A History of the Urban Underground Tunnel (Draft Version #1 - 7/22/2010)

Introduction:

One of the problems of correctly interpreting history, is that the original meanings of words and phrases are sometimes lost, or at least distorted. For example, the New York word "subway" is a contraction of a two word phrase: "Sub[terranean] [passage]way".

In addition to the term subway's most prevalent use in the NY area (as a label we affix to our urban rail transit system), the term "subway" can also refer to any underground passageway. Things such as an underground pipe gallery, utility area or water conduit. For example, in Manhattan "The Empire City Subway" is not a railway- it is underground vaulting, built to contain telephone company cables.

Linguistic terms, like technology itself, does not arise within a vacuum; there is always something similar that came before. We now present a brief outline on the evolution of the "Subway", or "Underground Passageway", covering a time period of roughly 2,700 years, starting with its ancient uses in Babylonia, Jerusalem, Greece, Bagdad and Rome, and then culminating with the modern urban underground railway tunnel

The Earliest Known Urban Underground Passageways (Mesopotamia & Greece):

Curt Merkel, in his circa 1899 German language book, gives us perhaps the most technically detailed description of the earliest known urban underground passageways and similar ancient structures. Keep in mind, all of Merkel's measurements are in Meters, and that 1 Meter ≈ 3.28 feet. Further, his particular use of a "comma" when citing dimensions, is equivalent to our decimal point.

Curt Merckel: Die Ingenieurtechnik im Altertum. Berlin: J. Springer 1899.Translated from the German by Ingmar Arnold.

Selected pages of Merkel's book follow (the indented section over the next few pages):

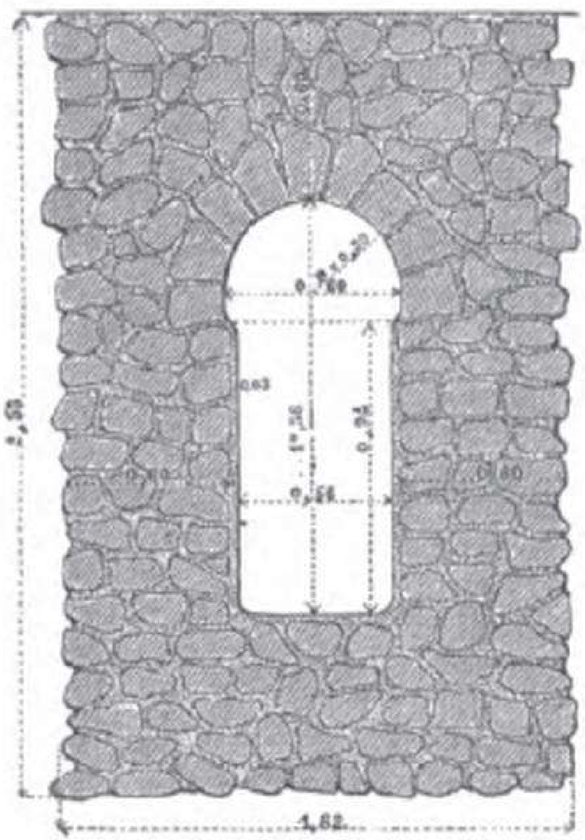


Abb. 254.
Querschnitt des Aquädukts von Sens.

Drainage of Cities and Street Cleaning) Canalization (p. 450):

At the moment when a larger group of humans started dwelling together at the same place over a longer period of time, unavoidably the question of water supply and the surface discharge of the service water masses and the garbage had to be solved. This is the reason why the history of water supply and drainage of cities (i.e. Canalization) goes back into the earliest times. Our knowledge about the earliest drainage systems is rather meager. The oldest reference concerning the existence of a drainage system known today so far has been discovered on an older sealing inscription. It was referred to as the construction of a palace and the drainage system of a warehouse. Other information concerning drainage systems in Mesopotamian cities is much younger.

Layard mentions in his writings that Babylon was in possession of very big watering sewers, that the private houses were connected via by-pass channels with the main sewers. In Nimrud, this scholar discovered a vaulted, pointed arched drainpipe beneath a building from the 7th century B.C.

The vault was made out of big burnt brick. The side walls are resting on the same material. The brick is quadrangular but not wedge-shaped. The central space (cf. fig. 166) is filled up with brick, laid down in linear length.

p. 451:

Vertical stand-pipes are discharged into this by-pass channel. This can be seen on page 270, fig. 77. They were used to discharge the waters into the drainpipe. Beneath the north-western palace in Nimrud, Layard discovered also a vaulted drainpipe. Beneath the road pavement of the ruins of the elder Palace in Nimrud several quadrangular drainpipes, made of burnt brickstone, led into different parts of this building. Round pipes, ending in a perforated plaster plate and normally situated in a corner, were connecting the drainpipes with those floors in different rooms which had to be drained. All junctions were united in a main sewer, and this one was emptied in the river.

In Bagdad, the above mentioned scholar [Layard] reports, the only remaining relics from the Babylonian times are the ruins of an imposing drainage ditch. A subterranean channel, made out of big quadrangular brick, and connected with the name of “Nebudkadnezar”.

In Jerusalem, several drainpipes from ancient sewer systems have been preserved. They have been pushed, tunnel-like, into the rocky underground. Schlick discovered a pipe, big enough for a man to enter, just a few meters beneath the soil. This channel is 60 cm wide and ca. 2 meters high. Initially, it was equipped with a vaulted ceiling This ceiling was composed of just a few worked stones; later, it was covered with bit flat stones. The channel leads towards the Kidron Valley, the outlet is blocked.

Some minor drainpipers are ending here also, close to the ceiling. Schlick considers that this gangway is much younger – dating from the times of Herod or Hadrian. The purpose of this channel was, obviously, to discharge the brackish sewers from the north-eastern part of the city. Schlick writes the following words about the sewer conditions during the old times of Jerusalem, before King David invaded the city: “Between the caves, rocks and stony houses pipes or trenches were proceeding, broken out of the rock, and completed by brickwork when the rock was lacking These pipes led all the rain and dirty waters towards the edge of the rock. In General, these “alleys” were small and sinuous; but the main sewer which came from the North, from Millo, was comparitively more spacious and more in a linear slope than the many short by-pass channels branching off to the left or to the right. Naturally, the outlets of these channels at the edge of the rocket were lower than the alley and the houses. But Joab entered Jerusalem through these channels, and David came into the possession of this City, without any bloodshed.”

Among the many alleyways that traverse the Underground of Jerusalem in various directions, one tunnel, discovered by Warren, in the South-East of Siloah, is believed to be recognized as a drainpipe.

<u>Ancient Rome</u>

The first large scale urban "underground passageway", was Rome's *Cloaca Maxima* (The Great Sewer). This drainage system, originally built for the purpose of transporting flood waters, predates Rome's famous aqueducts, and was the start of the "cut and cover" underground tunneling practice in urban environments.

This structure, is at the very least, approximately 531 meters (1,742 feet) in length (as per Merkel's drawing, pg 459), with a typical cross section of roughly 9 ft x 12 ft. Compare these figures with the Atlantic Avenue tunnel: 2,000 ft x 21 ft x 17 ft.

It was built by two Etruscan Kings of Rome. Construction is said to have started about 600 BC, and said to have been completed sometime around 500 BC, after a long political delay.

The Cloaca Maxima is also said to have been "the earliest application of the arch [vault] in Rome" (Italy. Handbook for Travellers, by Karl Baedeker, Ninth revised edition, 1886, pg 245).

"It goes without saying that such a vast and solid network of drainage involved enormous labor, and points to a despotic authority. The work was begun by the first Tarquin [Priscus]; it seems to have been in a degree suspended in the reign of Servius Tullius ; and it was completed by Tarquin the Proud [Tarquin Superbus]". (from: Rome Today and Yesterday: The Pagan City, by John Dennie, 1904, p 50)

Executing such a large construction undertaking with nothing more than human labor and hand tools, must have been an extremely formidable, and unpleasant task. Dennie continues:

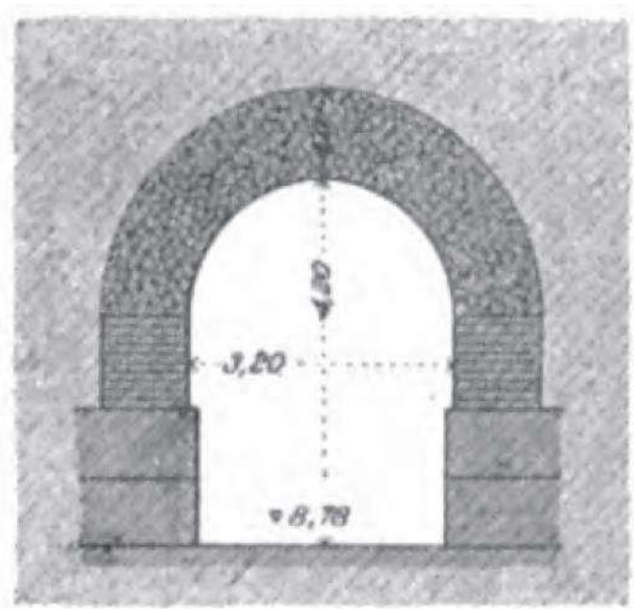
"In an address, which one of the old historians represents [Lucius Junius] Brutus [founder of the Roman Republic], as making to the people of Rome after the expulsion of the royal house [509 BC], occur these words, which plainly refer to the Cloacae" :

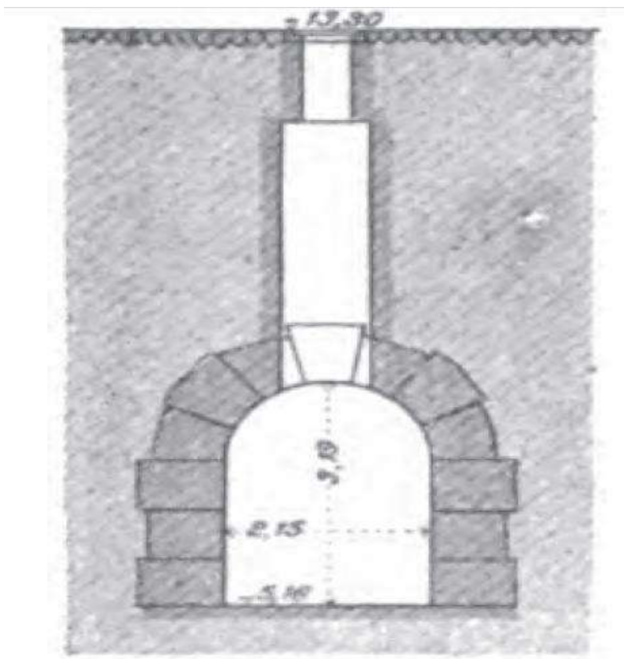
" He compelled you like slaves to lead a miserable life, hewing stone, cutting wood, carrying enormous loads, and passing your lives underground."

Compare this to Walt Whitman's writing on the Atlantic Avenue tunnel, some 2,300 years later: "***A Passage of Solemnity and Darkness***"

Dennie concludes: "Nevertheless, it is certainly true that no public work ever done in Rome surpasses in utility the Tarquinian sewers, for they rendered all the future possible. If the cloacae are, as they have been called, a monument of tyranny, they are also a monument of statesmanship".

<u>Vitruvius, sometimes referred to as the world's first known engineer, wrote of the "cut and cover" method in his 1st century BC work *The Ten Books on Architecture,*</u> <u>Book VIII, chapter VI.</u> **<u>"*Parietes cum camera in specu struanter*". In English: "If the tunnel (specus) was driven through...earth or sand, there must be massive vaulted masonry walls".</u>**





Cross-sectional drawings of Rome's Cloaca Maxima above

<u>Continued extracts of Curt Merkel's book follow:</u>

Curt Merkel, in his circa 1899 German language book, gives us perhaps the most technically detailed description of the Cloaca Maxima:

p. 454:

> There was a concept made by the chief engineer who, according to the legend, was commissioned by Tarquinius Priscus to create a drainage system. As a result, a discharge should be given in the plains between the seven hills to lead heavy rainfalls away. The plain part between the hills was exposed to many floods because it was situated so close to the river. The drainpipe should prevent the heightening of the waters and eliminate the sources of infection of the devastating fever. The plague of fever was known in Rome for a very long time, as can be seen by the fact that the earliest settlers dedicated their chapels and altars to the deity of fever and related gods of the household, for instance of Cloacina, Mala Fortuna and Mefitis. In this context, the old drainage systems of the Campagna should not be forgotten. Even in Rome, at the Capitol Hill, at the south-west corner of the Palatine Hill, and at the west side of the Aventine Hill, similar drains have been found. By erecting these important drainage channels, the further development of Rome was made possible. The water amount flowing of from the Quirinal, Viminal, Esquiline, Caelius, Palatine and Capitol Hills to the old Roman Forum were combined into a bundle and discharged into the Tiber River.
>
> **p. 455:**
>
> Jordan holds the view that by building the Cloaca and erecting the surrounding wall which was accomplished – due to popular belief – by the Tarquinii as well, Rome received its' specific imprint. The surrounding wall with all its' gates was for centuries the boundary of the City of Rome; it established the major traffic routes. The Cloaca Maxima enabled the agricultural cultivation of the plains between the hills and the river. Presumably, most of the Cloaca was uncovered in the beginning, at least a great deal of it. Draining was the major purpose;

in the course of time the system was used step by step to discharge human and animal garbage as well. To a certain degree, there is a point in regarding this dual use as a disadvantage. Probably, the ancient engineers did not know anything about how to avoid the escape of sewer gas. Thus, the Roman population was permanently exposed to the deleterious evaporation because no cut-off devices existed. Some of the big entrances, close to the streets, have been preserved until our days. In Pompeii, for instance. Best known is the Bocca della verita in Rome – a marmoreal disc, five feet in diameter, with the face of Oceanus, the rain waters were streaming through his mouth into the drainage channels.

Dionysius tells us that the drains had to be cleaned and restored due to their congestion. The censors spent a sum of about 1.000 Talents (ca. 4 ½ Million Mark) to solve this problem. According to Hirt, the extension of this sum is a sign that these works must have been much more than just cleaning and repairing.

Among the sewer channels of Rome there are some that were used already in ancient times. Among others, the drainpipes of the Circus Flaminius are still in use. The most famous among the ancient drains is the Cloaca Maxima. Her outlet is mapped by figure no. 168.

The course of the Cloaca Maxima shows a great many of windings and lay-bys that might be caused partly because the constructors tried to avoid existing buildings. The whole trace is similar to a watercourse in the Campagna Region. It is highly probably to regard the Cloaca Maxima as a channeled river which flows into the Merrana at St. Giorgio in Velabro (cf. fig. no. 169). In that respect, the development in Rome must have been rather similar to the development in Athens. In Rome, the river bank was fixed. Then the watercourse was overbuilt. The accuracy of this statement might be given by the fact that 22 meters behind the Basilica Julia,

p. 457:

… the ordinary Cloaca suddenly ends and an open conduit must have existed here for a certain time. The waters of the Palatine Hill were flowing into this conduit. A theory which is supported by the fact that the living condition in this area of miasmas were rather awkward, if not precarious.
The exact survey of the Roman sewer network is due to the Italian Engineer Pietro. Due to him, the Cloaca Maxima consists of big Gabine ashlars stones with the following measurements: Length: 2, 50 meters, Height: 0, 80 meters, width: 1, 00 meters. The stones had been connected without grout and mortar. The walls consist of 3 -4 ashlars layers. A semi-circular shaped arch is based upon them. This barrel vault has 7 to 9 ashlars layers formed by accurately arranged key stones. The river bed is paved with polygonal lava stones. The figures nos. 170 – 172 are illuminating the cross section resp. the longitudinal section of the Cloaca segment (up to the Forum Augustum) that was discovered in 1889.

Figure No. 173 shows the cross section of Point No. 2 from the fig. no. 169 site map. Here, as it can be seen in figure no. 173, only two original ashlars stones still exist. Above them, there is a semi-circular vault based upon brick layers. The width of the channel is variable, depending upon the hydraulic gradient conditions. Towards the estuary mouth, the cross section widens. This is an appropriate constellation because the quantity of water that has to be drained is also increasing. At this point, south of the Forum Romanum, the Channel leads into the area beneath the stairways of the Basilica Julia, and the vault has been replaced to make the construction of the stairway's bottom section possible. At this point, the Channel has a width of 1, 20 meters and is covered with 30 cm travertine ashlars stones. But where the Cloaca meets the Basilica Julia, the cross section is suddenly widening, the ashlars layers on both sides meet stumpy, without any sign of an integration. Due to Narducci, this section of the Cloaca Maxima, between points Nos. 6 & 7, with a length of about 180 meters, must have been uncovered originally. Also due to the opinion of Narducci, a by-pass channel leading into the Cloaca Maxima beneath the western pillars of the Janus quadrifons brought the waters flowing from Capitoline Hill in eastbound direction directly into the Cloaca Maxima.

From Point No. 9 until the confluence of the Cloaca Maxima into the Marrana at St. Giorgio (fig. no. 175), the sewer has a brick vault. Throughout the length of 13, 9 meters, the sewer is interrupted. But then it goes on another 207 meters. The width rises from 3, 7 to 4, 5 meters. The discharge shows three vaulted Peperin layers. This material was used during the time of construction of the outflow to cover the adjacent river bank also. Approx. 9 meters before the Cloaca comes to pass the so called Janus quadrifons in Velabrum, the sewer comes to an end,

p. 459:

having a height of about 1, 99 meters and a perpendicular front of travertine (fig. 174). The sequel section, 3, 19 meters high, is built with different layers. The by-pass channel mentioned above, emptying into the Cloaca Maxima at this point, has almost the same cross section as the lower section of the Cloaca. The air shafts in fig. 176 & 178 are from a later date. Just after the Cloaca has passed the Janus quadrifons, the same covering vault of key stones ends into a perpendicular front (fig. 177).

The adjacent 39 meters show a brick vault. Fig. 179 reproduces the longitudinal section of the Cloaca; fig. 180 is the view of the sewer at Point No. 10.

In many cases, the extensive drainage networks built in many cities in antiquity were of use only to a very small part of the population. In Rome, for instance, it was not an obligation to connect the houses ("insulae") with the drainage system. Real estate speculations were running wild in those days, so it is not very probable that the landlords did more investments than it was regulated by law. According to Livy, it was only regulated that the drainage channels in private homes had to be built on the landlords' own expenses, they had to pay the cloaricum exactly for that purpose. Initially, the sewers were put under the control of the censors, later of the aedils and eventually of the Curatores cloacorum.

Concerning the canalization, Pompeii allows us a good insight into the conditions of Ancient Roman rural towns. Nissen's opinion is that this city never ever had a Cloaca system like in Rome. Almost every house led the drainage directly into the streets. The pavement was continuously curved; so the waters were gathering at the curbstones. To cross the pavement – which was probably wet very often – on dry ground, special stepping stones were placed in the middle of the street. The tenants were responsible both for …

p. 460:

… the maintenance of the plaster and the unrestricted drainage of the waters. Before the invention of the sidewalks, the kennel must have been situated in the middle of the road. The waters flew off through discharge apertures – sometimes, here and there, they are still visible today in the sidewalks. But Nissen thinks that subterranean drainpipes were erected only at those places where greater amounts of waters were flowing off – for instance, at the Forum Romanum or at the Stabian therms. These drainpipes are in evidence to be seen on page 442, fig. 165.

Numerous drainpipes are to be found beneath the ruins of Nicomedia. This city is situated at the flank of a hill. She was built terraced. The various terraces were separated from each other by supporting walls. The lowermost terrace, initially situated directly at the sea, disposes of three flying buttresses with a distance of approx. three meters to each other. Drain pipes are leading to these buttresses. These pipes are big enough in their cross section that a man can walk into them without any problems. These pipes were made first and foremost to discharge the rain waters safely.

At the bottom of a hill in Orange, the ancient Arausio, there used to be a marsh. The sewage water of this city was lead into the marsh. To protect the lower districts of Arausio from flooding in case of heavy rainfall, a drainpipe was laid. Via the Meague River the waters were discharged into the Rhone. The width of this main collector was up to two meters.

In Aosta, a consistent sewer system was available. The pipe disposes of a clear width of 0, 64 meters to 0, 85 meters...

p. 461:

> … and a height of 1, 68 meters. On the back side, the pipe is 1, 33 meters beneath the road bed. The upper part is vaulted in a semi-circular shape.
>
> In Paris, fragments of the former drainpipes from Roman Times are still preserved upon the isle of Notre Dame. The height of these pipes is 0, 60 meters, the width 0, 50 meters.
>
> Remnants of Roman drainpipes have been found in Cologne and in Treves, Germany. Fig. 181 shows the cross section of the channel which was exposed in the neighborhood of Alteburg in Cologne. Interestingly enough are the applied forms of the cross section as well as the embedding of the pipe in blue colored clay. Another drainpipe, exposed in the Budengasse Alley, was made out of tufa ashleys and sealed with a semi-circular vault. The height is 2, 45 meters, the width 1, 20 meters. Most scholars believe that this channel was presumably made for the purpose of defense.
>
> Like in modern big cities, Ancient Rome was provided with public latrines. In a famous speech concerning the lex Fannia, Titius mentioned the public convenience already. Also, private house-owners were designating latrines for public use. This undertaking was charged with a tax by Emperor Vespasian. Overbeck's opinion is that the therms in Pompeii were equipped with closets and flush lavatories.
>
> These public latrines were used almost exclusively by the poor population. There was a debate whether private houses had latrines as well – but there were many different answers to that question. Some writers believe that vases were in use to take over the excrements, and that they were cleaned by slaves. About the place where this clearance took place the opinions also differ.
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> **p. 462:**
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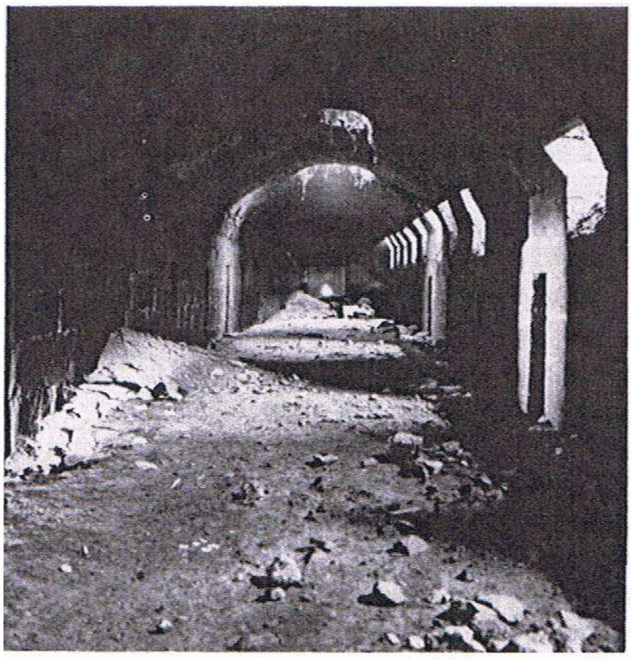
> But in the case of Pompeii, it has been proven that almost all the houses were equipped with latrines, which were situated pretty close to the kitchens. The feces were gathered in pit latrines, but nothing has been found out so far about a direct connection with the drainpipes. In most cases, the plebs got rid of the feces by throwing it simply into the streets. This was the same habit like in Medieval times.
>
> The sewage of the houses went directly into the streets. From there, they were discharged into channels, drainpipes or ditches.
>
> We do not have any information so far concerning the down-grade conditions, the ventilation within the urban channels, or a potential prevention of the escape of sewer gas. But we know that in Rome and in other cities (in Seleucia Pieria, for instance) the regular clearance of the sewer system was an obligation. The waterworks authorities in Rome were obliged to provide back-up facilities of mains waters for exact this purpose.
>
> An act of disposal, written down by Sextus Julius Frontinus, refers to this constellation and has the following wording: "My will is that no one who has not got permission by me or my predecessors, may discharge surplus waters because it is necessary that a certain part of the water volume delivered by the water basins is used not only for the purpose of the city's maintaining and clearance but also for the purpose of rinsing the drainpipes."
>
> In antiquity, the flowing off points of the sewers into the rivers were situated without exception within the cities' borders. Such an constellation must have had various evils as a result. In Rome, when the water level of the Tiber River was high, every now and then the waters of the Cloaca Maxima were blocked back. As the river itself was pretty heavily polluted, the so called swimming pond was established".

The Romans quickly made extensive use of these "vaulted underground passageways", in their system of aqueducts. Lofty masonry arches (such as Segovia, Spain) were built to carry the aqueducts over valleys (De Aqvs Et Aqvaedvctibvs Veteris Romae, by Raphael Fabretti, published in 1680, pg 8,18,19), while "cut and cover" aqueduct tunnels were extensively used (see fig __ Eifel Aqueduct, Germany, circa 70 AD, (from Roman Aqueduct & Water Supply, By A. Trevor Hodge), where the waters would best flow underground.

The Roman Cryptoporticus:

From the Cloaca Maxima, the Romans then developed a residential/commercial use for "cut and cover" vaulted underground passageways: the *Cryptoporticus*. See photos of the Palatine Cryptoporticus (Dennie), and the Bosra Cryptoporticus (MacDonald).



112. Bosra, cryptoportico

"Sometimes connective, functioning as covered passageways, Cryptoporticus are vaulted corridors. Cool and shaded, they are occasionally found alongside streets, sunken below pavement (Bosra) [Syria], but much more often they lined platforms or terraces erected to support major buildings and functioned as ambulatories (Arles [France]; Aeminium [Portugal]; Aosta [France]; Smyrna [Turkey]). The street type is lit by smallish, raking windows set in the haunch of the vault along one side". (From: *The Architecture of the Roman Empire Volume II: An Urban Appraisal*, by William L. MacDonald, 1986, pg 117, 118)

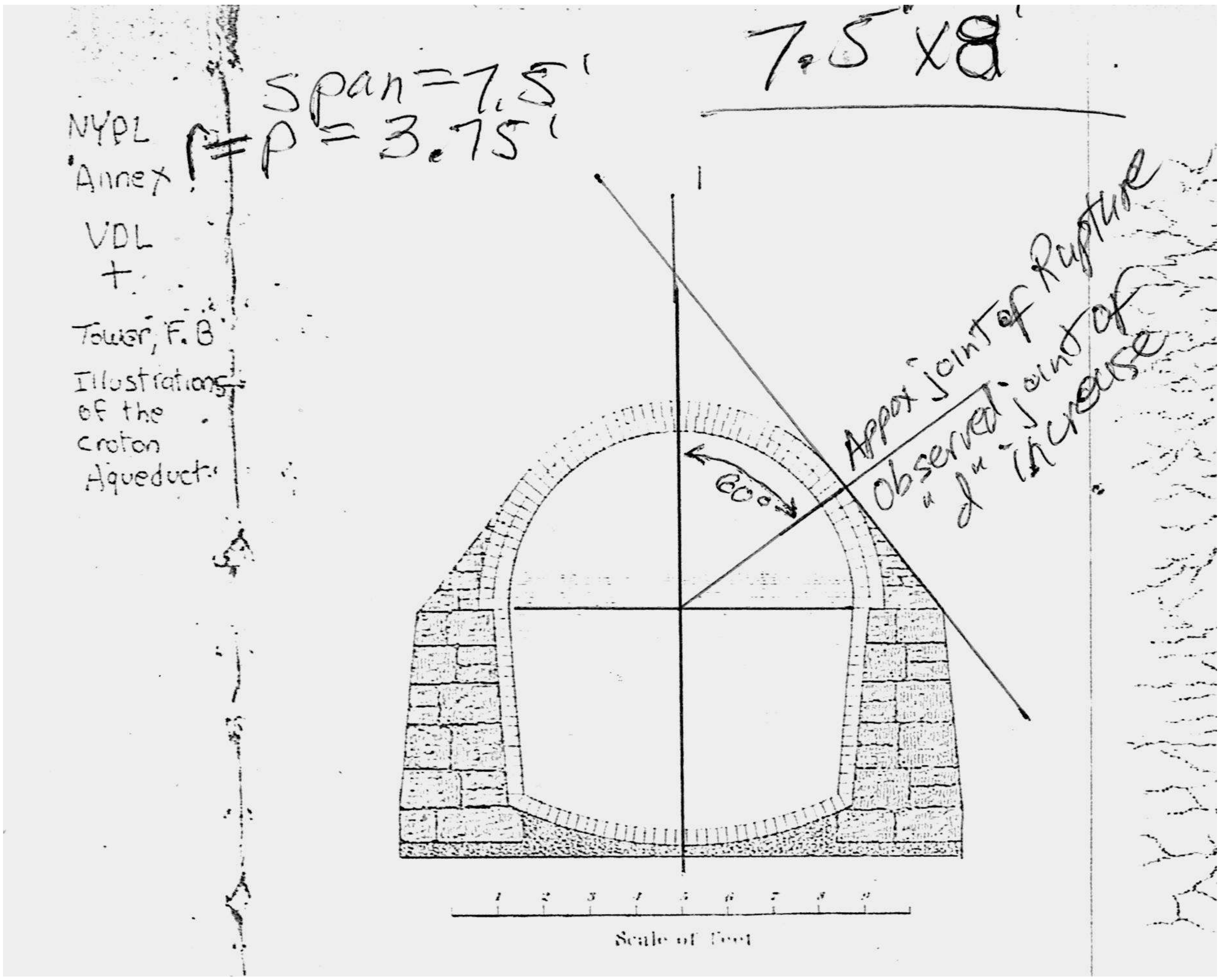
The Cryptoporticus of the Palatine

Source: The Rome Of Today And Yesterday: The Pagan City, By John Dennie, 1904, pg 162

Fast Forward To The Nineteenth Century:

Next, we jump about 2,000 years to New York City's first Croton Aqueduct, originally designed by Maj. David Bates Douglass circa 1833- 5, and later completed by noted engineer John B. Jervis in 1842.

While this mid nineteenth century American version of a Roman “underground vaulted passageway” was built to convey water from Westchester County, NY to Manhattan, its relatively large cross sectional design (7.5 ft x 9 ft) is clearly based upon the Roman Cloaca Maxima, the Aqueduct Arcade, or the Cryptoporticus, rather than a typical, small cross section (roughly 2 ft x 4 ft), classical Roman aqueduct “specus”.



Whats An Arch, How Does It Work?

However, before we go any further, let's take a brief look at precisely what an arch is, and how it works. In shape, arches can be circular, elliptical, horse shoe shaped (basket), skew, pointed, corbel- and even perfectly flat. From: ***A Dissertation On The Construction Of Arches***, By G. Atwood, 1801, pg iii,v, vi, 1, 19, 20

> “AN arch being formed (according to the usual modes of construction) by the apposition of wedges, or sections of a wedge-like form, the properties of arches seem to be naturally derived from those of the wedge, on which principle the inquiries in the ensuing Tract are founded.
>
> Supposing an arch to consist of any number of sections or wedges, adjusted to equilibrium ; this arch resting on the two abutments, may be considered analagous to a single wedge, the sides of which are inclined at an angle equal to the inclination of the two abutments the forces therefore which would be necessary to sustain such an arch or wedge when applied perpendicularly to the sides, ought to be equal to the reaction of the pressures on the two abutments ; this principle is found on examination to be verified by referring to the tables annexed ;f whether the arch consists of sections, without, or with the load of superincumbent weight, and whether the angles of the sections are equal or unequal : For according to all these tables, the weight of the semiarch is to the pressure on the corresponding abutment, or the reaction there.. of, as the sine of half the angle between the two opposite abutments, is to the radius; which is a proportion equally applicable to the wedge, and to the arch, when adjusted to equilibrium.
>
> From the second of these rules it appears, that the lateral or horizontal pressure of any arch adjusted to equilibrum depends wholly on the weight and angle between the sides of the highest, or middle section : If therefore the weight and angle of this highest section should continue unaltered, the lateral force or pressure will be invariably the same, however the height, the length, the span; and the weight of the whole arch may be varied. This lateral force is called, in technical language, the drift or shoot of an arch, and the exact determination of it has been considered as a desideratum in the practical construction of arches.
>
> As the exterior termination of an arch always exceeds the interior curve (usually called the curve of the arch), the sections or wedges of which it is composed will partake of a similar disproportion, the length of the exterior boundary in each wedge always exceeding that of the interior. A consequence of this wedge-like form is, that the weight of each section by which it endeavours to descend towards the earth, is opposed by the pressure the sides of it sustain from the sections which are adjacent to it. If the pressure should be too small, the wedge will not be supported, but will descend with greater or less obliquity to the horizon, according to its place in the arch. If the pressure should be too great, it will more than counterpoise the weight of the section, and will force it upward. The equilibrium of the entire arch will consequently depend on the exact adjustment of the weight of each section or wedge, to the pressure it sustains, and the angular distance from the vertex, measured by the inclination of the lowest surface to the vertical line. This equilibrium is understood to be established by the mutual pressure and gravity of the sections only, independent of any aid from friction, cohesive cement, or fastenings of any kind".

The following general rules are derived from the proportions, which have been inferred in the preceeding pages:

RULE I. The initial pressure is to the weight of the first section, including the weight superincumbent on it, as radius is to twice the sine of the semiangle of the middle, or highest wedge, or $p = \frac{w}{2 \times \sin. \frac{1}{2} A^{o}}$.

RULE II. The horizontal force, which is nearly the same in every part of the arch, is to the weight of the first section, as radius is to twice the tangent of the semiangle of the first section, or $p' = \frac{w}{2 \times \text{tang.} \frac{1}{2} A^{o}}$.

RULE III. The horizontal or lateral force is to the pressure on the abutment, as radius is to the secant of the inclination of the abutment to the vertical, or $Z = p' \times \sec. V^{x}$.

RULE IV. The horizontal force is to the weight of half the arch as radius is to the tangent of the inclination of the abutment to the vertical, or $S = p' \times \text{tang. } V^{x}$.

RULE V. The weight of the semiarch is to the pressure on the abutment, as the sine of the said inclination of the abutment is to radius, or $S = Z \times \sin. V^{x}$.

RULE VI. The horizontal force is to the pressure on the abutment as the cosine of the inclination of the abutment is to radius, or $p' = Z \times \cos. V^{x}$.

By these rules, the principal properties of the arch of equilibration are expressed in simple terms, and are easily applicable to practical cases.

Rule 3d. The horizontal force, or p', being the weight divided by twice the tangent of the semiangle of the first section, determines the pressure on any abutment of which the inclination to the vertical line is V^{x}; the pressure being $= p' \times$ secant V^{x}.

Rule 4th. The weight of the semiarch, when adjusted to equilibrium, is found by the fourth rule to be $= p' \times \text{tang. } V^{x}$; or the horizontal pressure increased, or diminished, in the proportion of the tangent of the vertical distance of the abutment to radius. From this property, the reason is evident, which causes so great an augmentation in the weights of the sections, when the semiarch, adjusted to equilibrium, approaches nearly to a quadrant, and which prevents the possibility of effecting this adjustment by direct weight, when the entire arch is a semicircle.

Rule 5th. The fifth rule exemplifies the analogy between the entire arch when adjusted to equilibrium, and the wedge. For let the angle between the abutments be made equal to the angle of the wedge, the weight of which is equal to the weight of the arch; and let Z be either of the equal forces, which being applied perpendicular to the sides of the wedge, sustain it in equilibrio: then by the properties of the wedge, the force Z is to half the weight of the wedge as radius is to the sine of the semiangle of the wedge, which is precisely the property of the arch; substituting the angle between the abutments instead of the angle of the wedge, and the pressure on either abutment instead of the force Z.

Rule 6th. The lateral pressure, or the pressure on the abutment, reduced to an horizontal direction, is nearly the same in all parts of the arc; being to the weight of the first section, as radius is to twice the tangent of the semiangle of the wedge.

The force of pressure on the abutment is therefore at every point resolvable into two forces; one of which is perpendicular to the horizon, and is equal to the weight of the semiarch; and the other is a horizontal or lateral force, which is to the weight of the first section, as radius is to twice the tangent of the semiangle of that section.

Continued On Next Page . . .

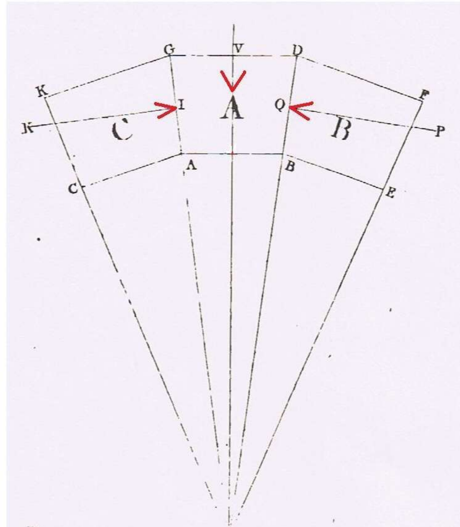
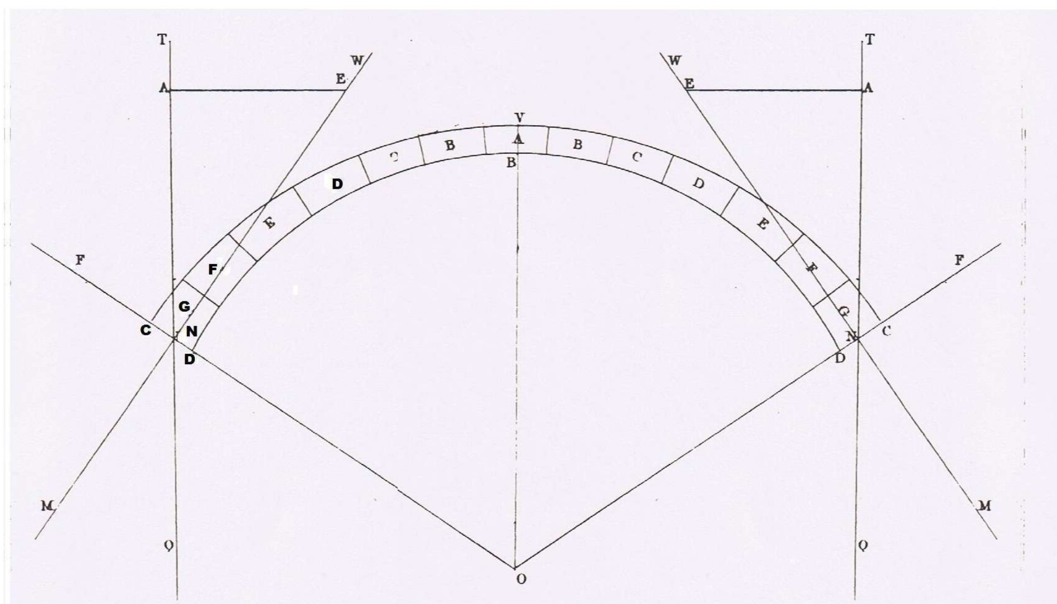


Fig. 2.

NOTES:

Angle formed by VOD = 1/2Aº in equations above.

The tendency of the Weight at "A" is to fall along the vertical axis line VO. However, this tendency is counterbalanced by the horizontal vectors PQ and KI, which prevent the arch from moving vertically.



Atwood, Fig 4

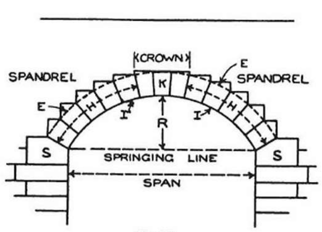


Fig. 33.

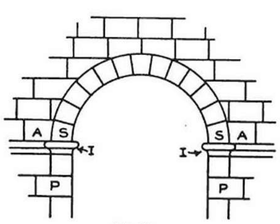


Fig. 34.

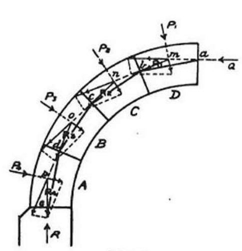


Fig. 35.

From: The Builder, Jan 30, 1904, pg 113

Now that we have a basic idea of what an arch is, and how it works, lets look at some simple equations for calculating the key dimensions of a 19th century masonry arch tunnel.

From " *A Treatise On Masonry Construction*, By I. O. Baker, 1909, pg 641- 646, we glean three important "empirical" formulas for designing a masonry arch, credited to Rankine, and known as "the English Method". Since the entire concept of the "empirical method" is based upon observation, we'll pick the formulas that fit best for both the Croton Aqueduct, and the Atlantic Avenue tunnel.

Let's first take the case of the circa 1842 Croton Aqueduct:

First, for calculating the thickness of the arch at its highest point, or crown, we'll use Rankine's method:

$\mathbf{d}(\text{crown}) = \sqrt{(0.12 \cdot r^2/s)}$

Where span "s" = 7.5 ft
And rise "r" = 3.75 ft

$d = \sqrt{0.225}$

d(crown) = 0.47434 ft x 12"/ ft = 5.69 inches by Rankine's method.

Since the y axis of a typical period brick laid longitudinally on its edge is about 3- 1/2 ", two layers of brick arch would be required. In fact, according to a circa 1842 scale drawing, the arch of the Croton Aqueduct is in fact 2 layers of brick thick, and adding 0.5" for a single cement mortar joint, making the crown of the Croton Aqueduct a total of 7.5" thick. This matches perfectly with the contemporary scale drawing.

Next, we must calculate the thickness of the arch at the ***springing line***: To understand this particular equation, one must first appreciate the concept of the "joint of rupture".

Essentially, this is the joint along any arch, that is subjected to the greatest force. Since taking the sum of moments around an arch is somewhat beyond the scope of this article, we'll use the simple fact that according to Baker, this "joint of rupture" usually forms an angle with the vertical, between 45º and 60º. The "joint of rupture" is also considered to be the point where the arch technically ends, and the abutment theoretically begins. The continuation of the arch from the joint of rupture to the spring line, is considered to be a prolongation of the abutment, rather than the arch.

By measuring the original scale drawings of the structures, and taking the joint of rupture to coincide with the joint at which the thickness of the arch begins to increase; on the Croton Aqueduct of 1842, this angle appears to be 60º from the vertical. For the Atlantic Avenue tunnel of 1844, this angle appears to be the average of the maxima and minima, as cited by Baker, or 52.5º from the vertical.

So, we now have the equation for calculating the thickness of the Croton Aqueduct at its spring-line:

$\mathbf{d}(\textbf{spring-line}) = \mathbf{d}(\text{crown}) \cdot \text{Secant } \Theta$

where Θ = angle made by joint of rupture with the vertical.

Using the trigonometric identity **Secant Θ = 1 / Cosine Θ**, our equation can be rewritten as:
$\mathbf{d}(\text{spring-line}) = \mathbf{d}(\text{crown}) / \cos\Theta$

Plugging in the numbers, we have:

d(spring-line) = 7.5" • (1/Cos 60°) = 7.5" • 2 = **15"**

According to the contemporary scale drawing, the Croton is 21" thick at its spring line. The additional 6" of thickness, is taken to be the safety margin (40%).

Finally, for the thickness of the Croton's abutments ***at their base***:

d(abutment**)** = 2/3 h

where h = clear height of abutment

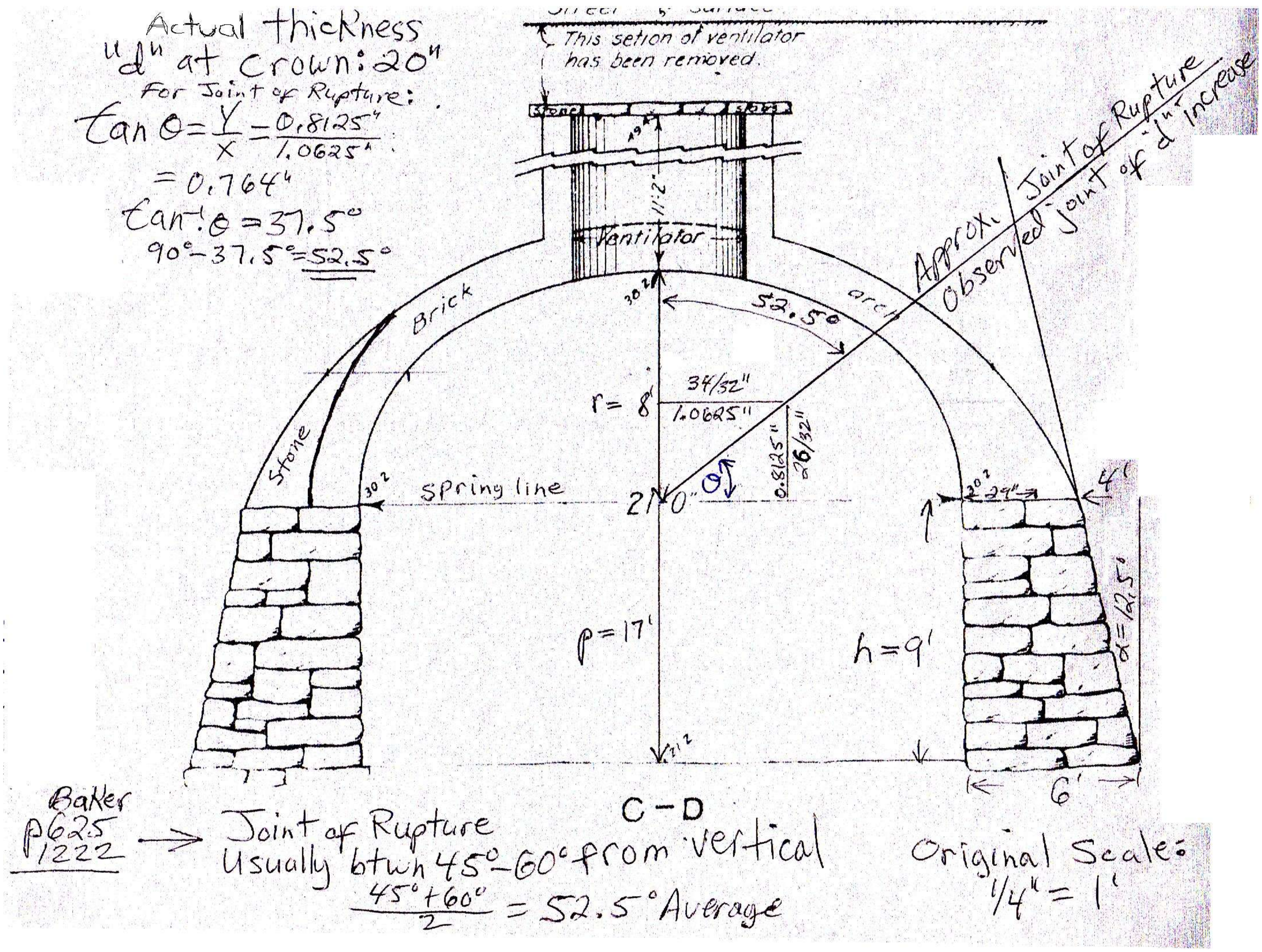
Plugging in the numbers, we have:

d(abutment**)** = (2/3 • 3.75 ft) = 2.5 ft thick at the base

Measuring from the contemporary scale drawing, the Croton's abutments are 2.6 ft thick at their base.

The Atlantic Avenue Tunnel

In Brooklyn, circa 1844, the ancient concept of the Roman "Underground Passageway" made the technological "jump" from water tunnels and cryptoporticus to the urban underground railway...



Since the Atlantic Avenue tunnel was built under a city street, by the "cut and cover method", for the specific

purpose of attaining grade separation for the LIRR, this structure is therefore the world's first transportation Subway: urban underground railway line.

See the following link for contemporary historical documentation:

http://brooklynrail.net/images/aa_tunnel/new_research/oct_09/events_leading_to_tunnel_creation.pdf

The ½ mile arch of the tunnel consists of 5 layers of high quality red burned brick, laid in bond with headers and stretchers, and additional external Spandrel material- Mica Schist rubble masonry (Manhattan bedrock) between the joint of rupture and the spring line, all layed in a Portland cement/sand mortar. The brick headers interconnect the 5 layers of the brick arch, thereby further strengthening the arch. The tunnel's abutments (walls) consist of massive Mica Schist rubble masonry, thoroughly grouted with Portland cement/sand mortar.

Lets now apply these formulas to the Avenue tunnel of 1844:

Applying Rankine's formulas, we get:

$\mathbf{d}_{(crown)} = 2 \cdot \sqrt{0.12 \cdot r^2/s}$

Where span "s" = 21 ft
And rise "r" = 8.0 ft

Note that in this particular application of Rankine's tunnel arch formula, we have doubled the result, as per Baker's instructions, to account for the fact that the tunnel is built within a sand matrix.

$d_{(crown)} = 2 \cdot \sqrt{0.12 \cdot 21^2/21}$

$\mathbf{d}_{(crown)} = 2 \cdot 0.604743$ ft

$d_{(crown)} = 1.209486$ ft = 14.50 inches by Rankine's method.

The actual measured thickness at the crown, is 20" (1.60 ft). It's assumed that the difference of 5.5 inches, is a safety factor of 38% at the crown.

For calculating the thickness of the Atlantic Avenue tunnel at its spring-line:

$\mathbf{d}_{(\mathbf{spring\text{-}line})} = \mathbf{d}_{(crown)} \cdot \text{Secant } \Theta$

where Θ = angle made by joint of rupture with the vertical.

Again, using the trigonometric identity **Secant Θ = 1 / Cosine Θ**, our equation can be rewritten as:

$\mathbf{d}_{(spring\text{-}line)} = \mathbf{d}_{(crown)} / \text{Cos } \Theta$

plugging in the numbers, we have:

$\mathbf{d}_{(\mathbf{spring\text{-}line})}$ = 14.50 inches • 1/Cos 52.5º

$\mathbf{d}_{(\mathbf{spring\text{-}line})}$ = 23.819 inches, say 24 inches.

The actual as built measured thickness at the spring-line, is 48 inches. It is assumed the 24 inch difference is a safety margin of 100% at the spring- line.

Now let's calculate the volume of masonry building material used in the Atlantic Avenue tunnel.

In mathematical terms, the arch of the tunnel is "an ellipse of the semi major axis (a) and semi minor axis (b)". Since the ellipse is centered at the origin (0,0), polar equations can be used.

The area of an ellipse centered at (0,0) = πab

Sources: Schaum's Outline Mathematical Tables and Formulae, 2nd Edition, pgs 15, 23.
CRC Standard Mathematical Tables and Formulae, 31st Edition, pg 330- 331.

Therefore, the general formula for the area of our arch of a single elliptical hemisphere is:

Area Tunnel Arch = $\pi ab/2$

To obtain the area of our arch, we must subtract the area of the inner arch surface (intrado) from the area of the outer arch surface (extrado):

Area intrado = $(3.14 \cdot 8 \cdot 10.5)/2 = 131.88$ ft^2
Area extrado = $(3.14 \cdot 9.6 \cdot 14.5)/2 = 218.54$ ft^2

Area tunnel arch = 218.54 ft^2 – 131.88 ft^2 = 86.66 ft^2

Multiplying 86.66 ft^2 by 2000 ft, and then dividing by 27 ft^3/ Yd^3, **we obtain an arch volume of 6,419 Yd^3.**

However, as we know from our core samples, the arch is not made entirely of brick. The arch is a constant thickness of 20 inches of brick, and supplemented in depth with mica schist rip rap laid in Portland cement mortar, from the joint of rupture to the spring line, as per the cross sectional view.

This was no doubt done as an economizing measure, as the Mica Schist was free, except for the cost of cutting in Manhattan and transport to Brooklyn. The brick on the other hand, had to be purchased and transported.

Lets now calculate the volume of brick in the arch, and then subtract this volume from the total arch volume:

Area brick extrado = $(3.14 ((10.5 + 1.6)) \cdot (8 + 1.6)/2 = 182.37$ ft^2

Area brick arch = Area brick extrado - Area Intrado = 182.37 ft^2 – 131.88 ft^2 = **50.49 ft^2**

Volume brick masonry in arch = 50.49 ft^2 • 2,000 ft = 100,980 ft^3/27 = 3,740 CY.

Deducting 20% of this volume to account for the Portland cement mortar, we get:

Sample brick taken from the tunnel, give us the following dimensions:

Length: 8 inches = 0.666 ft

Height: 2- 3/8 inches = 0.1979 ft
Depth: 3- 5/8 inches = 0.30208 ft

Therefore, **1 brick = 0.04 ft³**, making exactly 25 bricks per cubic foot, exclusive of mortar joints, which are approximately 3/8 inch each.

By deducting 1/5 of the total volume volume of Brick masonry, to account for the volume of the hydraulic cement mortar per cubic foot, and then dividing the result by 0.04 ft³ per brick, we get a grand total of 2,019,600 bricks in the Arch of the tunnel, exclusive of mortar joints:

100,980 ft³ – (100,980 ft³/5) = 80,784 ft³ Brick = 2,992 CY Brick, and 748 CY Portland cement mortar (for brick) in arch.

Finally, 80,784 ft³/0.04 ft³ per Brick = **2,019,600 Bricks in the Tunnel's arch.**

To calculate the volume of stone rubble masonry in the tunnel's arch:

6,419 CY(total arch) – 3,740 CY(brick masonry) = **2,679 CY Stone Rubble masonry in the arch, of which 2,143.2 CY is Mica Schist rubble, and 535.8 CY Portland cement mortar.**

Finally, lets calculate the the thickness of the abutment walls at the base, and then the volume of stone masonry contained in each of the tunnel's abutments (exclusive of the approach ramps):

d(abutment) = 2/3 h = 2(9 ft)/3 = **6 ft thick at the base of abutment**. This precisely matches the as built condition.

Area per Abutment = (9 • 4) + (9 • 2)/2 = 45 ft²/ (9 ft²/Yd²) = 5 Yd²

5 YD² • 2,000 ft/ (9 ft²/YD²) = 3,333 Yd³ per abutment • 2 = 6,666 Yd³ total volume. Our ratio of stone to mortar per cubic yard then gives us:

6,666CY – (6,666 CY/5) = 5,332.8 CY Stone Rubble and 1,333.2 CY Portland cement mortar total abutments.

Then total masonry work excluding approach ramps:

Stone Work:
Abutments: 6,666 Yd³
Arch: 2,679 Yd³
Sub Total Stone Work: 9,345 Yd³

Brick Work (Arch): 3,740 Yd³

Atlantic Avenue Tunnel Total Masonry Work (excluding approach ramps): 13,085 CY, of which 10,468 CY is Stone Rubble and Brick, and 2,617 CY is Portland cement mortar.

Using our proper definition of a railway subway, the second example of such a structure, is the the extant NY & Harlem River RR tunnel located in Park Avenue South between East 33rd Street and Grand Central Terminal (now a vehicular tunnel). Originally, this tunnel was begun about 1836, only as an open cut through a major rock obstruction, called “Murray Hill”, rather than for attaining grade separation.

This open cut rock structure was later arched over with brick circa 1850, thereby converting it to an urban grade separation tunnel, to facilitate and accommodate the real estate development, and the increased volume of pedestrian and horse drawn vehicular traffic, occurring all around it.

Innovation doesn’t happen in a vacuum...

The third railway “subway” constructed, was **London's [North] Metropolitan Railway**, first proposed circa 1853, and completed circa 1863.

Essentially a 2-1/4 mile short line railroad extension of the Great Western Railway, by necessity (traffic congestion), parts of this route had to be built in both open cut and tunnel (grade separation). It **was not** an isolated rapid transit line.

Originally proposed by the City of London's tenacious Corporation Solicitor, Charles Pearson, Esq., I suspect that he and his adherents were inspired by the tunnels in Brooklyn and Manhattan, which he, or an associate, probably studied on a trip to New York in the late 1840's or early 1850's.

This short line railway extension was built using the “cut and cover”, as well as the “open cut” methods, under both streets and private property, **to attain grade separation (congested streets)** for the Great Western Railway's new passenger and freight access to the Thames River via downtown London.

This structure is virtually identical in concept and execution to the Atlantic Avenue tunnel. However, the Metropolitan line tunnel was built to accommodate the 7 foot gauge trains of the GWR.

It needs to be adequately noted, however, that London's Metropolitan Railway wasn’t originally all contained within a tunnel, nor was it built as a strictly local, self contained, rapid transit line...

Writing of London's original Metropolitan Railway line, the Encyclopedia Britannica, 1911, Vol 22, page 856, states: **“Wherever possible the lines were constructed in open cutting...where this was not possible, they were built by a method suggestively called “cut and cover”**. Essentially, this first line of the London Underground ***is*** the Atlantic Avenue tunnel, but lengthened accordingly to suit its particular route.

As to its original purpose, London's Metropolitan Railway line was in fact part of a much larger system of railways (as was the Atlantic Avenue tunnel/ LIRR). London's Metropolitan Railway was also built to provide rail freight service to the massive Smithfield cattle stockyards and meatpacking facilities, pictured below. The original function of this London “underground” line was “mixed use” to say the least..I quote from Slaughter (1860):

> The main purpose of the Metropolitan Railway, as is well known, is the making [of] a line from the Great Western at Paddington to a point on the eastern side of Victoria Street (Holborn)“. Slaughter goes on to write: “the...Metropolitan Railway will be thus placed in direct railway communication not only with Dover and the Continent, but also with the southern portions and suburbs of the metropolis [London]”, and further, “Arrangements have been made by ***this Company*** **[Metropolitan Railway]*****, and the Great Western Railway Company,*** with the Corporation [City of London] for the use of the ground under the [Smithfield] market for the purposes of a goods' station “. Also of note, is this Wikipedia article on the history of the Smithfield market: http://en.wikipedia.org/wiki/Smithfield,_London

Above Picture: "before the Metropolitan line was built, herds of cattle were driven through the streets of London to Smithfield Market, causing massive traffic congestion problems" (London, a Social History, Roy Porter, 2001, p193)

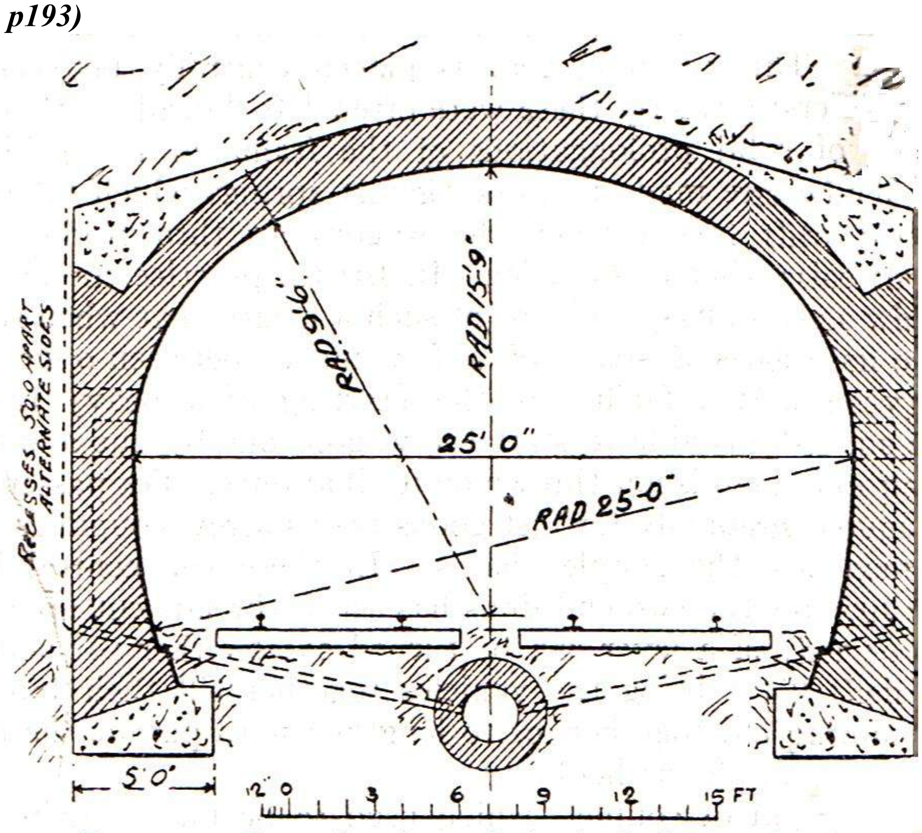


FIG. 30.—Type-Section of Arched Covered Way,

Metropolitan District Railway, London

Railway Intelligence, by Mihill Slaughter, No XI, Dec 31, 1860, pg 114- 115 gives us a detailed, first hand account, as to the origins and purposes, of the first of the London Underground lines:

METROPOLITAN.

Incorporated by 16 and 17 Vict., cap. 186, passed 15th August, 1853.

POSITION AND PROSPECTS OF THE UNDERTAKING.

The North Metropolitan (as the Company was originally called) became incorporated as far back as 1853, but until 1859 could scarcely be said to have taken any firm hold on the investing public. That it has at length done so is principally owing to the tact, perseverance, and influence of Mr. Charles Pearson, the City Solicitor, who having induced the Corporation to recognise their own interests in furthering the scheme, was at last able to conclude a subscription in their name for 20,000 £10 shares. From this period the undertaking has made steady progress, and its complete realisation is now a mere question of time.

The main purpose of the Metropolitan Railway, as is well known, is the making a line from the Great Western at Paddington to a point on the eastern side of Victoria Street (Holborn). Other objects more or less tending to the advantage of the Company have since been added, and these may be best explained in the following summary, compiled from the August (1860) Report of the Metropolitan Board :-

The Corporation of London have obtained the sanction of Parliament to establish extensive markets in Smithfield for the sale of meat and provisions, and to afford to Railway Companies facilities there, not only for traffic for the purposes of the markets, but also for receiving and delivering goods for the general trade of the city and the central districts of the metropolis.

An Act has been passed for a short line to connect the railway with the new markets, and with the large and convenient railway station which will there be formed.

Arrangements have been made by ***this Company, and the Great Western Railway Company,*** with the Corporation for the use of the ground under the market for the purposes of a goods' station

[Editor's Note: sounds a lot like the original LIRR passenger/ freight terminal at Atlantic Avenue & Columbia Street, and later at Flatbush & Atlantic Ave].

The rent to be paid by the two Companies for this large space is fixed at £ 2,000 per annum; the Companies bearing the cost of excavating the substructure and its retaining walls, and also a portion of the cost of the roof, the Corporation defraying the larger portion of the latter outlay, and all charges incidental to the erection of the market.

The London, Chatham, and Dover Company having obtained powers to extend their line to join the railway of the Company at its present terminus in Victoria Street (Holborn), the system of the Metropolitan Railway will be thus placed in direct railway communication not only with Dover and the Continent, but also with the southern portions and suburbs of the metropolis.

Considering the enormous traffic which the Metropolitan Railway will undoubtedly be required to accommodate, and more especially the need of space near the proposed goods' depot at Smithfield, the Company have purchased the whole of the vacant land belonging to the Corporation of London on the eastern side of Victoria Street (Holborn), and north of West Street. For this land, in quantity 5 acres 19 perches, the purchase money has been agreed at £ 179,157, of which £60,000 will ***be*** paid in money during the next 12 months, from August, 1860, and the remainder by a rent-charge at the rate of **41 per cent. per annum, redeemable in 40 years.**

PROGRESS OF WORKS.

The works have been satisfactorily let on guaranteed contracts to experienced Contractors, who have promptly commenced operations. Speaking generally, the works, both at King's Cross and at Paddington, are in full progress, and a very considerable portion of the land **for the line and stations has been purchased, and the buildings thereon are being rapidly cleared**

PROPOSED EXTENSION TO (OR NEAR) THE BANK.

Although the stations at Victoria Street (Holborn), and Smithfield will no doubt be sufficient for the previously contemplated traffic of the railway, it is felt that a station nearer to the Bank is a public requirement; and an application will be made to Parliament in the 1861 session for an extension from Smithfield to Finsbury **Circus. The length of this extension** will scarcely exceed half-a-mile, and it is considered that the property through which it would pass is not of a costly description.

It is believed that no preference stock need be created for this purpose, but that the necessary cost may be readily provided for by means of a separate capital of the Metropolitan Company, as the vast traffic over this portion of the line, comprising the combined traffic of both the Metropolitan and London, Chatham, **and Dover Railways, will, it** is believed, **secure a satisfactory dividend on the capital expended.**

From this point in the history of "subways", the next major innovations in subway construction, were:

1. The "deep tubes" built for the London Underground, circa 1886, using the Greathead Shield (a very early form of a tunnel boring machine).

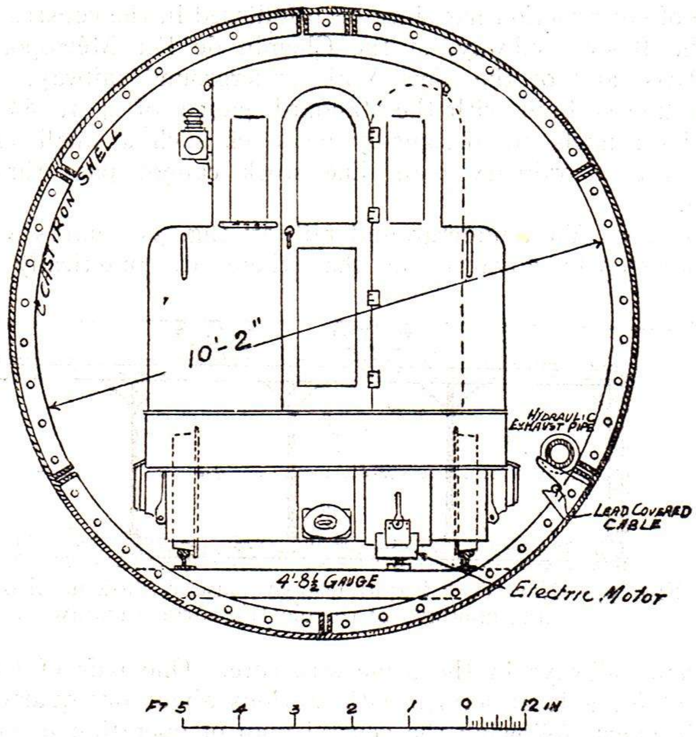


FIG. 33.—Section of Tunnel and Electric Locomotive, City & South London railway.

2. Circa 1893, the Budapest (Hungary) subway was opened, the first to utilize steel beams and reinforced concrete as its major structural "cut and cover" elements, rather than brick and stone masonry work.

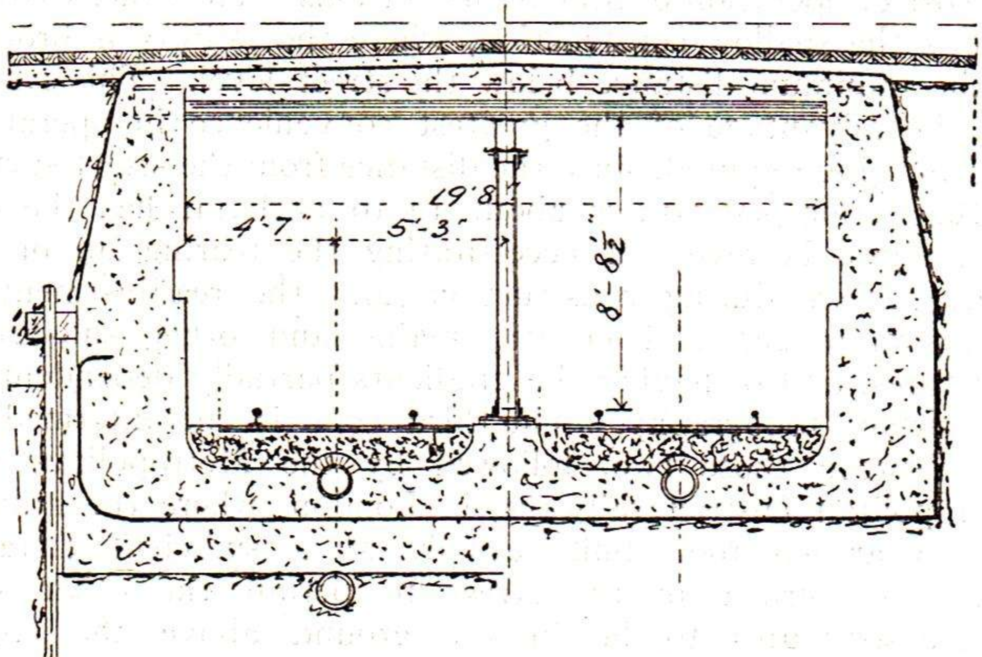


FIG. 34.—Electric Underground Railway, Budapest.

The drastically increased cost of labor during the 1890's, precluded any further great works of brick and stone construction, the cost of which had become prohibitive. Steel and concrete lent themselves well to mechanized mass production methods.

The Boston Subway:

In January, 1894, the concept of an urban underground railway, pioneered under Brooklyn's Atlantic Avenue in 1844, made a full circle back to the U.S...

Boston's Board of Subway Commissioners was appointed, with certain authority, to build “an elongated cellar" as it was called at the time, under Boston Commons, known as the “Hub”.

Built to remove 67 distinct streetcar lines from the surface (grade separation once again, as it always is with subways), this tunnel, built of concrete and steel using the “cut and cover” method (as per the Budapest subway), was only ¾ of a **mile in length when first opened to the public on September 1, 1897**. On the Boylston Street side of the Common, it cuts through a an old cemetery. A total of 910 bodies were dug up, and reburied.

(**Sources:** The Journal of the Franklin Institutute, November, 1897, pg 393; Elliott's Magazine, August, 1899, pg 45- 46.)

3. New York City's first IRT subway line, which opened circa 1904. The line's designer, William Barclay Parsons, innovated the concept of a 4 track subway route. In this way, two distinct services could be operated simultaneously along the same route: both an “Express” and a “Local” line. See fig # __, encyclopedia Britannica

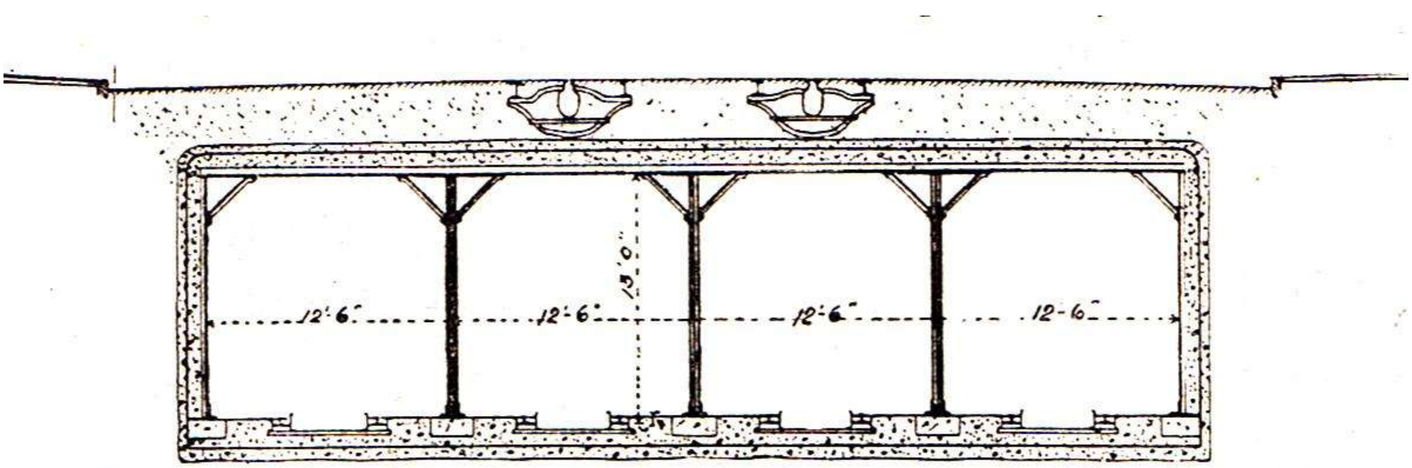


FIG. 35.—New York Rapid Transit railway, showing also the tracks and conduits of the electric surface tramway.