

circumstances. A very able description of the Pennsylvania tunnels The Author. with the columns would be found in a Paper which was under discussion by the American Society of Civil Engineers. In blasting the rock eight holes were generally used, and in the streets about 8-oz. sticks of dynamite; in the river sometimes twelve holes were drilled. The shield became damaged and the aprons were also injured, and the structures themselves often required repairs. As to the simplicity of tunnelling through silt, he admitted with Mr. Moir that it was not a very difficult question now that it was thoroughly understood, but the difficulty of blasting the rock under the North river with about 10 or 12 feet of silt above the heading and 60 feet of water was another matter. That work had required considerable courage and determination, and sometimes the men had been driven almost to the limits of physical endurance. He knew of no more dangerous work than blasting rock with a head of water above such soft silt as existed near the water. Another great difficulty about the work had been to carry tunnels through beds of sand under the streets, with elevated railways and huge buildings above them in every direction. It was a point in the work for which credit should be given, because it was a unique achievement to tunnel through rock, sand, and gravel under streets, with such superimposed weights that must not be disturbed in any way.

### Correspondence.

Mr. CRAWFORD BARLOW felt that the very interesting description Mr. Barlow. of the numerous works in connection with the Hudson River tunnels was, on account of the quantity of matter to be dealt with, rather of a skeleton-like character, and some interesting details were omitted. For instance, there was no account of the early history of these tunnels: more than 20 years seemed to have elapsed between the beginning of the first tunnel and the time when the Author was called in, and it was known that the assistance of the late Sir Benjamin Baker was obtained at one time. It would make a more complete record if some slight sketch were given of the history of these past struggles for the mastery of the Hudson River. The greatest novelty in the constructional work was the hardening of the clay in the river-bed by burning kerosene. It would be valuable to know the arrangements made for carrying off the gases from the burnt oil and keeping the tunnels habitable for the men during the process. Again, in reference to the scheme for carrying the live

Mr. Barlow. loads independently of the tunnel-lining, although this had not been carried out, certain queries suggested themselves, namely, the sizes of the piles or piers, the method of carrying them through the bottom of the tunnel so as to keep out the water and sand, and the character of the girders for carrying the rails from pier to pier, considering the limited area of the tunnel. This scheme was another exemplification of a modern branch of engineering, which might be said to have been initiated when the Tower subway was constructed. Brunel's patent of 1818 had defined a circular shield, but neither at the Thames Tunnel nor in any of his works had he employed his patented arrangement. When the Tower subway was opened for traffic it was described as a model of a system of tunnelling especially applicable for driving under the streets of cities or under rivers, and Mr. Peter Barlow in the following year obtained an Act for the first sub-metropolitan scheme on this system, namely, the City and Southwark subway. Unfortunately, financiers had not then realized its future value, and the scheme was abandoned. On Mr. Barlow's retirement from practice, on account of ill-health and age, the scheme was handed to Mr. Greathead, who revived it in 1884, and eventually extended it to south London, hence its present name, City and South London Railway. There was a fact connected with the Tower subway which he believed had not been made generally known. When the Tower bridge was completed the subway lost the little traffic it possessed and was for sale. The Hydraulic Power Company made an offer for it (for laying their mains from south to north London) subject to the iron lining being found to be in good order, that was, not corroded away, as had been predicted by many people. Holes were cut through the iron to the clay, and in every case the cast iron was found to be as good as when first put in, the cement ring on the outside and the tarring on the inside having kept it in perfect preservation—a fact which was reassuring to those who were concerned with the future of these iron tunnels.

Mr. Berridge. Mr. HAROLD BERRIDGE, having been connected with the work for about 7 months, could bear testimony to the skill, energy, and foresight with which it had been conducted. With regard to the design of such subaqueous cast-iron tunnel-linings, he had found that by plotting the weight per foot ( $W$ ) against the product of the hydraulic depth,  $H$ , and the external radius of the tunnel ( $R$ ), that

$$\text{For heavy tunnels } W = 11.9 \times H \times R$$

$$\text{For ordinary } ,, \quad W = 9.5 \times H \times R$$

The latter seemed to be a minimum weight, as the old Hudson

tunnel-lining, which failed, came below this figure, as did also a Mr. Berridge. Rapid-Transit tunnel between the Battery and Joralemon Street (Brooklyn), which had also given trouble. The higher weight-factor coincided with such linings as the St. Clair and the heavy Blackwall section. There was of course a desire to cut down the weight of linings, owing to their cost forming such a large portion of the total; but in gravel and ballast the stresses set up in the lining by pushing the shield ahead were very severe and concentrated, and, especially in smaller tunnels, were apt to cause longitudinal fractures if the lining was not strong enough. There seemed to be little information generally available as to the quantity of compressed air necessary for tunnel work. The supply for several tunnels appeared to be about 15 to 20 cubic feet of free air per minute per square foot of face. Perhaps the Author could state on what basis the air-compressor plant had been laid down for work in gravel and silt respectively. The Hudson silt was fairly good for plastering crevices, and he had a vivid recollection of spending a whole Christmas Day, when hands were short, in finding air-leaks in the face by the light of a candle and plastering them up from a bucket of Hudson silt, with the object of keeping the compressor-revolutions down to a reasonable figure. The silt, however, dried very quickly when so used; so that, on that occasion at any rate, he had put in a full day's work, the temperature at the face being  $90^{\circ}$ , and on the top  $-4^{\circ}$ , which afforded an example of the local conditions sometimes occurring. The use of reinforced concrete for caissons appeared to be eminently successful and showed that the material could be trusted to develop the required strength for this class of work within the comparatively short time necessary.

Mr. A. FAIRLIE BRUCE observed that some information regarding Mr. Bruce. the setting-out of the lines of tunnel, which must have been somewhat troublesome, would be of interest. He considered that the Author had shown great wisdom in making such free use of reinforced concrete, on account not only of its economy in construction, but also of its freedom from risk of corrosion, to which all ironwork was liable in confined positions difficult of access for painting. Mr. Bruce would be glad to learn the result of the Author's experience of the twisted rods used for reinforcement. Judging from his own experience, he was not inclined to attribute any great virtue to patented forms of reinforcement, which were open to the objection that where they overlapped at junctions they would not lie so close together as plain rods, whether round or square: this was a serious consideration in thin work, or in places where two or more systems of reinforcement

Mr. Bruce, intersected. The Author might also be kind enough to state whether in making the connections between different lengths of rod, especially in the columns, he merely overlapped and wired them together, or adopted some special method. It would also be of interest to know how the plugs in the caissons were arranged for connections with the tunnels, and whether they were of plain concrete or were reinforced; also whether the reinforcement had to be cut through for their removal. Lastly, when Caisson No. 3 was stopped on reaching the rock, was it supported merely by skin-friction while the rock was removed and the walls were built up from below?

Mr. Deane. MR. HENRY DEANE, having sat recently on a Royal Commission dealing with the question of communication between North and South Sydney, was glad to see that some of the difficult problems likely to be encountered if the tunnel scheme recommended were adopted had been dealt with successfully by the Author. At the present time communication between the two shores of Port Jackson was entirely by private ferry, and as the Author referred to the way in which the ferry-traffic across the Hudson had been conducted, it might be mentioned that Mr. Deane, during his term of office as Engineer-in-Chief under the Government of New South Wales, had recommended on more than one occasion the introduction of the American practice of double decks and end loading, in order to facilitate the movements of passengers when embarking and disembarking. Port Jackson was much narrower than the Hudson River at New York, but it resembled that waterway in that it was frequented by large ocean-going vessels. The desirability of keeping the fairway clear of the obstruction caused by bridge-piers and superstructure was strongly insisted upon by some of the Sydney authorities on navigation. The tunnel method of communication was at any rate cheaper to start with, as it consisted of comparatively small units; a tunnel did not require to be in an absolutely straight line, but could be curved in order that the best ground might be selected, and it could be extended up and down the stream, and also added to as required, by the construction of additional tunnels. The conditions met with in carrying out the Hudson River tunnels had been dealt with very successfully. They appeared to have been almost unique as to variety. Soft silt, fine running sand, boulders, made ground, and rock, had offered no impediment to the Author's operations, although rock had frequently occurred at the bottom of the tunnel sections only. It was reassuring to the engineers who would have to deal with the Sydney case to note that the Author had pushed his tunnels through material which was much softer and more treacherous

than they were likely to find at the bottom of Sydney Harbour. Mr. Deane. He was glad to observe that the Author condemned the crossing of opposing traffic at junctions on the level as dangerous, and avoided this by taking the lines in single tunnels and passing one over the other. He had already resorted to that principle in a proposal worked out by him for the Minister for Works some years ago, and also later on in dealing with the junction of the eastern suburban line with the city railway scheme, which was at the time under consideration by the Minister then in office. He considered that by adopting this method not only would the danger of opposing traffic crossing on a level in the tunnel be avoided, but also the number of trains that could be passed through the junction would be very largely increased, as the traffic in one direction would not have to wait for the passing of that in the other. The Author's arrangement of the lifts, whereby entrances and exits were provided on opposite sides, was much to be commended. One of the most important sections of the Paper was that under the heading "Stability of Tunnels in Silt." It was certain that most engineers would have hesitated to trust such material, and the experience recorded was therefore very valuable. The Paper was full of details which, on account of their variety and novelty, would be of the greatest service to engineers.

Mr. E. P. GOODRICH, of New York, remarked that the subject of Mr Goodrich. tunnel-building had made great strides in the United States in the last few years, and unquestionably the tunnels described in the Paper were examples of the highest development yet reached. This was true because of the adverse conditions encountered and surmounted as well as on account of the application of such miscellaneous devices as reinforced-concrete caissons, the baking of clay to be excavated, tunnel-construction by displacement, etc. His own special interest centered perhaps more particularly on the earth-conditions encountered, and on the reinforced-concrete work. The pressures developed in the jacks which projected the shields forward, when analysed on the basis of the lateral earth-pressures produced, in terms of the vertical weight above any given level, served as a basis for computing coefficients which might be used under similar conditions for the determination of lateral earth-pressures in retaining-walls, foundations, etc. Again, the information given with regard to the movements of the tunnel due to tidal changes and occurring in the course of time proved conclusively that soils possessed the property of resiliency or elasticity. This point had been brought to the attention of the American Railway Engineering and Maintenance of Way Association in a Paper by Mr. Goodrich at its last

Mr. Goodrich, annual convention, and the Author's notes were particularly interesting in this connection. With regard to the subject of reinforced concrete, he was surprised that a higher ratio was allowed between the moduli of elasticity of steel and concrete in compression than in so-called tension, which latter he understood to be the tension developed by bending. The majority of experiments with which he was familiar showed that in direct compression the ratio was usually in the vicinity of 10, rarely rising above 12; while in the case of bending it was rarely below 15, and often rose to 18 or 20. The various applications of reinforced concrete, such as those in the caissons and the stations, were of considerable interest and illustrated strikingly the possible uses of the material.

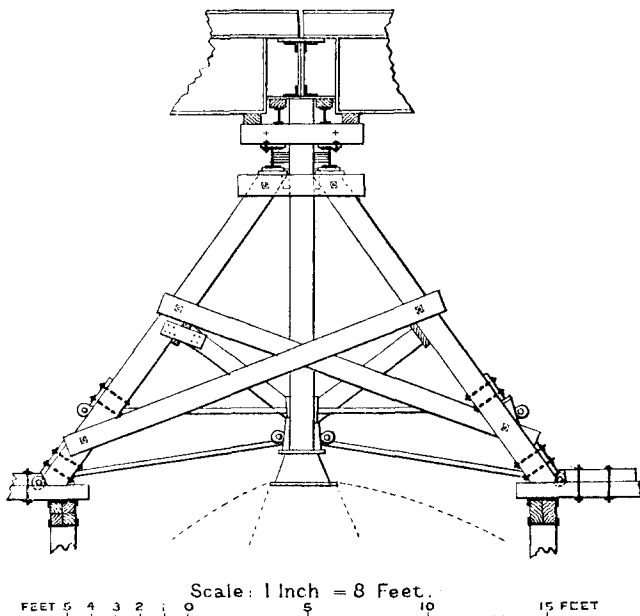
Mr. Leitch. Mr. W. O. LEITCH observed that the completion of the old Hudson River tunnel was an event of historic interest. The original promoter was the first to use compressed air for tunnelling, and the pilot-tunnel supporting a lining of thin plating, inside which the brickwork was built, was also first adopted there. The past history of the tunnel obviously could not be included in the present Paper, but it was to be hoped that the Author would cause to be prepared a memoir which might well be called "The Romance of the Hudson Tunnel." Two striking facts were the magnitude of the work and the large portion done under the direction of the engineer. Large undertakings had been frequently carried out by executive engineers in India and China, but in countries where occidental customs prevailed the contract method was more common. For a speculative work such as tunnelling under the Hudson, and under valuable property, a contractor must allow for risk as well as profit. If the risk did not arise, presumably the railway-company gained by undertaking the work itself, but, on the other hand, contractors accustomed to such work might be able to work more economically. Consequently the cost was a matter of much interest. The  $12\frac{1}{2}$  miles of single tunnel were stated to have cost £6,000,000, which worked out at £91 per lineal foot. The cost of the concrete arched tunnels would be below the average, and that of the iron-lined tunnels above, so that the cost given for subaqueous iron-lined tunnels—£60 per lineal foot—appeared to require some further explanation. Did the £60 include engineering, management, plant, and all general and operating expenses? The same question might be asked in connection with the price per cubic yard for excavation. It would be interesting if the Author could say something about the 500 feet of 19-foot tunnel that failed. Were the joints all machined? With such peculiar material as the Hudson silt, excavating might have caused move-

ments in the surrounding material, bringing unequal pressure on the Mr. Leitch. tunnel. The 16-foot ring was of thicker plating, and ramming the shield into the silt probably consolidated the latter. Were there any records to show whether the old shield used by Messrs. Pearson had sunk during the time work was suspended? Also, had any of the tunnels been built with the segments breaking joint? With regard to air-locks, could the Author state the pattern found to be best from the point of view of rapid working, including bulkhead- and caisson-locks, as well as small locks where the man- and material-locks were in one? The description of the run of silt through a door of the shield helped one to realize the difficulties of the early days. The shields apparently had a single diaphragm, and if so it was rather doubtful if the saving in cost and the greater ease in manipulating a lighter shield balanced the risk of a run of silt. The placing of the canvas sheet so as to block the mouth of the tunnel was a very ingenious operation, and it might be worth while recalling that Trevithick tried it under the Thames almost exactly 100 years ago. During the last 15 years many bridge-caissons had been sunk by compressed air in North China. No very high pressures had been required, but up to 30 lbs. per square inch the Chinese workmen had stood it very well, and had proved apt at the work. There were at present a few sub-contractors, trained by the engineers of the Imperial Railways of North China, able to undertake the running of the machinery and the sinking at remarkable rates. Thus bridge-caissons recently sunk through sand and silt and founded on rock 30 to 55 feet below water-level had cost on the average 2s. 6d. per cubic yard for excavation. Plant and coal, etc., were supplied free. Other expenses counter-balanced the cheap labour; cement and steel were expensive, and, for example, in the case of the Lanchow bridge (Kansu), all plant and workmen had had to be sent 1,100 miles over rough roads.

Mr. J. C. MEEM, of New York, remarked that under the guiding Mr. Meem. hand of the Author and his able assistants there had been evolved a practically new idea in tunnelling, which had rendered apparently simple that which at one time was almost prohibitive: he referred to the method of driving a shield through the Hudson River silt without taking in any, or at least only a small portion, of the displaced material. He had been studying for some time the effects of skin-friction on piles and caissons, and he was convinced that friction was largely an element of pressure, and that between similar faces it would always be constant at the same pressure; owing to the arching tendency of ground over small areas, such as the space occupied by piles, it would therefore be materially

Mr. Meem. less on piles than on large caissons. While he was not able to analyse the Author's notes on the skin-friction of the large caissons, with respect to this particular theory, he believed that such records were always of great value, even though they might not differentiate between skin-friction pure and simple and that due to binding, which was in reality of bearing value. Referring to the Author's description of the underpinning of the elevated railway in Sixth Avenue, New York, the following description of similar work in Brooklyn might be of interest. The Brooklyn extension of the New

Fig. 21.



York Rapid Transit Railroad, as finally built, comprised four tracks along Fulton Street and six tracks along Flatbush Avenue, some of which were depressed. Along Fulton Street, for a distance of 2,700 feet and along Flatbush Avenue for a distance of 2,000 feet, the route lay under double-track elevated railways, the columns of which had to be underpinned in order that they might be seated on the roof of the structure. In Fulton Street the columns were of the Phoenix type, carrying cross lattice-girders, which in turn carried longitudinal girders supporting the track, the columns being seated just inside the curb. Along Flatbush Avenue the columns were seated

in the roadway, just outside the surface tracks, and were of the Mr. Meem. channel-lattice type with flared heads, carrying cross plate-girders, which in turn carried longitudinal girders. The two types of structure thus presented very different problems. Omitting mention of the special cases where turn-outs of the surface tracks introduced complications, the following was a description of the method of underpinning adopted in typical cases for each type of structure. Box-sheeted pits 5 feet square were first sunk about 10 feet each way longitudinally from the columns to or slightly below the formation-level of the adjacent structure. On floor-grillage in these pits 12-inch by 12-inch posts were set, and from longitudinal caps on these, double **A** frames of 10-inch by 12-inch yellow-pine timber were set up, on the tops of which a grillage of **I** beams and timber bore against the columns and structure as shown in *Fig. 21*. Eye-bars with 3-inch pins were then placed, the pins bearing on 4-inch by 4-inch wrought-iron bars, bolted to the legs of the **A** frame as shown. The bars were tightened as much as possible by hand, and then hydraulic jacks were set on the pins on one side, and they were pressed down till the column showed signs of being lifted from its base. The pins were then made tight and a secondary set of eye-bars was placed and tightened down, and such other bracing and protection as might be required was inserted. As the ground above the footing of the columns was excavated in the course of the regular work, the masonry base was dropped and blasted so that it could be removed, and the column was left on a temporary footing till the permanent structure was erected underneath. The uprights, etc., were incorporated in the general scheme of bracing as the work advanced. The Phoenix columns along Fulton Street were supported by a collar which was bolted to the column, being supported by the outside legs of the **A** frame, above which the head of the column was blocked up. The inside legs, abutting each other and carrying cross caps, were blocked up under the main cross girder. Side rakers of 10-inch by 12-inch timber were used to prevent lateral swaying. Bearing-channels were used between the heads of posts or steel beams and flat timbers where necessary, to distribute the load. In most cases there was some settlement of  $\frac{1}{4}$  inch to 2 inches, and when the column was ready to be set on its new base the bars were tightened and jacked down until the column was back to its original elevation plus  $\frac{1}{4}$  inch. The 2 to 3 inches of space between the bottom of the column and the top of its base was then wedged up with steel shims and grouted, being allowed to set for several days before the bracing was removed. At one time the exigencies of the work were such that seventy-six columns along

Mr. Meem. both Avenues were off their permanent footings. At Flatbush Avenue and Fulton Street there existed five tiers of standard tracks, including two elevated railroad lines crossing each other, standard surface lines, a five-track subway and one standard subway. Mr. Meem was indebted to Mr. F. L. Cranford, of the firm who carried out this work, for his courtesy in allowing these particulars to be given, he himself being engineer for the firm.

Mr. Taylor. Mr. C. P. TAYLOR noticed that in describing the novel arrangements made for driving the tunnel partly in rock and partly in silt, the Author referred to a steel apron for the overhead protection of the men while drilling, and as a safeguard against the inflow of silt. Later on he referred to a removable protecting hood used for the same purpose, and serving as a poling-board in soft ground. Presumably the silt met with just above the rock was as soft as that through which the tunnel had been driven either without removing any material at all or by allowing only a small percentage to flow into the heading through the shield. Under these circumstances it would appear that something more than overhead protection had been required during the process of drilling the rock. It would be interesting if the Author could give a diagram showing exactly how the space necessary for the drilling-operations had been secured.

Dr. Zollinger. Dr. A. ZOLLINGER, of Berne, remarked that such works as the tunnels between New York and New Jersey would be carried out only in large cities where the traffic had become so dense that ordinary methods of communication failed. Intercommunication by means of large bridges had the disadvantage of being very costly, for on account of their height above the banks of navigable rivers and their great length, as well as the space taken up by approaches, it was not possible to obtain such direct communication with the centres of traffic as was to be desired. Hence recourse was had to tunnels, which could be constructed more easily without interfering with traffic, and, especially, which could be connected with busy centres as needed. The difficulties with tunnels were the sewers and mains under the streets; but in course of time subways would be constructed to carry these, which would greatly facilitate the proper maintenance of the streets and prevent them from being obstructed so often. The greater part of the work had been carried out under compressed air; with that system there was a limit to the depth, because it was not possible to exceed a gauge-pressure of 45 lbs. per square inch, or a depth of about 100 feet below high water. If this depth were exceeded it was necessary to employ freezing methods, which required very uniform ground and large installations, but which usually enabled excavation and

masonry work to proceed very quickly. The longitudinal profiles Dr. Zollinger. indicated that the rock had been avoided as much as possible in tunnelling through the silt. Would it not have been better to remain more in the rock? because construction was less costly than maintenance. Probably enough soundings had not been made to determine exactly the profile of the rock, which in the case of the down-town tunnel (Fig. 4, Plate 2) was very irregular; but why had the tunnel not been kept at the same depth between Caisson No. 2 and the crossing of the Hudson, in which case it would have remained in rock all the way on the right bank of the river? A gradient of 1 in 25 should have been avoided for a line with heavy traffic, on account of the great fluctuations in the current. Concrete offered great advantages over masonry, being executed very rapidly, but it was necessary to employ skilled workers, and the concreting must be done carefully. In the Lötschberg tunnel,  $8\frac{3}{4}$  miles long, through the Alps, blocks of concrete were used. Two plants had been laid down for making these blocks, and the concrete, which was made with Portland cement and crushed-stone sand, had a resistance to crushing of 2,550 lbs. per square inch after 28 days. Three qualities of matrix were used, having resistances to tension, after 28 days, of 230 lbs., 142 lbs., and 114 lbs. per square inch respectively. These were used according to the resistance required in the different kinds of work. The use of cast iron for tunnels subjected to bending action was not to be recommended, for usually the excavation was never made so exactly that the tube rested everywhere on the ground; the only advantage of cast iron was that it resisted chemical action better. But steel tubes could very well be employed if surrounded with a sufficient thickness of concrete; steel resisted movements better owing to its elasticity. The permanent way consisted of rails resting on wooden cross sleepers, the whole supported on ballast, as was usual in America. In London special rails were used resting on longitudinal sleepers, and the bed was of concrete. Dr. Zollinger preferred the latter form in a long single-line tunnel; the construction cost more, but the upkeep less. In the former there were less fastenings and the changing of the ballast was avoided—work which was very costly in a single-line tunnel where there was not much room or time for adjusting the track. With a concreted bed the drainage was always maintained and the track lasted longer. The workmen's wages were high, but the work was done by skilled men, from whom more could be expected. The continuous-current third-rail system was always appropriate where the traffic consisted of a large number of light trains. In the Simplon tunnel electric traction by three-phase

Dr. Zollinger. current at a pressure of 3,000 volts had been employed from the beginning. Electricity had been chosen because of the great heat in the tunnel. The traffic consisted of about twenty-six trains in the two directions every 24 hours, their speeds being 42 and 21 miles per hour. The tunnel was continuously ventilated with 1,765 cubic feet of fresh air per second (the cross section being 250 square feet) and the maximum gradient was 1 in 143. In spite of these favourable conditions it had been found that in the damp parts of the tunnel an extraordinary amount of wear occurred on the tops of the rails—which weighed 108 lbs. per yard—there being places where the wear had amounted to nearly  $\frac{1}{4}$  inch after 3 years' working. Such wear had not been found in a similar long tunnel, also very damp, and having a gradient of 1 in 37, through which seventy to eighty steam-trains passed per day. The wear in the Simplon tunnel had been attributed to electric traction, but the actual causes had not yet been discovered.

The Author. The AUTHOR, in reply, remarked that no special arrangements had been made for carrying off the gases when hardening the clay in the face by burning kerosene. A large quantity of air was escaping at the time, which helped to remove the gases, but this was one of those emergency measures so common in engineering which had to be carried out in spite of conditions involving considerable discomfort, and in fact some danger and risk to the workmen. Regarding the size of the piles or piers which were designed for the Pennsylvania tunnels to carry the live load independent of the tunnel-lining, it would of course be understood that while within these tunnels segments with cast-steel bores in the inverts of the tunnels had been installed, permitting the introduction of piles without exposure of the ground, the piles had been omitted after a full investigation of the stability of the tunnels. For the information of Mr. Barlow, however, it might be stated that the keeping out of the water between the tunnel-lining and the piles was to have been accomplished by means of an ordinary stuffing-box, in some respects similar to the stuffing-box of a steam-engine, except that the packing was intended to be metallic and so arranged that the gland could be kept tight. As the piles were to be placed 15 feet apart between centres, the longitudinal girders to carry the track were themselves carried on transverse bolsters, or girders, resting on the top of each pile and were necessarily quite shallow. The piles were to be  $29\frac{1}{4}$  inches in diameter. This matter was being fully dealt with in the Papers at present under discussion by the American Society of Civil Engineers, treating on the construction of the works involved in extending the Pennsylvania Railroad into

New York City by means of tunnels under the Hudson River, to The Author. which the Author had already referred. In response to Mr. Berridge's inquiry as to the basis of compressed-air supply, as explained in the beginning of the Paper, the work had not been planned as a whole at the start, but the system as built had been developed and enlarged from the original tunnel after several years of study, during which time work had been in progress on portions of the undertaking. It had therefore been neither necessary nor desirable to lay down a compressor-plant of sufficient size to carry on all the work at once. The compressors used on the tunnels which were completed first had been transferred to new locations and used on the later tunnels, or else the air had been piped, either through the completed tunnels or on the surface over the uncompleted land tunnels, to new points of attack. An accurate forecast of the quantity of compressed air required under all conditions could not be made. The Author had had a single face using 20,000 cubic feet of free air per minute in gravel, and also in silt when the bed of the river was torn; while, on the other hand, one-fifth of that quantity had sufficed under normal conditions. As each of the five principal plants on this work had supplied air to two to four or more faces, the chances were that these abnormal conditions would not prevail at all faces at once. At any rate, the ability to concentrate the supply of air on one face, temporarily ceasing work on the others, had given a great reserve of air for emergencies. In reply to Mr. Bruce, steel reinforcing-rods were overlapped at points where rods in one continuous length could not be used. Twisted steel rods were used throughout, no patented form being used. The plugs in the caissons were made by first putting in the ends a ring of the 19-foot  $5\frac{1}{4}$ -inch tunnel-lining left over from the old original tunnel, inside which a plug of plain concrete was made; this was cut out when a shield was driven through the tunnel-lining, telescoping inside the larger ring, and the small annular space was filled with concrete. In regard to the support of caisson No. 3 while the rock was being removed and the invert and walls were being built, it was held in position partly by the skin-friction, partly by the bearing of the cutting edge on the rock, and partly by the air-pressure; but as an additional precaution wooden blocks and props were used, the points of the support being shifted as the excavations progressed. In regard to the ratio between the moduli of elasticity of concrete and steel, Mr. Goodrich had been misled by a misprint in the proof of the Paper. The ratio  $\frac{1}{2}$  to  $\frac{1}{5}$  related to beams, and the lower ratio had been used as a rule, as that conformed to the requirements of the New York building laws, the higher ratio having been used in only a few

The Author. cases where the necessities required it and the building laws did not govern. The ratio of  $\frac{1}{15}$  to  $\frac{1}{20}$  related to columns, and also in this case the lower ratio had been used in most cases, and the higher in only a few extreme instances. As to the apparent discrepancy between the cost of the tunnels per lineal foot, as obtained by dividing the total cost of £6,000,000 by the  $12\frac{1}{2}$  miles of single-tunnel construction, which worked out at £91 per lineal foot, against £60 per lineal foot given as the cost for subaqueous iron-lined tunnels, the Author would state that the unit cost of £60 per lineal foot included engineering, management, plant, and general charges, but that the  $12\frac{1}{2}$  miles of single tunnel included all stations, switch and junction enlargements, and the like, and that the total cost of £6,000,000 included the cost of such stations, switch and junction enlargements, and in addition all shafts, foot-passages and stairways, chambers for ventilating and pumping-machinery, and in fact all underground structures accessory to the tunnels. It would thus be seen that the cost of these structures distributed over the total length of line accounted for the unit rate being about 50 per cent. higher than that given as the bare cost of the tunnel. As to the 500 feet of 19-foot tunnel that failed, some of these rings had machined joints, but most of them had unmachined joints filled with wooden packing. Owing to the records of the elevations of the old Pearson shield not being referred to a bench-mark on solid ground, no reliable facts could be deduced as to the amount of sinking, if any, during suspension of work. As a rule tunnels were built with the segments breaking joint. The standard type of air-lock for materials consisted of a cylinder, of  $\frac{1}{2}$ -inch boiler-plate, 20 feet long and 6 feet in diameter, with the usual type of doors. The man-locks were oval in shape, 4 feet 1 inch by 3 feet 1 inch and 15 feet long. For sinking caissons various types of locks were used, some of which were patented and were leased from those controlling them. They all had various devices to permit the hoisting-cable to pass through the closed outside or top door. In what was perhaps the simplest and most successful kind, the top door consisted of a circular disk with the hoisting-cable passing through a stuffing-box, and remained always attached to the cable. The door was closed by clamps around the edge of the lock, and when the lock was open it was swung to one side with the material-bucket. In reply to Mr. Taylor, the steel apron for overhead protection while drilling rock had been attached to the old Pearson shield, while the removable protecting hood for the same purpose had been made so that it could be attached to any of the standard shields where necessary. In addition to the protection afford by these devices attached to the shields the soft-ground face

from the surface of the rock to the sliding platform or protecting hood was held in place with breast-boards strutted to the shield or through the doors. In regard to Dr. Zollinger's question why the tunnels had not been kept at the same depth from Caisson No. 2 right across the Hudson (Fig. 4, Plate 2), if the traffic from Hoboken terminal to Church Street terminal had been the only thing to be considered it would have been proper to build the tunnel at a deeper level; but as the tunnels under Washington Street were also to serve the traffic from Summit Avenue to the up-town tunnels, and it was desired to have the Erie station as near the surface as possible, the higher level was decided upon as being the more desirable.

1 March, 1910.

WM. CAWTHORNE UNWIN, LL.D., F.R.S., Vice-President,  
in the Chair.

The Council reported that they had recently transferred to the class of

*Members.*

JOHN PEACHEY CROUCH.  
ALFRED JOHN HILL,  
FRANK MILLS,  
ANDREW HOME MORTON.

EDWIN BENNETT BRIERLEY NEWTON.  
HENRY SADLER.  
CHARLES WATSON.

And had admitted as

*Students.*

ERNEST EDWIN BAILEY, B.Sc. (Engineering) (*Lond.*)  
RUPERT OWEN BEIT.  
GEORGE LYNTON HOWIS BRADLEY.  
JOHN STEPHEN BURNS.  
ERNEST EDWARD DAWSON, B.A. (*Cantab.*)  
DONALD MCKENZIE DINWIDDIE.  
CHARLES LAMBERT DRUITT.  
HERBERT GEOFFREY EDLESTON.  
STUART THOMAS FARRIN.  
KENNETH BYRES FINDLAY.  
LEWIS JEX-BLAKE FORBES.  
ARTHUR TREVOR GOUGH, B.Sc. (*Birmingham.*)  
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CLIFTON MACNEE KEILLER.  
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STANLEY EDWARD WESTON TAYLOR.  
ARTHUR TEMPLE THORNE.  
ERIC HINTON GRIFFITH TOMBLINGS.  
ARTHUR PERCY WILLIAMS.

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