applied to a mere frame with wooden walls which is floated to the site of the pier, and there sunk so as to form an enclosure, inside which concrete can be shot and can set undisturbed by the wash of the water.

Concrete in a shell is a name which might be applied to all the methods of founding a pier which depend on the very valuable property which strong hydraulic concrete possesses of setting into a solid mass under water. The required space is enclosed by a wooden or iron shell; the soil inside the shell is removed by dredging, or some form of mechanical excavator, until the formation is reached which is to support the pier; the concrete is then shot into the enclosed space from a height of about 10 feet, and rammed down in layers about 1 foot thick; it soon consolidates into a permanent artificial stone. The shell, unless of small size or very strong form, requires to be braced to meet the outward pressure of the concrete. The concrete used for this purpose is often called béton, to distinguish it from inferior mixtures used for foundations on land. It may consist of angular stones 1½ to 2 inches diameter, mixed with strong hydraulic mortar in the proportion of from one to two volumes of stones with one of mortar; the final volume may be from $\frac{5}{9}$ to $\frac{5}{8}$ of the unmixed materials. Béton used at Biarritz consisted of one part Portland cement, two parts sand, and three parts broken stones; at Genoa one part rich lime, two parts pozzuolana, three parts broken stones.

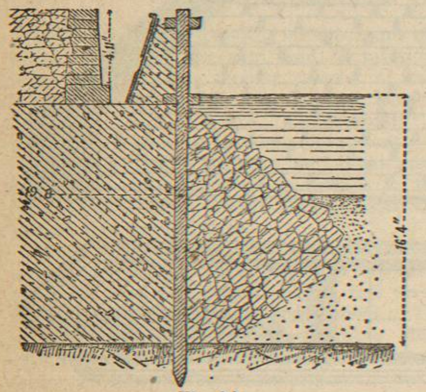


Fig. 94.

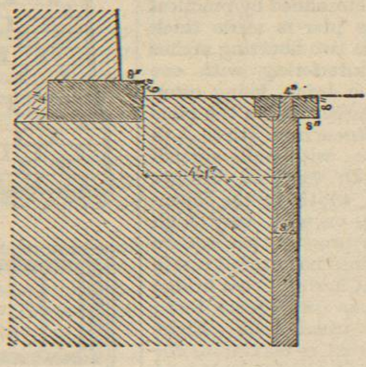


Fig. 94a.

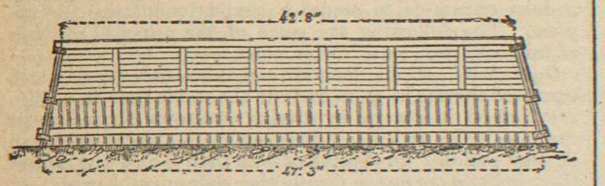


Fig. 95.—Caisson used for a Bridge over the Cher.

Fig. 95a.

Fig. 94 shows a section of foundations constructed by filling a casing of piles with concrete in this manner; the shell is protected against scour by large stones heaped round the outside, part of the loose earth having been removed by digging. Fig. 94a shows the manner in which the concrete foundation was finished after removal of the temporary external wall shown in fig. 94.

Figs. 95 and 95*a* show a longitudinal elevation and cross section of a wooden shell, or caisson without a bottom, intended to be sunk to receive concrete. Cast-iron guide piles and sheet piling are also used for this class of foundation.

Cast-iron tubular shells are now frequently employed; the tube forms a large hollow pile, which may descend into the ground by its own weight, or by added weight while the soil inside is removed by some kind of dredge or excavator, such as Milroy's, worked from the surface. When the lower edge of the shell has penetrated the formation to be used as a foundation, the water inside may be pumped out if the soil forms a water-tight joint, or the shell may simply be filled up with concrete shot into the enclosed water. The piers of Charing Cross bridge (fig. 96) were constructed in this way; the excavation inside the tube (14 feet diameter), was carried on by divers with helmets until the shell had entered a few feet into the London clay. The water was then pumped out and excavation continued; the cylinders were loaded with about 150 tons to sink them to the final depth.

Compressed air is now very generally employed inside a metal shell for those foundations in which the excavation requires the presence of workmen at the bottom of the shell. The metal shell is open at the bottom, but air-tight and water-tight at all other points; there is a chamber called an ***air-lock*** at the upper part. This "air-lock" serves for the exit and entrance of the workmen and materials; the air in this comparatively small space is lowered to the pressure of the atmosphere before the chamber is opened for the passage of men or materials to the open air; the air is again compressed in the air-lock before it is opened for communication with the body of the shell in which the air is permanently kept at such a pressure as will keep the water down to the required level. The shell thus acts as a diving bell acts. It is found that men cannot in general be safely employed under a greater pressure than two atmospheres above the ordinary atmospheric pressure, corresponding to a depth in water of about 65 feet. The centre pier of Saltash Bridge was, however, in 1855 by this plan carried down to a depth of 87 feet 6 inches below high water. Recently the foundations of St Louis bridge over the Mississippi have by the same method been established at a depth of

110 feet from the surface of the water. Figs. 97 and 97 A show the pier of the bridge of Argenteuil. Excavation was carried on in the lower chamber, the roof of which was very strongly built of metal, and served as the foundation for masonry and concrete built up round an inner tube, serving as a passage for men and materials to the upper chamber and "air lock." This lock is formed of two concentric cylinders of 3·9 feet and 10·8 feet diameter respectively (fig. 97*a*). The annular space was divided by two vertical partitions; the doors of communication (which were air-tight) were 1·8 feet wide and 2·14 feet high. A small engine worked the hoist by a stuffing-box passing through the shell. A safety-valve is of course required. The upward pressure of the air requires to be counterbalanced by weights. In the Argenteuil bridge this necessary weight was afforded by the masonry built in the tube as the tube sank. This plan seems preferable to the method of loading the shell externally with pig or railway iron. Frequently, owing to the tenacious nature of the soil, the water cannot be driven out below the tube, and in that case a syphon must be provided passing out at the top. The Argenteuil tube was sunk at a mean rate of about 18 inches per diem. This method is not confined to cylindrical tubes. Fig. 98 shows the method employed in building the piers of the bridge at Kehl over the Rhine. In this case four rectangular working chambers were sunk side by side and bolted together; each chamber communicated with the surface by two air-passages, and one central elliptical passage which remained full of water. This central passage served for the exit of the excavated material. A mass of concrete was built resting on the working chambers, and contained by wooden framework. The concrete was added at the top above water as the foundations gradually sank. At Mantes and Chalons wrought iron caissons, shaped like the usual masonry piers, have been sunk by analogous methods.

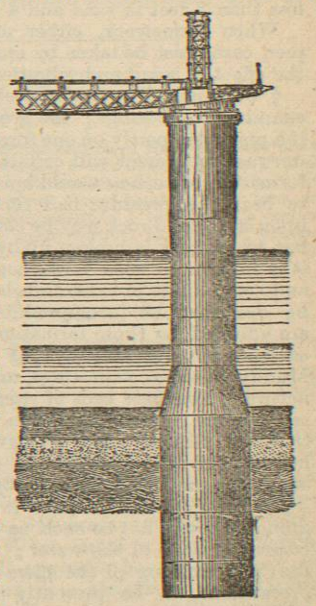


Fig. 96.—Cylinder, Charing Cross Bridge.

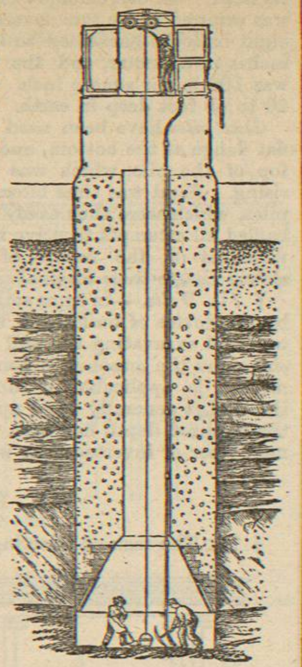


Fig. 97.—Foundations, Bridge of Argenteuil.

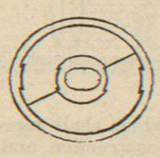


Fig. 97a.

The method of sinking cylinders by compressed air was invented by Mr Triger in 1841, and was first used on a large scale by Mr Hughes at Rochester. The tubes at this bridge were designed to be sunk by having the air *exhausted* inside the tube, a system invented by Dr Potts.

§ 69. *Piles* are used either to enclose a space or to bear part of the weight of a structure; for the former purpose a wooden pile may be a round or square pointed piece of timber, 6 or 9 inches in diameter and 8 or 12 feet long. Bearing piles may be of any dimensions which can practically be procured, and several lengths of timber are often jointed so as to form one long strut. The point is armed with metal, and the head protected by a metal ring, which prevents it from spreading when struck by the rammer which drives the pile. Bearing piles are usually placed at a distance from centre to centre not less than 2 feet 6 inches or more than 4 feet; 3 feet is a common distance. The diameter of bearing piles varies from 9 inches to 20 inches; a pile may be considered to be driven home when, with thirty blows of a ram weighing 800 lb and falling 5 feet, it does not move $\frac{1}{5}$th of an inch (Rankine). A French rule gives as a limit $\frac{1}{6}$ inch motion with twenty-five blows from a ram weighing 6 cwt. and falling 4 feet 3 inches. A pile which does not move more than this will bear from 600 to 1000 lb per square inch. This would give a load of 50 tons for a 13-inch pile; if, as is more usual, the load be only 8 or 10 tons for a 13-inch pile, the ultimate rate of descent may be three, four, or five times as much as the above.

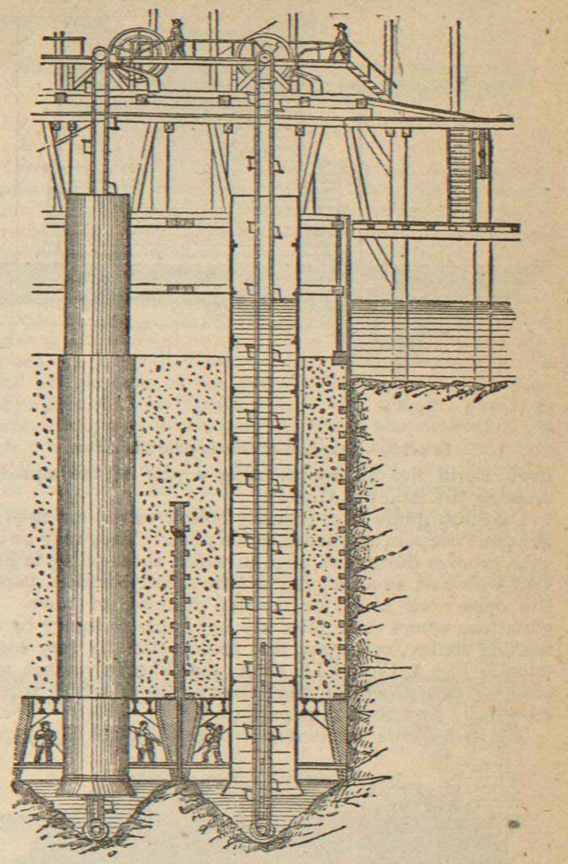


Fig. 98.—Foundations, Bridge of Kehl on the Rhine.

Piles are used as foundations in those grounds which are compressible, or which would be squeezed out from beneath masonry under the weight to be borne. The wooden bearing piles are usually sawn off so that all the heads may be level, and a wooden grating or platform rests on the heads, over which the concrete or masonry pier may be built; in other cases the piles come up for some distance into the concrete. An external row of wooden piles is not unfrequently employed as a precaution against scour, but these should always be further protected by a stone bank, which will continue to protect the pier if the piles decay. A

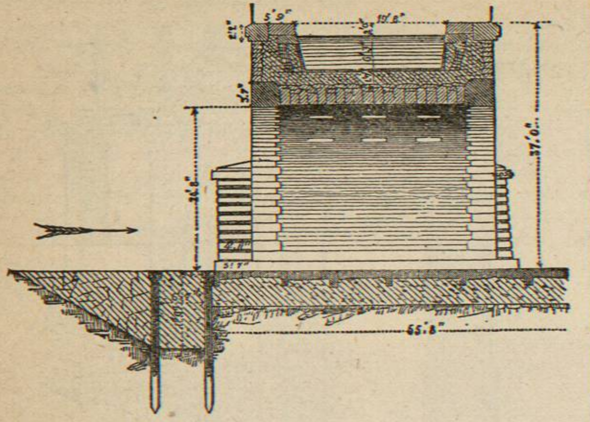


FIG. 99.—Aqueduct of Guétin over the Allier.

more thorough protection against scour is provided by covering the centre bed of the river with a concrete or stone floor, as in fig. 99, representing a pier of the aqueduct crossing the Allier at Guétin.

Cast-iron guide piles (usually hollow tubes) are used for the same purpose as wooden guide piles. They may be cast with grooves down one edge in which sheet piling is held. Cast-iron and wooden piles are frequently used as part of the open-work metal or wooden framing of piers. In situations where these piles are not liable to injury by ice, floating timber, or barges, this construction is very economical. Fig. 4, Plate XIX. shows the Crumlin viaduct, with piers of this character, the construction of which will be more fully described in paragraph 79

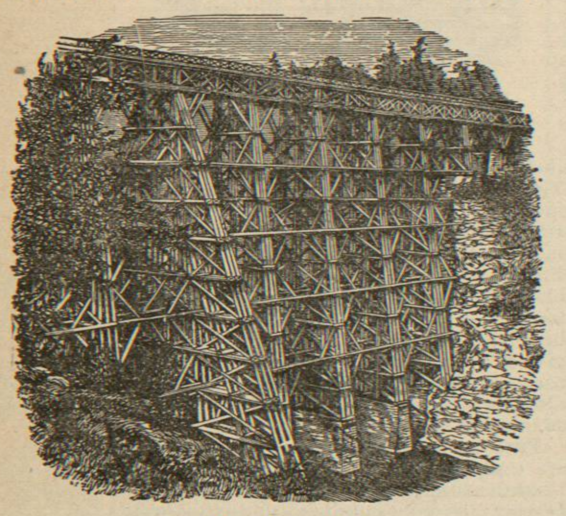


FIG. 100.—Portage Bridge.

Fig. 100 shows the Portage bridge (234 feet high) spanning the Genesee River, in the State of New York. The piers are large wooden frames.

§ 70. *Screw piles* are cast-iron piles which are screwed into the soil instead of being driven in. At their end is fixed a blade of cast-iron from two to eight times the diameter of the shaft of the pile; the pitch of the screw varies from one-half to one-fourth of the external diameter of the blade. The pile is turned by levers radiating from its head. In one example of their use (Rankine) the pile was screwed in by four levers, each 40 feet in length, with eight bullocks harnessed to it. The screws were 4 feet 6 inches in diameter, and the working load borne by them was 100 ℔ per square inch. The piles were screwed from 20 to 45 feet deep in earth.

Disc piles have been used in sand. These piles had a flat flange at the bottom, and water was pumped in at the top of the pile, which was weighted to prevent it from rising. Sand was thus blown or pumped from below the piles, which were thus easily lowered in ground which had baffled all attempts to drive in piles by blows. In ground which is of the nature of quicksand, piles will often slowly rise to their original position after each blow.

§ 71. *Wells.*—In some soils foundations may be obtained by the device of building a masonry casing like that of a well and excavating the soil inside; the casing gradually sinks and the masonry is continued at the surface. This method is applicable in running sands. The interior of the well is generally filled up with concrete or brick when the required depth has been reached, but in some cases a mere floor or inverted arch would be preferable.

VIII. EXAMPLES.

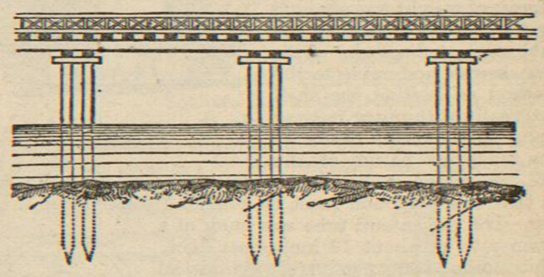


FIG. 101.—Pons Sublicius.

§ 72. The task of selecting a limited number of bridges which shall represent the gradual progress in the art of construction and illustrate our present practice is one of much difficulty. Many very admirable and interesting structures must necessarily be passed over in silence, and space will not admit of full details being given even of those bridges which are noticed.

§ 73. *Bridges built before the year* 1000 A.D.—Herodotus mentions a bridge erected by Nitocris over the Euphrates at Babylon. It appears to have consisted of stone piers connected by planking, which was removed at night. The river was diverted to allow the piers to be built. Diodorus Siculus ascribes the work to Semiramis.

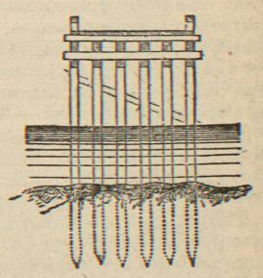
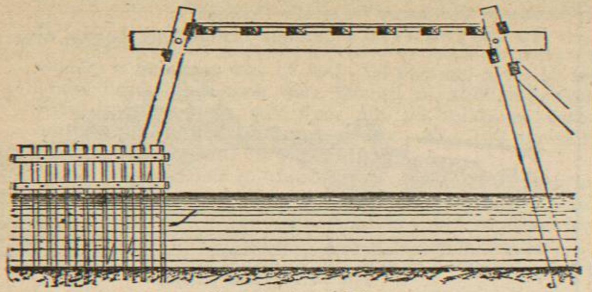
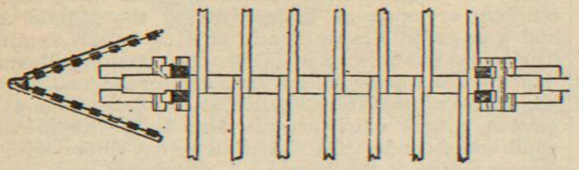


Fig. 101*a*.

The first bridge constructed at Rome was called the *Pons Sublicius*, or wooden bridge (*sublica* meaning a stake or pile). It is said to have been built by Ancus Martius, and rebuilt by the chief priests, who from this circumstance were called "Pontifices." Fig. 101 shows the design of this bridge as restored by Colonel Emy (*Traité de l'art de la charpenterie*) from the descriptions given in the historians. This was the bridge defended by Horatius Cocles.



Cross Section at Pier.



Plan at Pier.

FIG. 102.—Bridge thrown across the Rhine by Julius Cæsar.

Fig. 102, also taken from the work of Colonel Emy, is intended to represent the design of the bridge thrown across the Rhine in ten days by Julius Cæsar (*De Bell. Gall.* iv. 17).

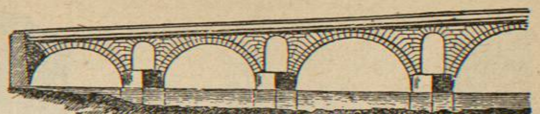
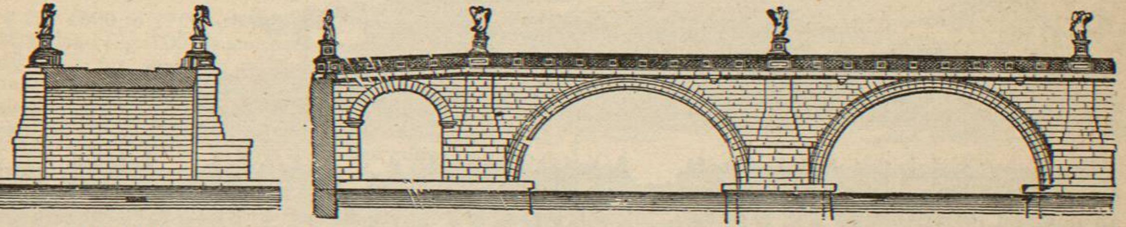


FIG. 103.—Pons Milvius.

The *Pons Milvius* (fig. 103), now Ponte Molle, was built a mile and a half from Rome by the Censor Ælius Scaurus, about 100 B.C. Some part of the first bridge is supposed to remain, although it has been altered from time to time. The arches vary in their opening from 51 feet to 79 feet 9 inches; the waterway between the piers is 413 feet 3 inches; the breadth of the bridge, 28 feet 9 inches; these dimensions are given on the authority of Cresy (*Encyclopædia of Civil Engineering*). The following bridges also crossed the Tiber at Rome:—The *Pons Palatinus*, which stood on the site of the present Ponte Rotto; the *Pons Fabricius* and *Pons Cestius*, which still remain; the *Pons Janiculanus*, which occupied the site of the modern Ponte Sisto; the *Pons Vaticanus*, which has disappeared; and the *Pons Ælius*, built by Hadrian (13 A.D.), now the bridge of St Angelo. This bridge (fig. 104) was repaired by Popes Nicholas III. and Clement IX. The largest arch has a span of 62 feet 4 inches, and the width of the bridge is 50 feet 9 inches.

Other Roman bridges.

Trajan's Bridge.



Cross Section.

Elevation.

FIG. 104.—Bridge of S. Angelo.

The bridge erected by Trajan (104 A.D.) across the Danube, just below the rapids of the Iron Gate, has been the subject of much controversy. The drawing (fig. 105) was originally taken from a bas-relief on the Trajan column at Rome. A description of the bridge is given by the ancient historian Dion Cassius, who states that the bridge had twenty piers of hewn stone, 150 feet high and 60 feet wide, with openings between them of 170 feet, spanned by arches. Doubt has been thrown on the accuracy of this description, because the design shown in fig. 105 is obviously unsuited to a span of 170 feet; nevertheless thirteen piers are still visible out of the twenty, according to Murray's *Handbook* The writer has not been able to find any accurate measurement of the width between these piers, but as the *Handbook* speaks of the length of the bridge as perhaps 3900 feet, and as the Conte Marsigli, writing from personal observation, in a letter to Montfaucon, gives the total length as probably 3010 feet, there can be no doubt that the spans were very considerable, and that the representation of the design in the bas-relief is almost wholly conventional. The one point as to which it gives clear information, not supplied elsewhere, is that the superstructure was of wood. The piers seem to have been founded by sinking caissons. Murray's *Handbook* gives the depth of the river as 18 feet. Apollodorus of Damascus was the architect of this remarkable bridge. The bridge at Rimini, built during the reign of Augustus, was especially admired by Palladio (Rondelet, *L'Art de bâtir*). The bridge at Narni, on the road from Loretto to Rome, also built by Augustus (Montfaucon), and the bridge of Alcantara over the Tagus, built in the reign of the Emperor Trajan, are often cited as remarkable works.

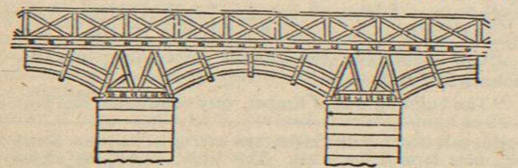


FIG. 105.—Trajan's Bridge

The Romans frequently adorned their bridges with a triumphal arch. A small example of this kind of bridge at St Chamas, in France, is shown in fig. 106 (Cresy's *Encyclopædia of Civil Engineering*). The span of the arch is 42 feet, and the voussoirs are 3 feet 5 inches deep. Fig. 107 shows the bridge of Narses, built in the 6th century, and which carried the Via Salaria across the Anio or