The writer has chosen Hydraulic Shield Tunnelling as the subject for this paper because it is the most important of the methods of tunnelling of which he has experiential knowledge, because the subject has not yet been written upon in relation to Victorian Works, and because it is a process by which extended and varied work has been done here, and by which most important and valuable services have been rendered. The Shield tunnelling carried out in Melbourne is notable on account of the number of sewers of small diameter built in this way, for the novel methods adopted for lining the tunnels, and for the variety and extent of the soft ground to be passed through.

The descriptions and particulars given are taken mainly from Melbourne Sewerage Works and from the writer's own experience. The source of the information is given in all other cases.

The importance and success, indeed, almost it might be said, the necessity of this system for carrying out the tunnelling for the Melbourne sewers, is manifest to everyone having knowledge of what has been done. The extent of Melbourne Shield work is indicated by the following list, and it is safe to say that were the whole of the Sewerage works to be carried out with present knowledge, this list would be much longer.

<table>
<thead>
<tr>
<th>Contract</th>
<th>Lining</th>
<th>Dia. of Sewer</th>
<th>Length Length Length of</th>
<th>of rings. in feet</th>
<th>work done in</th>
<th>compressed air in feet</th>
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<td>1 8 &amp; 2 9</td>
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</tr>
<tr>
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<td>1611</td>
<td>1486</td>
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<td>1 9</td>
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<td>1760</td>
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HYDRAULIC SHIELD TUNNELLING IN MELBOURNE.

<table>
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<tr>
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</table>

Total length 37,145

* Section under Yarra. About 560ft. subaqueous. † Alternative tenders called for wood and c.i. lining. Tunnelling nearly completed.

The first introduction of the Shield in Victoria was for the purpose of constructing the Hobson's Bay Main Sewer with cast-iron lining, under the Yarra at Spottiswoode, but the first shield tunnelling was done with concrete block lining at Port Melbourne. Though difficulties were met with, little experience was needed to meet them, and the use of the shield may be said to have been immediately successful, for the troubles of the earlier works were certainly owing to undue delay in adopting the use of air compressed to pressures approximating to those of the water in the soil to be tunnelled through. Naturally with present experience, more use would have been made of it in earlier works. For in every case the use of the shield and a proper air pressure have practically removed the difficulties due to water and running ground.

THE SHIELD.

The shield consists generally of an iron cylinder about four to five times the length of the lining rings to be used with it. There is a diaphragm, or bulkhead, fixed in it at some distance from about one foot to half the length of the shield from the forward end, having one or more openings in it fitted sometimes with drop or sliding doors. In front of the bulkhead there may be horizontal and vertical longitudinal partitions forming compartments into which the soil is forced when the shield is shoved forward. Behind the bulkhead around the shield are fitted hydraulic jacks, the piston heads abutting on the end of the already constructed tunnel. By these the shield is forced forward after the rings have been built within the rear end of the shield.

Five types of shield are shown in outline in the following figures 1 to 5.

Fig. 1 shows the type of shield used here in small sewers. It was built of diameters from 4' 11½" to 6'. It had one opening in the bulkhead from 2' 6½" to 3' 6" square fitted with guides for drop planks. Some designs were of the Greathead type using a combination of cast and wrought iron with one opening in the bulkhead from 3' 6½" to 4' 11½" square fitted with guides for drop planks.
HYDRAULIC SHIELD TUNNELLING IN MELBOURNE.

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Iron; others were built entirely of wrought iron or steel of \( \frac{1}{4} \)" and \( \frac{5}{8} \)" in thickness.

The Clark design of shield is shown in figure 2. Seven shields from 10' 9" to 11' 6" in diameter were built. It was designed to tunnel through bad ground without compressed air, and it worked successfully, especially in silt.

A type of shield suitable for bad ground but having the bulkhead nearer to the front is shown in Fig. 3. It is suitable for good ground also.

Fig. 4 shows a shield of medium size having the bulkhead towards the middle of the length. It presents less resistance at the face when being pushed into the ground and provides more room for the workmen or for the earth than No. 2.

The Mersey type of shield is shown in Fig. 5.

The shield with the bulkhead about one foot from the cutting edge, especially the Greathead Shield, has been called in Great Britain the Assisted Shield, as it has been largely used there with a system of advance timbering. In this practice the ground is excavated and timbered for a short distance in front of the shield, the forward end of the timbering resting on props, the rear end resting on the front end of the shield. The shield with compartments in front has been called the independent shield. It has usually had the bulkhead further from the cutting edge and sometimes at the middle of the length of the shield with partitions in front of the diaphragm. The object of the partitions is to divide up the “face” in order to facilitate excavation, and the compartments provide room for the earth forced in during the advance of the shield for a ring length, so that it is not necessary to excavate in front of the cutting edge. The nomenclature, Assisted and Independent Shield, was not entirely accurate for Melbourne procedure. Here the Assisted Shield was frequently used independently of advance timbering, and the Independent Shield with it.

In the small shields of about 6 feet diameter there is neither space nor necessity for compartments and they are not used. And in order to allow as much room as possible for the men within the shield, and to keep the length as short as possible, the bulkhead is necessarily put within about one foot of the cutting edge (Fig. 1).

The operation and suitable construction of the shield may be described for hard ground, wet silt and sand.

In hard or firm ground the bulkhead will be placed near the cutting edge and the ground will be excavated for about an average distance equal to a ring length ahead of the shield, the ground being taken chiefly from the diaphragm. When the shield is shoved forward, the cutting edge will break down a large amount of the ground readily for shovelling. A large door in the bulkhead is advisable.

In work here in silt there has been no apparent advantage in having the bulkhead far from the cutting edge, but in the larger shields partitions in front are advisable, especially in soft silt, in order to control the “face.”

The shield will be shoved into the ground and the spoil shovelled as it squeezes up to or through the doors. The silt has been pressed, sausage like, two feet through the doors of a shield with the bulkhead four feet from the front. Soft ground, such as sandy clay with water, will squeeze similarly though not so freely as soft silt.

The most difficult material to deal with is fine running sand, especially if there be hard material in the bottom through which the shield cannot be forced. It is impossible to force the shield through sand as through silt without undue pressure. The face must be excavated back. Unless the pressure of the water is so great that compressed air is necessary or at least distinctly advisable, it is not difficult to excavate out as far as the front of the shield. There should then be sufficient room in the compartments to hold the soil for the shove for a ring length. When working in this way the ring length should be short, not more than 18\(\text{"}\). In the Graham-st. shield tunnelling at Port Melbourne, the shield (Fig. 2) was 8\(\text{"}\) long, 10\(\text{"}\) 9\(\text{\prime}\) in diameter, with the bulkhead in the middle of the length. There were four compartments and plates tapering from the full diameter at the edge, to about 6\(\text{"}\) diameter at the bulkhead, where there were 4 openings each about 2\(\text{\prime}\) square fitted with drop doors. Drop planks fitting in channels beside the doors would be about as effectual as the doors, and would permit a larger and more convenient opening. This type of shield was most effective in compressing the silt, but the sand would not compress. The conical form of the front compartments presented too much resistance to the shield and required more compression than could be obtained except with silt. And although the chambers 4\(\text{ft}\) deep might be full of sand, at times the water would rush through carrying slurry. Finally it became necessary to employ air pressure to enable the chambers to be properly cleared. The distance of the bulkhead from the front of the shield was then found to be a source of considerable inconvenience when excavating. The rings were 18\(\text{in.}\) long, and when shoving in the running sandy ground, and especially before compressed air was used, extreme difficulty and great delay were continually experienced in pushing the shield through the last few inches. Frequently the chambers were cleared twice for each ring length, and sometimes it was necessary to clear them to allow the shield to move the last one or two inches. For a considerable distance here, there was a layer of about 2\(\text{ft}\) of cemented gravel in the bottom with silt and sand above. The horizontal front partition was kept pressed into the face, and, notwithstanding the running ground in the top of the excavation, the men were able to go safely under the partition so as to pick down the gravel in front of the cutting edge.

For use in cases where variable ground will be met with, every shield large enough to allow subdivision of the front into compartments, should be arranged so that partitions and doors can be bolted in and removed at any time. Thus the Greathead type of shield used for the Yarra Tunnel at Spottiswoode was subdivided in front into four compartments in this manner, by the second contractor, and the partitions were removed when the tunnel had been carried forward some distance into firm clay. There was considerable inconvenience in working with them; and they possibly
HYDRAULIC SHIELD TUNNELLING IN MELBOURNE.

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were at no time entirely necessary. They doubtless gave a feeling of security to the workmen.

The position as to the type of shield may be summed up in this way:—
The short front type of shield is most suitable in good ground. Bad ground should be made good by the use of compressed air. But if the material is very soft or sandy, or if sufficient air pressure cannot be obtained, front partitions will assist in holding up the face. But the front should be arranged to give as much working-room as possible for the men. The horizontal partition in variable ground is specially valuable. Finally in bad ground, where air pressure cannot be used, partitions should be used in the larger shields. In this case the principal matter for consideration is the position of the bulk-head. The writer favors putting it about a ring length from the cutting edge in shields of medium size, such as 10 ft. diameter, and leaving the whole front clear of rams for the spoil forced in when shoving into the ground (Fig. 3). In very large shields the Hudson River type would be adopted (Fig. 4). The matter largely depends on the size of the shield, and consequent possible size of the compartments. If the compartments must be made so small as to prevent a man from working with reasonable ease the bulkhead will be placed forward so that the man can excavate standing behind it. If the compartments are large enough for a man to work freely in them, the bulkhead may be placed well back, say 4 ft. from the cutting edge so as to leave full room for the man to work in the compartment, and for this purpose at least 5 ft. of height is necessary and 6 ft. would be better. The larger size of shields such as that at the Hudson River tunnel permit this. There has not been apparently any case in Melbourne where the front large compartments would have been necessary or advantageous if full air pressure had been used.

A projecting circumferential hood and partitions were bolted in front of a shield under the Stony Creek. The effect of thus prolonging the upper cutting edge by the hood was to allow the face to be battered so that it would stand better, and to cut off any inrush from the top by keeping this hood cutting edge always thrust into the solid ground.

The Mersey tunnel shield (Fig. 5) has a curved bulkhead, 2 1/2 to 3 1/2 ft. from the cutting edge, with small openings for access to the face. These small openings caused the work of excavation to be slow. Afterwards an enlarged opening was made in the curved bulkhead, and a second bulkhead rising to mid-height was fitted behind it, as shown by the dotted lines, with a movable trap-door closing the top opening across to the front diaphragm. This second bulkhead was put in to check sudden rushes of sand and water. Here the horizontal partition in front, together with a ready means of closing the top openings, effected the same purpose. The Mersey shield was 10 ft. 3 in diameter. If this were considered too small to have four front compartments, the horizontal partition could be placed 6 in to 9 in below the middle, and the upper vertical partition alone used with it.

In the construction of the outer shell there are two practices. Either it consist of two plates of equal thickness breaking joint, or of one plate with cover plate joint. The second is undoubtedly the better construction.
The first would require the most accurate abutting of the plates at the joint. The writer has examined a shield built of two plates, and found in several places one plate broken and the other not. This showed, as might be expected, that they did not act in unison.

Projecting teeth for breaking down the ground in front of the cutting edge have been proposed but not used here. They have been used in England successfully.

Two special types of shield, neither of which has been used in Melbourne, may be briefly referred to. These may be called “non-circular” and “roof” shields.

The use of the non-circular shields has been discussed both in England* and Victoria. It will not be difficult or unduly expensive to secure strength and stiffness—at least, in small shields necessary for oval sewers. The difficulty will be to prevent rolling. In discussion at the Institution of Civil Engineers it has been contended that with a non-circular shield there will not be the same facility for rolling as there will be resistance both from the ground and the lining. Their successful use, even in good ground, would be very uncertain, and only slight advantages would be gained.

The roof shield consists of an overhead arch pushed forward by hydraulic jacks. The shield rests at the sides on longitudinal timbers or beams upon which it rolls or slides. It has been successfully used in America and France.† The use for this class of shield must be limited.

**Fittings and Power.**

No considerable improvement has been made, or appears necessary, in the arrangement of rams and fittings of the Greathead Shield, described and illustrated in connection with various tunnels.

Each ram should be fitted so that it can be thrust or withdrawn independently of the others, and, as in the Greathead Shield, so that the whole can be simultaneously withdrawn, when the stroke is completed, by the reversal of one valve. In the Greathead Shield—and especially in the _advance timbering system_ of working—manual power is used to operate the hydraulic pumps fixed in the shield. This system was found unequal to the requirements of Victorian work, and the writer has not had experience with it. Here, with some inconsiderable exceptions, the water for the hydraulic jacks, at pressures, up to two tons per square inch, has been conveyed from pumps at the surface through 1" and 1½" piping to the shield. A telescopic fitting with a stroke of about 8ft. is attached at the shield. Manual power might be used where very little power would be required, or where the small amount of work to be done made it desirable to reduce the cost of plant. But it seems fair to say, generally, that the power pumps are preferable in all cases. Manual pumps take up too much room in very small shields, and they entail hard labour on the workmen in the larger ones, and delay in all cases. While the shield is being shoved forward, most of the men can be otherwise engaged, as in preparing for building the ring and getting the lining materials forward.

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† *Engineering News*, 9th and 1st January, 1892; 9th July, 1896; 24th June, 1897.
Three processes are adopted in regard to the excavation—advance timbering, or the assisted shield method; clearing away a space in front of the shield without timbering—at least, without any complete system of timbering; and the independent shield system, in which the shield is forced into the earth which is excavated within the shield.

The only case in which advance timbering has been adopted here as a regular system was at the Yarra tunnel, at Spottiswoode, during the earlier half of the work. There the shield, hand-pumps, and system of working was substantially that used in the Glasgow tunnels, except that no heading was carried in advance, each 2' 9' ring-length being taken out ahead of the cutting edge successfully. With full air pressure equal approximately to the hydrostatic pressure, this plan was practicable but slow and costly. It was afterwards amply demonstrated that with 18' ring lengths, and proper air pressure, this complete system of timbering was not required. In the system in practice at the Glasgow tunnel it is difficult to see the use of a shield, and particularly the strong cutting edge. Here the advance timbering system has not been found necessary.

At the Yarra tunnel, in the second contract, the next system of excavation was practised. In front of the bulkhead there were bolted in one vertical and one horizontal partition projecting about 2ft. All the ground above the horizontal partition, converted by the full air pressure to good standing, firm, sandy clay, was excavated away, especially in the interior, sufficiently to allow the shield to be pushed an 18' ring length. Timbering was not necessary, but light temporary timbering sufficient to steady the face could have been used, consisting of boards across the face with light temporary props against the bulkhead. These props could be removed, or would be broken as the shield was pushed forward. (This was done when necessary at Graham-street, Port Melbourne.) Below the horizontal partition the ground was coarse and fine sand. Above the level, where the air and water pressure balanced, this stood well; below that level light timbering was adopted to hold back the wet running sand around and in front for the bottom two or three feet to enable the sand and the rock boulders to be removed. The shorter ring lengths greatly facilitated progress, though the longer rings would probably have been quite safe, especially if the 2' 9' advance were made in two stages. Afterwards, in firm clay, when all partitions had been removed, the ground was excavated far enough ahead of the cutting edge, but to a smaller diameter, to allow the shield to be pushed forward for a 2' 9' ring. In this way from one-third to one-half of the clay would be broken down for the shovellers.

The plan of forcing the shield forward and allowing the soft material, especially silt, to squeeze through the door, was adopted in several contracts. It may be said generally that it is a suitable method only in silt.

**Direction.**

To ensure accuracy of line and level is difficult, especially in bad ground. It should be most easy in the advance timbering method of excavation,
HYDRAULIC SHIELD TUNNELLING IN MELBOURNE.

and, possibly, this is partly the cause and justification for that system.

Simple but frequently repeated observations (depending, of course, on the rate of progress) are necessary to determine the position of the shield and its parallelism with the centre line. Accurate grade—at least, on sewer work—is much more important and more difficult of attainment. No rules can be given; it is simply a matter of care and observation. In soft ground the shield must usually be kept with a considerable rising grade to allow for the continuous settlement that takes place. A large number of powerful rams materially assist in keeping and in rectifying the course of the shield. There should be a ram for every three to four feet of circumference of shield, with 6" to 7" cylinders. The top ram may well be omitted, as less power is required there, and more head-room will be left, especially in very small shields, for working and erecting the key piece.

Two special matters only need be dealt with. The shield has a tendency to roll. This is due to some peculiarity of the construction and sometimes it may be due to the ground. Rolling may be prevented and sometimes rectified by incompletely excavating the upper portion of the face on the side to which the shield is tending to roll, and the lower portion on the opposite side.

Rolling is stated by Greathead to be due simply to the combined thrust of the hydraulic presses being not parallel to the axis of the shield, and he has suggested that some of the jacks be fitted so that their direction of thrust may be adjusted. Such an arrangement would certainly be necessary if it were attempted to use a non-circular shield.

In hard ground, it is difficult to turn the ordinary shield; for it cuts out exactly its own space and the material being incompressible, it cannot be deflected in its course. In one case here it was necessary to pick away the ground to an approximately oval shape larger than the shield to allow it to turn either in a horizontal or vertical direction and to impose special resistance by strong struts from the face to the bulkhead on the side towards which the shield was to be turned. Adjustable steel cutters are provided for this purpose on the Greathead Shield, but the method described, though troublesome, was used here.

THE LINING.

The lining used with the shield should be strong, impervious to water, easy of erection, and require as little underground work as possible while working the shield. The construction should be such that the joints will not wash out with water, and the ring will not readily yield to unequal pressures. The various systems used in Victoria will now be described.

CONCRETE BLOCKS.

The first lining used in Melbourne shield work consisted of concrete blocks set in cement. The following dimensions were adopted for an 8' sewer at Port Melbourne. The rings were 18½" long containing seventeen blocks 18" long and twenty-two blocks of half that length equivalent when set to eleven of the former. The lining was 15' thick, having 1½"
of outer rendering and $12\frac{3}{4}''$ of concrete in the block and a final $\frac{3}{4}''$ rendering when in position.

The blocks were made in tapering moulds with the sewer face of each block underneath, and the $1\frac{1}{4}''$ rendering was applied while the concrete was quite fresh.

The concrete block system of lining was fully tried, and it must be admitted that it only partially realized the anticipation generally held when it was first introduced. Its advantages were such as to make it eminently suitable to our circumstances and worthy of trial. It was cheap, and if it could be effectively constructed it would be most reliable and durable. But it had two radical inherent constructional defects. As the shield was pushed forward, the joints, partially set, were broken by the pressure used in shoving the shield, and by the alteration of form of the ring of blocks in passing out of the shield into the larger area of excavated ground. No means to sufficiently overcome these defects have yet been brought forward. If they could be overcome the merits of the system would be great, and its extended success assured.

The remaining difficulties were remediable. The water washed out the fresh joints, the block sometimes crushed under the heavy pressures of the hydraulic jacks, and as the work was practically completed as the shield advanced, any departures from the proper level or direction could not be corrected without reducing the size of the sewer. In most cases the use of sufficient air pressure would prevent the joints washing out until set. The crushing of the blocks could be prevented by a better distribution of the pressures, by increasing the end areas of the blocks, and by increasing the strength of the concrete if necessary. The head of the ram pressed against the middle of a "pressing beam" resting against the ends of the blocks. The short toothings were brought up by $4\frac{1}{2}''$ "toothing blocks." This arrangement could be improved. Even with $12'' \times 6''$ pressing beams there would necessarily be unequal pressures on the blocks. And it was difficult to get the toothing blocks to accurately fit and give an equal bearing for the pressing beam. Should they be too small, the long toothing blocks might be crushed, while the short toothing blocks might be unloaded. By diminishing the number of the blocks in the ring, or increasing the number of hydraulic rams, there could be arranged a ram for every three blocks, and upon these the pressure could be more equally distributed. The shield could be pushed forward without exceeding a thrust of 36 tons by any one ram, and this thrust could be distributed so that not more than 18 tons could be imposed on any one block. This pressure in working conditions of blocks of suitable size would not be excessive for the few repetitions to which they would be subjected. Bluestone blocks were used in conjunction with the concrete in order to prevent crushing.

The difficulties of securing correct alignment and level were mainly due to the bad ground, and could be proportionally removed by the use of compressed air.

Bluestone Blocks.

Bluestone blocks were suggested instead of concrete for the sewer under Stoney Creek in order to get greater strength to resist the thrust of the
jacks. Their use presented no other gain and could not obviate the inherent defects of the system. Under the particular circumstances regulating the respective prices of stone and concrete blocks in late years, the bluestone would cost about $\frac{3}{4}$ more than the concrete blocks delivered at the shaft, and as the strength would be very much greater, the bluestone is relatively cheaper. But under past normal conditions in the stone trade, the bluestone rocks would have cost from two to three times as much as concrete blocks, and as a minimum stable thickness would be necessary, the strength of the bluestone would be too dearly purchased.

One special case of successful work may be given. For part of the length of a 4ft. 3in. sewer to be constructed of brickwork there was about 30ft. of wet sand with 3ft. to 4ft. of excellent clay above the crown of the tunnel. In timbering this ground about 18in. at least of the clay above the tunnel would necessarily be broken down and the remainder could not be held up as tightly as it would be over a shield. The water would come through, disintegrate the clay, and "runs" of sand would follow. It was decided to abandon the ordinary timber method in favour of shield tunnelling. Bluestone block lining was selected. There were eighteen stones 18in. long and nine inches thick in each ring set in 2 to 1 cement mortar with 4\frac{1}{2}in. toothing. All the blocks were of the full length but the nine lower blocks were larger occupying 9-16th of the full circle. After the sewer had progressed some distance the following method of carrying out the work was adopted. Instead of building the ring within the tail of the shield, only three or five of the invert stones of a ring were built there, and the remainder of the ring, really the completion of the preceding ring, was built immediately behind the shield, the clay standing up unsupported for the length and time necessary to allow of this being done. In building in this way the space due to the thickness of the shield and any other vacuities were filled with sand packing. Thus, one of the already mentioned inherent defects of the block system could be overcome. No spreading deformation of the sewer took place, and excellent work was effected. Of course the circumstances were unusual but the method selected was certainly a good one to meet them. In one or two places wet ground was met with and the building of the ring was done within the shield. The defects of the system at once asserted themselves.

CAST IRON LINING.

In the ordinary systems of cast iron lining the length of ring has varied from 12" to 33". The most suitable length will be from 18" to 24". Long plates are not economical. With the same design of flanges any lengthening of the ring simply reduces the proportion of metal in the circumferential flanges, where metal can be most suitably disposed to give strength to the lining.

The depth of the flange in inches is usually about 2 inches plus one-third of the diameter of tunnel in feet; and the thickness of metal about one inch for 6 ft. diameter of tunnel and one-fortieth of an inch for each extra foot of diameter. The circumferential length of the plate should be as great as is practicable for manufacture and erection, but the key-piece should be short, only 9in. to 18in. long. It is well to avoid a longitudinal joint in the bottom in wet ground as it is difficult, if there is much water
present, to fit it well, and afterwards to clean round it before concreting. Cast iron plates have usually been made of the same thickness throughout. It would be better to increase the thickness of metal at the flange angles, as in the St. Clair tunnel lining, § or to use brackets from the flanges to the plate, as in the Glasgow subway lining.†

The circumferential joints can be flat, with strips of tarred felt or better of soft wood one quarter of an inch thick. Tarred felt was extensively used here. It is an excellent packing except that it is too thin with unplaned joints. These strips should fit closely, especially at the ends, to prevent leakage. A small space should be left at the face to be caulked if required to stop leakage, and it generally will be required. The longitudinal joints are more important. If, as is usually done, these joints are made continuous along the tunnel, the stiffness of the ring is dependent upon the rigidity of the longitudinal joint. The best joint then will be a machined joint fitting coated metal to metal, and tightly held together by strong bolts well screwed up at about 6in. pitch, and with brackets between each pair of bolts. These brackets will help to transmit any unequal pressure or any tensile stress from the flange to the plate and prevent breaking at the angle. If the joint be not machined it will be made as at first described for circumferential joints. This was the practice in Melbourne, and it is a good one, especially if soft wood packing is used.

Different designs of joints are shown in Figs. 6, 7, 8 and 9.

In Fig. 6 a longitudinal machined joint fitted metal to metal is shown with a space for caulkng with cement, or for a rust joint. This is the best form.

Fig. 7 shows a good type of joint for general use and for both flanges. A ¼in. soft wood packing is placed between the flanges. This packing will tend to swell and so correct any slight inequalities in the fitting of the cast iron. It will be better, but not entirely necessary, to have the flanges, especially the longitudinal ones, machined. There should be a space of about one inch deep left for caulkng so that the lining may be made watertight. This joint is stated to have been made entirely watertight in wet ground in London, using iron cement for caulkng.

Fig. 8 and 9 show types used more particularly for circumferential joints. The joint shown in Fig. 9 has, however, been largely used between the longitudinal flanges with soft wood packing into which hardwood wedges are afterwards driven in order to make it tight.

In the East River Gas tunnel in New York, the practice of having the longitudinal joint continuous was departed from, in order to obtain a more rigid lining ring. The matter is discussed and some tests given showing the comparative stiffness of the two systems. An 18ft. ring at the Hudson river tunnel flattened 3in. when erected on the ground. This result accords with local experience. At the gas tunnel two rings of 10ft. 2in. diameter were bolted together breaking joint, one ring being revolved two holes, when erected no flattening could be detected. With a measured strain of 16,000lbs. applied along the vertical diameter, it shortened 3in. and the flanges of the plates cracked. The advantages claimed for the

§ Engineering L 576. † Engineering LXII 574.
system of breaking joints are rigidity, the prevention of a tendency for the plates to warp so that true joints cannot be made, and the retention of a more truly circular form of ring.

The rigidity and the truly circular shape of the ring are of great importance, and the breaking of the joints should be a superior plan in both respects, for in this way each plate becomes a cover plate over the joints of the adjoining rings. If the rings are tightly and strongly bolted together the lining must evidently be more rigid than when it depends for stiffness entirely upon the longitudinal joints. The shield and the iron lining are made circular and with from 1 lin. to 2 lin. of difference in diameter.

In building the ring with the lower half of the iron lining in contact with the shield, the ring has an initial departure from the circular shape, and defective bearing at the longitudinal joints. If now it were attempted to attach another ring, with considerable breaking of the joints, the rings would not fit accurately, and unless the bolt holes were considerably larger than the bolts, they might not fit at all. Therefore it becomes necessary to build the ring more accurately to the circular shape. The importance of the bolting of the circumferential flanges is greater when the rings are not continuous; and as the bolts do not fit the holes closely, their efficiency depends upon the tightness of the screwing up.

There should be no special difficulty in arranging the rings to break joint.

Where, as in Melbourne, the longitudinal joints are continuous along the tunnel, the purpose of the bolts in the circumferential joints is mainly to draw and hold the plates together in order to ensure a close joint in all cases. If the rings be closed together by the hydraulic ram pressure, as can readily be done, the bolts only require sufficient strength to retain the plates in close contact. It is impossible to estimate what forces these may be tending to separate the rings, but it does not seem likely that they would increase more rapidly than the diameter of the tunnel. If then a constant pitch be adopted, it follows that the diameter of the bolt need not increase with the diameter of the lining. There does not seem any necessity for more than 3/8 lin. bolts for any size of tunnel. Unless then a greater length of spanner is insisted upon, there is no advantage in any case in increasing the size of the bolt, for its strength will not be utilised. The pitch should be from 6 lin. to 12 lin., and probably 9 lin. would be about right. For the longitudinal joints the case is different, for the rigidity of the joint depends upon the depth and fitting of the flange joint, and the tightness of the bolting. This relates to the total strength of the bolting. The strength of each bolt may be whatever the spanner used will utilise. The size may be 3/8 lin. for 6 lin. diameter and 3/8 more per 4 lin. increase with 6 lin. to 8 lin. pitch according to the class of the ground and strength of flange.

In a 5 lin. 9 lin. sewer lining in Melbourne the C.I. rings were 15 lin. long with 1 lin. metal and flanges projecting 3/8 lin. They were bolted together with 3/8 lin. bolts at 6 lin. pitch. This lining collapsed in two cases under exceptional circumstances, mainly through the ground getting away underneath, and thus causing an undue strain in the lining. In this case the
Iron and bolts both failed, but the C.I. much more extensively than the bolts. It was clear that fewer bolts would have sufficed to utilise the strength of the cast-iron plates. There were no brackets.

In designing and constructing sewers, especially in pumping schemes, it will be of importance to consider the extra cost to which it is advisable to go in order to exclude leakage. The expenses due to leakage will be extra cost of pumping, reduction of effective area of sewer, and general charges.

Suppose 1 mile of sewer 8ft. in diameter costs £60,0000 and admits 3000 c.f. of water per hour. Estimating* the cost of pumping 1,000,000 cubic feet per day one foot high at £30 a year, and taking the lift as 120 feet, the annual cost of pumping this leakage will be £260, and at 4 per cent. interest this will represent a capital sum of £6500, or about 10 per cent on the cost of the sewer.

Again, assuming a velocity of 3 feet per second, the discharge of the sewer will be about 540,000 cubic feet per hour, of which 3000 cubic feet will be leakage, being in this case 1-180th of the hole. And this will apply to every succeeding mile of the sewer to the point of discharge. If this length be 12 miles there is a sum equivalent to 7 per cent. of the cost of the sewer rendered non-effective.

There would be further charges for distribution and treatment.

In the case stated then it would probably be better to spend £75,000 on a watertight sewer, if it were possible to get it, than to spend £60,000 on the one which leaks. (Of course this calculation is rough, and is made simply to show the importance of the matter.) Now cast-iron and wood are the only linings used here which could certainly be made watertight. The cost of a cast-iron sewer in a shield tunnel is one-half more than that of a brick sewer in an ordinary timbered tunnel, and the wood lined sewer about the same as the brick sewer. The extra cost to exclude leakage would not be considerable for iron or wood lined tunnels.

In the Melbourne sewers a thick concrete lining was put in. In some European and American tunnels for traffic, it is omitted, or only a thin lining is used to give a smooth surface over the flanges. The life of the cast-iron appears to be considered as equal to that of the brickwork or concrete. In the Melbourne sewers this would not be so, and the cast-iron lining could not alone have been relied upon. The writer's opinion is that where the tunnel can be thoroughly grouted and examined at any time the iron lining may be relied on, but it should be left exposed for examination as much as possible. In other cases such as sewers, it should be lined, and the lining should be sufficiently strong to be complete in itself.

With cast-iron lining the concrete or other internal lining should not be put in under compressed air, at least until the iron lining has been made as watertight as possible, and tested by reducing the air pressure. Otherwise leaks in the lining, which might be caulked, will be covered up.

Erectors are used for putting the plates in place in large tunnels. In the St. Clair tunnel the erector was attached to the shield and moved for-
ward with it. It was worked by hand power. In the Hudson River tunnel
the erector was worked by hydraulic power and mounted on a traveller moving
on rails at about mid-height of the tunnel.

Two erectors were built in Melbourne. Each consisted of a truck, upon
which was fixed the erector, consisting of an arm raised and extended by
toothed gearing. The trucks were mounted on rails of wide gauge, under
which there was room for the earth trucks to pass. The erector was
cumbrous, and on the one occasion that the writer saw it working, it
appeared to be slow and clumsy. The second erector was not used to any
extent. These designs were not suitable, and they appeared to have discour-
aged the use of erecting machinery. The plates were erected generally by
the men without such assistance.

The writer sketched the following arrangement for an 11' shield for
erecting heavy plates, but it was never designed:—A square shaft would
project from the bulkhead, and upon this would slide a collar around
which the crane or erector arm would be fixed on a bearing. The collar
could be clamped to the shaft and the crane to the collar. The shaft
would be fixed to the bulkhead at about 4' 6" from the top. For the
bottom plates can be thrown into place from the truck. The plates will
come in about 2' above invert, and the crane would be pivoted mid-way
between this level and the top of the tunnel; and it would cause less
inconvenience to the shovellers here. The crane would consist of two
arms, one having an adjustable counterweight and the opposite one having
a gearing for extending and withdrawing the arm, with a suitable arrange-
ment at the end for picking up the plates. The plate could be lifted by
the men depressing the counterweighted end of the erector, or, perhaps,
by gearing. When the plate was brought opposite to its proper position,
the arm would be fixed on the shaft and the plate thrust out into its place.
When the ring was fixed the crane would be pushed back along the shaft
to the bulkhead, where it would be less an obstruction while excavating.
Of course, hydraulic power could be used. When the weight of plate
exceeds 6 cwt. and the diameter of the lining exceeds 10 or 11 feet, the
erector would be advisable.

Wood Lining.

A patented system with wooden lining has been designed, and used with
the shield at work at North Yarra Main section, No. 6a, at North
Melbourne. As this system is comparatively unknown, a model and a
design for a small sewer are shown. (Figs. 10 & 11.) This design was
prepared by the writer for the construction (for exhibition) of two full
size rings shown in the photograph (Fig. 12.) The suitability and safety
of the system have now been determined by its successful use over a
length of more than half a mile of tunnel of 10ft. in diameter.

The costs of 6' 9" sewer given later indicate the objection to cast-
iron clearly. It is too costly. But in Melbourne work in bad ground
it has these great advantages over such systems of lining as concrete and
bluestone blocks—that the joints are not such as will be affected by water,
the lining can be caulked more readily, and, above all, whatever deforma-
tions may take place in the outer lining, the final internal concrete lining
can be placed in position in a continuous mass, and without being exposed
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Half the cost of the completed work is about the actual price paid in Melbourne for the iron lining delivered at the shaft. The similar actual cost of the wood lining would be about one-fifth of the total completed cost of work. The cost of a finished concrete sewer with wood lining would be about 70 per cent. of the cost with cast-iron lining.

As shown in the drawing and model, the wood lining is built in rings composed of sections. Each section consists of two rib segments spaced the ring length apart, and covered on the outer side with boarding. Between the rib segments are placed thrust blocks, which will form continuous lines of struts to resist the pressure of the rams of the shield. Each succeeding ring is built so that the joints of its sections "break" with those of the preceding ring. Thus the lining has, at ring-length intervals, ribs really composed of two layers of wood secured together by bolts and breaking-joints so that the whole will act as one piece. Of course, this result can only be secured by spiking the ribs together, or by drawing them together with strong bolts well screwed up. Probably the former would be the more efficient, and the latter the more convenient method. What has been written before about breaking joint in cast-iron lining applies here.

Some of the more evident peculiarities of this system may be criticised. There will be an unusually large number of joints, but the swelling of the wood will tend to prevent leakage through them. But if it were necessary to use boarding such that the joints cannot close up, the whole of the outer surface of the section may be covered with waterproofing material, as thin sheet metal, even overlapping across the joints with the sheathing of adjoining sections. The connection between the separate pieces of each section cannot be made sufficiently strong to render it nearly as rigid as a cast-iron plate. But the use of the thrust blocks properly fitted will relieve the sections from the pressure of the rams, which is the principal cause requiring such rigidity. The more bulky timber will require a larger shield and excavation. This, however, will be compensated for by the lighter weight of sections in erection. It may be said that all the outer boarding is useless except for the purpose of transmitting the loading of the earth to the rib segments, and that in cast-iron lining the whole metal is available to resist the compressive loading of the ground. The primary purpose of the outer boarding is to transfer the earth loading to the ribs, which resist the compression. But if the boarding be closely fitted the swelling of the boards will cause them to act to a considerable extent as an arch, and, in any case, the subdivision of duties enables the designer to concentrate the material for resisting compression in stout and efficient sections. This cannot well be done with the cast-iron plates. In an alternative design of this system iron is used for the ribs. For the laggings to resist cross breaking timber is, price considered, the strongest material.

It is of importance that each leading ring of rib pieces be accurately retained in shape until the next ring has been securely attached to it.

When the shield is shoved forward the earth on top of the lining will usually close down and press upon it before, or heavier than it will at the
sides. To prevent deformation in the larger excavated area behind the shield it has been proposed to use a strong square "sett" of timber temporarily. This sett will be removed when the ground has closed around the lining.

**Grouting.**

The grouting generally used abroad consists of hydraulic lime only. Here it is composed of cement, lime, and sand, usually in 1, 2, and 5 parts respectively. The writer is not aware of the reason for the different practice here. The cost of each would be about the same. The lime would make a finer and better running grout; the cement and sand grout would probably be quicker setting. It is difficult to get a sufficiently light and fine sand to run easily as grout, and to stir freely in the machine.

The objects of grouting are to secure an outer protecting lining to the iron shell, to fill the vacuity due to the thickness of the shield in order to prevent settlement of the ground, and, possibly, to prevent the spreading of the tunnel lining in the large excavated area after the shield has passed forward. It also should assist in rendering the work water-tight.

Greathead prefers lime because it does not set hard suddenly like cement; because it can be used containing only so much water as it will retain in setting; it adheres firmly to the surface of the iron; and it expands in setting. As there is no objection in having the coating of grout harder than the surrounding clay, he says that a mixture of sand might be used with advantage but for the extra trouble of mixing, handling, and injecting.

In England and in Victoria grouting has been useful in rendering air-tight the outside of the cast-iron lining at air locks.

It would seem, both to prevent the deformation of the ring and to form a continuous coating, that the grout should be injected simultaneously with the advance of the shield, or, at least, for every one or two rings. The writer has never obtained any precise information as to the practice in this respect in other countries. Matters such as this apparently, perhaps, trivial, but really important, are not dealt with. Grouting will not be so useful in silt not carrying water, for the silt will close in quickly and evenly around the lining. In running ground, such as sand, unless air pressure is used, the grouting is not likely to form a continuous coating to the iron as the sand in the roof falls too quickly. Besides the grout will blow into the ground opposite the grout-hole, and though the vacuities may ultimately be filled up, in many parts it will be with the sand, or with a mixture of sand and grout. Grout will form a most effective coating in ground so firm that it will temporarily retain its place unsupported till the grout can be injected, but where the injection of the grout is not simultaneous with the advance of the shield, or substantially so, the coating of grout is so imperfect that it is of use merely as a filling to prevent settlement of the ground and deformation of the lining.

**Compressed Air.**

Whenever it becomes necessary to use special timbering and precautions compressed air should be used with the shield in wet ground, to assist to hold up the face and to deal with the inflowing water, unless the amount of
work of this class is so limited as to render the cost of air plant too great. The advantages of compressed air are, that water can be excluded, or so much as cannot be excluded can be readily dealt with, and that running ground in which effective work is impossible can be converted into good ground. The pressure to be adopted should be sufficient to render the ground easily worked and no more, unless it is necessary for safety in subaqueous work, or purely for the exclusion of water in order to facilitate building the lining. With pure air up to a pressure of one atmosphere no effect is apparent upon men of good constitution and in good health, and persons not in good health should not subject themselves to compressed air. Under these circumstances men can work hard and regularly for eight hours per day without inconvenience. At the Yarra tunnel at 20 lbs. pressure the men worked 6 hours per day. Pressures of 2 1/2, 3 and 3 1/2 atmosphere have been used with short hours. In the highest pressures the working time appears to have been 4 hours. The greatest air pressure to which the human body has been subjected was about 77 lbs. per square in. for a period of two hours in some experiments in France. About 35 lbs. per square inch may be classed as the greatest ordinary feasible working pressure for large operations.

The air should be as pure as possible. The electric light only should be used, candles are very objectionable. At the Yarra tunnel at first the escape of air was so great at the shield that the atmosphere was naturally pure. Later on the shield passed into clay with little escape of air at the face, and the air became very impure, especially as, in addition to the electric light, candles were largely used. The men now suffered from muscular pains. Personal experience on this and other works show that with the pressure used in Victoria up to 21 lbs. per square inch, the impurity of the air is much more impressive than greater pure air pressure would be, and more detrimental to health.

No trouble was experienced at Graham St., Port Melbourne, after compressed air was used, from foul gas which had shown itself in the shield before. If it be possible to maintain an air pressure greater than the hydrostatic pressure, with a free current of fresh air supplying an exhaust from the face, foul gas cannot collect in dangerous quantities in a tunnel. With less than the hydrostatic pressure if gas is present in the soil it may be expected to enter.

At the Yarra tunnel repeated careful levels showed that the water showed itself in the sand at about the level where the air and hydrostatic pressures became equal. As the water could come freely through the ground around this would be expected. It appears not to have been so elsewhere.

Three types of air lock was used here. In the Yarra tunnel an air lock consisting of two brick bulkheads with heavy cast iron doors were used. In the second contract another lock was added and the first was left as a safety lock. This was a wrought iron riveted cylinder 10 ft. long 5 ft. 6 in. in diameter, with 4 in. plates and ends 3 in. thick with stiffening gussets, and with door openings just large enough to pass the ordinary mining truck used on the works. The third type of air lock was used in small c.i. lined tunnels. It consisted simply of two w.i. bulkheads bolted to the
circumferential flanges of the iron segments with w.i. doors as before.
This portion of the tunnel lining was thoroughly grouted. The connection
between the bulkhead and c.i. lining was made air tight with neat cement
plaster over the joints. The c.i. longitudinal flanges were cut away where
the bulkheads were attached, and the bulkheads were stayed to the tunnel
lining. This and the wrought iron locks are most suitable in their respective
circumstances. The brick type is expensive and slow of erection, and
still more expensive and slow in removal. It has been said that the work-
men preferred brick air locks to iron ones in London as the chilling effect
of the fall in temperature when coming out of the lock was less. In air
locks in England it is the practice to build the iron air locks in, and entirely
to support them against the internal air pressure by a brick bulkhead wall.
A better plan practised here is to strut the air lock by strong timbers to
the tunnel lining behind and so reduce the necessary thickness of the brick
wall. A 9in. brickwall with a man-hole opening in the centre has thus
been used successfully in a 4ft. 3in. sewer against 15lbs. of air pressure.
The wrought iron locks could be more readily moved forward if required on
the work, and might be used elsewhere.

The fittings that should be furnished may be enumerated briefly.
The air pipe will lead from the the compressor through a receiver,
and pass through the lock into the working chamber. The electric
light and telephone wires may be carried through with or without
a pipe. There will be the hydraulic power pipe. If the lock is
shorter than the rails there will be a large pipe for passing them
through. There will be an ejector pipe for forcing water through the lock
by the air pressure. This pipe is carried forward along the tunnel with
branches and valves at intervals for pumping out inflowing water, and if
there is much water at the face there will be a flexible hose with a rose and
valve so that the water which collects in the bottom of the shield can be
forced out before building the first pieces of the ring. Where there is
reason to anticipate any danger a reliable lockman should be placed in
charge of the lock. But in cases where no danger has been anticipated
and the air pressure was simply required to facilitate work, there has been
used a complete system of valves, so that the lock can be passed through
freely without any lockman in charge. This consists simply of a series of
valves so that the lock can be filled and emptied from without or within
the lock and from the working chamber. The doors are closed by arms
which can be operated from either side of the door. An arrangement of
locks for subaqueous work is described later.

Sub-aqueous Tunnelling.
Sub-aqueous tunnelling differs in two respects only from ordinary bad
ground tunnelling. Special adjustment of the air pressure must be made,
independent of the hydrostatic pressure to be restrained in order to avoid
blowing out the overlying ground; and special safety provisions must be
made for the men in case of a sudden inrush of water.
The air pressure is approximately the same at the crown and at the
invert of the shield, while the hydrostatic pressure is not so. If now the
weight of earth be taken as double that of water, it follows that the air
pressure necessary at the invert of the shield to balance the hydrostatic
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Pressure there, will be safe, provided the depth of ground above the shield is not less than its diameter. In the Yarra tunnel at Spottiswoode the shield was 11ft. 2½in. in outside diameter, and the minimum depth of ground overhead was 12ft. There was no reason then to fear blowing out with any pressure necessary to restrain the inflow of water. It has been stated that the air pressure was at one time kept low in order to avoid this supposed danger. Of course it is advisable to keep the air pressure lower than the weight of earth and water above, especially if the ground were very loose.

When the overhead depth of ground becomes less than the diameter of the shield, either a further loading of earth should be placed upon it or the air pressure should be reduced. Such a reduction to a limited extent would cause no great difficulties. A pressure of water in the “face” of 3 or 4 feet and upwards, according to the nature of the ground, would not be seriously troublesome, and 10 feet and upwards could be successfully met with in special cases. In the Blackwall Tunnel, so far as the writer knows, the minimum depth of clay and filling would be 18ft. and the shield diameter 27½ft. There might thus be an unbalanced water pressure up to about 9ft. If the bottom 9ft. of “face” was in bad ground, this would undoubtedly be troublesome, but it must be remembered there would be 36ft. of ground above it in which the water pressure would be balanced by the air. The blowing out here referred to is of course a general upburst due to excessive air pressure. The blowing out from excessive air escape is due to the weakness or porous nature of the soil, but with reasonable precautions the result will not be dangerous. The material used for the filling should be as clayey as can be procured, and soft clay or silt and bags should be at hand in the shield to plug holes which may develop and weak places where the air is blowing out. There must be ample air supply, and proper safety provisions for escape for the men.

There will be two necessary safety provisions for the men sufficient for ordinary cases. There should be in every case a safety lock with the inner door always open while any man remains in the tunnel, and a diaphragm should be placed in the upper part of the tunnel so as to impound a cushion of air to enable the men to avail themselves of the safety lock. The safety lock necessarily cannot be frequently moved forward, and may sometimes be a considerable distance from the shield. In the event of a sudden heavy inrush of water it would be quite possible for the safety lock to be flooded before the men could reach it, especially in a small tunnel or where the safety lock is placed low in the tunnel. By placing a diaphragm in the tunnel, even though the air should escape to atmospheric pressure, the rising water between the air lock and the diaphragm will imprison a cushion of air sufficient to retain breathing room for the men to enable them to reach the safety lock. The safety lock should be placed as high as possible in the tunnel so that it may remain above the water as long as possible. There should be two diaphragms in order that they may be kept close to the shield, the second being erected before the former is removed. Thus safety is ensured without the stoppage of work that would be involved in moving the lock. The diaphragm would be attached to the tunnel, and not to the shield, for an inrush might occur between the tail of the shield...
and the lining. The writer is aware that diaphragms are attached to the shield. But these are working diaphragms, not escape diaphragms. The diaphragm will not require great strength but must of course be substantial and airtight. The pressure at all times will be fairly balanced except just after the water reaches its lower edge if the velocity be high. There might afterwards be back pressure from reflux, but the main danger would be from blows of floating timber. To obviate this, the lower edge of the diaphragm should be stiffened as by bolting a beam of wood to it, and probably it would be well to leave the space below the lower edge as clear as possible of all obstruction for the passage of the water.

It is advisable that the grouting should be kept close up to the shield to prevent fretting away of the ground into the vacuity left behind. Ample air compressing power and plant are necessary. At the Yarra tunnel there were three air compressors with air cylinders 16in. x 14in., 20in. x 12in., and 14in. x 12in., with two portable engines and one vertical crane boiler equal in all to 42 H.P. This machinery was at one time fully taxed to maintain 20 lbs. of air pressure. The ground was good firm sandy clay but full of small holes up to ½in. diameter through which the air escaped.

It has been stated* that it is an important precaution to bore in advance of the excavation in different parts of the face, as was done at the St. Clair tunnel. Doubtless it would be in many cases, but it does not seem that it was necessary here. With a suitable safety lock, and a diaphragm kept close up to the shield, and with the water pressure nearly equalled by the air pressure, it is difficult to see how any inburst could occur so suddenly that the men could not escape. But in variable ground the information acquired by advance boring would be valuable.

**Comparison With Other Methods of Tunnelling.**

The shield system may now be compared with former methods of tunnelling with regard to safety, expedition and costs.

The shield system properly carried out is safe especially in all cases where full or nearly full air pressure can be used, and in this respect much superior to ordinary timbering in difficult ground.

As to the rate of progress, the following examples afford a fair comparison. In a contract for a small sewer the ordinary tunnelling was carried forward 10ft. per day without the concrete and brick lining. The rate of progress with a shield would have been about the same with block lining, and about 30 per cent more with cast iron. At Graham-street the best rate of progress with concrete blocks and compressed air in sandy silt was about 100ft. in 14 days or 7ft. per day. With ordinary tunnelling in sandy clay 17 days were spent in driving the advance heading and 6 days in excavating to full size and lining, or a total of 23 days for 100ft. Rates of progress up to 20ft. per day have been made here with iron and wood lining in good material such as silt and clay.

With cast iron and concrete lining, the shield system will not be adopted in Melbourne so long as satisfactory construction can be attained with

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ordinary methods because of the high cost of cast iron. Wooden lining can be successfully constructed, and the shield system will be advisable so soon as the ground becomes soft enough to require what may be called complete close timbering, especially in wet ground. The relative costs of sewers hereafter given show this, the costs of ordinary brick sewers being given.

An important matter concerning the relative advantages of the shield and the ordinary timbered methods of construction may be noted here. In the shield system the area of excavation does not largely exceed the area of the construction placed within it. The small space left is either specially filled with grout or gradually filled by a comparatively slight closing in of the unsupported earth. Afterwards water outside of the sewer cannot flow freely around it seeking access to the interior at every weak point. And this is just what does happen in the ordinary timbered system. Spaces about the timber, necessarily left in position around the sewer, form channels for the water and the whole outer surface is exposed to its pressure.

In giving the following costs for a 6ft. 9in. diameter circular sewer, it is not considered necessary or proper to illustrate by drawings the various constructions, nor to give the detailed schedules and the quantities and rates from which they are compiled. The brick sewer constructed in the ordinary timbered tunnel, the cast-iron shell and concrete sewer, and the wooden shell and concrete sewer are all ordinary types suitable for soft ground. The cast-iron lined sewer with concrete filling between the flanges only, is given, although such a construction here is not recommended for a sewer. All the prices are estimated.

1. Brick Sewer. Ordinary tunnelling ... £6 15 0
2. Cast Iron Shell and Concrete, soft ground ... 10 0 0
3. Wooden Shell and concrete ... 6 15 0
4. Cast Iron Shell with Concrete lining between the flanges only ... 8 5 0

Of these types it may be said that fairly good ground is presupposed in the first case, and if the ground is wet the sewer will leak. Types 2, 3 and 4 can be made practically watertight in any ground, and for Melbourne sewers, where iron has been used, type 2 is worth more than the excess cost over type 4.

**Future Developments.**

The developments that may be expected with the shield system in future are mechanical excavation, improved systems of lining, and the use of the shield for what may be called sub-surface tunnelling as in streets.

At present half or more than half time is required in breaking down the ground and shovelling, and any system of more rapidly effecting this work would increase the rate of progress, and thereby reduce the part of cost due to the heavy charges outside of those for labour within the shield. Mechanical excavation has long been suggested, but it will probably be found difficult to effect, except in firm ground.
The following figures are compiled mainly from actual contract prices, and they afford fairly accurate comparative information as to the relative costs of different types of 4ft. 3in. circular sewer. The differences in the ground are indicated.

<table>
<thead>
<tr>
<th>Lining Type</th>
<th>Estimated Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete lining in good ground with no water</td>
<td>100</td>
</tr>
<tr>
<td>Bluestone lining in good ground with no water</td>
<td>107</td>
</tr>
<tr>
<td>Wooden lining in wet ground with compressed air and no grouting</td>
<td>114</td>
</tr>
<tr>
<td>Brick sewer in good ground for ordinary timbered tunnel.</td>
<td>126</td>
</tr>
<tr>
<td>Cast-iron lining in wet ground with compressed air and no grouting</td>
<td>190</td>
</tr>
</tbody>
</table>

These figures indicate how largely the shield should displace the former systems of tunnelling in wet ground, since the cheaper wooden linings can be effectually constructed.

It should be less difficult to effect improvement in the iron lining. In some recent designs the maximum stress due to loading by the whole weight of ground above the shield (neglecting questions of unequal loading) would be from 750 to 1250 lbs. per sq. inch. And these designs were certainly not wasteful of material according to ordinary practice. It is simply that the crushing strength of cast iron cannot be made available to any reasonable extent by the present type of construction. Of course this applies to those tunnels where it is intended to put in a full concrete or other lining. What has been said would not apply where the iron forms the sole lining and thickness is necessary for permanence. It appears that pressed iron or steel plates are being used in a tunnel in Scotland, but the writer has not been able to find any details. No doubt a more suitable lining to permit high unit stress could be rendered practicable in this way.

At the present time it is most objectionable to have to break up the street surface and impede traffic in order to carry out underground work in open trench. It is believed that a most important extension of shield work will be made in this direction in busy and especially narrow streets in future. In wet ground such work could be carried out with a shield, and if necessary with light air pressure, with much greater safety to surrounding buildings than in open trench, and without unreasonable cost when a cheaper lining can be adopted than cast iron, such for instance as wood or concrete blocks. This system would be suitable also for such work as pipe laying in deep soft ground.