CHAPTER II.

12. The Beginnings of Engineering Works of Record.—In a later period of the world's history we reach a stage in the development of engineering works of which we have both records and remains in such well-defined shape that the characteristics of the profession may be realized in a definite manner. This is particularly true of the civil-engineering works of the Romans. In their sturdy and unyielding character, with their limitless energy and resolution, the conditions requisite for the execution of engineering works of great magnitude are found. An effeminate or generally æsthetic nation like the Greeks would furnish but indifferent opportunity for the inception and development of great engineering works, but the resolute and vigorous Roman nation offered precisely the conditions needed. They appreciated among other things the absolute necessityof the freest possible communication with the countries which they conquered and made part of their own empire. They recognized water transportation as the most economical and effective, and used it wherever possible. They also realized the advantages of roads of the highest degree of solidity and excellence. No other roads have ever been constructed so direct, so solid, and so admirably adapted to their purposes as those built by the Romans. They virtually ignored all obstacles and built their highways in the most direct line practicable, making deep cuts and fills with apparently little regard for those features which we consider obstacles of sufficient magnitude to be avoided. They regarded this system of land communication so highly that they made it radiate from the Golden Mile-stone in the Roman Forum. The point from which radiated these roads was therefore in the very centre of Roman life and authority, and it fitly indicated the importance which the Roman government gave to the system of communication that bound together with the strongest bonds all parts of the republic and of the empire.

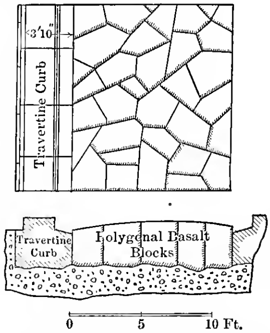
The design and construction of these roads must have been a matter to which their constructors gave the most careful attention and study. They were works involving principles deduced from the most careful thought and extended experience. There were incorporated in them the most effective materials of construction then known, and it was evidently the purpose of their constructors that they should possess indefinite endurance. The existence of some of them at the present time, with no other attention given to them than required for ordinary maintenance, demonstrates that the confidence of the builders was not misplaced.

Street Fountain and Watering-trough in Pompeii. Called the Fountain of Plenty, from the figure with Horn of Plenty on the perforated upright post.

13. The Appian Way and other Roman Roads.—Probably the oldest and most celebrated of these old Roman roads is the Appian Way. It was the most substantially built, and the breadth of roadway varied from 14 to 18 feet exclusive of the footwalks. Statius called it the Queen of Roads. It was begun by Appius Claudius Cæcus, 312 years before the Christian era. He carried its construction from the Roman gate called Porta Capena to Capua, but it was not entirely completed till about the year 30 B.C. Its total length was three hundred and fifty miles, and it formed a perfect highway from Rome to Brundisium, an important port on what may be called the southeastern point of Italy. It was built in such an enduring manner that it appears to have been in perfect repair as late as 500 to 565 A.D.

The plan of construction of these roads was so varied as to suit local conditions, but only as required by sound engineering judgment. They wisely employed local materials wherever possible, but did not hesitate to transport proper material from distant points wherever necessary. This seemed to be one of their fundamental principles of road construction. In this respect the old Romans exhibited more engineering and business wisdom than some of the American states in the beginnings of improved road construction in this country. An examination of the remains of some Roman roads now existing appears to indicate that in earth the bottom of the requisite excavation was first suitably compacted, apparently by ramming, although rollers may have been used. On this compacted subgrade were laid two or three courses of flat stones on their beds and generally in mortar. The second layer placed on the preceding was rubble masonry of small stones or of coarse concrete. On the latter was placed the third layer of finer concrete. The fourth or surface course, consisting of close and nicely jointed polygonal blocks, was then put in place, and formed an excellent unyielding pavement. This resulted in a most substantial roadway, sometimes exceeding 3 feet in total thickness. It is difficult to conceive of a more substantial and enduring type of road construction. The two lower layers were omitted when the road was constructed in rock. Obviously the finer concrete constituting the second layer from the top surface was a binder between the pavement surface and the foundation of the roadway structure.

The paved part of a great road was usually about 16 feet in width, and raised stone causeways or walls separated it from an unpaved way on each side having half the width of the main or paved portion. This seemed to be the type of the great or main Roman roads. Other highways of less important character were constructed of inferior materials, earth or clay sometimes being used instead of mortar; but in such cases greater crowning was employed, and the road was more elevated, possibly for better drainage. Then, as now, adequate drainage was considered one of the first features of good road design. City streets were paved with the nicely jointed polygonal blocks to which reference has already been made, while the footways were paved with rectangular slabs much like our modern sidewalks.



EXAMPLE OF EARLY BASALT ROAD. BY THE TEMPLE OF SATURN ON THE CLIVUS CAPITOLINUS.

FIG. 7.

The smooth polygonal pavements of the old Romans put to the keenest shame the barbarous cobblestone street surfaces with which the people of American cities have been and are still so tortured.

The beneficial influence of these old Roman highways has extended down even to the present time in France, where some of them were built. The unnecessarily elaborate construction has not been followed, but the recognition of the public benefits of excellent roads has been maintained. The lower course of the foundation-stones apparently began to be set on edge toward the latter part of the eighteenth century, the French engineer Tresaguet having adopted that practice in 1764. At the same time he reduced the thickness of the upper layers. His methods were but modifications of the old Roman system, and they prevailed in France until the influence of the English engineers Macadam and Telford began to be felt.

14. Natural Advantages of Rome in Structural Stones.—Although the ancient Romans were born engineers, possessing the mental qualities and sturdy character requisite for the analytic treatment and execution of engineering problems, it is doubtful whether they would have attained to such an advanced position in structural matters had not the city of Rome been so favorably located.

The geological character of the great Roman plain and the Roman hills certainly contributed most materially to the early development of some of the most prominent of the Roman engineering works. The plain surrounding the city of Rome is composed largely of alluvial and sandy deposits, or of the emissions of neighboring volcanoes, of which the Alban Hills form a group. While these and other volcanic hills in the vicinity are, and have been for a long period, quiescent, they were formerly in a very active state. The scoriæ, or matter emitted in volcanic eruptions, is found there in all possible degrees of coherence or solidity, from pulverulent masses to hard rock. The characteristic Roman material called tufa is a mixture of volcanic ash and sand, loose and friable, as dropped from the eruptions in large quantities or again compressed into masses with all degrees of hardness. The hard varieties of yellow or brown tufa form building material much used, although a considerable percentage of it would not be considered fit building material for structures of even moderate height at the present time. The most of it weathers easily, but forms a fairly good building-stone when protected by a coating of plaster or stucco.

Another class of building-stones found at or in the vicinity of Rome is the so-called "peperino," consisting chiefly of two varieties of conglomerate of ash, gravel, broken pieces of lava, and pieces of limestone, some possessing good weathering qualities, while others do not. Ancient quarries of these stones exist whence millions of cubic yards have been removed, and are still being worked. The better varieties of "peperino" possess good resisting qualities, and were much used in those portions of masonry construction where high resistance was needed, as in the ring-stones of arches, heavily loaded points of foundations, and other similar situations.

Some of the prehistoric masonry remains of the Romans show that their earliest constructors appreciated intelligently the qualities of this stone for portions of works where the duty was most severe.

Lava from the extinct volcanoes of the Alban Hills called "silex" was used for paving roads and for making concrete. It was hard and of gray color. At times considerable quantities of this stone were employed. A species of pure limestone called "travertine," of a creamy white color, was quarried at Tibur or

Tivoli, and began to be used about the second century B.C. Vitruvius speaks of its having good weathering qualities, but naturally it is easily calcined. Its structure is crystalline, and it is strong in consequence of that quality only when it is laid on its bed.

15. Pozzuolana Hydraulic Cement.—The most valuable of all building materials of old Rome was the "pozzuolana," as it furnished the basis of a strong, enduring, and economic concrete, and permitted almost an indefinite development of masonry construction. Had there not been at Rome the materials ready at hand to be manufactured into an excellent cementing product, it is highly probable that neither the structural advance nor the commercial supremacy of the Roman people could have been attained. It is at least certain that the majority of the great masonry works constructed by the Romans could not have been built without the hydraulic cementing material produced with so little difficulty and in such large quantities from the volcanic earth called pozzuolana. The name is believed to have its origin from the large masses of this material at Pozzuoli near Naples. Great beds are also found at and near Rome. The earliest date of its use cannot be determined, but it has given that strong and durable character to Roman concrete which has enabled Roman masonry to stand throughout centuries, to the admiration of engineers.

It is a volcanic ash, generally pulverulent, of a reddish color, but differs somewhat in appearance and texture according to the locality from which it is taken. It consists chiefly of silicate of alumina, but contains a little oxide of iron, alkali, and possibly other components. The Romans therefore pulverized the pozzuolana and mixed it with lime to make hydraulic cement. This in turn was mixed with sand and gravel and broken stone to form mortar and concrete, and that process is carried on to this day. The concrete was hand-mixed, and treated about as it is at present. After having been well mixed the Romans frequently deposited it in layers of 6 to 9 or 10 inches thick, and subjected it to ramming. In connection with this matter of mortar and concrete production, Vitruvius observes that pit sand is preferable to either sea or river sand.

16. Roman Bricks and Masonry.—The Romans produced bricks both by sun-baking and by burning, although there are now remaining apparently no specimens of the former in Rome. Bricks were used very largely for facing purposes, such as a veneer for concrete work. The failure to recognize this fact has led some investigators and writers into error. As matter of fact bricks were used as a covering for concrete work, the latter performing all the structural functions.

The old Roman aqueducts were frequently lined with concrete, made of a mixture of pozzuolana, lime, and crushed (pounded) bricks or potsherds. The same material was also used for floors under the fine mortar in which the mosaics were imbedded.

Marble came into use in Rome about 100 B.C., from Luna, near modern Carrara, Mt. Hymettus, and Mt. Pentelicus, near Athens and the Isle of Paros, nearly all being for sculpture purposes. Colored and structural marbles were brought from quarries in various parts of Italy, Greece, Phrygia, Egypt, near Thebes (oriental alabaster or "onyx"), Arabia, and near Damascus.

From the latter part of the first century B.C. the hard building-stones like granites and basalts were brought to Rome in large quantities. Most of the granites came from Philæ on the Nile. The basalts came both from Lacedæmonia and Egypt. Both emery (from the island of Naxos in the Ægean Sea) and diamond-dust drills were used in quarrying or working these stones. Ships among the largest, if not the largest, of those days, were built to transport obelisks and other large monoliths.

The quality of ancient Roman mortar varies considerably as it is now found. That of the first and second centuries is remarkably hard, and made with red pozzuolana. In the third century it began to be inferior in quality, brown pozzuolana sometimes being used. The reason for this difference in quality cannot be confidently assigned. The deterioration noted in the third-century work may be due to the introduction of bad materials, or to the wrong manipulation of material intrinsically good, or it is not unlikely the deterioration is due to a combination of these two influences. The use of mortar indicates a class of early construction; it is found in the Servian wall on the Aventine, of date 700 B.C., or possibly earlier.

Under the empire (27 B.C. to A.D. 475) large blocks of tufa,

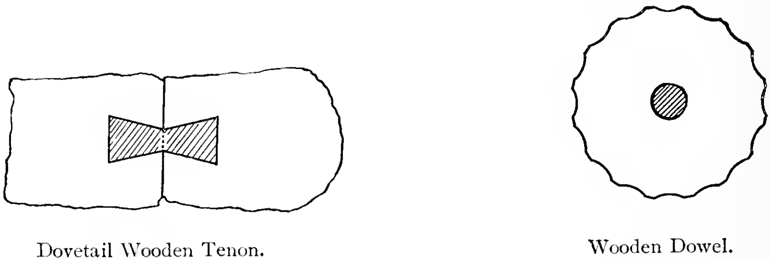


FIG. 8.

limestone (travertine), or marble were set with very close joints, with either no mortar or, if any, as thin as paper; end, top, and bottom clamps of iron were used to bond such stones together. It was also customary, in laying such large, nicely finished blocks of stone without mortar, to use double dovetailed wooden ties, or, as in the case of columns, a continuous central dowel of wood, as shown in the figures.

The joints were frequently so close as to give the impression that the stones might have been fitted by grinding together. In rectangular dimension stonework (ashlar) great care was taken, as at present, to secure a good bond by the use of judiciously proportioned headers and stretchers. Foundation courses were made thicker than the body of the superincumbent wall, apparently to distribute foundation weights precisely as done at present. Weaker stone was used in thicker portions of walls, and strong stone in thinner portions. Also at points of concentrated loading, piers or columns of strong stone are found built into the bodies of walls of softer or weaker stone. Quarry chips, broken lava, broken bricks, or other suitable refuse fragments were used for concrete in the interest of economy, the broken material always being so chosen as to possess a sharp surface to which the cement would attach itself in the strongest possible bond.

At the quarries where the stones were cut the latter were marked apparently to identify their places in the complete structure, or for other purposes. The remains of the quarries themselves as seen at present are remarkable both for their enormous extent and for the system on which the quarrying was conducted. It appears that the systems employed were admirably adapted to the character of the stone worked, and that the quarrying operations were executed as efficiently and with as sound engineering judgment as those employed in great modern quarries.

17. Roman Building Laws. — So much depended upon the excellence of the building in Rome, and upon the materials and methods employed, that building laws or municipal regulations were enacted in the ancient city, prescribing kind and quality of material, thickness of walls, maximum height of buildings, minimum width of streets, and many other provisions quite similar to those enacted in our modern cities. The differences appear to arise from the different local conditions to be dealt with, rather than from any failure on the part of the old Romans to reach an adequate conception of the general plans suitable for the masses of buildings in a great city. Prior to the great fire A.D. 64 in Nero's reign, an act prescribing fire-proof exterior coverings of buildings was under consideration, and subsequently to that conflagration it was enacted into law. Many of the city roads or streets were paved with closely fitting irregular polygonal blocks of basalt, laid on concrete foundations, and with limestone (travertine) curbs and gutters, producing an effect not unlike our modern streets.

18. Old Roman Walls.—In no class of works did the ancient Romans show greater engineering skill or development than in the massive masonry structures that were built not only in and about the city of Rome, but also in distant provinces under Roman jurisdiction. Among the home structures various walls, constituting strong defences against the attacks of enemies, stand in particular prominence. Some of these great structures had their origin prior even to historic times. The so-called "Wall of Romulus," around the famous Roma Quadrata of the Palentine, is among the latter. It is supposed by many that this wall formed the primitive circuit of the legendary city of Romulus. That, however, is an archæological and not an engineering question, and, whatever its correct answer may be, the wall itself is a great engineering work; it demonstrates that the early Romans, whatever may have been their origin, had attained no little skill in quarrying and in the building of dry masonry, no mortar being used in this ancient wall. Portions of it 40 feet high and 10 feet thick at bottom, built against a rocky hill, are still standing. The courses are 22 to 24 inches thick, and they are laid as alternate headers and stretchers; the lengths of the blocks being 3 to 5 feet, and the width from 19 to 22 inches. The ends of the blocks are carefully worked and true, as are the vertical joints in much of the wall, although some of the latter, on the other hand, are left as much as 2 inches open.

Civil engineers, who are familiar with the difficulties frequently experienced in laying up dry walls of considerable height, as evidenced by many instances of failure probably within the knowledge of every experienced engineer, will realize that this great dry-masonry structure must have been put in place by men of no little engineering capacity. The rock is soft tufa, and marks on the blocks indicate that chisels from $\frac{1}{4}$ to $\frac{3}{4}$ inch in width were used, as well as sharp-pointed picks. In all cases the faces of the blocks were left undressed, i.e., in modern terms they were "quarry-faced."

19. The Servian Wall.—Later in the history of Rome the great Servian Wall, built chiefly by Servius Tullius to enclose the seven hills of Rome, occupies a most prominent position as an engineering work. Part of the wall, all of which belongs to the regal period (753 to 509 B.C.), is supposed to be earlier than Servius, and may have been planned and executed by Tarquinius Priscus. A part only of the stones of this wall were laid in cement mortar, and concrete was used, to some extent at least, in its foundation and backing. The presence of cement mortar in this structure differentiates it radically from the wall of Romulus. Probably the discovery of pozzuolana cement, and the fabrication of mortar and concrete from it, had been made in the intervening period between the two constructions. Tufa, usually the softer varieties but of varying degrees of hardness, was mostly used in this wall, and the blocks were placed, as in the previous instance, as alternate headers and stretchers in courses about two feet thick. Portions of the wall 45 feet high and about 12 feet thick have been uncovered. At points it was pierced with arched openings of 11 feet 5 inches span, possibly as embrasures for catapults or other engines of war. The upper parts of these openings are circular arches with the usual wedge-like ring-stones. The voussoirs were cut from peperino stone. This wall, like that of Romulus, was constructed as a military work of defence, and at some points it was built up

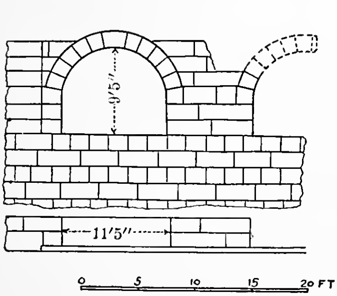


FIG. 9.—Part of Servian Wall on Aventine.

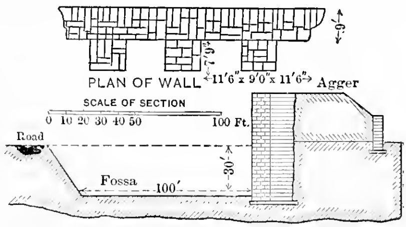


FIG. 10.—Wall and Agger of Servius.

from the bottom of a wide foss 30 feet deep. At such places it was counterforted or buttressed, a portion of wall 11 feet 6 inches long being found between two counterforts, each of the latter being 9 feet wide and projecting 7 feet 9 inches out from the wall.

20. Old Roman Sewers.—It is demonstrable by the writings of Vitruvius and others that the old Romans, or at any rate the better educated of them, possessed a correct general idea of some portions of the science of Sanitary Engineering, so far as anything of the nature of science could then be known. Their sanitary views were certainly abreast of the scientific knowledge of that early day. The existence of the "cloacæ," or great sewers, of the ancient city of Rome showed that its people, or at least its rulers, not only appreciated the value of draining and sewering their city, but also that they knew how to secure the construction of efficient and enduring sewers or drains. It has been stated, and it is probably true, that this system of cloacæ, or sewers, was so complete that every street of the ancient city was drained through its members into the Tiber. They were undoubtedly the result of a gradual growth in sewer construction and did not spring at once into existence, but they date back certainly to the beginning of the period of the kings (753 B.C.). The famous Cloaca Maxima, as great as any sewer in the system, and certainly the most noted, is still in use, much of it being in good order. The mouth of the latter where it discharges into the Tiber is 11 feet wide and 12 feet high, constituting a large arch opening with three rings of voussoirs of peperino stone. Many other sewers of this system are also built with arch tops of the same stone, with neatly cut and closely fitting voussoirs. We do not find, unfortunately, any detailed accounts of the procedures involved in the design of these sewers, yet it is altogether probable that the old Roman civil engineers formed the cross-sections, grades, and other physical features of their sewer system by rational processes, although they would doubtless appear crude and elementary at the present time. It would not be strange if they made many failures in the course of their structural experiences, but they certainly left in the old Roman sewers examples of enduring work of its kind.

Some portions of this ancient sewer system are built with tops that are not true arches, and it is not impossible that they antedate the regal period. These tops are false arches formed of horizontal courses of tufa or peperino, each projecting over that below until the two sides thus formed meet at the top. The outline of the crowns of such sewers may therefore be triangular, curved, or polygonal; they were usually triangular. Smaller drains forming feeders to the larger members of the system were formed with tops composed of two flat stones laid with equal inclination to a vertical line so as to lean against each other at their upper edges and over the axis of the sewer. This method of forming the tops of the drains by two inclined flat stones was a crude but effective way of accomplishing the desired purpose.

The main members of this great sewer system seem to have followed the meandering courses of small rivers or streams, constituting the natural drainage-courses of the site of the city. The Cloaca Maxima has an exceedingly crooked course and it, along with others, was probably first formed by walling up the sides of a stream and subsequently closing in the top. Modern engineers know that such an alignment for a sewer is viciously bad, and while this complicated system of drains is admirably constructed in many ways for its date, it cannot be considered a perfect piece of engineering work in the light of present engineering knowledge. It is probable that the walling in of the sides of the original streams began to be done in Rome at least as early as the advent of the Tarquins, possibly as early as 800 B.C. or earlier.

We know little about the original outfalls or points of discharge into the Tiber, except that, as previously stated, these points were made through the massive quay-walls constructed during the period of the kings along both shores of the Tiber, probably largely for defence as originally built. The discharge of the old Roman sewers through the face of this quay-wall and into the river is precisely the manner in which the sewers of New York City in many places are discharged into the North, East, and Harlem rivers.

The Cloaca Maxima is not the only great ancient sewer thus far discovered. There are at least two others equal to it, and some of the single stones with which they are built contain as much as 45 cubic feet each. These cloacæ were not mere sewers; indeed they were more drains than sewers, for they carried off flood-waters and the natural drainage as well as the sewerage. They were therefore combined sewers and drains closely akin to the sewers of our "combined" systems. The openings into them were made along the streets of Rome and in public buildings or some other public places. There is no evidence that they were ventilated except through these openings, and from each noxious gases were constantly rising to be taken into the lungs of the passers-by. It is a rather curious as well as important fact that so far as excavations have been made there is practically no evidence that a private residence in Rome was connected with the sewers. The "latrines" were generally located adjacent to the Roman kitchens and discharged into the cloacæ.

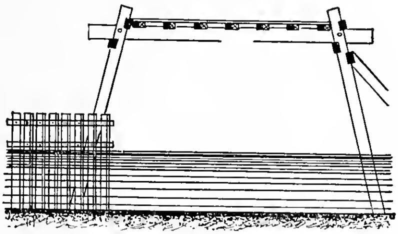
21. Early Roman Bridges.—The early Romans were excellent bridge-builders as well as constructors in other lines of engineering work. Although the ancient city was first located on the left bank of the Tiber, apparently it was but a comparatively short time before the need of means for readily crossing from bank to bank was felt. The capacity of the Roman engineers was equal to the demands of the occasion, and it is now known that seven or eight ancient bridges connected the two shores of the river Tiber. The oldest bridge is that known as Pons Sublicius. No iron was used in its construction, as bronze was the chief metal employed in that early day. The structure was probably all of timber except possibly the abutments and the piers. A French engineer, Colonel Emy, has exhibited in his "Traité de l'Art de la Charpenterie" a plan of this structure restored as an all-timber bridge with pile foundations. Lanciani, on the other hand, believes that the abutments and piers must have been of masonry. The masonry structures, however, known to exist at a later day may have been parts of the work of rebuilding after the two destructions by floods. The date of its construction is not known, but tradition places it in the time of Ancus Marcius. This may or may not be correct. A flood destroyed the bridge in 23 B.C., and again in the time of Antoninus Pius, but on both occasions it was rebuilt. The structure has long since disappeared. The piers only remained for a number of centuries, and the last traces of them were removed in 1877 in order to clear the bed of the river.

Fig. 11 shows Colonel Emy's restoration of the plan for the pile bridge which Julius Cæsar built across the Rhine in ten days for military purposes. This plan may or may not include accurate features of the structure, but it is certain that such a timber bridge was built, and well preserved pieces of the piles have been taken from under water at the site little the worse for wear after two thousand years of submersion.

The censor Ælius Scaurus built a masonry arch across the Tiber about a mile and a half from Rome in the year 100 B.C. This bridge is now known as the Ponte Molle, and some parts of the original structure are supposed to be included in it, having been retained in the repeated alterations. The arches vary in span from 51 to 79 feet, and the width of the structure is a little less than 29 feet.

In or about the year 104 A.D. the emperor Trajan constructed what is supposed to be a wooden arch bridge with masonry piers across the Danube just below the rapids of the Iron Gate.

A *bas relief* on the Trajan Column at Rome exhibits the timber arches, but fails to give the span lengths, which have been the


Cross-section at Pier.

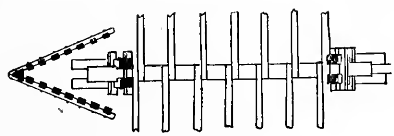

Plan at Pier.

FIG. 11.—Bridge thrown across the Rhine by Julius Cæsar.

subject of much controversy, some supposing them to have been as much as 170 feet.

The ancient Pons Fabricius, now known as Ponte Quattiro Capi, still exists, and it is the only one which remains intact after an expiration of nearly two thousand years. It has three arches, the fourth being concealed by the modern embankment at one end; a small arch pierces the pier between the other two arches. This structure is divided into two parts by the island of Æsculapius. It is known that a wooden bridge must have joined that island with the left bank of the Tiber as early as 192 B.C., and a similar structure on the other side of the island is supposed to have completed the structure. While Lucius Fabricius was Commissioner of Roads in the year 62 B.C. he reconstructed the first-named portion into a masonry structure of arches. An engraved inscription below the parapets shows that the work was duly and satisfactorily completed, and further that it was the custom to require the constructors or builders of bridges to guarantee their work for the period of forty years. Possession of the last deposit, made in advance as a guarantee of the satisfactory fulfilment of the contract, could not be regained until the forty-first year after completion.

The Pons Cestius is a bridge since known as the Pons Gratianus and Ponte di S. Bartolomeo. Its first construction is

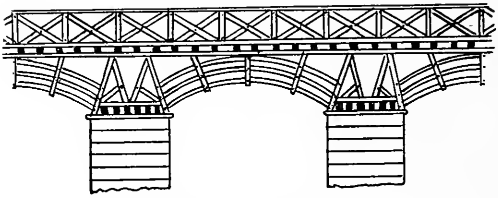


FIG. 12.—Trajan's Bridge.

supposed to have been completed in or about 46 B.C., and it was rebuilt for the first time in A.D. 365. A third restoration took place in the eleventh century. The modern reconstruction in 1886–89 was so complete that only the middle arch remains as an ancient portion of the structure. The island divides the bridge into two parts, the Ship of Æsculapius lying between the two, but it is not known when or by whom the island was turned into that form.

Another old Roman bridge, of which but a small portion is now standing, is Pons Æmilius, the piers of which were founded in 181 B.C., but the arches were added and the bridge completed only in 143 B.C. It was badly placed, so that the current of the river in times of high water exerted a heavy pressure upon the piers, and in consequence it was at least four times carried away by floods, the first time in the year A.D. 280.

The discovery of what appears to be a row of three or four ruins of piers nearly 340 feet up-stream from the Ponte Sisto seems to indicate that a bridge was once located at that point, although little or nothing is known of it as a bridge structure. Some suppose it to be the bridge of Agrippa.

The most historical of all the old Roman bridges is that which was called Pons Ælius, now known as Ponte S. Angelo, built by Hadrian A.D. 136. Before the reconstruction of the bridge in

1892 six masonry arches were visible, and the discovery of two more since that date makes a total of eight, of which it is supposed that only three were needed in a dry season. The pavement of the approach to this bridge as it existed in 1892 was the ancient roadway surface. Its condition at that time was an evidence of the substantial character of the old Roman pavement.

Below the latter bridge remains of another can be seen at low water. It is supposed that this structure was the work of Nero, although its name is not known.

The modern Ponte Sisto is a reconstruction of the old Pons Valentinianus or bridge of Valentinian I. The latter was an old Roman bridge, and it was regarded as one of the most impressive of all the structures crossing the river. It was rebuilt in A.D. 366–67.

The most of these bridges were built of masonry and are of the usual substantial type characteristic of the early Romans. They were ornamented by masonry features in the main portions and by ornate balustrades along either side of the roadway and sidewalks. The roadway pavements were of the usual irregular polygonal old Roman type, the sidewalk surfaces being composed of the large slabs or stones commonly used in the early days of Rome for that purpose.

22. Bridge of Alcantara.—Among the old Roman bridges should be mentioned that constructed at Alcantara in Spain, supposedly by Trajan, about A.D. 105. It is 670 feet long and its greatest height is 210 feet. One of its spans is partially destroyed. The structure is built of blocks of stone without cementing material. In this case the number of arches is even, there being six in all, the central two having larger spans than those which flank them. It is a bridge of no little impressiveness and beauty and is a most successful design.

23. Military Bridges of the Romans.—In the old Roman military expeditions the art of constructing temporary timber structures along lines of communication was well known and practised with a high degree of ability. Just what system of construction was employed cannot be determined, but piles were constantly used. At least some of these timber military bridges, and possibly all, were constructed with comparatively short spans, the trusses being composed of such braces and beams as might be put in place between bents of piles. As already observed, some of the sticks of these bridges have been found in the beds of German rivers, and at other places, perfectly preserved after an immersion of about two thousand years. These instances furnish conclusive evidence of the enduring qualities of timber always saturated with water.

24. The Roman Arch.—The Romans developed the semicircular arch to a high degree of excellence, and used it most extensively in many sewers, roads, and aqueducts. While the aqueduct spans were usually made with a length of about 18 or 20 feet, they built arches with span lengths as much as 120 feet or more, comparing favorably with our modern arch-bridge work. They seldom used any other curve for their arches than the circular, and when they built bridges an odd number of spans was usually employed, with the central opening the largest, possibly in obedience to the well-known esthetic law that an odd number of openings is more agreeable to the eye than an even number. Apparently they were apprehensive of the safety of the piers from which their arches sprang, and it was not an uncommon rule to make the thickness of the piers one third of the clear span. Nearly one fourth of the entire length of the structure would thus be occupied by the pier thicknesses. Although the use of mortar, both lime and cement, early came into use with the Romans, they usually laid up the ring-stones of their arches dry, i.e., without the interposition of mortar joints.

CHAPTER III.

25. The Roman Water-supply.—There is no stronger evidence of engineering development in ancient Rome, nor of the advanced state of civilization which characterized its people, than its famous system of water-supply, which was remarkable both for the volume of water daily supplied to the city and for the extensive aqueducts, many of whose ruins still stand, as impressive monuments of the vast public works completed by the Romans. These ruins, and those of many other works, would of themselves assure us of the elaborate system of supply, but fortunately there has been preserved a most admirable description of it, the laws regulating consumption, the manner of administering the water department of the government of the ancient city, and much other collateral information of a most interesting character. In the work entitled, in English, "The Two Books on the Water-supply of the City of Rome," by (Sextus) Julius Frontinus, an eminent old Roman citizen, who, besides having filled the office of water commissioner * of the city, was governor of Britain and three times consul, as well as having enjoyed the dignity of being augur. He may properly be called a Roman engineer, although he evidently was a man of many public affairs, and so esteemed by the emperors who ruled during his time that he accompanied them in various wars as a military man of high rank. He wrote seven books at least, viz., "A Treatise on Surveying," "Art of War," "Strategematics," "Essays on Farming," "Treatise on Boundaries, Roads, etc.," "A Work on Roman Colonies," and his account of the water-works of Rome, entitled "De Aquis." It is the latter

* The first permanent water commissioner in Rome was M. Agrippa, son-in-law of Cæsar Augustus, who took office B.C. 34. He was one of the greatest Roman engineers and constructors, if indeed he was not the first in rank.

book in which engineers are particularly interested. The translation of this book from the original Latin is made from what is termed the "Montecassino Manuscript," an account of which with the translation is given by Mr. Clemens Herschel in his entertaining work, "Frontinus, and the Water-supply of the City of Rome."

As near as can be determined Frontinus lived from about A.D. 35 to A.D. 103 or 104. Judging from the offices which Frontinus held and the honors which he enjoyed throughout his life, it would appear that he was a patrician; he was certainly a man of excellent executive capacity, of intellectual vigor and refined taste, and a conscientious public servant. The water-supply of the city was held by the Romans to be one of the most important of all its public works, and its administration during the life of Frontinus was entrusted to what we should call a water commissioner, appointed by the emperor. It was considered to be an office of dignity and honor, and the proper discharge of its responsibilities was a public duty which required a high order of talent, as well as great integrity of character.

26. The Roman Aqueducts.—Frontinus states that from the foundation of the city of Rome until 313 B.C., i.e., for a period of 441 years, the only water-supply was that drawn either from the river Tiber or from wells or springs. The veneration of the Romans for springs is a well-known feature of their religious tenets. They were preserved with the greatest care, and hedged about with careful safeguards against irreverent treatment or polluting conditions. Apparently after this date the people of Rome began to feel the need of a public water-supply adequate to meet the requirements of a great city. At any rate, in the year 313 B.C. the first aqueduct, called the Appia, for bringing public water into the city of Rome was attempted by Censors Appius Claudius, Crassus, and C. Plautius, the former having constructed the aqueduct, and the latter having found the springs. Appius must have been an engineer of no mean capacity, for it was he who constructed the first portion of the Appian Way. The origin of this water-supply is some springs about 10 miles from Rome, and they may now be seen at the bottom of stone quarries in the valley of the Anio River. This aqueduct, Aqua Appia, is mostly an underground waterway, only about 300 feet of it being carried on masonry arches. At the point where it enters the city it was over 50 feet below the surface; its clear cross-section is given as $2\frac{1}{2}$ feet wide by 5 feet

Claudia, of dimension stone, and Anio Novus, of brick and concrete, on top of it.

high. The elevation of its water-surface in Rome was probably under 60 feet above sea-level.

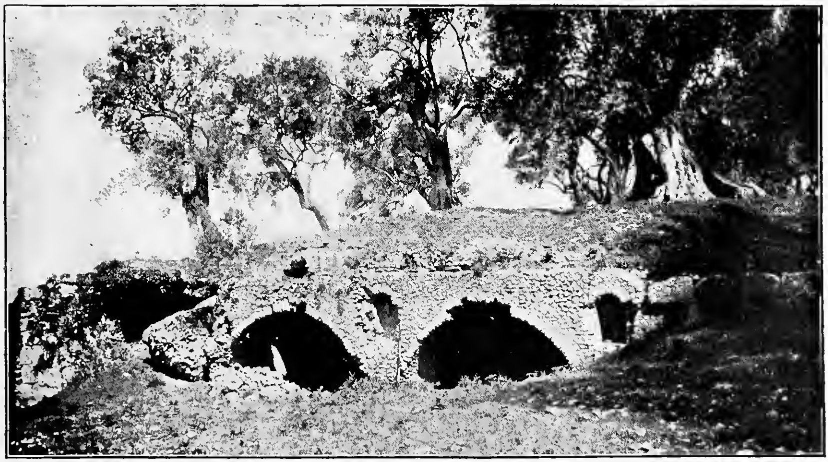
27. Anio Vetus.—The next aqueduct built for the water-supply of Rome was called Anio Vetus. It was built 272–269 B.C., and is about 43 miles long; it took its water from the river Anio. About 1100 feet of its length was carried above ground on an artificial structure. It also was a low-level aqueduct, the elevation at which it delivered water at Rome being about 150 feet above sea-level. It was built of heavy blocks of masonry, laid in cement, and the cross-section of its channel was about 3.7 feet wide by 8 feet high. In the year 144 B.C. the Roman senate made an appropriation equal to about $400,000 of our money to repair the two aqueducts already constructed, and to construct a new one called Aqua Marcia, to deliver water to the city at an elevation of about 195 feet above sea-level. This aqueduct was finished 140 B.C.; it is nearly 58 miles long, and carried water of most excellent quality through a channel which, at the head of the aqueduct, was $5\frac{7}{8}$ feet wide by $8\frac{3}{10}$ feet high, but farther down the structure was reduced to 3 feet wide by $5\frac{7}{10}$ feet high. The excellent water of these springs is used for the present supply of Rome, and is brought in the Aqua Pia, built in 1869, as a reconstruction of the old Aqua Marcia. This aqueduct, like its two predecessors, is built of dimension stone, 18 inches by 18 inches by 42 inches, or larger, laid in cement; but concrete and brick were used in the later aqueducts, with the exception of Claudia.

28. Tepula.—The aqueduct called Aqua Tepula, about 11 miles in length, and completed 125 B.C., was constructed to bring into the city of Rome a slightly warm water from the volcanic springs situated on the hill called Monte Albani (Alban Hills) southeast of Rome. The temperature of these springs is about 63° Fahr. In the year B.C. 33 Agrippa caused the water from some springs high up the same valley to be brought in over the aqueduct Aqua Julia, 14 miles long. This latter water was considerably colder than that of the Tepula Springs. The two waters were united before reaching Rome and allowed to flow together far enough to be thoroughly mixed. They were then divided and carried into Rome in two conduits. The volume of water carried in the Aqua Julia was about three times that taken from the Tepula Springs, the cross-section of the latter being only 2.7 feet wide by 3.3 feet high, while that of Julia was 2.3 feet by 4.6 feet. The water from Aqua Julia entered Rome at an elevation of about 212 feet above sea-level, and that from Aqua Tepula about 11 feet lower.

29. Virgo.—The sixth aqueduct in chronological order was called Virgo, and it was completed 19 B.C. It takes water from springs about 8 miles from Rome and only about 80 feet above sea-level, but the length of the aqueduct is about 13 miles. The delivery of water in the city by this aqueduct is about 67 feet above that level. The cross-section of this channel is about 1.6 feet wide and 6.6 feet high.

30. Alsietina.—The preceding aqueducts are all located on the left or easterly bank of the Tiber, but one early structure was located on the right bank of the Tiber to supply what was called the Trans-Tiberine section of the city, and it was known as Aqua Alsietina. The emperor Augustus had this aqueduct constructed during his reign, and it was finished in the year A.D. 10. Its source is a small lake of the same name with itself, about 20 miles from Rome. The elevation of this lake is about 680 feet above sea-level, while the water was delivered at an elevation of about 55 feet above the same level. The water carried by this aqueduct was of such a poor quality that Frontinus could not "conceive why such a wise prince as Augustus should have brought to Rome such a discreditable and unwholesome water as the Alsietina, unless it was for the use of Naumachia." The latter was a small artificial lake or pond in which sham naval fights were conducted.

31. **Claudia.**—The eighth aqueduct described by Frontinus is the Aqua Claudia, built of dimension stone, which he calls a



Sand and Pebble Catch-tanks near Tivoli. Dimension-stone aqueducts of Marcia at either end of the tank built of small stone; *opus incretum*. The arches are chambers of the tanks.

magnificent work on account of the large volume of water which it supplied, its good quality, and the impressive character of considerable portions of the aqueduct itself, between 9 and 10 miles being carried on arches. It was built in 38–52 A.D. and is forty-three miles long. The sources of its supply are found in the valley of the Anio, and consequently it belongs to the system on the left bank of the Tiber. The cross-section of its channel was about 3.3 feet wide by 6.6 feet high. It was a work greatly admired by the Roman people, as is evidenced by the praise "given to it by Roman authors who wrote at that time." It delivered water at the Palatine 185 feet above sea-level. According to Pliny, the combined cost of it and the Aqua Anio Novus was 55,500,000 sestertii, or nearly $3,000,000. This aqueduct probably belongs to the highest type of Roman hydraulic engineering. It follows closely the location of the Aqua Marcia, although its alignment now includes a cut-off tunnel about 3 miles long, the latter having been constructed about thirty-six years after the aqueduct was opened. Mr. Clemens Herschel observes that the total sum expended for these two aqueducts makes a cost of about $6 per lineal foot for the two. The arches of this aqueduct and those of the Anio Novus have clear spans of 18 to 20 feet, with a thickness at the crown of about 3 feet.

32. **Anio Novus.**—The ninth aqueduct described by Frontinus is called Anio Novus. It was also constructed in the years A.D. 38–52. This aqueduct has a length of about 54 miles and takes its supply from artificial reservoirs constructed by Nero at his country-seat in the valley of the Anio near modern Subiaco. This structure is built of brick masonry lined with concrete. That portion of the Aqua Claudia which is located on the Campagna carries for 7 miles the Anio Novus, and it forms the long line of aqueduct ruins near Roma Vecchia. The upper surface of the arch ring at the crown forms the bottom of the channel of the aqueduct. The cross-section of the channel of the Anio Novus was 3.3 feet wide by 9 feet high. The elevation of the water in this, as in the Claudia, when it reached the Palatine was about 185 feet above sea-level. The Anio Novus in some respects would seem to be a scarcely less notable work than the Claudia. About 8 miles of its length is carried on arches, some of them reaching a height of about 105 feet from the ground.

33. **Lengths and Dates of Aqueducts.**—These nine aqueducts constituted all those described by Frontinus, as no others were completed prior to his time. Five others were, however, subsequently completed between the years 109 A.D. and 306 A.D., but enough has already been shown in connection with the older

structures to show the character of the water-supply of ancient Rome.

The following tabular statement is a part of that given by Mr. F. W. Blackford in "The Journal of the Association of Engineering Societies," December, 1896. It shows the dates and lengths of the ancient aqueducts of Rome between the years 312 B.C. and 226 A.D., with the length of the arch portions. The list includes those built up to the end of the Empire. It will be observed that the total length of the aqueducts is 346 miles, and that of the arch portions 44 miles. The figures vary a little from those given by Lanciani and others, but they are essentially accurate.

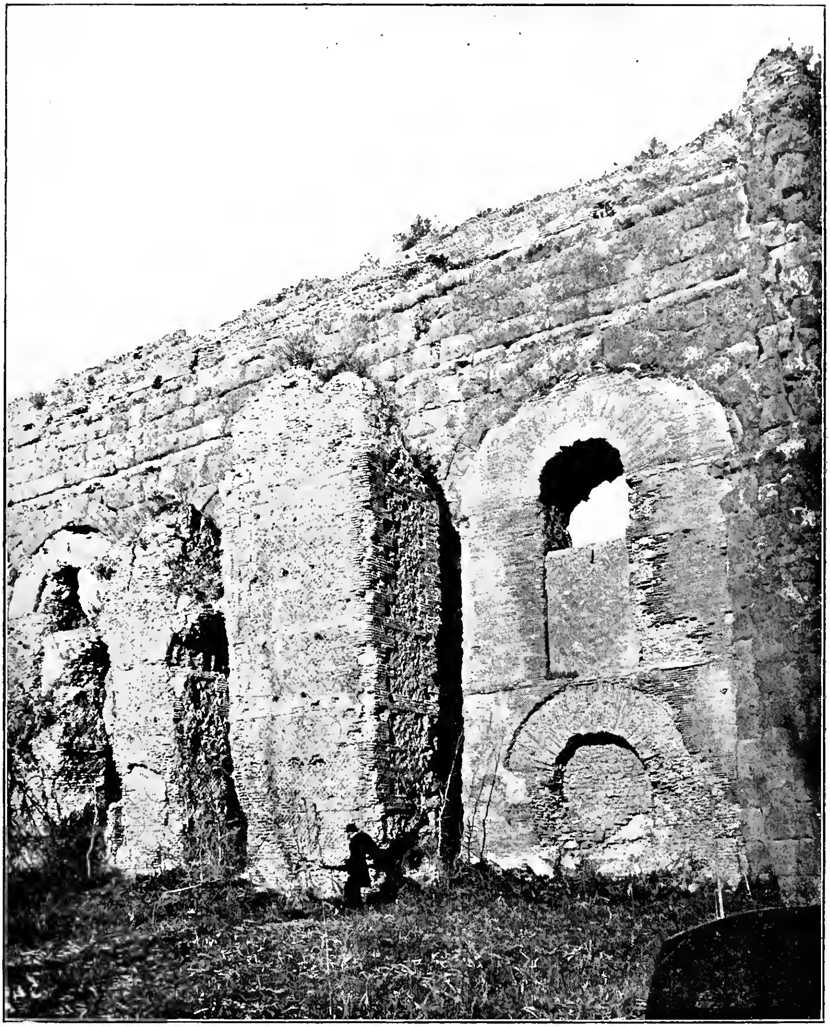
Name.	Date. B.C.	Total Length in Miles.	Length of Arches in Miles.
Appia	312	11	Little
Anio Vetus	272–264	43	"
Marcia	145	61	12
Tepula	126	13	Little
Julia	34	15	6
Virgo	21	14	Little
	A D.		
Alsietina	10	22	Little
Augusta	10	6	"
Claudia	50	46	10
Anio Novus	52	58	9
Triana	109	42	Little
Alexandrina	226	15	7
Totals	....	346	44

34. Intakes and Settling-basins. — The preceding brief descriptions of the old Roman aqueducts give but a superficial idea of the real features of those great works and of the system of water-supply of which they were such essential portions. Enough has been shown, however, to demonstrate conclusively that the engineers and constructors of old Rome were men who, on the one hand, possessed a high order of engineering talent and, on the other, ability to put in place great structures whose proportions and physical characteristics have commanded the admiration of engineers and others from the time of their completion to the present day. If a detailed statement were to be made in regard to the water-supply of ancient Rome, it would appear that much care was taken to insure wholesome and potable water. At the intakes of a number of the aqueducts, reservoirs or basins were constructed in which the waters were first received and which acted as settling-basins, so that as much sedimentation as possible might take place. Similar basins (picinæ) were also constructed at different points along the aqueducts for the same purpose and for such other purposes as the preservation of the water in a portion of the aqueduct in case another portion had to be repaired or met with an accident which for the time being might put it out of use. These basins were usually constructed of a number of apartments, the water flowing from one to the other, very much as sewage in some sewage-disposal works flows at the present time through a series of settling-basins. The object of these picinæ was the clearing of the water by sedimentation. Indeed there was in some cases a use of salt in the water to aid in clarifying it. This is an early type of the modern process of clarifying water by chemical precipitation, not the best of potable-water practice, but one that is sometimes permissible.

35. **Delivery-tanks.**—The aqueducts brought the water to castellæ or delivery-tanks, i.e., small reservoirs, both inside the city and outside of it, and from these users were obliged by law to take their supplies; that is, for baths, for fountains, for public uses, for irrigation, and for private uses. When Frontinus wrote his "De Aquis" a little less than three tenths of all the water brought to Rome by the aqueducts was used outside of the city. The remainder was distributed in the city from 247 delivery-tanks or small reservoirs, about one sixth of it being consumed by 39 ornamental fountains and 591 water-basins.

36. **Leakage and Lining of Aqueducts.**—These aqueducts were by no means water-tight. Indeed they were subject to serious leakage, and Frontinus shows that forces of laborers were constantly employed in maintaining and repairing them. As has been stated, the older aqueducts were built of dimension stones, while the later were constructed of concrete or bricks and concrete. The channels of these aqueducts, as well as reservoirs and other similar structures, were made as nearly water-

tight as possible by lining them with a concrete in which pottery, broken into fine fragments, was mixed with mortar.



Claudia and Anio Novus near Porta Furba. Repairs in brickwork and in a composite of concrete and brickwork.

37. Grade of Aqueduct Channels.—The fall of the water-surface in these aqueducts cannot be exactly determined. The levelling-instruments used by the Romans were simple and, as we should regard them, crude, although they served fairly well the purposes to which they were applied. They were not sufficiently accurate to determine closely the slope or grade of the water-surface in the aqueduct channels. The deposition of the lime from the water along the water-surface on the sides of the channels in many cases would enable that slope to be determined at the present time, but sufficiently careful examinations have not yet been made for that purpose. Lanciani states that the slopes in the Aqua Anio Vetus vary from about one in one thousand to four in one thousand. An examination of the incrustation on the sides of the Aqua Marcia near its intake makes it appear that the slope of the surface was about .06 foot per 100 feet, which would produce a velocity, according to the formula of Darcy, of about 3.3 feet per second. In some aqueducts built in Roman provinces it would appear that slopes have been found ranging from one in six hundred to one in three thousand.

38. **Qualities of Roman Waters.**—The chief characteristic in most of the old Roman waters was their extreme hardness. They range from 11° to 48° of hardness, the latter belonging to the water of the Anio, while the potable waters in this country scarcely reach 5°. The old Romans recognized these characteristics of their waters and, as has been intimated, used the best of them for table purposes, while the less wholesome were employed for fountains, flushing sewers, and other purposes not affected by undesirable qualities. The water from Claudia, for instance, was used for the imperial table. The water from the Aqua Marcia was also of excellent quality, while that brought in by the Aqua Alsietina was probably not used for potable purposes at all.

39. **Combined Aqueducts.** — In several cases a number of aqueduct channels were carried in one aqueduct. A marked instance of this kind was that of Julia, Tepula, and Marcia, all being carried in vertical series in one structure. Numerous instances of this sort occurred.

40. **Property Rights in Roman Waters.**—In reading the two books of Frontinus one will be impressed by the property values which the old Romans created in water rights. The laws of

Rome were exceedingly explicit as to the rights of water-users and as to the manner in which water should be taken from the aqueducts and from the pipes leading from the reservoirs in and about the city. The proper methods for taking the water and using it were carefully set forth, and penalties were prescribed for violations of the laws pertaining to the use of water. There were many abuses in old Rome in the administration of the public water-supply, and one of the most troublesome duties which Frontinus had to perform lay in reforming those abuses and preventing the stealing of water. The unit of use of water (a "quinaria," whose value is not now determinable) was the volume which would flow from an orifice .907 inch in diameter and having an area of about .63 of a square inch. Mr. Herschel shows that in consequence of the failure of the Romans to understand the laws of the discharge of water under varying heads, the quinaria may have ranged from .0143 cubic foot to .0044 cubic foot per second or between even wider limits.

41. Ajutages and Unit of Measurement.—Frontinus describes twenty-five ajutages of different diameter, officially approved in connection with the Roman system of public water-supply; but only fifteen of these were actually used in his day. All of these were circular in form, although two others had been used prior to that time. They varied in diameter from .907 to 8.964 English inches and were originally made of lead, but that soft metal lent itself too easily to the efforts of unscrupulous water-users to enlarge them by thinning the metal. In his time they were made of bronze, which was a hard metal and could not be tampered with so as to enlarge its cross-section. The discharge through the smallest of these ajutages was the quinaria, the unit in the scale of water rights. The largest of the above ajutages had a capacity of a little over 97 quinariæ.

This unit (the quinaria) was based wholly on superficial area, and had no relation whatever to the head over the orifice or to the velocity corresponding to that head. Although Frontinus refers in several cases to the fact that the deeper the ajutage is placed below the water-surface the greater will be the discharge through it, also to the fact that a channel or pipe of a given area of cross-section will pass more water when the latter flows through it with a high velocity, he and other Roman engineers seem to have failed completely to connect the idea of volume of discharge to the product of area of section by velocity. In the Roman mind of his day, and for perhaps several hundred years after that, the area of the cross-section of the prism of water in motion was the only measure of the volume of discharge. This seems actually preposterous at the present time, and yet, as observed by Mr. Herschel, possibly a majority of people now living have no clearer idea of the volume of water flowing in either a closed or open channel. Existing statutes even respecting water rights bear out this statement, improbable as it may at first sight appear. This early Roman view of the discharge is, however, in some respects inexplicable, for Hero of Alexandria wrote, probably in the period 100–50 B.C., that the section of flow only was not sufficient to determine the quantity of water furnished by a spring. He proceeded to set forth that it was also necessary to know the velocity of the current, and further explained that by forming a reservoir into which a stream would discharge for an hour the flow or discharge of that stream for the same length of time would be equal to the volume of water received by the reservoir. His ideas as to the discharge of a stream of water were apparently as clear as those of a hydraulic engineer of the present time. Indeed the method which he outlines is one which is now used wherever practicable.

It has been a question with some whether Frontinus and other Roman engineers were acquainted with the fact that a flaring or outward ajutage would increase the flow or discharge through the orifice. The evidence seems insufficient to establish completely that degree of knowledge on their part. At the same time, in the CXII. chapter of Frontinus' book on the "Water-supply of the City of Rome," he states that in some cases pipes of greater diameter than that of the orifice were improperly attached to legal ajutages. He then states: "As a consequence the water, not being held together for the lawful distance, and being on the contrary forced through the short restricted distance, easily filled the adjoining larger pipe." He was convinced that the use of a pipe with increased diameter under such circumstances would give the user of the water a larger supply than that to which he was entitled, and he was certainly right in at least most cases.

The actual unit orifice through which the unit volume of water called the quinaria was discharged was usually of bronze stamped by a proper official, thus making its use legal for a given amount of water. The Roman engineers understood that such an orifice should be inserted accurately at right angles to the side of the vessel or orifice, and that was the only legal way to make the insertion. Furthermore, the law required that there should be no change in the diameter of the pipe within 50 feet of the orifice. It was well known that a flaring pipe of increased diameter applied immediately at the orifice would largely increase the discharge, and unscrupulous people resorted to that means for increasing the amount of water to be obtained for a given price.

42. The Stealing of Water.—It appears also that Frontinus experienced much trouble from clandestine abstraction of water from reservoirs and water-pipes. The administration of the water commissioner's office had been exceedingly corrupt prior to his induction into office, and some of his most troublesome official work arose from his efforts to detect water-thieves, and to guard the supply system from being tapped irregularly or illegally. We occasionally hear of similar instances of water-stealing at the present time, which shows that human nature has not altogether changed since the time of Frontinus.

43. Aqueduct Alignment and Design of Siphons.—The alignment of some of the Roman aqueducts followed closely the contours of the hills around the heads of valleys, while others took a more direct line across the valleys on suitable structures, frequently series of arches. Judging from our own point of view it may not be clear at first sight why such extensive masonry constructions were used when the aqueduct could have been kept in excavation by following more closely the topography of the country. There is little doubt that the Romans knew perfectly well what they were about. Indeed it is definitely stated in some of the old Roman writings that the structures were built across valleys for the specific purpose of saving distance which, in most instances at least, meant saving in cost.

These masonry structures, it must be remembered, were built of material immediately at hand. Furthermore, these aqueducts were generally only made of sufficient width for the purpose of carrying water-channels. They were not wide structures. In some cases they were not more than 8 feet or 9 feet wide for a height of nearly 100 feet. The cost of construction was thus largely reduced below that of wide structures.

Old Roman Lead and Terra-cotta Pipe.

The Romans were perfectly familiar with the construction of inverted siphons. As a matter of fact Vitruvius, in Chapter VII of his Eighth book, decribes in detail how they should be designed. His specific descriptions relate to lead pipes, but it is clear from what he states at other points that he considered earthenware pipes equally available. He sets forth how the pipes should be carried down one slope, along the bottom of the valley, and up the other slope, the lowest portion being called the "venter." He realized the necessity of guarding all elbows in the pipe by using a single piece of stone as a detail for the elbow, a hole being cut in it in each direction in which the adjoining sections of pipe should be inserted, the sections of lead pipe being 10 feet long, and even goes so far as to describe the stand-pipes that should be inserted for the purpose of allowing air to escape. Vitruvius also advises that the water should not only be admitted to inverted siphons in a gradual manner, but that ashes should be thrown into the water when the siphon is first used in order that they may settle into the joints or open places so as to close any existing leaks. Lead-pipe siphons, 12 to 18 inches in diameter, with 1 inch thickness of metal under 200 feet head, built in ancient times, have been found at Lyons in France. Also a drain-pipe siphon with masonry reinforcement was built at Alatri in Italy 125 B.C. to carry water under a head of about 340 feet. There are other notable instances of inverted siphons constructed and used during the ancient Roman period, some of them being of lead pipe imbedded in concrete.