Mr. J. F. Bateman, F.R.S., said the Paper clearly and ably described the mode of construction adopted in the formation of the Plantation Quay, by the side of the River Clyde, opposite the Broomielaw. As he was the person principally responsible for the introduction of that form of construction he would explain the reasons which had led to its adoption.

For some twenty years before he became officially connected with the Clyde Trustees, there had been docks intended and laid out, and one or two Acts of Parliament were obtained for docks at Stobcross, on the opposite side of the river to that on which the Plantation Quay had been constructed. In co-operation with Mr. J. Deas, M. Inst. C.E., the resident engineer of the Clyde trust, he had laid out works of construction upon this area, including some 4,000 yards of quay wall, besides those for the excavation of tidal basins, called docks. No information existed as to the character of the ground. He knew, from borings in the Clyde, taken with reference to the removal of the old weir above Hutchesontown Bridge, that .the bed of the river at that spot consisted of a quicksand 80 ft. deep, of which 30 ft. or 40 ft. had been cleared out by the water falling over the weir. He knew also, by borings taken two years before for the selection of the best place for the construction of graving docks, that lower down the Clyde the ground was a mixture of silt and mud, and sand. He was therefore apprehensive that the ground, in which the Stobcross docks had to be constructed, would consist of the same material, and cause great trouble. It was therefore determined that Mr. Deas should make borings of the whole of the area, which he did, and, when that was done, they met to consider how the work was to be constructed. Mr. Bateman found, as he expected, that the whole area of the ground in which they had to work consisted of various qualities of sand, from coarse to fine—but all quick and water-bearing—with occasional masses of mud and silt, to a depth varying from 25 ft. to 67 ft. below low water. Ordinary modes of construction in such ground were out of the question. To form coffer-dams, within which to build walls, on a quicksand 80 ft. in depth, would probably have failed, and would have been a tedious and expensive work. He then, so far from thinking the ground which they had to deal with was an obstacle to the work, considered it might be turned to advantage; and his first thought was to adopt iron cylinders. But iron cylinders for the purpose of forming quay walls which were to support the ground beyond, especially when that ground was running sand, was a different construction to isolated iron cylinders within a river way, for the purpose of supporting a bridge. Therefore it was necessary to consider how the cylinders could be combined so as to make a continuous wall. He found that for that purpose iron cylinders would be inadmissible, on account of the cost. He then thought of the old Indian system of sinking wells, and whether that principle could be successfully applied under the circumstances they had to deal with. He mentioned this to Mr. Deas, and suggested that Mr. Milroy, who had been employed in sinking iron cylinders for carrying a bridge on the Clyde,[1] immediately above this work, and who had successfully performed that operation by means of the excavator which bears his name, should be consulted, and that gentleman fell in at once with the idea, and spontaneously suggested that brick wells should be used instead of iron cylinders. It was in that way, probably, that Mr. Milroy claimed the merit of suggesting the construction. The result was a general consultation between Mr. Deas, Mr. Milroy, and himself, as to the best mode of performing the operation. Being an experimental work, which would altogether cost some £70,000, there was some probability of a difficulty in inducing the Clyde Trustees to carry out an experiment on so large a scale, but, fortunately for engineering science, they adopted the suggestion. It was desirable to reduce the cost of the experiment to the smallest limit; and as brick cylinders of large diameter, to be united as a continuous wall, had never previously been constructed, they determined—and, he must say, with some little hesitation as to the result—to adopt cylinders of 12 ft. diameter.

The first idea was, to join the cylinders together by leaving hollow grooves on each side, in which to insert a wooden plug, in the same manner as the iron cylinders of the coffer-dams of the Thames Embankment below Westminster Bridge were united. That idea gave way for the adoption of an iron tongue fixed in one cylinder, to be slid down a groove in the other, the object of the tongue being to prevent the possibility of the fine, quick or running sand passing through any openings which might exist between one cylinder and another; and that this difficulty, which it was apprehended might exist, should not cause the failure of the experiment. That junction was afterwards altered to a brick tongue, 16 in. long and 4 in. deep, fitting in a groove of corresponding dimensions in the adjoining cylinder. A little hoop-iron was placed in front of the tongue to reduce rubbing-contact. The cylinders were put down one after

[1] *Vide* Minutes of Proceedings Inst. C.E., vol. xxviii., p. 339.

the other, and where no great haste was adopted there was no material difficulty in carrying them down properly and regularly; but many sank unequally in consequence of being unequally weighted.

There were, however, only 2 or 3 out of the 100 cylinders which were not got down to the depth intended, namely, 20 ft. below low water. The depth of water at low water was 20 ft., and the rise of a spring-tide 9 ft. The height of the quay wall above high water was 9 ft., which would make a total height of 38 ft. from the bottom of the river, when it was excavated or dredged to the depth intended, to the top of the quay wall—60 feet was nominally the depth to which the cylinders were to be sunk. The average depth to which they were sunk was only 52 ft. or 53 ft.; and when it was considered that many of these cylinders carried 7 tons to the square foot, before they were sunk to the final depth, upon the ring, 2 ft. 4 in. broad, and that the internal space of 7 ft. 4 in. diameter was afterwards plugged up with concrete, so as to become united with the adjacent ring, capable also of carrying an additional weight, there was no great fear of cylinders so united sinking with any possible weight that could be brought upon them. Therefore, if the question of bearing only were to be considered, the depth to which the cylinders were sunk might have been reduced: but the peculiar character of the soil had also to be considered. Had the depth been shallower, then the weight of the semi-fluid sand behind might have blown up under the cylinder, and let the quay wall down. It was necessary, having reference to that contingency, that the cylinders should be sunk to a considerable depth.

The work was extremely well arranged by Mr. Milroy, who was associated with Mr. Brassey as contractor for the works. There was no lack of energy, capital, or plant. It must be remembered that the iron rings, employed as weights to sink the cylinders, alone cost £4,000 or £5,000, in addition to the other plant necessary for the execution of the work, the gross value of which was about £70,000. This showed the energy and enterprise of the contractors; and everything was done which skill and ample means could accomplish.

The work commenced in August, 1869, and was completed, as to the cylinders, in January, 1871; giving about 16 months, or 17 months, as the time in which the whole length of 400 yards was executed. The cost of the wall, completed, was about £113 per lineal yard; and that, when compared with the cost of any other possible wall, was a cheap construction, though perhaps not much cheaper than an ordinary quay wall in favourable ground. It was a perfectly safe wall; and the only danger, which he from the first apprehended, was that of the sand blowing from behind. It so happened, just as the cylinders were nearly completed, that that danger not only showed itself, but was at one moment a source of anxiety. When four-fifths of the whole of the cylinders were done, he—being in Glasgow at the time—saw a dredger at work in front of the cylinders. The dredger was excavating the sand in front of the wall to the required depth of 20 ft. It seemed there were some old piles left in the river, which the men employed were anxious to get out, and, thinking that the wall was strong enough to bear anything, they dredged to 27 ft., and sent down divers to attach chains to lug out the piles, like pulling out the teeth of a man; in doing which they heard a rushing noise as of falling water, but no other apparent result. Next morning a slight bulge, or variation from a straight line, of about $1\frac{1}{2}$ in. was observed in the wall. On being informed of the occurrence, he concluded that the noise which had been heard was a blow of sand. It was found that the depth, which had been 23 ft., or 24 ft. the day before, was only 17 ft. the next morning, showing undoubtedly that the sand had blown, in the way which he apprehended from the first might possibly occur, and which was the only danger in the construction of the work. The damage, however, was so extremely slight that it in no way impaired the works. It was necessary to guard against this mischief in future; and it was done by constructing very heavy blocks of concrete and brick on the other side of the wharf, 60 ft. or 70 ft. off, and then running tie-rods from the blocks to the front of the cylinders, between every other cylinder. The weight of the blocks was some 3 tons or 4 tons, which added to the expense of the wall £3 or £4 per lineal yard, but that was not a very great addition. He believed the wall so constructed was almost the cheapest form of cylinder construction that could be executed. It was perfectly successful. The sheds had been erected on it, and had been in use eight months or ten months. He had always urged that concrete should be used, believing it was cheaper and better for the purpose than bricks, but Mr. Milroy preferred to use bricks in cement. Mr. Bateman had previously had considerable experience in building sea walls in concrete, composed of Portland cement, and beach shingle, the cost of which was about 12*s.* per cubic yard. In the case of the harbour works at Dublin, as to which he was consulted by the Ballast Board, Mr. Stoney, M. Inst. C.E., built blocks of 350 tons, with a granite ashlar facing, in Portland cement concrete, at a total cost of 16*s*. 6*d*. per cubic yard. Mr. Bateman having that experience present to his mind, was anxious to have concrete in preference to bricks. Mr. Milroy, although he preferred brick at that time, now appeared to consider that concrete in Portland cement was the best material for this construction.

After the completion of a portion of the work, the necessity arose for considering how the remainder should be carried out; there being 4,000 yards more of quay wall to construct in similar ground. The slight accident that occurred was of value, showing the danger they had to guard against; and a minute account was kept of every occurrence that could possibly bear upon the subject, and every detail of the work was as well known to those who superintended it, as it was to the contractor himself. A variety of suggestions were made as to the best form of construction for the remainder of the work; Mr. Milroy considered that 2, 3, or 4 cylinders might be sunk together, of the diameter of 12 ft. each, the spaces between being filled with concrete to prevent the sand blowing a passage through; and his favourite plan, to which he still adhered, was that shown in Figs. 4 and 5, the latter especially, in which four cylinders, forming a square, were to be sunk together, and the intermediate space between that group and the next group of four cylinders plugged up with concrete. There would have been some difficulty in extracting the sand in this space, and in filling the space or pocket with concrete to the depth necessary to prevent its further passage. Mr. Bateman might mention that on two or three occasions, where the cylinders were nearly down to full depth, the sand suddenly rushed up from the bottom, flowing out of the top of the cylinder. There would have been the same danger again that the sand would have blown from the inside to the outside, from the probable difficulty of completely filling the intermediate space with concrete. Mr. Deas turned his attention to every detail, for the purpose of preventing the passage of sand in this particular way, or under the cylinders, or through the joints. The plan finally determined upon, and on which fresh contracts had been made for the remaining portion of the work, was that shown in Fig. 7; namely, in groups of three cylinders: two in front and one behind; and one in front and two behind, alternately. The small spaces in the middle were the only places where any sand could accumulate between cylinder and cylinder; and the sand passing from behind to the front must pass from behind through a joint to the first small space, and from thence through a second joint to the other small space, and then through a third joint. It thus had three joints to pass through, and two of those intermediate small spaces or pockets, all of which might be filled either with wooden plugs or iron piles, after the sand was withdrawn. Although Mr. Milroy deprecated the plan which had been adopted, as incurring a greater amount of friction during the operation of sinking than would be incurred by the sinking of four cylinders together, it must be remembered that by sinking three cylinders instead of four, the work would probably be more easily accomplished. The only difference was the increased rubbing surface on the groups of three cylinders alternately, which for some distance would be not touching only, but in pretty close contact, for the sides had to be cut off for some distance, in order to make the groups fit in properly. This plan was still in course of trial. If the work was accomplished in the way in which it was designed, it would be a more solid construction than if groups of four cylinders had been employed, inasmuch as it would more effectually prevent the passage of sand. It also gave a broad base of nearly 18 ft. for the subsequent erection of the superstructure of the wall, which would be built in the ordinary way of ashlar face and rubble stone backing. This plan, he believed, would be carried out with tolerable facility. He would conclude with one word of caution. This construction of wall was not suited to any ground which was not mud or sand; in stiff ground it would be of no use; nor was it a suitable construction for rough gravel with boulders; but in quicksand, or soft mud, he believed it was the most suitable and economical construction that could be adopted.

Mr. C. B. Lane could not concur in the opinion that brick cylinders were only suitable for foundations in sand or mud. It appeared to him that the system was applicable to other engineering constructions where large vertical cylindrical spaces were required below the surface of the ground. It was nearly fifty years ago since the sinking of brick cylinders was adopted in England on a scale, perhaps, the largest ever known in the world. He alluded to the brick cylinders which had been sunk by Sir Isambard Brunel, in the year 1823, on the opposite sides of the river, preparatory to the construction of the Thames Tunnel. The Author deserved the thanks of the Institution for bringing before it a record of successful application of the system to the peculiar conditions involved in the construction of the Plantation Quay.

Mr. W. Crouch said, the point brought forward as one of novelty in this application was the building of the cylinders in rings, and so applying them that they could be more conveniently used than upon the old plan of building them up gradually as they sank down. He noticed this while the Plantation Quay was in progress, and was satisfied that the method adopted possessed considerable advantages over the old plan in rapidity of construction.

As regarded the arrangement of the cylinders, he considered that indicated by Figs. 4 and 5 to be superior to that shown by Figs. 6 and 7. In sinking, it was not easy to get the cylinders quite uniform or in close contact; and the difficulty in the case of the Clyde was that the sand and other fine materials were apt to find their way through any small apertures at the junction of the cylinders. Figs. 4 and 5 appeared to have this advantage, that the spaces left by those arrangements of the points of contact of the groups of cylinders could be cleaned out, after the sinking was completed, and filled in with concrete, which would have the effect of preventing any run of sand or other fine material between them from the back of the wall. He had the opportunity of seeing Mr. Milroy's apparatus at work, and he regarded it as the most effectual way of sinking cylinders, in sand and light soils where water was met with, that he had hitherto witnessed.

Mr. A. M. Rendel said that he was the Engineer to the works at Hermitage Wharf, which had been alluded to in the Paper. He reported to his directors that iron was not the best material for the cylinders, and that brick should be used instead. He was glad to find that Mr. Milroy was now in favour of brick, but at that time he was very strongly in favour of iron.

Mr. Redman said, the Paper was to a certain extent deficient in illustrative diagrams. If the Author had given a cross-section of the River Clyde where this important work was situated, showing the foreshore behind the work to the natural surface of the ground, there would have been data to form some opinion as to the conditions under which the quay had been constructed. At present the diagrams only showed the appliances for sinking the cylinders.

There was another item of information which the Author had not given, that was the absolute weight upon the cylinders. He should assume that the weight per superficial foot of the cylinders themselves, and the structure standing upon them—excluding the internal diameter because it was filled with sand—was from 2 tons to 3 tons per foot superficial. That was not a great weight upon such foundations. Having had experience in similar work, he was under the impression that where the cylinders could be carried down to a harder stratum below, a modification of this plan might be adopted; and that keeping an intervening space between the cylinders, and closing the front spaces next to the river with sheet piles, the same object of an extended base area might be obtained at comparatively less cost, and the labour of sinking the cylinders would be materially reduced.

The Author stated that the greatest weight required to sink one of the cylinders was 300 tons, and that the frictional resistance was 7 cwt. per square foot of surface. Taking the height of the cylinder by the circumferential surface, the frictional resistance amounted to 3 tons per foot superficial; but that was not due solely to the frictional resistance of the material through which the cylinder was sunk, but to the system adopted of locking the cylinders together as described in the Paper. It would have been interesting to have known what was the resistance of one of these cylinders sunk fairly through the silt. In the case of the wharf described, the resistance 'in situ' afforded by the material in which the cylinders were buried, was due to the front and back surfaces of the block of cylinders alone. In the case of a large cylinder, such as a cylinder supporting the column of a bridge, it was difficult to estimate the absolute weight on the area of the pier, on account of the frictional resistance which acted in supporting the load.

The cast-iron shoe described in the Paper had been adopted successfully in London in sinking artesian wells, and also through the alluvial soil of the valley of the Thames.[1] No better adjunct to the work could be selected; it gave weight to the cutting edge. But it was questionable whether an instrument of this kind was well adapted for sinking cylinders through an almost semi-fluid mass. However much it might assist the cylinder in sinking, it must be, when the work was finished, a dead weight on the cylinder, and to a certain extent reduce its area. In the event of a settlement in such a material, it would aid, rather than retard, such a tendency.

The shafts sunk by the elder Brunel for the Thames Tunnel were 60 ft. diameter.

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[1] Reference may be made to a cast-iron curb which was used by Messrs. Walker and Burgess for sinking a well at Woolwich Dockyard in October, 1839. It was 7 ft. diameter and 1 ft. 6 in. deep, with a rebate outside for planks, and inner bracketted diaphragm for the support of the brickwork of the well. Its weight was 3½ tons. Mr. Townsend, who had charge of the works at Woolwich, writes:—

"*Devonport, February 16th*, 1873.

"The curb, when in place, after a few feet of the upper surface had been removed, was sunk simply by excavating within its circumference. The brickwork on its ledge adding to the downward tendency."

J. B. R.

Mr. FREDERICK RANSOME said there were circumstances under which iron was the best material for foundation cylinders. It was a well-known and well-tried material, and was to a certain extent in popular favour; but there were other circumstances wherein iron might not be considered so expedient as brick or 'apœnite.' In many cases where foundation cylinders were proposed to be sunk, there was a certain amount of débris to be removed. This could be used in the construction of 'apœnite' cylinders. In estimating the comparative cost much depended upon the facility with which the material was produced and brought to the works; but, all conditions being equal, he ventured to say that the balance was in favour of such a material as 'apœnite,' the more particularly as that substance could be produced on the spot, lowered into position, and remain there as a permanent part of the structure. In most instances where iron cylinders were used they were to a great extent regarded merely as the shell of that which they were permanently to contain, and when the iron gave way the stone or concrete would remain. 'Apœnite' was employed for the cylinders sunk under the direction of Mr. Rendel at Hermitage Wharf; and although in some cases the 'apœnite' cylinders at the time they were sunk were only three days old, the work had been carried out most successfully. The tests of strength of the material and its power to resist crushing weight showed that, at the age of a month or six weeks, it would sustain a pressure of 4 tons to 5 tons per superficial inch.

Mr. IMRIE BELL, through the Secretary, said he considered the increasing use of brick and concrete cylinders for foundations would be attended with a saving of time and expense. He had previously, in 1869, shown that it was a system of construction specially applicable for quay walls, aprons to graving and wet docks, and for engine-seats.[1] While approving of Mr. Milroy's plan of building the brickwork rings, and of fixing them in position, he thought the dimensions of the wells were insufficient for the great height of the superstructure of quay wall, which was 38 ft. above the level of the dredged channel. It would be well that the Author should state whether the counterforts and iron tie-rods, by which the quay wall was strengthened, were included in the original design, or if they were found necessary afterwards to prevent the wall from bulging? He considered it might be preferable to construct the cylinders of different diameters, according to the depth required to be dredged

[1] *Vide* Minutes of Proceedings Inst. C.E., vol. xxviii., p. 338.

in front of the wall. It would be easy to arrange for a well or cylinder 15 ft. or 20 ft. diameter for the lower portion, decreasing towards the upper portion, and carrying out the form at the points of contact to suit the square tongue and recess (Fig. 1), so as to bind the whole into one uniform mass or wall. It was also desirable that the Author should place on record the several costs of the cylinders in brickwork and in concrete, together with the proportions of cement in the mortar of the one, and of concrete in the other. Also the cost per foot on an average in sinking, as distinguished from the total cost of sinking the one hundred cylinders. It was only from an average of the total cost of sinking all the cylinders that reliable data could be determined for works of such magnitude. Concrete was used almost entirely in the works connected with the new harbour at St. Helier, Jersey, which Mr. Bell was carrying out under, and from the designs of, Sir John Coode, M. Inst. C.E. The large blocks in this structure weighed about 12 tons each, and they could be lifted and removed three days after making. The completed portion of the sea wall—about 100 yards in length—had withstood intact the storms of the past winter, which had caused so much destruction to many works of a similar character. He considered it likely that concrete, as applied to river or harbour works, would come very generally into use, because the manufacture of Portland cement had attained great perfection. Where gravel or sand was not easily obtained, stone or shingle could be employed. By the appliance of steam power, combined with the use of stone and sand-crushing machines, any necessary amount of material could be manufactured.

Mr. Milroy, through the Secretary, in reply, stated that the object of the Paper was not so much to give a detailed account of the Plantation Quay as to describe his system of constructing non-metallic cylinders in rings and combinations, in connection with an important application of that system in actual practice. Nor did he claim any merit for the suggestion of brick cylinders, a form of construction long established in India for river-wall and other foundations, and well known to every Engineer. There was no record of the use of brick wells in Great Britain—at any rate, for foundations. The two large shafts sunk in connection with the Thames Tunnel were for a different purpose. It, however, by no means followed that they had not been so applied. They certainly had been used many years ago in France for the piers of a bridge. Instances so trifling, however, would not affect the statement in the Paper that the Engineers of the Clyde Navigation had been the first to adopt them in this country " on a large scale;" by which expression he meant to refer, not to the dimensions, but to the number of the cylinders. The works already contemplated on the Clyde might require about two thousand cylinders. With regard to the Hermitage Wharf, to which Mr. Rendel had referred, iron cylinders had been suggested by Mr. Falshaw, one of the directors of the Company, before either Mr. Milroy or Mr. Rendel was consulted; and the suggestion was afterwards adopted, owing to the difficulty anticipated in sinking a blunt brick cylinder, 18 ft. diameter, by excavating machinery, through the Thames gravel, and to the risk of injury apprehended to adjoining buildings if pumping were resorted to. He had no prejudice in favour of any particular kind of cylinder, believing that iron, brick, or concrete should be used according to the requirements of the case; but he was decidedly of opinion that a great deal of money had been wasted by the exclusive use of iron. What he advocated was, that metal, on account of its cost, should not be employed to a greater extent than was absolutely necessary. He ventured to differ from Mr. Bateman's opinion that non-metallic cylinders were only suited for mud or sand. Mr. Milroy conceived that they were equally well adapted to hard, stony ground, provided the shoes were so constructed as to afford free penetration. An iron cylinder certainly possessed one advantage in its thin cutting wall; but that advantage resided entirely at the bottom of the cylinder, and could be secured for the brick well by retaining a length or two of iron cylinder at the bottom, and building thereon brick, concrete, or stonework resting on strong iron brackets. Not only would such an arrangement be more economical, but it provided, to a greater or less extent, the load necessary for weighting. It was worth remarking generally, with regard to non-metallic cylinders, that they required less loading than iron cylinders, and when isolated in soft ground might be sunk, under proper management, without weights. The selection of brick, concrete, or stone for columnar foundations could be determined only by the conveniences or exigencies of the work under consideration: the question resolved itself into one chiefly of expense. Though preferring concrete so long as it was the cheaper form of construction, the Author had, since the Paper was written, advised brick combinations for a work on the Continent where bricks could be more readily obtained than stone. Any information which he could give as to the relative cost of the various kinds of non-metallic cylinders would probably only be misleading, as the cost would vary according to the locality and circumstances of any particular work. With regard to the system of combinations, he adhered to the opinion that the concreted space between, was the most convenient and efficient contrivance for interlocking them. The space could certainly be excavated as easily as the interior of a cylinder, and, when filled with concrete, it secured the advantages claimed for it. He might add that, since the Paper was written, he had sunk a number of combinations of three cylinders each on the Clyde with complete success. In addition to the advantages detailed in the Paper, it was found that by excavating simultaneously in the three openings the workmen had complete control over the mass, so as to be able to sink the combinations evenly, close to each other, and that the amount of weight required to force them down was very much diminished.

The seeming discrepancy between his statement of the weight required to overcome friction, &c., in sinking the cylinders, and the amount estimated by Mr. Redman, must arise from a different mode of calculating or of stating the result. Mr. Milroy took the load, 310 tons, with the weight of the cylinder, 120 tons, and, dividing the sum, 430 tons, by the area of the outside of the cylinder, obtained a result of nearly 7 cwt. for every superficial foot of that area, or per square foot of lateral friction.