Reinforcing foundations with wood piles: Origin and historic development

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It is an almost universally accepted fact that the earliest known references to architecture and building construction are found in Vitruvius’ *Architectura Decem Libri*. As far as the use of piles to compensate for the low level of soil resistance, the famous author stated:

But if a solid foundation is not found, and the site is loose earth right down, or marshy, then it is to be excavated and cleared and re-made with piles of alder' or of olive or charred oak, and the piles are to be driven close together by machinery, and the intervals between are to be filled with charcoal (Vitruvius, trans. Granger 1962, 1: 181).

Although this is all Vitruvius stated about the use of piles to solidify foundations, interesting conclusions can be inferred from his statement:

— Piles were driven close together to increase resistance;
— they were driven by machinery;
— they were made of alder (*Alnus incana* or *Alnus glutinosa*), olive (*Olea europaea*), or oak (*Quercus petraea*);
— they were slightly burnt to increase their endurance (a well-known process to many who live in rural zones in Brazil).

One of the most distinguished translators of Vitruvius’ work — 16th century architect Claude Perrault— added a note to the text quoted above (Vitruvio, trans. Perrault 1684, 85). Perrault explained that according to Philander and Baldo, there were two types of machinery used to drive the piles close together: a large type moved by capstans, cables, and pulleys, and a smaller one that consisted of a manual beater in a tee shape to be operated by two people. Perrault also noted that the piles were not effective in swampy ground and an orthogonal reticular structure was used instead. It was made of resistant wood and the small squares were filled with small rocks on which the foundation rested, Figure 3.

Vitruvius mentioned elsewhere in his work that foundations supported by piles were used in the city of Ravenna, Italy. This city was a port and its ground was known to be extremely marshy. Thus, foundations supported by piles must have been common at the time of the great architect. He probably observed the use of this technique by the Julius Caesar’s legions he served. In *De Bello Gallico* Caesar mentioned the use of piles in the construction of bridges and other structures.

Archeological testimonies confirmed that Roman builders used piles to solve the problem of low resistance soil. The perforating end of the pile was reinforced with iron while the other end was reinforced with a ring to avoid fissures under the hit of the machinery. This technique survived all the way to our times.

From Medieval times only archaeology informs us about the use of wood piles in construction since construction techniques were not discussed by members of the *loggias*, but Venice is an example of
the large use of this technique in those times. During Renaissance, however, treatises on architecture brought to light recommendations on this construction technique. As usual, the humanist and architect Leon Battista Alberti, in his pioneer work *De Re Edificatoria*, recommended the use of wood piles and for the first time established the empirical parameters for their dimension and application. He stated:

Si configgano molti pali e pertiche, dalla cima abbrustolita, com la base rivolta in alto, in maniera tale Che l'area di quest'opera venga larga il doppio di quella che dovrà essere il muro; i pali devono essere lunghi almeno 1/8 dell'altezza che si vuol dare al muro, e grossi non meno di 1/12 della propria lunghezza (Alberti, trans. Orlandi 1966, 184).

Following Alberti many writers of classic treatises on architecture recommended the same technique be used in low-resistant soils. Noteworthy among these writers is Andrea Palladio *da Vicenza* who said:

Ma se'l terreno sarà molle, e profonderà molto, come nelle paludi; all'ora si faranno le palificate, i pali delle quali saranno lunghi per la ottava parte dell'altezza del muro, e grossi per la duodecima parte della loro lunghezza. Si deono ficcare i pali più spessi, che fra quelli nove non possano entrare degli altri; & deono esser battuti con colpi piuttosto spessi, Che gravi, accioche meglio venga a consolidarsi il terreno, e fermarsi (Palladio 1570, 10).
As far as the dimensions, Palladio repeated the same empirical recommendation made by Alberti. The same view regarding reinforcing foundations can be found in the work of Vincenzo Scamozzi (Scamozzi 1615, 2: 286) as well as in the work by other writers.

A 17th century drawing by a military engineer and housed at the National Library in Lisbon, Portugal, shows a detail of the use of piles. Since the drawing is represented in a graphic scale, it allows some interpretations. Clearly, the piles were not driven as close together as recommended by older treatises, possibly because of the variation in soil-resistance and the weight the foundation would bear. The piles in this drawing show length and diameter approximately equivalent to the old specification (1/12). The piles are topped by the traditional wood frame. Evidently, not all soils are identical to the soil of the Venice Lagoon that required 16,000 piles to support the two foundations of the Rialto Bridge. But Venice is a special case because practically the entire city has its buildings laying over piles which the specialized literature affirms to be larix (may be Larix decidua).

The end of the 16th century and the beginning of the 17th century witnessed the birth of military engineering followed by new concepts on fortifications with bulwarks whose more complex architectural plans often required building in less trustworthy soils. Military engineers followed the classic treatises and continued to use the same recommended technique to stabilize the soil. To avoid a tedious reference to the dozens of treatises of military engineers that flourished in Europe, we limit our comments to the Iberian Peninsula since the practices used there lead to the Brazilian practices that closes this paper.

Figure 3
Drawing representing reinforcing piles (scale in Dutch rods) BNL, D-250 P
The seed of the Spanish and Portuguese fortifications came from Italy, a country associated with Spain through technical and cultural ties in addition to dominion of territories; however, it was the Academia de Matemáticas y Arquitectura Militar (Academy of Mathematics and Military Architecture) that in 1582 became the first school to formally train military engineers. Many illustrious professors taught at the academy, among them Juan de Herrera, Ferrariño, Cédillo, Juan Ángel, Cristóbal Rojas, Spanocchi. Other schools followed the academy such as the Escuela de Palias (Pallas School), 1630, the Academias de Castilla y Andalucía (Castile and Andalusia Academies), 1635, the Academia de Matemáticas Española (Spanish Mathematics Academy), Milan, 1630, the Academia Real y Militar del Ejército de los Países Bajos (Royal Military Academy of the Army of the Low Countries), 1675, the Real y Militar Academia de Matemáticas de Barcelona (Barcelona Royal and Military Academy of Mathematics), 1710, (Zapetero 1985, 66) and others. As a consequence, the construction techniques described in the classic treatises were very influenced by Italian writers were delivered to new generations of engineers in Spain as well as in Spanish America. In these countries many buildings foundations were reinforced by piles. It is possible that the use of piles was more prevalent in the Spanish America because of the presence of marshy or low resistance soil as it is the case of Mexico City.

The father of the Portuguese military engineering was without doubts Luis Serrão Pimentel, the inspirer of the first school of military engineering founded in Lisbon shortly after the Restoration. The most well-known version of the Portuguese treatise Método Lusitânico (Lusitania Method) (Pimentel 1680) however, makes no reference to the use of piles as a technique to reinforce foundations since the focus of this treatise is the design of fortifications, not the techniques used to build them. Pimentel recommended the use of piles and wood frames in the construction of platforms for the cannons because of the low resistance of the soil of the terreplein. On the other hand in a work entitled O Engenheiro Português (The Portuguese Engineer) (Fortes 1729, 2: 278) another distinguished Portuguese engineer —Manoel de Azevedo Fortes— made specific reference to the use of piles. Azevedo Fortes addressed the characteristics of the soil and recommended methods to probe the soil. In his opinion «weaker and soft soils» required the use of frames nailed to the top of the piles with large headless nails (Fortes 1729, 2: 280). Azevedo Fortes considered oak and cork oak as the best types of wood to be used as piles, adding that a certain type of pinewood known as «pinho da terra» had also resisted well under water and under the blows of the «bogio» (pile drive equipment) (Fortes 1729, 2: 281).

The use of pinewood piles was also recommended by other Portuguese engineers, among them Carvalho de Negreiros. In one of his unpublished treatises on architecture Carvalho de Negreiros prescribed foundations on freshly cut green pinewood piles that should be driven into the soil in a way that the water would not exceed one palm and ½, or twice the width
of the piles. It is interesting to see that he did not recommend the reinforcement with iron because the oxidation of the metal could damage the wood. Nevertheless, he mentioned that iron-reinforced piles were used in some places of the foundations of the Praça do Comércio (Commerce Square) in Lisbon during the constructions directed by Carlos Mardel. The exclusive use of piles made of pinewood can be confirmed by excavations around most of the buildings in the Baixa Pombalina (Pombal’s Basin) in Lisbon.

As the wood piles are above all subject to the decomposition and attack by aerobic microorganisms, in general their use has been recommended below the water level. Usually, they have been used as piles working through lateral friction, but they sometimes work through point resistance. In this last case, special care was taken to avoid damages due to driving excesses, the hammer height being reduced above all and using hammer weights not inferior to half the weight of the pile, but never superior to its weight.

When the piles are driven through soft clay or silt soils until reaching more consistent soils, in depths smaller than 20 diameters, an adhesion coefficient of the order of 0.5 should be used. Penetrations inferior to 10 diameters should not be used. The type of pile material has little influences on the adhesion coefficient.

Of course the working load of a group of piles in clay cannot only be estimated based on the behavior of an isolated pile, because the effects of the elapsed time, of the disturbance and of the scale for a single pile is very different than for a group of piles.

To verify a rupture in block, the hypothesis often used that admits the behavior of the group is equivalent to that of a virtual mat foundation resting on 2/3 of the length of the piles and occupying an area that bounds the group of piles.

When wood piles are driven through layers of soft clay to firmer layers, the piles will be submitted to the effect of the negative lateral friction, besides the structural loads.

In cases where a superficial layer of soft clay is present (N<sub>spt</sub> between 3 and 5), an approximate estimate of the bearing capacity (Q<sub>b</sub>) and of the working load (Q<sub>W</sub>) of those piles (D = 0.20 m and L = 2.40 m) can be made, for the project criteria recommended empirically by Alberti (L/H = 1/8 and D/L = 1/12), based on the method of Décourt-Quaresma (1982, 1: 23) and in the verification of the rupture in block.

Thus:

\[ Q_b = Q_{s} + Q_{f} = 120N_s\pi D^2/4 + 10\left(4\pi + 1\right)\pi DL = 15 + 27 = 42 \text{kN} \]

\[ Q_{W} = \frac{Q_s}{2} + \frac{Q_f}{2} = 24 \text{kN} \]

In the case of a reinforcement with a framing of approximately 1 m x 5 m, the working load would be of the order of 400 kN, as follows:

\[ Q_{s,\text{group}} = 0.6 \times \frac{Q_s}{2} = 432 \text{kN} \]

\[ Q_{W,\text{shock}} = s_n A_{\text{shock}} = 20 N_{\text{spt}} A_{\text{shock}} = 400 \text{kN} \]

**Pile drive machinery**

As mentioned above Vitruvius already referred to pile drive machinery, but since the illustrations were not preserved with the text, one can only make conjectures as to the pile drive machinery, as did Perrault. Perrault’s conjecture does not render invalid the hypothesis that metal sledgehammers were used to drive piles in the soil. After the first half of the 17th century there is an extensive list of pile drive machines with drawings by their manufacturers, some more realistic than others, and some very elaborate and represented by excellent technical drawings. One of them was presented by Alessandro Capra, an architect and military engineer from Cremona and a machinery expert who served in Italy the army of Spanish King Philip IV. In the reprint edition of Capra’s treatise on architecture (Capra 1717, 267) there is a model of a pile drive machine that more or less illustrates how this machinery worked in the past. The same is not true of Giovanni Branca’s visionary project for a machine moved by hydraulic power and to be used in swampy areas (Branca 1629).

As far as contributions from the Spanish engineers to this topic many examples of interesting drawings can be found in the Archivo General de Simancas (Simancas General Archive), Spain. Dalambert and Diderot’s French Encyclopedia also has a rich repertoire of pile drive machines.
Colonial Brazil was extremely poor in written technical information. Even Brazilian scientists as Mathias Ayres Ramos d'Eça made his publication in Portugal. The only remaining source is the very interesting manuscript by Brigadier Diogo da Silveira Velloso, who wrote the work in Recife, Pernambuco, Brazil. The manuscript is part of the collection of the Biblioteca da Ajuda (Ajuda Library, Lisbon, Portugal). Velloso includes recommendations on the use of piles to reinforce foundations. As a follower of Vitruvius (whom he considered to be without doubts the master of civil architecture), and other authors of Italian treatises, Velloso’s recommendations repeated the same empirical parameters defined by Alberti, three hundred years before, i.e., that the area where the piles are driven must equal twice the width of the wall; the length of the piles must be at least 1/8 of the height of the wall and the thickness at least 1/12 of their own length. Following Alberti, Velloso also recommended that the piles were pounded down into the soil.

The systematic investigation of the historical archeology in Brazil, limited regarding quantity, has not yet yielded a proof to this construction technique.
that, as previously seen, has been used for thousand of years in other countries. On the other hand, there is documented proof found through the observation of a concrete case.

The fort of *S. José de Macapá* (St. Joseph of Macapá Fort) in the state of Amapá in northern Brazil, is one of the most important military monuments. Not only the plan but also the scale make this fort remarkable. Soil analysis conducted in preparation for the current restoration of the fort identified low-resistance argiliferous soil on the north side of the fort (sediments from the Amazon River). The iconographic documents of the area shows an old *igarape* formed by the waters of the great Amazon River.

Exactly toward the direction of the previous marshy area one can observe wall lesions in the vicinity of the St. Joseph bastion, Figure 8. A long time ago the structure had been reinforced with discharge arcs made of bricks.⁴

These lesions and the reports of soundings led all to suspect that at least part of the foundations of the fort were pile-reinforced. In an attempt to clarify the issue through historical investigation pertinent drawings were found on a 18th century report of the progress of the construction. As suspected, these drawings clearly demonstrated the use of piles in the foundation. The oldest of the drawings shows only the bastion and the place where the piles were to be driven.

A subsequent research in the Brazilian Army Military Archive disclosed a specific image of piles being used to reinforce a foundation, Figure 8, with details shown on Figure 9. The piles are square shaped because are cut from large trunks. The spacing of the piles shows peculiar details. The face to face longitudinal distance of the piles was always the same, the equivalent to 4 3/4 palms (1.045 m). The transversal distance from axle to axle varied from 4 palms (0.88 m) in high-stress areas that supported the wall, to 4 1/2, palms (0.99 m) in the counterfort area, and to 4 1/24 (0.92 m) in the inclined area of the wall (scarpment).

In Brazil there is a great variety of wood⁴ that resist to decay even when buried. The easy access to this type of material lead to its wide use in
construction until the 1950’s and even later on. Even later a well-known type of wood — *Beriba* or *Biribá* (*Duguetia lanceolata*) — was heavily used as piles supporting piers and landing docks. *Biribá* is extraordinarily resistant and for this reason popular. It is now an endangered vegetal specie protected by the Brazilian Government.

Among countless examples of important constructions of more recent periods with wood piles it is worth mentioning the customs building of the of Rio de Janeiro (1866), built on wood piles driven by a steam operated pile drive (Vargas 1996, 35); stretches of the docks of Rio de Janeiro (1866) and of Santos (1891); the Municipal Theater of Rio de Janeiro (1905); countless buildings from 6 to 8 stories in the flat land bordering the rivers Tamanduatei, Tieté and Pinheiros, in São Paulo (Teixeira 2000, 1: 9), many buildings of the Lower City of Salvador and so on. At the beginning hardwood was used but with the shortage of the rarest species eucalyptus started to be used.

A foundation that deserves special mention was built, in 1959, for the COSIPA sheet-metal ovens, with the driving of about 7,000 wood piles from 11 to 13 m topped with a 1 m thick rigid mat foundation measuring 33,50 m × 163,50 m. The largest problems faced in these piles foundations, crossing layers of soft soils, resulted in the lateral stress of negative friction coming, as much from the vertical settlement of the clay under the weight of the embankment (that arrives to have 7 m of thickness) as from the disturbance due to the great concentration of piles. This concentration also caused lateral displacements of the piles, it is tended measured where values of up to 10 cm of displacement were measured (Teixeira 2000, 1: 13). Depending on the type, the driven piles crossed or not a gravel layer from 1 to 4 m thick, resting on silt-sand residual soil, with SPT larger than 30. The piles leaning that layer suffered settlement of up to 9 cm, due to the consolidation of the underlying residual soil. Those that penetrated in the residual soil (some reaching the rock, to a depth of 35 m) suffered settlement of a few millimeters. Floors without piles supported directly on the embankment had settlements superior to 1 m.

One of the most recent examples of the use of wood piles is in Itajaí, State of Santa Catarina, in the 90’s with the building of 4 «dolphins» destined to the docking of ships. For two of those dolphins 33 «peroba» (*Aspidosperma polyneuron*) piles were driven and for the other two 51 eucalyptus piles were used. On average, the piles had a 23 cm diameter and they were driven to a depth of 18 m.

**Final Considerations**

The foundation system with reinforcement of wood piles, when located below the groundwater level, is a solution that has been efficient in practice along the years.

For grounds that can’t support direct foundation, the empiric parameters established by Alberti, to use wood piles at the time seem to be reasonable when compared with the results obtained by modern methods of semi-empiric estimate of bearing capacity.

**Notes**

1. In other copies of the Vitruvian text the wood mentioned is the willow (*saligneis* from *salignus*, a. um).

2. (Many piles are driven in the soil, the sharp end down, the base up, in a way that the area is twice the width of the wall; the length of the piles must be at least 1/8 of the height of the wall and the thickness at least 1/12 of their own length).

3. (But if the non-resistant soil is deep, as in the swamps, one must use piles whose length equals 1/8 of the height of the wall and whose thickness equals 1/12 of their own length. The piles must be driven so close together that there is no room for inserting a new pile and they need to be pound down into the soil in order to become stable).


5. Arquivo Militar (Portuguese Army Military Archive), Mss. n° 3770, 37. Negreiros, Joze Manuel Carvalho de. *Jornada pelo Tejo*. One can conclude that the proposed diameter was = 0,19cm.

6. Architect and military engineer of Hungarian descent who worked for the Portuguese government during the 18th century and arrived in Brazil in 1733.

7. [...] *subiculoque machinis adigitur quam creberrime* [...]


11. “Se o fundo do alicerce for pouco firme, e paulozo (sic.) se cravará de estacas em dobrada largura do que há de ser a parede, e as ditas estacas terão de comprido ao menos a outava parte do que há de ser a altura da muralha, e terão de grossura o que corresponde à duodecima parte de seu comprimento antes mais que menos; e cravarsão múdias metendo entre ellas outras estacas menores, ate que não fique lugar de meter mais; cavilharsão com outros paes atravessados, e principalmente por fora, enchendo os vaos com cal e cascalho de pedra múida, e por sima boas lages compridas e largas” (Idem, Cap. 24, fl.218v). (If the bottom of the foundation is not firm enough and swampy we must drive piles in an area twice as large as the designed wall, and the so called piles should have the length of at least 1/8 of the height of the wall and its width should have 1/12 of its length, better more than less; and they will be driven close together and other thinner piles will be driven between them until there’s no more place to any other piles. Then they will be jointed with other transverse pieces of wood, especially in the outside, filling in the spaces inside with lime and gravel, and on the top good, large and long stone slabs will be placed).

12. Igarapé is a word that originates from the tupy language (*i'ara pé*) and it means waterway: short arm of river or narrow canal.


14. Maçãranduba (*Monilius spp.*), Pau d’Arco (*Tabebuia spp.*), Sucupira (*Boudichia nitida*), Acaçu (*Vouacapoua Americana*) and many others, but mainly the Biriba also known as Pindiba (Duguetia lanceolata) which was the most prestigious one in Bahia (Brazil) with this purpose.

**REFERENCE LIST**


