinion, than when carried out subsequently under atmospheric pressure. Mr. Manton's proposal to cut off the water from the bolts was interesting, but would have been unnecessary for the Rotherhithe tunnel, which was practically watertight. For a tunnel in very porous material, saturated with water, some such method would possess many advantages. The shield had worked very satisfactorily, and the absence of a riveted skin throughout had not appeared to be of any disadvantage in operation; nor had the tail shown any such weakness as to require additional support. The bead at the rear end of the tail was of doubtful value and the Author did not advocate its use, but would prefer to reduce the shield slightly in diameter to give less clearance outside the lining. The two erectors used had been found effective, being employed for adjusting the segments in place after erection; as a rule they had been in operation simultaneously. The steel bulkhead had about $1\frac{1}{2}$ inch play radially at its connection with the $\frac{3}{8}$-inch annular plate referred to in the Paper. No distortion or movement due to the air-pressure had been observed anywhere. He was much interested in the description of the methods adopted in shaft-sinking and tunnelling in Brooklyn, and agreed as to the great difficulty in driving a shield of large diameter through such material as that described by Mr. Meem. With reference to the lateral pressure of the earth on two sides of the open excavations, the strata met with were so variable in their nature that the Author thought it would be unwise to make any comparison of their behaviour with that of homogeneous material on a vertical face. In reply to Mr. Stern's question, it had not been thought desirable to underpin any of the buildings adjoining the cut-and-cover excavation. These buildings were, as a rule, of no great importance, and it was thought that the cost of underpinning would be greater than that of making good any damage which was likely to occur if proper precautions were taken. This view had proved to be justified; but of course if any structures approaching in size those mentioned by Mr. Stern had stood near the work, extensive underpinning would have been necessary. The bed of rock encountered in the work lay between two strata of the formation known as the "Woolwich and Reading beds," of which, geologically, it formed part. It consisted chiefly of limestone, with some pebbles, and had been met with in other places in the vicinity of London. As regarded the skin-friction of the shafts, little inconvenience had been caused by that. The practice of reducing the air-pressure almost to that of the atmosphere while the men were in the air-chamber, stated to be common in New York, was an interesting feature. At Rotherhithe, however, having more than once seen the caisson sink suddenly 2 or 3 feet in as many seconds, with an accompanying rise of 4 or 5 lbs. per square inch in the air-pressure, the Author was strongly of opinion that the withdrawal of the men was a wise precaution. The Author.

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15 December, 1908.

JAMES CHARLES INGLIS, President, in the Chair.

The discussion upon Mr. E. H. Tabor's Paper, "The Rotherhithe Tunnel," was continued and concluded.