Practical Engineering in Ancient Rome.[1]

By THOMAS ASHBY, D.Litt.

THE Palatine, the nucleus of the City of Rome upon the Seven Hills, had great natural advantages of position; it was an almost flat-topped hill, with two distinct summits and a slight depression between them, protected by lofty cliffs, far more formidable than they seem at present, and almost entirely surrounded by two marshy valleys traversed by winding streams. Its neighbourhood to the Tiber enabled it to command the crossing, which, no doubt, existed in some form long before the foundation of Rome, probably just below the island, where the Pons Sublicius stood later. This crossing was of great importance, for it was the only permanent one over the whole lower course of the river.

Even in the palmiest days of Rome there were no bridges over the Tiber below the city, and those that there are now are all quite modern; while if we look upstream we find that above the city the only bridge for forty miles was that by which the Via Flaminia recrossed the river into Umbria just below Otricoli—and of that the last traces were obliterated by a flood some twenty years ago, which led to a complete change of course of the river. The traffic between the two banks was probably carried on by ferries, as at present.

Tradition ascribes the building of the Cloaca Maxima to a powerful race of foreign kings, the Tarquins, from the city of Tarquinii in southern Etruria. Little or nothing remains that belongs to the original structure; and indeed in the time of Plautus it was called *canalis*, and may have still been open at any rate for part of its course; for the whole this seems an almost impossibly insanitary supposition. We have, too, a number of branch drains which must have eventually led into it from the slopes of the Capitol—though conditions have been so altered that some of them now give into the open. I think they may be claimed as dating from the sixth or fifth century B.C., and as being thus by more than a century the earliest Roman arches in existence.

In this connexion I would recall that here we are dealing with a soft volcanic stone—the kind of tufa known as cappellaccio. When Appius Claudius built the Via Appia in 312 B.C., and his engineers had to build an embankment wall to carry the road along a hillside, we may see that, where they had to deal with the hard local limestone, they did not waste labour either in making a curved arch for the culvert, contenting themselves with inclining the sides gradually and then putting a lintel over, or in making the courses of the embankment wall horizontal.

The course of the Cloaca Maxima, as shown on the map, resembles, as Lanciani remarks, rather that of an Alpine torrent than of a carefully constructed drain; and its origin, from the canalisation of a stream meandering at the bottom of a flat valley, as the Tiber does at present, is sufficiently clear. The mouth of the Cloaca, with its three concentric arches of volcanic tufa, which may be assigned to 100 B.C. or a little before, was much more picturesque before the construction of the modern embankment. It is now a mere dummy, as the Cloaca itself, which still performs its functions, has been conducted into the new main sewer (the Collettore, as it is called) which runs just inside the embankment.

The Cloaca Maxima is a drain of considerable size, having an average measurement of 14 ft. high by 11 ft. wide, while the other two principal sewers of ancient Rome are rather smaller. Both these drains were built, like the Cloaca Maxima, of large rectangular blocks of stone, with a vaulted roof of the same material; and some of the minor drains were built in the same way, while others were covered with a flat block of stone, or with two slabs inclined to form a gable. This last shape, with the gable formed of large flat tiles, was that adopted in the brick-faced concrete sewers of imperial times, which vary in width from 2 ft. to 4 ft. and in height from 6 ft. to 9 ft.

Notwithstanding their splendid construction, which still bids defiance to the lapse of time, Lanciani is undoubtedly right in maintaining that the Roman Cloacæ have been overpraised. The modern sanitary engineer cannot approve of their use for carrying off sewage and rain-water together. Such contrivances as traps and syphons being unknown, the openings for the reception of the latter served to let out the effluvia from the former. Still more dangerous was the direct admission of sewage into the Tiber, which must have been odoriferous in the extreme when the water was low; while in times of flood the drains were dammed back, as was the case even in 1902.

In the time of the Republic the drainage system was under the general control of the censors, who let out contracts for the necessary constructions or repairs in this as in other classes of public works. They also had charge of the river banks and channel, and in 54 B.C. they erected a series of boundary stones (*cippi*) along both banks to prevent encroachment by private persons. Under Augustus in 8 B.C. the consuls of the year erected another series of terminal stones, and Augustus himself a third in 7-6 B.C.

Besides the erection of boundary stones, a good deal was done in the way of actual regulation of the river bank. There was no continuous embankment wall, as at present, but walls seem to have been built at the points where they were most needed. The Romans, at one point at any rate, at the Pons Aelius built by the Emperor Hadrian (the modern Ponte S. Angelo), were wise enough to provide three different widths of channel for different seasons of the year, in correspondence with which the bridge was provided with extra flood arches. The bridge was brought to light in its entirety in 1892, and it was found that, as originally constructed, it had three arches for low water, corresponding with a channel 66½ metres wide. Two more slightly smaller arches were available when the river was moderately full, with a channel 97½ metres wide. For great floods three smaller arches came into use, giving a total width of 135 metres to the stream. It was these three smaller arches and the bridge-heads characteristically sloping up on each side that were brought to light in 1892; and it is much to be regretted that it was impossible to preserve this remarkably perfect specimen of a Roman bridge.

[1] From the presidential address delivered at Southampton on August 28 before Section H (Anthropology) of the British Association.

From the consideration of the bridges of the city of Rome we naturally pass to that of the roads. The Via Appia, the queen of roads, as Statius calls it, was built as far as Capua in 312 B.C., and later on prolonged to Venusia (291 B.C.), Tarentum, and Brundusium (244 B.C.). It runs in a practically straight line from Rome to the Alban Hills. There it finds its first serious obstacle in the small extinct volcanic crater below Aricia, where Horace spent the night *hospitio modico*, not in the high-lying town, but at the post station below; and on the steep ascent from this post station it has, on the lower side of it, a massive embankment wall, about 200 yards in length. This, there is little doubt, is the *Pons Aricinus*, of which Juvenal speaks as being infested by beggars—like many another steep hill. The road soon reaches its summit level at Genzano, and descends once more in a straight line along the south-eastern slopes of the Alban Hills, passing at one point of its course over a smaller embankment, almost unknown to archæologists, and then, still perfectly straight, through the Pomptine Marshes.

Thence we arrive at Terracina. Above the town is the mountain, crowned by a temple of Jupiter Anxur, behind which the old road ran, keeping high above the sea, and descending again several miles farther on. Trajan is in all probability the author of the cutting at the foot of the isolated dolomitic mass of rock at the lowest extremity of the promontory, by which the road was enabled to pass round on the level. The height of the cutting is marked in splendid Roman numerals in swallow-tail tablets at frequent intervals.

After the two roads have rejoined, there is a flat stretch for some miles, with a number of ancient culverts and bridges, still used by the modern road; and then beyond Fondi the road enters the picturesque gorge of S. Andrea, where it is supported by massive embankment walls, well seen from the modern road, which has here abandoned the ancient line.

On the descent, in the modern village of Itri, we see the "Cyclopean" wall to which I have already directed attention, and shortly afterwards reach the Bay of Gaeta and Formiae, where Cicero had his villa. From this point onwards the road proceeded on the level. Just before the fine bridge over the Volturnus, it joined up with the Via Latina-Labicana, and crossed to Casilinum, the modern Capua. Shortly after the ancient Capua the road enters the mountains once more, and after passing through the famous defile of the Caudine Forks, we find three finely preserved ancient bridges, of which the modern road still makes use. They are probably assignable to the period of Trajan.

We soon reach Beneventum, beyond which the course of the ancient Via Appia is so doubtful that there is no question of there being any remains of great interest. We shall, therefore, do well to follow instead the Via Traiana, which Trajan built as an alternative route to Brindisi, following an older mule-track of which Strabo speaks.

The road passes through some difficult country with frequent ups and downs, and there are a number of bridges in concrete faced with fine brickwork, stonework being used sparingly, and then only at the base of the piers. These bridges are all 24 Roman feet wide, which is more than the usual standard width (14 feet) of the Via Appia and other Roman highroads—though even they widened out somewhat at the bridges. From the summit, about 3000 feet above sea-level, there is a long winding descent, the Buccola di Troia, to the city of Troia, the ancient Aecae, with its fine cathedral. Here we enter the *regna arida Dauni* and the plain of Apulia. The road crossed two rivers, the Cervaro and the Carapelle, both of which have changed their course, and so left their bridges high and dry in the fields. They are, from the great width of the valleys and the character of the streams, which are wide and shallow—in fact, almost dry except in times of flood, when they carry a great quantity of water—structures of great length. The first is about 280 metres in length, about half of which is accounted for by the bridge proper, a structure with at least fourteen arches, the principal one having a span of about fifteen metres. The second is much longer, beginning with a causeway 200 or 300 metres long; then follows the bridge proper, some 200 metres long, with about ten arches; and then follows a causeway about 250 metres long, with supporting buttresses on each side.

We may turn now to the Via Flaminia, the "great north road" of ancient Rome, built by Gaius Flaminius during his censorship in 220 B.C. The Via Flaminia, unlike the Via Appia and the Via Latina, is not able to maintain its straightness of line for very long after leaving the Tiber valley. It comes into some heavy country among the hills on the right bank, but the first really serious obstacle by which it is confronted is the valley of the river Treia, which is subject to violent floods, one of which, only four years ago, carried away the modern bridge just below Civita Castellana. The valley is about 1300 yards wide, and the drop in level to the bottom is about 250 feet on the south, while the ascent on the north is some 150 feet. The difficulties were considerable, but have been very well dealt with; and the causeways and bridge by which the Roman engineers took the road across the valley form a splendid monument of their skill.

After crossing the plateau to the north, the Via Flaminia descends to the valley of the Tiber, which is followed by the railway to Florence; and here we may see its parapets still preserved beside a modern road which has recently been constructed along its line. A few miles farther on, below Otricoli, it crossed the Tiber and entered Umbria, traversing a hilly district as far as Narni, perched on a lofty cliff above the river. Ascending through the town, it reached the famous Bridge of Augustus, one of the wonders of Italy even in the sixth century after Christ, as Procopius tells us. Of the four arches by which it crossed the stream, only one is now preserved. Many other ancient bridges are preserved along the course of the road. The only other important work of which I shall speak is the tunnel by which the passage of the road through the Furlo Pass is facilitated; the inscription recording its construction by Vespasian may still be seen above the entrance.

The aqueducts of ancient Rome are among its most celebrated monuments; but, conspicuous as are their remains within the city and in its immediate neighbourhood, less is known of them at a greater distance than might have been expected. I have myself been engaged in the study of them for more than twenty-five years, and hope shortly to be able to complete the work with which I have been occupied for so long.

For the present purpose, I shall confine my attention almost entirely to the four aqueducts which drew their supplies from the upper valley of the Anio, the Anio Vetus (272–269 B.C.), Marcia (144–140 B.C.), Claudia, and Anio Novus (both built by Caligula and Claudius, A.D. 38–52)—two of them, as their name implies, taking their water from the river itself; while the other two made use of excellent and very abundant springs which are for the most part conveyed to Rome by the modern Acqua Marcia, though a few of them still gush forth freely in pools which have a beautiful bluish tint (one of the springs was, indeed, known to the Romans as Caeruleus). These springs, indeed, as has been ascertained by the engineers of the modern aqueduct, come from holes in the roof of the original Roman headings. They rise under the rocks at the edge of the floor of the Anio valley, only a little way above the river-level, and come probably from huge reservoirs in the interior of the massif of Monte Autore, being supplied by percolation from a great basin about 1500 metres above sea-level, which is snow-clad for the greater part of the year. As the Roman headings lie some seven or eight metres below the present level of the valley, which has been much raised by floods, it seems useless to try to identify, as previous authors have done, the individual springs of which the Romans made use.

It will be convenient to follow the course of all the four aqueducts together, observing their principal remains as they occur. The Anio Novus originally drew its water from the river four miles above the springs of the Aqua Claudia, at the forty-second mile of the Via Sublacensis; but as the water was apt to become turbid, Trajan carried out a project of Nerva, according to which the three lakes used by Nero for the adornment of his villa above Subiaco were used as filtering tanks. This increased its length considerably, the new intake being some six or seven miles farther up. Considerable remains of the dam still exist on the way up to the far-famed monasteries; but the centre of it collapsed in a flood in 1305—as the story goes, partly owing to the malice or imprudence of some of the monks who began to tamper with it. Otherwise there are no remains of any particular interest until we reach the gorge of S. Cosimato, some fifteen miles farther down. It lies a couple of miles above Vicovaro, where the road from the valley of the Digentia and Horace's Sabine farm joins the main road down the Anio valley, the ancient Via Valeria.

From Vicovaro onwards, all the four aqueducts remain on the left bank of the Anio. The deep valleys of some of its tributary streams create considerable difficulties for the aqueducts, and great bridges were required to cross them.

Farther down, the Aqua Claudia and the Anio Novus leave the river valley, and reappear in a small valley leading southward to the Valle d' Empiglione, which is traversed by the road from Tivoli to Ciciliano and Genazzano. In this valley we find only one channel (where we should expect to find two), of rough concrete, belonging to the original construction, and measuring 1·20 metre wide and 2·60 or 2·70 metres in height—characteristic dimensions of the channel of the Anio Novus when running alone. It runs along the side of the valley, so that only one external wall is exposed, and this has later facing. The same difficulty presents itself when we reach the main Valle d' Empiglione, for whereas previous observers have supposed that the two aqueducts which are here visible can be assigned respectively to the Aqua Claudia and the Anio Novus, the line going south belonging to the construction of the tunnel under the Mons Aeflanus by Paquedius Festus in A.D. 88, mentioned in an inscription, careful investigation shows that they branch off from one another at the north edge of the valley, and that the south branch falls slightly more rapidly than the other.

The south branch is undoubtedly still attributable to Paquedius Festus, and the western to the main aqueduct; but the problem of the existence of one specus only (which confronts us again at Ponte degli Arci, though not after we have passed Tivoli) remains at present insoluble.

The level of the bottom of the specus, at the beginning of the existing arches going southward (the northern extremity of the aqueduct near the road has disappeared), is 248·57, and at the end of the bridge it has fallen to 248·17, or 40 cm. in 349 m., which represents a fall of 1 in 872·5, or 1·15 per 1000. On the western branch the levels are 249·91 at the beginning of the bridge, and 249·83 at the end, or 8 cm. in 156 m., *i.e.* 1 in 1950, or 0·51 per 1000. Both of these falls are below the average fall in the long stretch of arches between Capannelle (where the aqueducts emerge from their long underground course) and Rome, which varies from 3·22 to 0·96 per 1000. The general average is 2 per 1000, but there is much variation.

In the next valley to the south is the only instance known to me of the existence of an alternative channel on an aqueduct bridge, which perhaps was provided in order to allow of cleaning before the beginning of the long tunnel, in which it would naturally have been exceptionally difficult. The tunnel must be about 2¼ kilometres long, and the fall is 5·90 m. to the tank where the branch rejoins the main aqueduct, or 1 in 381, or 2·62 per 1000.

We must now return to the main line, which has a fine bridge, the so-called Ponte degli Arci, over a tributary of the Anio. The original bridge was a massive structure in *opus quadratum*, most of which has disappeared, though the impressions of the blocks are visible on the pier of the great brick arch on the south-west bank, and some of the masonry itself in the base of the last pier on the north-east bank. The brickwork with which the concrete of the greater part of the bridge is faced is, once more, Severan in character. When the aqueducts emerge on the hillside above Tivoli we find the four specus distinct from one another once more.

There is a very interesting point where from a reservoir of the Anio Novus a branch channel runs off, falling sharply (about 1 in 10), and supplying when required, by means of vertical shafts, the channels of the three lower aqueducts.

After passing the point of junction of the tunnel built by Paquedius Festus, the next feature of interest is the fine bridge known as the Ponte S. Antonio, which served to carry the Anio Novus across a deep and narrow valley. We may note here a right-angled turn, which often occurs, to break the speed of the water immediately before reaching the bridge. The channel is surprisingly narrow, being only 80 centimetres wide and about 3·12 metres high. The bridge was originally a massive structure in ashlar masonry of volcanic tufa, and the fine central arch, 32·30 metres in height and 10·40 in span, is still visible on the west side. The width was originally only 2·60 metres and the total length is about 120 metres.

In the next valley, that of the Mola di S. Gregorio, there is a long bridge of the Anio Vetus, which, however, is a construction of the time of Hadrian, itself restored later—the change of period occurs in the arch over the stream. The original channel ran underground up the north bank of the valley until it could pass under the stream, and then returned on the south bank, where its channel may still be seen. It is, after all, unlikely that in 270 B.C. the Romans would have constructed an aqueduct above-ground which could so easily have been cut by an enemy, and Augustus followed the older line in his reconstruction. The bridge has a rapid descent of 2·92 in 25·30 metres, or 1 in 8·66, or 116·5 per 1000, at the end (the only case known to me at the end of a bridge) into the newer channel, which is some six metres higher than the older channel, with which it seems to have no communication. It continues to run for some way along the valley before it turns at right angles to tunnel through the ridge separating it from the next one, that of Ponte Lupo. The bridge had a total length of about 165 metres (with a fall of 1·06 in the main portion of 136 metres, or 1 in 129, or 7·75 per 1000), and a maximum height of 24·50; it has two tiers of arches for the most part, though the last seven on the left bank originally had only one.

We now arrive at the valle of the Acqua Nera, which is crossed by the Ponte Lupo, the best-known and the largest of the aqueduct bridges in this district.

It has hitherto been believed—and Mr. Newton and I still held that view when the drawings were made—that it carried all the four aqueducts. Accurate levelling has shown that this is not the case, and that the Anio Novus and Claudia both pass under the floor of the valley considerably higher up. This, indeed, gives them a much better line than the devious course which they would have taken supposing they had passed over Ponte Lupo.

The upper channel is, therefore, that of the Aqua Marcia; the fall from Ponte S. Pietro is 186·79-182·27, or 4·52 metres in about a kilometre, or perhaps more; for the specus, as usual, runs along the side of both valleys for some way both before and after the tunnel through the ridge. But there is a problem in regard to the Anio Vetus. At the last shaft of the earlier channel in the Valle della Mola di S. Gregorio the intrados is 168·86 metres above sea-level, while at the last shaft of the newer channel, after the bridge which Hadrian built, the intrados is about 172 metres above sea-level; the floor of the specus would be about 2·80 metres lower in each case. The level of the water of the Fosso dell' Acqua Nera is 155·19, and the bottom of the specus at the Ponte Taulella is 155·61. The distance between the last two points in a straight line would be not much over two kilometres; but along the line of the aqueduct it should be 21,120 Roman feet, or more than 7 kilometres according to the *cippi*.

It is thus quite impossible that the Anio Vetus should not have been above-ground at the Acqua Nera, unless it was carried under it by a syphon. There is, about 17 metres below Ponte Lupo, on the right bank of the stream, a massive concrete buttress, faced with *opus reticulatum*, probably belonging to the time of Augustus, and containing a shaft, which, though blocked up, certainly seems as if it went down at least as far as the level of the stream, and might very well reach down to a channel passing under it.

The question why syphons were not made use of to take the aqueducts in a straight line (like the modern Acqua Marcia) across the Campagna from Tivoli to Rome (in which they would have come to intermediate levels considerably lower than that which they reach at Porta Maggiore), in order to avoid the long detour which we are now following, has been well answered by M. Germain de Montauzan in his book on the four Roman aqueducts of Lyon, in which no less than ten syphons have been observed. The Romans did not trust their concrete and cement for making syphons, though they might have done so. They were unable to make a large metal pipe that would stand pressure; and at Lyon the contents of a channel 0·58 by 1·75 metre are transferred to nine or ten lead pipes with a bore of 0·20 when the syphon is reached. We have only to calculate the enormous quantities of lead that would have been required to take the water from four channels, the largest of which measured nearly 1·20 metre wide and 3 metres high, and to remember that small-bore pipes would have been choked almost at once by the heavy calcareous deposit, to realise how impossible it would have been to adopt this method here. On the other hand, all the building material required was quite easy to obtain on the spot or not far off. But there is no objection to its use in a rock-cut channel for a short distance; and if we do not accept this view, we have to find a place for the specus of the Anio Vetus in the lower part of Ponte Lupo; and a careful study of its construction and of the dating assigned to its various parts by Miss van Deman has shown me that this is by no means easy, though from the levels it is admissible.

Raffaelle Fabretti, one of the pioneers of the investigation of the aqueducts, whose work "De Aquis et Aquaeductibus Urbis Romae" was first published in 1680, marks the so-called Ponti Diruti as the last remains of the aqueducts visible towards Rome; and, indeed, it was believed until a few years ago that they ran underground from this point to the well-known line of arches which begin at Capannelle. Even Prof. Lanciani had written of all the four that there were no traces from Cavamonte to Roma Vecchia and Capannelle respectively. But the casual discovery of a part of the channel of the Aqua Claudia on the farm road leading to the Casale della Pallavicina directed his attention to the possibility of discovering the course of the aqueducts in this district; and he further suggested that the large amounts of calcareous deposits thrown out at the shafts (*putei*) which occur at frequent intervals in the subterranean course of the aqueducts were bound to reveal their course still further towards Rome, where they traverse the lower slopes of the Alban Hills. This proved to be the case; and it has thus been possible to follow them from point to point in their gradual descent towards the plain, until they emerge between the Via Latina and the Via Appia.

In all this stretch, however, there were no complicated problems of engineering to be solved; and we may therefore turn to the consideration of the remains of the aqueducts after their emergence. The arches of the Claudia and Anio Novus gradually increase in height from Capannelle to Roma Vecchia, until beyond it they reach their greatest elevation in this section, estimated by Lanciani at 27·41 metres. In this stretch they are extremely well preserved and have not required restoration to any considerable extent. The lower stone channel of the Claudia is surmounted by the concrete specus of the Anio Novus, faced with brick and *opus reticulatum*—an obvious afterthought, the detrimental effects of which we have already seen.

Further on, as we come nearer to the city, considerable reinforcements have become necessary. In many places the original stonework of the piers has been removed for building material, and Lanciani quotes the records of the sale of, *e.g.*, two or four peperino pillars by the Hospital of Sancta Sanctorum at the Lateran, to whom the ground belonged. But, as he also points out, sometimes the brickwork was removed and the stonework left; or, again, the brick facing is sometimes hammered away from the concrete.

The question as to the amount of water carried by the aqueducts depends upon the value given to the *quinaria*, the official unit of measure, explained by Frontinus, who, as *curator aquarum* under Trajan, wrote a treatise upon the aqueducts. The most probable value has recently been determined as 0·48 litre per second or 41·5 cubic metres in twenty-four hours; and we thus get the following table:

	Quinariae (Frontinus).	Litres per second.	Cubic metres per diem.
Anio Novus . . .	4738	2274	196,627
Claudia	4607	2211	191,190
Marcia	4690	2251	194,365
Anio Vetus . . .	4398	2111	182,517

There were no large clearing or settling tanks within the city, only comparatively small reservoirs (*castella*) from which distribution was made by lead pipes; and this is the case with the modern aqueducts also, so abundant is the supply.

The Romans, as we have seen, having at their disposal comparatively little theoretical knowledge of mechanics, they yet succeeded in achieving marvellous results, largely from their practical ability. They must have solved such problems as the transportation of an obelisk by the multiplicity of simple elements of traction employed and by the ingenuity displayed in their arrangement. When it is a question of sea transport, we cannot but admire the courage of those who succeeded in bringing such huge masses of stone through the Mediterranean from Egypt to Italy without the aid of steam — an even greater enterprise than dragging them along the land without the appliances that we now have at command. The study of practical engineering among the Romans shows us that in this, as in other spheres, they added very considerably to the sum of human achievement, and thus contributed in no small measure to make the condition of the human race what it is.

The Science Museum, South Kensington.

WORK has just been commenced on the eastern portion of the new Science Museum buildings in South Kensington, and by the spring of 1927 a handsome façade (Fig. 2) should have replaced the plastered brickwork which has stood on the west side of Exhibition Road since the War.

Behind this east face, however, much has already been done, and a series of galleries on each of the four floors have been completed during the past three years to replace the Western Galleries on the north side of Imperial Institute Road, which were transferred to the Imperial War Museum in 1922. With the completion of the eastern front, which includes four galleries facing Exhibition Road, the first portion of the new Science Museum buildings will have been provided, following the recommendations of Sir Hugh Bell's Committee of 1911.

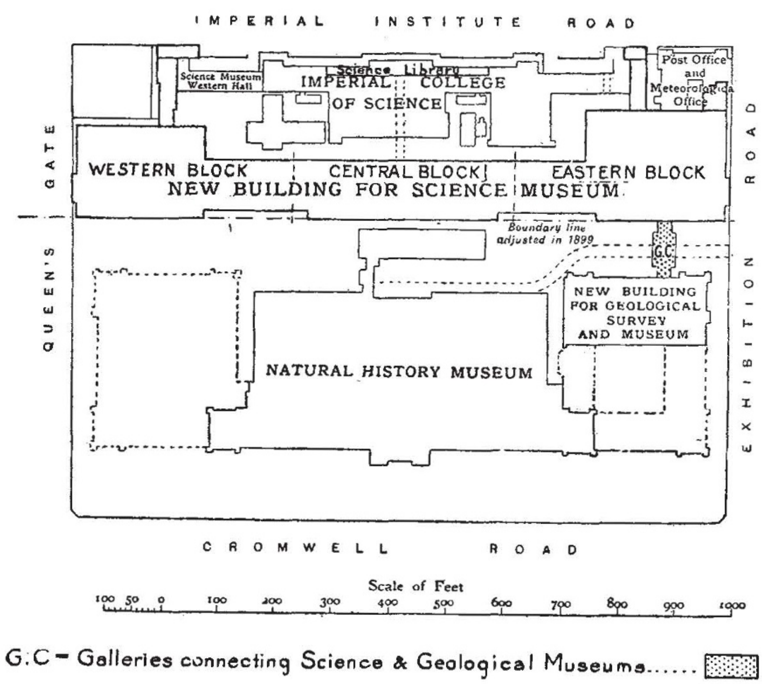

FIG. 1.—Plan of museum buildings, South Kensington.

This Committee recommended[1] that the existing buildings, which had been originally erected for the refreshment rooms of the Exhibition of 1862, should be replaced by three main blocks with connecting galleries, to be erected on the existing site and to extend ultimately from Exhibition Road to Queen's Gate between the Natural History Museum and the Imperial College of Science. The eastern block, which is now nearing completion, will provide 100,000 sq. ft. of exhibition space, and so much of the connecting galleries as are in use, though not completely finished,

[1] H.M. Stationery Office, Cd. 5625 and 6221, 1911, 1912.