Proceedings of the First International Congress on Construction History, Madrid, 20th-24th January 2003,
ed. S. Huerta, Madrid: I. Juan de Herrera, SEdHC, ETSAM, A. E. Benvenuto, COAM, F. Dragados, 2003.

The evolution of traditional types of building foundation prior to the first industrial revolution

Ana María García Gamallo

The aim of this paper is to describe the chronological evolution of the traditional types of building foundation used in buildings constructed within the borders of the former European provinces of the Roman Empire, during the period of time spanning from the appearance of the first of these types of foundations up to the dawn of the first Industrial Revolution.

With this aim in mind, archaeological, historical and bibliographical information related to sizing and building processes used in the construction of foundations, both shallow and deep, over the period studied, has been critically gathered and ordered.

Both the geographical scope and the time span chosen are very wide, because given the scarceness of doctrine on these matters, it is intended to lay down a general approach and open up the way for future and more in-depth investigation.

Antecedents of shallow foundations

Before going into the study of the chronological evolution of shallow foundations, it would seem convenient to carry out a brief critical analysis of the different prototypes and of how they came into being, because, as will be seen, the causes behind their origins had a huge influence on their later evolution.

Prototypes of footings

The antecedents and/or prototypes of footings appear to be much more related to constructional and compositional matters than to specifically geotechnical ones. These prototypes are the following:

- Of isolated pad foundations: the embedded block of stone and the stone pedestal.
- Of strip foundations: the trench foundation under wall.

The origin of the embedded block of stone coincides with the erection of the first megalithic constructions.

Towards the year 4000 B.C., European man already knows how to drive a tree trunk into the ground. But knowledge of this technique does not enable him to embed a great block of stone, of several tonnes in weight, so that it remains upright.

The solution given to this specifically constructive problem is making an excavation that allows the position of the stone block to be changed, tipping it from the horizontal to the vertical position. (See figure 1).

Once this problem had been solved, it was very likely realized that varying the depth of the excavation made it possible to achieve an approximately horizontal plane at the top of the building, even though

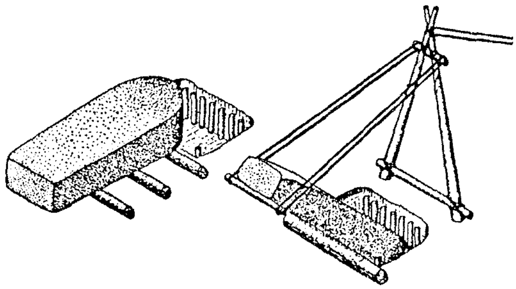

Figure 1
Erection of menhirs (Atkinson 1956)

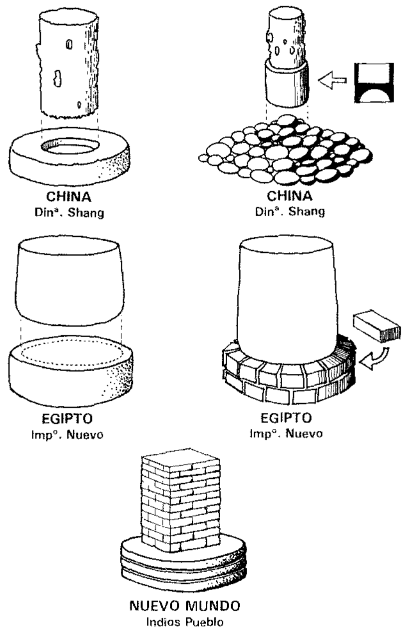

Figure 2
Types of pedestal

stone blocks of different heights had been used. Through this discovery, excavation took on a compositional function, closely linked to the origin of post-and-lintel architecture.

The origin of the stone pedestal, on the other hand, coincides with the appearance of the first buildings using true columns (in stone, timber or brick).

The great typological variety of these pedestals and their appearance in geographical regions far apart do not enable any relation between their use and the quality of the soil to be drawn. (See figure 2).

Moreover, it seems that these pedestals were built with no mechanical purpose in mind, and if they did have such a purpose, they were not well-resolved, because in most cases, the small surface area of their bases and their insufficient depth do not allow any mechanical function to be fulfilled by the stone: neither the spreading of loads nor the transmission of loads to the ground.

However, these pedestals did allow the position of columns to be fixed, and the bases and tops of the columns to be perfectly aligned in horizontal planes. So they did in fact carry out constructional and compositional functions.

Something similar happened with the prototype of the trench foundation under wall. In fact the first examples of walls built in an excavation form part of buildings resting on rocky ground, in which, from the mechanical and geotechnical point of view, there was little need to build footing foundations below the walls.

Besides, these first masonry strip foundations are elements completely indistinguishable from the structure they bear, for which reason it does not seem they were built with the intention of serving as elements for spreading or transmitting loads to the ground.

However, there is no doubting that the excavations these walls were built on, facilitated the process of setting them out and levelling them extraordinarily, for which reason the origin of these excavations would seem to be related more to constructional and compositional needs than to mechanical ones.

Prototypes of raft foundations

Without a doubt, the antecedents and/or prototypes of raft foundations are elevated plinths, whose origin would appear to be strictly compositional. As a matter of fact, most authors agree that these artificial topographies were used exclusively to emphasize the importance of the building atop them.

It seems likely that this compositional, and non-mechanical, origin should influence the method of construction used for these plinths, insofar as real stone or brick masonry was not used in the process,

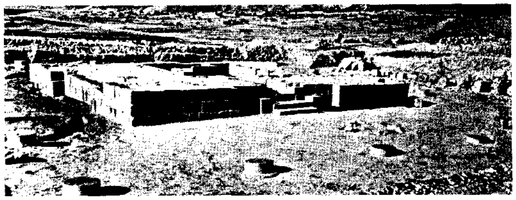

Figure 3
Stone plinth in Altinpepe (Özgüc 1966)

but instead only the products resulting directly from earth movements for site preparation.

But, at least in those plinths which have survived to our day, these materials were not simply dumped but carefully placed and treated so that they could work as a real structure and perform mechanical functions.

So it seems likely that plinths evolved from their originally purely compositional function to become real foundation structures, in this case raft foundations. Proof is found in that towards 800 B.C. the first plinths with real stone masonry were built. (See figure 3).

Prototypes of timber grillages

The antecedents and/or prototypes of timber grillages appear to be the plinths made from logs in primitive lakeside dwellings in the danubian region, belonging to the Neolithic period. As a matter of fact, it is from this time onwards that Man carries out the first attempts at improving the quality of his living spaces, which allow him to prolong his stay at the chosen settlement.

In those places where timber was readily available and the ground was very soft and wet (boglands), the timber plinth provided a certain degree of insulation against the dampness of the ground and some kind of reinforcement which made the floor of the dwelling fit for walking on.

In the beginning, these plinths did not perform any function related to resistance, as they are completely independent of the vertical elements which hold the dwelling up. But they evolved and, towards 3000 B.C., they became plinths of timber grillage supporting vertical elements, placed directly on the ground or built over piles, as in the case of lakedwellings. (See figure 4).

So, starting from a modestly utilitarian purpose, log plinths evolve into real foundation structures, which, in contrast to the rest of the prototypes of shallow foundations, do appear to be closely linked to the geotechnical characteristics of the ground, and in particular with those of soft grounds, in contact with water.

Chronological evolution of shallow foundations

Within the borders of the former European provinces of the Roman Empire, during the period of time studied in this paper, shallow foundations are almost always resolved with footings, and only exceptionally with raft foundations or timber grillages.

In these lines, we are only going to deal with the evolution of footings, because the lack of true raft foundations makes it hard to detect any kind of evolution at all, and because the timber grillages built up to the first Industrial Revolution do not display any real signs of evolution with respect to those employed in primitive lakedwellings, but simply become widespread, especially after the Middle Ages, when they began to be used as the base for footings on very soft grounds, in contact with water.

Ancient Greek architecture provides several important milestones in the evolution of footings, amongst which the following are worth a mention:

— The construction of footings completely distinct from the structure they bear.

— The occasional use of projecting and tapered section foundations.

— The introduction of bracing between footings.

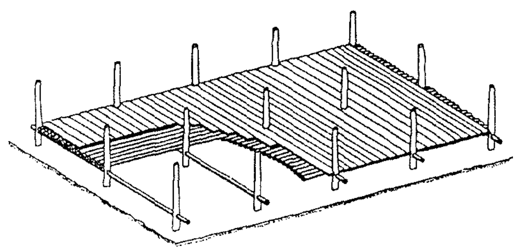

Figure 4
Lakedwellings belonging to the third phase of settlement at the archaeological site in Le Weier (Pétrequin 1984)

The most commonly used footings are strip foundations, usually built with a rectangular cross-section with no projection and resting directly on bedrock. (See figure 5).

Footings with projections or those with tapered cross-sections are only very rarely used, when, on excavating the foundations for singular buildings the bedrock does not appear at the expected depth. (See figure 5, again).

This cross-section, decreasing in width towards the foot of the wall, may have arisen due to economic reasons. But the widening of the foundation towards its base reveals a clearly mechanical intention and enables us to say that the Ancient Greeks were intuitively aware of the distribution of loads across a surface.

Moreover, there is no doubt that the use of these tapered cross-sections made it necessary to plan the dimensions of the foundation prior to its construction. What remains less clear is whether the dimensions were calculated according to the width of the element supported or according to the depth excavated to establish the footing's plane of support.

Tied footings appear in the Hellenistic period and are the culmination of a long process of struggling against the effects caused by earthquakes on Greek buildings.

Towards the year 800 B.C., the greeks are already aware of the fact that the horizontal direction is the most unfavourable component of seismic movements. The first attempts made to tie the building fabric through the insertion of logs and metallic cramps, from this moment onwards, bear witness to this. These solutions are followed, in the Classical period, by full bracing of the structure and transitional elements between it and the foundations (footings known as orthostatae).

So it does not seem strange that after all these experiences, the greeks should also try using ties in foundations, in one or both of the main directions. In fact, in some examples (temple of Apollo in Didyma), these ties form true load-bearing stone lattices beneath the buildings.

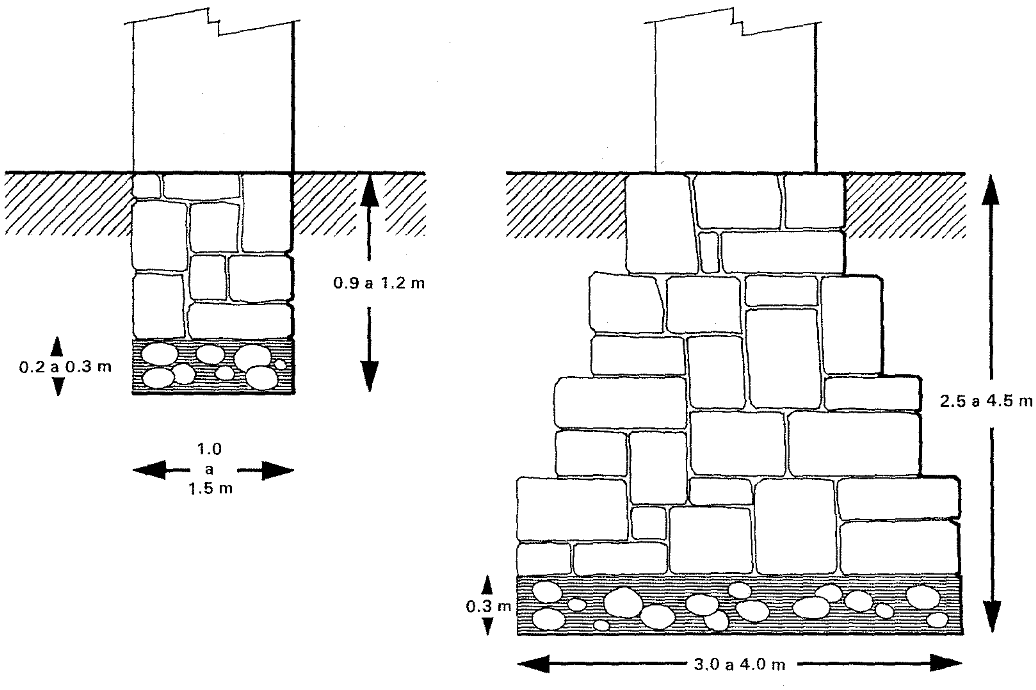

Figure 5
Strip foundations in Ancient Greek architecture

In Roman architecture, footings are already usually built with projections and a great variety of cross-sections. But it seems there was no rule for determining the size of the footings, because in the different examples, all the projections are different too, and because according to the translator Ortiz Sanz (1787), although Vitruvius *«orders that foundations be given greater width than walls above ground level»* he never defines the magnitude of that width, *«leaving it to the architect's discretion»*.

However, it seems likely that the Romans sized their foundations according to the loads to be born, and the load-bearing characteristics of the ground, at least qualitatively. In fact, Vitruvius himself (Book I, Chapter V) points out that the projection *«should be in relation to the quality and the magnitude of the building»*. And the foundations of the many notable buildings which have survived to this day show that the Romans paid heed to this recommendation, and also to the one contained in Chapter IX of that same Book I, in which Vitruvius remarks on the need to excavate the foundations until *«a solid bottom»* be found, and even to deepen further *«within it, as much as is necessary in relation to the importance of the construction»*. The foundations of Roman buildings destined for defensive purposes provide numerous examples.

But in the regions of northern Italy and Gaul, the Romans did not find that *«solid bottom»* at a reasonable depth, but instead very soft and wet soils, in great depths. This unfavourable circumstance led to a new constructional technique, which became widespread later throughout all the provinces of the Empire, remaining in use until well into the 19^{th} century.

This new technique involved the construction of footings on soil improved by driving stakes into it, at very close intervals. (See figure 6).

It should come as no surprise that this solution should have become widespread because it is one of the greatest successes over the whole of the period studied in this paper. By driving stakes into the soil, three objectives were achieved: first, compacting the soil; second, inserting a material of higher resistance into the soft ground; and third, increasing the depth of the foundation's plane of support, all three of which improved the load-bearing capacity of the ground noticeably. And all these improvements were achieved without the need for excavating, something which was especially interesting where water was present.

Judging by Vitruvius (Book II, Chapter IX), the use of posts driven into the ground in order to compact it may have originated in Ravenna, a city with old timber buildings resting on piles, in which it seems very likely that the first masonry constructions were built on the remains of primitive buildings, that is to say on the timber posts driven into the ground to support the old pile-dwellings.

When faced with the problem of supporting new buildings on this type of ground, the solution consisting of extracting the old piles and then excavating trenches in the mire was obviously of much greater difficulty and far superior cost to that of resting directly on the remains of former constructions. So the most likely thing was that the builders of Ravenna, in the same way as builders of all times, adopted the simplest and most economic solution. And seeing their success, this same solution must have been tried out at other lakeside locations, but this time newly settled, where as a phase prior to construction of the buildings, stakes were driven into the soil, on top of which the foundations proper were then laid. Some authors, such as Fleming (1985), state that this procedure was followed in Venice, though at a later date.

Another event of the Roman era which also has a great repercussion on all later construction of foo-

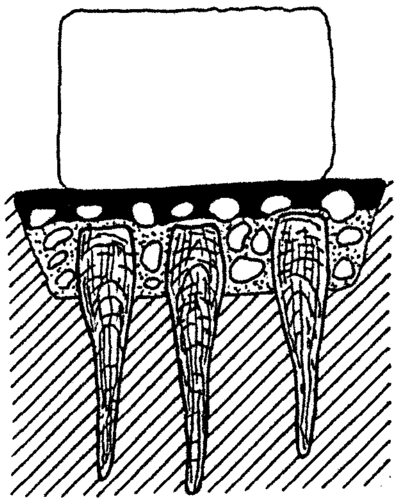

Figure 6
Roman foundations in «La Patonnière», Paulnay, Lower Berry, France (Kérisel 1985)

tings, is the introduction of a certain kind of plain concrete, made on-site with mortar and stones for foundation structures.

The earliest of these structures were used for economic reasons, in the city of Rome, when it was necessary to build foundations of great depth in section. But the advantages of these concrete structures (significant saving in both materials and labour) as compared to those made of stone or brick, led to their being used systematically at later stages.

From the fall of the Roman Empire to aproximatly the 15th century, there were not many new developments in foundations, because the shortage of resources characteristic of the Middle Ages did not allow large building projects to be undertaken until well into the 11th century, and once this stage had been reached, it was only using acquired knowledge and well-tested techniques, albeit with means much simpler and more limited than those available under the Roman Empire. This disadvantage affected both sizing and construction of all foundation types, including footings.

Just as the Romans had done before them, mediaeval builders also built their foundations with projections. But when they determined the sizes of the footings, both in plan and in cross-section, they did not take into account either the magnitude of the loads born or the nature of the load-bearing soil.

This carefree attitude regarding mechanical problems, combined with the construction of buildings of great height (towers, cathedrals) are the principal cause of the movements, cracks and collapses suffered by many of these buildings.

We may, however, highlight a building solution which is used with great frequency from the 11th century onwards, to form the solid base for foundations on soft ground in the presence of water. It consists of placing boards to form a grillage under the foundations, with the intention of reinforcing and levelling out the ground to become the plane of support.

It is no surprise that the use of these boardings should have become widespread, nor that it lasted until well into the 19th century, because amongst its several advantages, the following may be singled out:

- In muddy ground, the bottom of the footing could be made level simply and with ease.
- The timber grillage was comparable to the reinforcement of the foundation, the only kind available at that time, when steel was not yet in use in building construction.
- In comparison to piles, which as will soon be seen were the other typical solution for laying foundations on soft grounds in the presence of water, timber boardings required no special means for their setting and consumed much less in the way of materials.

The period spanning between the Renaissance and the first Industrial Revolution is notable mainly for the appearance of the first written rules for the sizing of foundations.

In theory, these rules take into account (or at least attempt to) the magnitude of the loads born and the nature of the load-bearing soil. But in practice, the inability to evaluate these parameters make such considerations simply declarations of intent.

The fact that the criteria proposed by the different authors of treatises should be so widely varied indicates the confusion reigning on such matters, although we could point out that in all treatises prior to the 18th century, authors agree on determining the size in plan of footings exclusively in relation to the width of the element they supported. (See figure 7).

In relation to these pre-18th century criteria it would seem convenient to list some facts gleaned on reading the texts. (See figure 7, again):

- With no apparent motive (although, no doubt, for economic reasons) the sizes of the foundations proposed by different authors become smaller and smaller.
- Since when sizing structural elements only their own dead load was taken into account, internal walls were mistakenly given less width than external façade walls. And the dimensions of the foundations carried the same error, depending as they did on the width of the element they supported.
- From the 17th century onwards, some authors of treatises (Bullet, Belidor), recommend that for external façade walls excentric foundations be built, with greater projections outwards than towards the interior of the building, basing this on the fact that «all external façade walls tend to lean outwards».

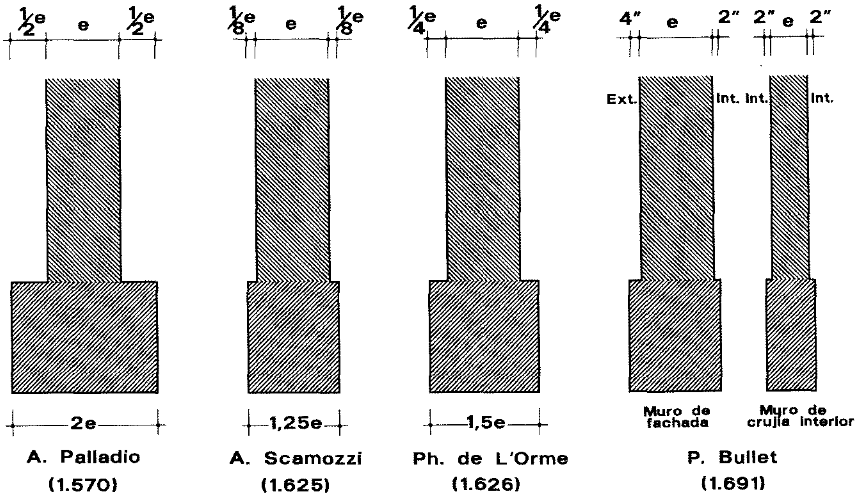

Figure 7
Sizing of foundations in treatises prior to the 18th century

This off-centre placement of the foundations for external façade walls is neither fanciful nor mistaken, since the make-up of old walls (with more or less noble, quality linings concealing heterogeneous infill, loose, very porous rubble or even earth) allowed neither the loads due to the structural elements holding the roof up nor those loads caused by the swelling of infill materials induced by water infiltration to be resisted. And these thrusts acted mainly on the outer face, the inner one being far more sheltered, drier, and, thanks to the bracing provided by the flooring, kept in a more stable position.

In relation to the depth of foundations, authors of treatises before the 18th century almost always state a fixed size, probably the one commonly used in their native homeland or region. However, these authors always recommend that if having excavated to this depth no *«firm ground»* had been found, digging should continue until it was.

In the latter years of the 17th century two new criteria for determining the size of footings appear, namely those due to Goldmann and Penther, which turn out to be the most successful of the whole period of time studied in this paper. It is a pity these treatises should have enjoyed such little dissemination, a fact probably due to the difficulty experienced by readers of latin descent when consulting the original German texts.

In these two criteria, the width of the footing does not depend on the width of the element supported, but rather on the depth of the foundation itself. And what is a complete novelty is that this depth is in turn determined in relation to the load-bearing characteristics of the ground.

In particular, Goldmann recommends the depth of the foundation be determined beforehand, by means of site investigation with dynamic penetrometers.

It would be convenient to note that Nicolaus Goldmann, an architectural theoretician who lived between 1611 and 1655, was the inventor of the first known dynamic penetrometer, whose construction, in the year 1699, signified the first great transformation of site investigation techniques for building purposes.

Indeed, until the construction of this first penetrometer, the characterization of the ground which was to support any given kind of building foundation was arrived at purely in relation to the physical and organoleptic properties of the uppermost layers of soil. On the other hand, from the early years of the 18th century onwards, when plenty of equipment was constructed (see the book *«Civil Engineering around 1700»*, by Jensen), the ground's resistance to penetration at depth became the essential information for evaluating its quality, at least in the case of important buildings erected near water, or in it, belonging to what is today the field of Engineering.

However, in normal everyday building construction, and within the particular field of Architecture, the recommendations of 18th century authors of treatises in relation to the sizes of footings hardly differ from those of previous treatises.

Nevertheless, given their repercussion, two of the recommendations which appear in some of these 18th century treatises could well be quoted here:

- That in order to determine the size in plan of footings, not only the width of the element supported should be taken into account but also its height.
- That if on excavating a set depth (varying between 2 and 5 feet) no *«firm ground»* should be found, the excavation should be stopped and the foundations laid in good quality masonry.

The first of these two recommendations is quite reasonable, insofar as taking the height of the supported element into account represents, to a certain extent, the introduction of the magnitude of loads into the design process of footings.

But the second of these recommendations is not only completely unjustifiable but also totally mistaken, since the load-bearing properties of the ground disappear from the process of sizing the foundations altogether. And this at the onset of the first Industrial Revolution.

ANTECEDENTS OF DEEP FOUNDATIONS

As with shallow foundations above, we will begin with a brief critical analysis of the causes which led to the appearance of the prototypes of deep foundations before going on to study their chronological evolution.

Prototypes of shafts

There is no doubt that in all regions and cultures the excavation of pits is closely linked with mining and with the search for subterranean water. Proof of this is that shortly before the Neolithic period flint was already being sought using underground galleries, dug out with animal bones and entered by means of vertical shafts (Kérisel 1985).

But the earliest shafts linked to building foundations seem to be those built in the eastern Mediterranean, and more specifically in the regions of Mesopotamia and Egypt.

Several shafts have been discovered in the region of Mesopotamia which date back to the period going from 3000 B.C. to 2000 B.C., and which form part of some of the earthworks serving as supporting structures for the ziggurats. However, the excavation of these shafts seems to be related to some kind of esoteric ritual.

In Egypt, according to professor Rodríguez Ortiz (1989), the use of a limestone caisson for the foundations of tombs, towards the year 2000 B.C., is the most outstanding antecedent of shaft foundations. In particular, of those built below water using the characteristic and traditional system of the Egyptians: the *«zarbbiyeh»* also known as *«the mining caisson»*. (See figure 8).

In Babylon, the ruins of the Hanging Gardens, dating back to the year 600 B.C., may belong either to shaft foundations or to a structural system based on piers interconnected at their tops by arches or vaults, depending on whether when starting the foundations the builders dug shafts or removed earth wholesale. (See figure 9).

But whatever the building system used for these gardens, the use of their structural system for the construction of foundations could be very advantageous from the economical point of view. In

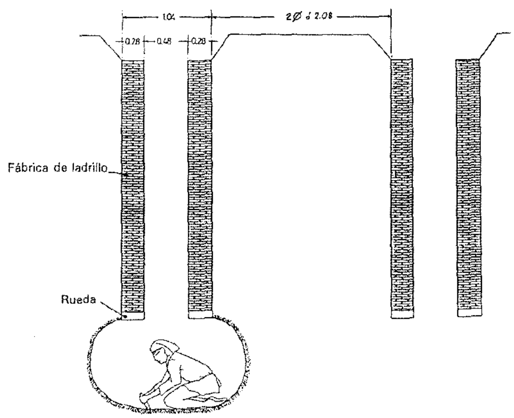

Figure 8
The *«zarbbiyeh»* or *«mining caisson»* (Kérisel 1985)

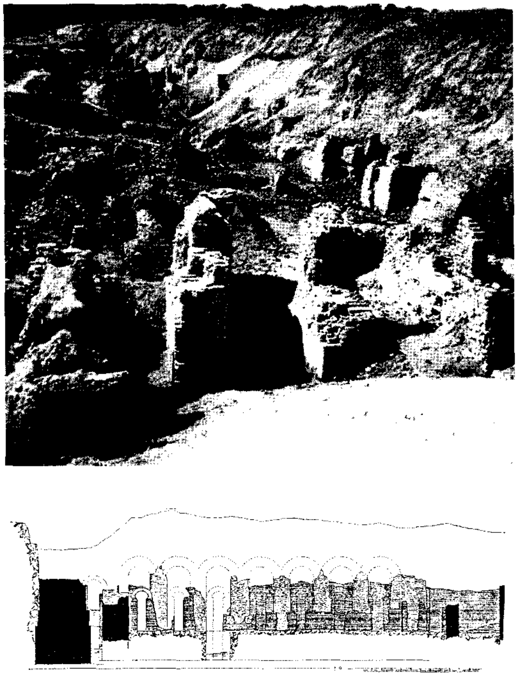

Figure 9
Foundations of the Hanging Gardens of Babylon (Giedion 1966)

fact, in those cases where the adequate strata were at a greater depth than expected it was far cheaper to build a set of shafts, at intervals to each other, and tied above by arches or vaults, than a strip foundation excavated to the same depth as these shafts.

Prototypes of piles

The antecedents and/or prototypes of piles are the log walls built in the primitive lakedwellings of the danubian region, belonging to the Neolithic period.

In the beginning (5000 to 4000 B.C.), these walls are completely independent of the flooring plinth, their logs driven into the ground to a depth of between 1 and 3 metres.

But, as has already been mentioned, the evolution of primitive plinths led to the appearance, towards 3000 B.C., of the first timber grillages built on piles. (See figure 4, again).

It seems that the location of these early lakedwellings was initially by the lakeside. But this building type also allowed a much more advantageous kind of settlement, from the defensive point of view: settlement within the lake itself. All that was needed for this was to lengthen the piles, but this entailed two new and important problems:

— Keeping the piles upright, even against the current or the waves.
— Finding tree trunks which were on the one hand long enough to be driven into the bed of the lake and on the other hand light enough to ensure penetration, given the scarce means then at hand.

The need to keep the piles in their proper position leads to the first solutions using bracing to reduce the free spans of the logs and to stabilize them, between 3000 B.C. and 2700 B.C. These solutions are already employed in some of the lakedwellings belonging to the third phase of settlement at the archaeological site in Le Weier. (See figure 10).

And the need to find long and lightweight tree trunks which would penetrate with greater ease leads, between 1800 and 1300 B.C., to the first solutions using composite piles, and the first treatments of the tips of the piles (carving and hardening by fire). As examples of composite piles we could cite those built at Fiavè, some of which reached 12 or even 13 metres in length, in two approximately equal sections.

All these solutions prove that towards 1300 B.C. there was a rather accurate knowledge of pile foundations, arising from the need to support certain structures (lakedwellings) on particularly soft and wet ground.

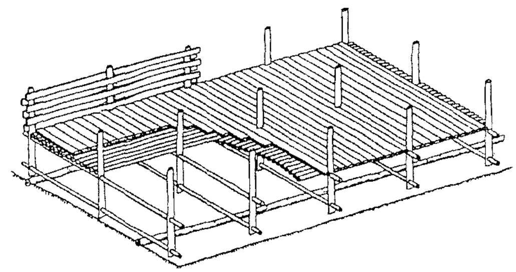

Figure 10
Bracing between piles in lakedwellings of the third phase of settlement at the Le Weier site (Pétrequin 1984)

Chronological evolution of deep foundations

Within the borders of the former European provinces of the Roman Empire, during the period of time studied in this paper, deep foundations were built using shafts or piles.

It should be noted that the word «deep» applied to these foundations is in fact relative, and only valid for their period of time, since until well into the 18th century the depths reached with this type of foundation rarely exceeded 3 or 4 metres.

It should also be noted that in the period studied and within the field of Architecture, the use of deep foundations is fairly rare and confined to a few cases, but not all, of building on poor ground.

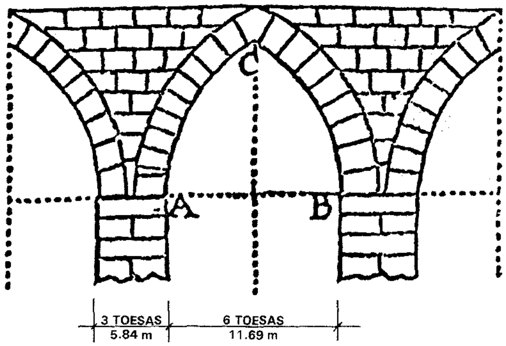

Figure 11
Sizing shaft foundations according to Bullet's treatise

Evolution of shafts

Within the borders of the former European provinces of the Roman Empire, it seems no true shaft foundations were built until well into the 19th century. Proof of this is found in the following:

- Examples of such foundations are scarce.
- Until the latter half of the 17th century, treatises contain no rule specific to this kind of foundation, no method of determining shaft dimensions or their configuration in plan.
- The fact that when at last these specific rules do appear it seems that the authors determine the dimensions of the shafts and their configuration with no other aid but experience in the cross-section of piers and the spans of arches and vaults forming part of superstructures previously built. (See figure 11).
- Until the 18th century, it does not seem to have been deemed necessary to take shafts down to firm ground. Moreover, almost all authors agree in considering tying shafts with inverted arches a way of avoiding differential movements between columns, movements which would have been almost negligible had those same columns been built over shafts resting on firm ground.
- Until the 18th century, techniques of site investigation for building purposes were very basic and their use did not allow prospecting depths beyond 2 or 3 metres, so that the quality of the ground lying under those levels of inspection was unknown.
- Until the 18th century, according to the contents of treatises, the characterization of ground as the plane of support for buildings was always carried out according to its physical and organoleptic properties, and not its mechanical properties.

Judging by the antecedents there is no doubt that this type of foundation was known at least since the Roman period, but in real constructional practice, shaft foundations were reduced to simple tied footings, albeit at a slightly greater depth than usual.

From the 18th century onwards, almost all authors of treatises recommend shafts *«built off a firm bottom»* for the foundations of buildings of a certain size on poor ground.

These recommendations appear closely linked to the phenomenon of urban growth, from which derived the need to build in formerly marginal areas, where, besides having to cope with grounds whose properties for building purposes were unknown, former rubbish dumps, tips and quarries for building materials were located.

However, it does not seem that true shaft foundations were built even during the 18th century. And this because almost all authors of treatises base their recommendations on one same example, which moreover is not in fact a shaft foundation at all, but simply a case of soil improvement by substitution: the church of Sainte Généviève, placed over a former quarry, whose architect, M. Soufflot, ordered all the holes encountered during excavations for the footings initially intended to be filled with brickwork.

The 19th century is the age in which shaft foundations go beyond mere theory to become a fairly frequent type of foundation used in real building practice.

This was entirely logical, bearing in mind that use of this system is conditioned by the presence of great depths of poor ground, and until that time, when the steam engine was incorporated to prospecting equipment, the available techniques for site investigation, even with the most modern 18th century penetration equipment, could not reach depths of over 7 or 8 metres. And so it was not possible to ascertain the nature of ground at great depths.

However, although during the 19th century it was already possible to investigate ground at great depths, the inability to evaluate its parameters of resistance led to the sizing of shafts being carried out completely independent of the ground's properties, as if they were no more than pillars subject to simple compression.

According to this criterion, the indispensable condition for the proper mechanical functioning of this type of foundation was to take them deep enough to encounter very firm ground, of a rocky nature, which would offer at least the same resistance as the masonry with which the shafts were filled. And this seems to have been done in some of the singular buildings where this type of foundation was used. In fact, various authors agree in stating that for the church at Montmartre, shafts were excavated to more than 30 metres depth, in order to rest on a rock of gypsum.

Evolution of piles

Within the borders of the former European provinces of the Roman Empire, during the period of time studied in this paper, piles are employed mainly as a technique for soil improvement, not as a type of building foundation.

Moreover, one can safely say that from the Roman Empire until halfway through the 18th century, most of these foundations are really footings resting on a set of closely-packed stakes driven into the ground.

As has already been mentioned when dealing with shallow foundations, the Romans developed this technique in order to build on very soft ground, and its good results led to its use becoming widespread and lasting, with slight variations, over the centuries. The foundations of mediaeval buildings erected in the cities of Venice and Amsterdam bear witness to this.

In the city of Venice, a somewhat clumsy method was used which consisted in, for one same building, supporting the footings of the external façade walls facing the canals on stakes driven into the ground, but resting those of the internal walls directly on the ground. (See figure 12).

Some authors (Fleming 1985) declare the origin of this absurd building system was related to the existence of two different phases of construction: an early one which might be termed the urbanization of the city, in which before buildings were undertaken the ground was compacted by driving stakes into it, and a later, more gradual one during which buildings were erected.

But even if this had been the case, this supposed second stage, which must have spanned a rather long period of time, made the dismal results of the construction method employed evident. So much so, that Venetian builders learnt to use numerous ties in the superstructures of their buildings, in both timber and iron, in order to minimize the effects of ground settlement. (See figure 12, again). And yet these same builders failed to realize that they should change the system of building foundations used, no doubt due to their inability to evaluate any loads other than those directly derived from dead loads.

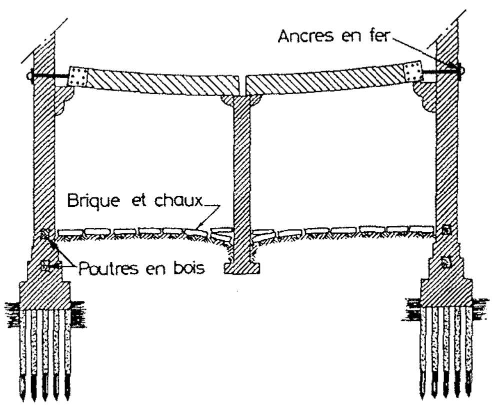

Figure 12
Traditional foundations of Venetian buildings (Kérisel 1985)

It should be remembered that Renaissance authors of treatises make the same mistake as Venetian builders when giving internal walls and footings widths far smaller than those of external façade walls. The only difference is that, in Venice, the façades were in direct contact with water, and so not only were their footings larger than internal ones, but they were supported on stakes driven into the ground. And this combination of poor ground conditions, erroneous sizing and the use of two different systems of building foundation for the same building simply worsen the effects of a kind of movement very typical of old buildings: the subsidence of their central section.

In the city of Amsterdam, a variant of the Roman solution was used which consisted in sawing the tops of the stakes off to a true horizontal plane, on which were then laid thick planks, far easier to build the foundations proper on. (See figure 13).

This solution, combining piles and timber grillage, spread to all areas of present-day Holland, and the remainder of the former European provinces of the Roman Empire, in which it must have been used quite frequently. As a matter of fact, the pile foundations proposed by all authors of treatises until well into the 18th century always combine piles and timber grillage, in three different variants, that are:

— Boarding resting directly on piles, as in Amsterdam.
— Boarding resting directly on the ground, with sheet piling surrounding the foundations, enclosing them and protecting them, in the presence of water, from subsidence.
— Boarding resting directly on the ground, combined with piles driven into it between the timber beams.

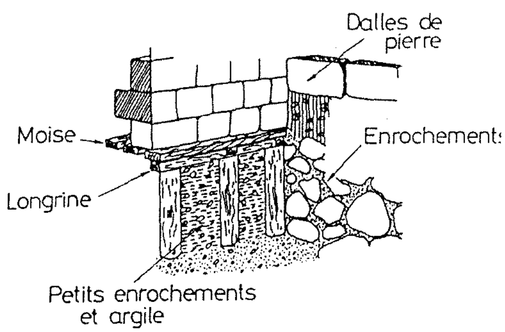

Figure 13
Foundations of a pier for a bridge across the Loire at Beaugency (Kérisel 1985)

But besides the building solutions recommended, the treatises also reveal considerable evolution in the criteria used for sizing and arranging piles in plan, offering ever more successful solutions over the whole of this period spanning from the 15th century to the dawn of the first Industrial Revolution.

With respect to sizing criteria, it should be pointed out that authors prior to the 18th century determine the diameter of piles in relation to their length, and their length in relation to the height of the element supported by them. Later authors also determine the diameter in relation to the length of the pile, but this length is now determined in relation to the quality of the ground.

As a result, in the theoretical field dealt with in the treatises, and coinciding with the turn of the 18th century, piles cease to be merely a technique of soil improvement and become a fully blown system of building foundation.

However, this change is delayed much further in real building practice, due to the fact that the length of piles was strongly limited and conditioned by the defficient machinery used for driving piles. So much so, that a length of only 5 m was already thought to be exceptional. And this situation lasted until the steam engine was incorporated into the equipment used, well into the 19th century.

With respect to the criteria used for the arrangement of piles in plan, it would seem that until Gautier's treatise, published in 1728, the interval between piles had always been determined according to the old rule of *«as much space empty as full»*, with which the separation obtained was obviously equal to a diameter. This was reasonable, bearing in mind that at the time, the main aim of using piles was to compact ground which was to support foundations.

However, Gautier proposes that the distance between piles be variable, depending on the depth to be reached and the load to be born. As a result it isn't strange that it should be this same author who provided what seems to be the first reference to the pile driving sequence, in which he states the order to be followed. (See figure 14).

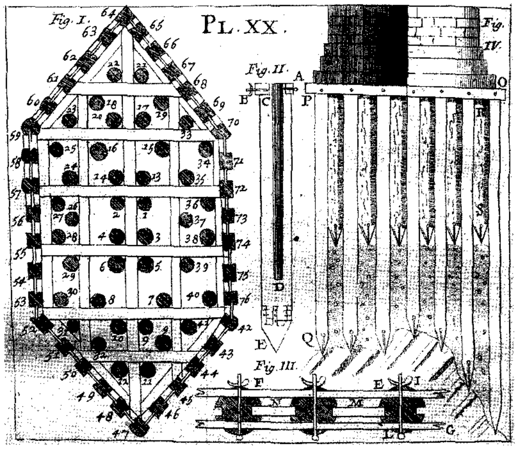

Figure 14
Pile driving sequence in a timber grillage foundation with infill piles (Gautier 1728)

It is not strange that Gautier's new criteria should modify what had until then been understood by driving to refusal. Since the Roman period, the need to arrive to refusal was maintained, but this was judged solely on account of the penetration achieved with each individual blow.

But halfway through the 18th century, Perronet already links refusal to the load-bearing capacity of the piles, and the method employed to drive them into the ground, possibly because it was at this time that the real transformation of pile-driving equipment took place.

Sure enough, although since the mid-15th century various attempts to invent pile drivers followed one another, such as those proposed by the authors Francesco di Giorgio (1450) and Juanelo Turriano (1595), the truth is that they had no immediate practical application in building construction, either because such machines were never built or because they were not adopted by their contemporaries.

As a matter of fact, until the beginning of the 18th century, when the first automatic mechanisms for releasing the drop hammer appeared, pile-driving used to be done manually, using very primitive hammers, whose origin would seem to pre-date even the Roman era. (See figure 15).

Figure 15
Manual drop hammer (Fontana 1980)

Conclusions

In the light of what has been said, and as a final conclusion to this brief summary, it can be stated that within the borders of the former European provinces of the Roman Empire, during the period of time spanning from the appearance of the first prototypes of foundations up to the dawn of the first Industrial Revolution, the evolution of both the techniques used for building foundations and the criteria governing their sizing and construction has been very slow, and limited mainly by the following factors:

- Inadequacy of the means available for site investigation.
- Ignorance of the ground's load-bearing properties and methods of evaluating them.
- Ignorance of the mechanical functioning of structures and the methods of evaluating any loads other than those derived directly from dead loads.
- Ignorance of mechanical soil-structure interaction.
- Iinadequacy of the means available to put into practice certain kinds of foundations (shafts and piles).

It can also be said, however, that in this same period did see an improvement in the building techniques used for foundations, linked mainly to the need to resolve problems arising from the construction of buildings of a certain importance on poor ground.

Refeence list

Alberti, L. B., 1414–1472. *«De Re Aedificatoria ó Los Diez Libros de Architectura»*. Madrid, Alonso Gómez, 1582. Edición Facsimil del Colegio Oficial de Aparejadores y Arquitectos Técnicos de Asturias, 1975, Oviedo.

Atkinson, R. J. C., 1956. *«Stonehenge»*. Hamish Hamilton, London.

Bails, B., 1796. *«Elementos de Matemática, Tomo IX, Parte I: Que trata de la Arquitectura Civil»*. Imprenta de la Vª. de D. Joaquín Ibarra. Madrid. Reedición Facsimil y estudio crítico de Pedro Navascués Palacio. Colegio Oficial de Aparejadores y Arquitectos Técnicos de Murcia. 1983.

Belidor, B. F. de, 1739. *«La Science des Ingenieurs dans la Conduite des Travaux de Fortifications et d'Architecture Civile»*. Charles Antoine Jombert, Paris.

Blondel, J. F. et Continué Par M. Patte, 1777. *«Cours D'Architecture»*. Chez Vᵉ Desaint, Libraire, Paris.

Bullet, M. P., 1691. *«L'architecture Pratique»*. Chez Estienne Michallet, Paris.

Fleming, W. G. K.; Weltman, A. J.; Randolph, M. F. and Elson, W. K., 1985. *«Piling Engineering»*. Surrey University Press.

Fontana, V., 1980. *«Architettura e Utopia nella Venezia del Cinquecento: Tecnica, Scienza e Architettura»*. Electa Editrice, Milano.

Giedion, S., 1966. *«L'Éternel Présent. La Naissance de L'Architecture»*. Editions La Connaisance, Bruxelles.

Gautier, H., 1728. *«Traité des Ponts»*. Chez André Coilleau, Libraire, Paris.

Jensen, M., 1969. *«Civil Engineering around 1700»*. Danish Technical Press, Copenhagen.

Kérisel, J., 1985. *«Histoire de l'Ingénierie géomécanique jusqu'à 1700»*. Congres International de Mecanique des Sols et des Travaux de Fondations. San Francisco, Aout 1985. A.A. Balkema, Rotterdam.

L'Orme, Ph. De, 1626. *«Architecture»*. Chez Regnauld Chaudière, Paris.

Özgüc, T., 1966. *«Altintepe. 1. Mimarlik anitlari ve duvar resimleri. Architectural monument and wall paintings»*. Türk Tarih Kumuru Yayinlarindan. Ser. 5, 24.27. Türk Tarh Kur, Ankara.

Palladio, A., 1797. *«Los quatro libros de Arquitectura de Andrés Palladio»*. Traducidos por Don Joseph Francisco Ortiz y Sanz. Presbítero. Imprenta Real, Madrid.

Patte, M., 1769. *«Memoire sur les Objets les Plus Importans de l'Architecture»*. Chez Rozet, Libraire, Paris. Minkoff Reprint, 1973, Génève.

Pétrequin, P., 1984. *«Gens de l'eau, gens de la terre»*. Ed. Hachette, Poitiers.

Rodríguez Ortiz, J. M., 1981. *«Memoria para la Oposición a la Cátedra de Mecánica de Suelos y Cimientos de la E.T.S.A.M.»*. Madrid.

Turriano, J., Siglo XVII. *«Los Veintiún Libros de los Ingenios y de las Máquinas»*. 2 Volúmenes. Colegio de Ingenieros de Caminos, Canales y Puertos, 1983. Ediciones Turner, Madrid.

Vitruvio Polión, M., 25 a.C. *«Los Diez Libros de Archîtectura». Traducidos del latín y comentados por Joseph Ortiz y Sanz, presbítero 1787.* En la Imprenta Real. Madrid