

Substructure design of ancient master builders

E. G. Arun

Prof. Emeritus PhD /Yıldız Technical University, İstanbul, Türkiye, email: goruna@gmail.com

ABSTRACT

To achieve preservation in a building's historical and cultural context, diagnostic studies for understanding the causes and mechanism of decay based on historical information, environmental monitoring, evaluation of the present level of safety and selection of appropriate preservation methods and materials are indispensable scientific and technical basis for correct interventions. For proper intervention, understanding of structural behaviour and good engineering judgment with sufficient experience of the old construction techniques and concepts and correct interpretation of the analysis results of comprehensive structural analyses are needed. Generally, the old foundation systems that support the historical structures are different from the current practice in terms of materials used, foundation-structure connections and the functionality. Ancient master builders had introduced special techniques to make the structure withstand the lateral forces and control the underground water level and humidity to minimize weakening effects on the building. In investigating heritage buildings, for proper interpretation of the causes of the failures and for decisions on proper intervention, it is important to consider the engineering knowledge and practice of their construction time. This study is made through reviewing archaeological and history of architecture publications, discussions with archaeologists and experiences met during diagnosis phase of restoration works.

Keywords: ancient foundations, ancient water drainage, ancient underground water control

INTRODUCTION

In seismic areas, vulnerability of ancient masonry structures to dynamic actions is mostly due to ageing, environmental factors and lack of knowledge in the interpretation of the building construction methods during intervention. The construction method of the past is different than today. Therefore, the design of foundations and other related infrastructure elements, which are crucial in the dynamic behavior of a building, is also different from current practice. Before intervention decision, it is important to study the building construction methods and details

The ground response to earthquake-induced shaking depends on local soil conditions, the amplitude, frequency content, and duration of strong ground motion. The intensity of earthquake shaking varies depending on the geometry and properties of the subsurface materials, the soil topography, and the characteristics of the superstructure. To prevent long-term deterioration of the building's seismic instability, the structure must withstand lateral forces and moisture caused by groundwater movement must be kept under control.

Master builders had to adapt to the conditions of natural environment. Substructure design was an important consideration for them to control the underground water movement and to make their structure withstand the lateral forces. Ancient building masters, using techniques developed by previous cultures, their own trial and error, and techniques transferred from one generation to another, were able to empirically size and design an effective underground drainage and a foundation system.

The main objective of this paper is to point out the design of historical foundation and water drainage systems of master builders through reviewing history of architecture and archaeological publications,

discussions with archaeologists and experiences met during diagnosis phase of restoration works. During the investigation, it has been noticed that in seismic areas, the master builders had introduced special techniques to make the structure withstand the lateral forces in substructure and superstructure. The study of ancient design methods can improve the evaluation of the failures so that proper measures can be taken for the rehabilitation of architectural heritage and contribute to today's design considerations. The ignorance of the accumulation of master builder's knowledge and construction technique of their time may lead to incorrect intervention and long-term harmful effects on the structure.

ANCIENT FOUNDATIONS

The foundations of heritage structures usually are the best surviving part of a building. But they are often the least studied portions because it is difficult to excavate and very few information is available. Foundations, distributing loads from superstructure to the earth below, have to resist compression, tension and shear stresses imposed by the soil pressure and earthquake forces. Generally, the old foundation systems that support the historical structures are different from the current practice in terms of materials used and foundation organization. Through history, methods and materials of foundations were generally the same as the walls which they support.

Structures on old Foundations

In many cases of archaeological excavations, it is seen that new structures have been built upon old foundations. The ninth-century church of Hagia Sophia in Vize, Trabzon and Fatih Mosque in Istanbul was constructed on the foundations of an Early Christian Basilica. On the buildings constructed over old foundations, the old foundations were first covered with a layer of lime mortar with pozzolanic aggregates forming a level set and the new building's foundations constructed over this layer [Eyice, 1973]. The inner grillage of foundation walls was not completely bound to the perimeter wall foundation [Ousterhoud, 1999: AE Report, 2007: Nauman, 1991]. At the top of the foundation walls, timber beam sets were laid within each wall connected by iron spikes and covered with a protective layer of mortar at the point where walls meet. Soft soil was consolidated by timber piles. The foundation walls rested on timber grillage embedded in a Khorasan mortar over these timber piles.

Foundation Organization

In the organization of building foundation grillage, if different components of a building were not of the same weight and therefore would settle differently, the foundations of these components were not joined (Figure 1). The superstructure of these buildings was also separated as seismic joints. Such practice may be observed in Hagia Eirene Museum and Süleymaniye Mosque at Istanbul, and Double Hamam in Skopje. In Fatih Mosque at Enez, the foundations of the lightweight, wooden-roofed exonarthex to the heavier main block of the building were not bonded, although these different weighing blocks were constructed at the same time [Ousterhoud, 1999].



Figure 1. Foundation of different weighing parts not bounded in Sardes

The construction of foundation wall was either solid or a three leaved wall, where the space between the two rows of stones is filled with rubble and mortar or earth. The thick ancient building foundations of stone or brick masonry generally were vertical walls going deep into the soil. The foundations of the buildings usually didn't pass the underground water level. During the process of time, as the wall thickness reduced, the foundation walls widened as steps at the foot were practiced. If the wall was composed of closely spaced piers and there was not sufficient depth to step the foundations, sometimes inverted arches or vaults were made [Colliery Engineer, 1899] (Fig. 2). Soft soil was consolidated by timber piles. The foundation walls rested on timber grillage embedded in a Khorasan mortar over these timber piles.

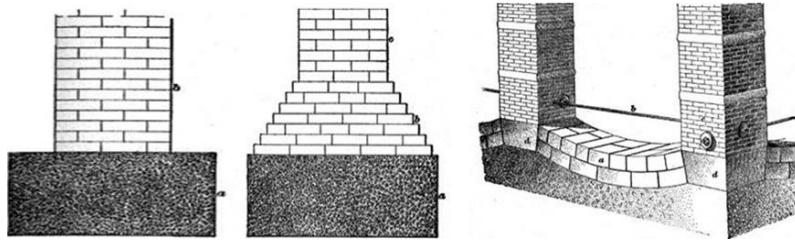


Figure 2. Foundation footings [Colliery Engineer, 1899]

The foundation construction of the walls depended on the grain structure of the soil and the geological way the soil was laid down. Acceleration generated by ground displacements is amplified or attenuated by the structure. To minimize amplification of acceleration input and prevent resonance, adequate construction would be stiff structure on soft soils, flexible structure on hard soils and rock. In high seismic zones, building masters introduced special techniques to provide the lateral stability of masonry structures.

If the rock bed or hard soil was deep, the foundation walls rested on a pillow layer of sand, gravel or small stones as in Phaselis, Antalya (Fig. 3). It is well known that a subsurface layer such as pillow of sand, gravel or small stones can change the natural frequency of soil so that the heavy masonry building doesn't experience resonance. An Assyrian tablet says that the soil was cut to the rock and the foundation was placed after filling the trench to 28 elbows height small stones [Sevin, 1998]. Pouring sand under the foundation was also practiced in Greek, Egypt and Mesopotamian buildings. As pronounced by old villagers, the foundations of masonry village houses at east Anatolia were constructed on a layer of ~40cm sand till 1960s. Afterwards, with the entrance of reinforced concrete construction to the villages, this traditional construction method was forgotten, and many masonry buildings constructed afterwards suffered during the earthquakes.

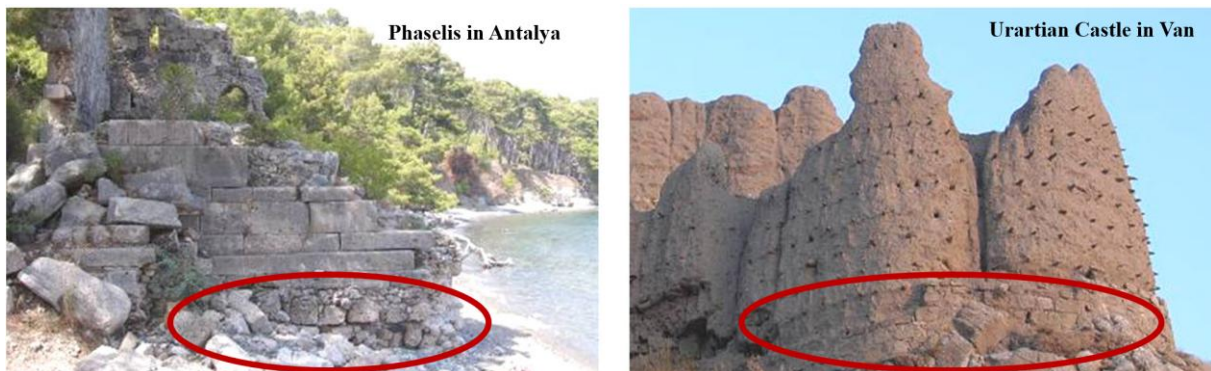


Figure 3. Foundation of a building in Phaselis, Antalya

If the bedrock is close to the surface, the rough surface of the rock is smoothed with small stones, and the foundation walls rest on single or more layers of wooden grillage [AE Report, 2007; Nauman, 1991 [Colliery Engineer, 1899] (Figure 4). In early Bronze Age of Beycesultan, Denizli on west of Turkey, 1.25m thick, 0.8m high rubble stone foundation walls of a palace rested on a single layer of round woods projecting out 1.0-1.5m out from the foundation wall filled with small stones [AE Report, 2007; Nauman,

1991]. The foundation of Konjic Bridge constructed in 1682 also rests on two layers of wooden grillage in between dolomite stones [Sert, 2007] (Figure 5). The foundation of the Süleymaniye Mosque rests on a bedrock via wooden grids filled with mortar, with piers that widen as they deepen [Aksoy, 1982]. During metro excavations in Istanbul, two chapels in Sirkeci and Üsküdar resting on two layers of wooden grillage were found (Figure 6). Use of wooden layers provides flexible base for buildings. Edirnekapı Cistern constructed late 19th century has inverted vault foundation resting on a timber grillage placed under the piers (Figure 7).

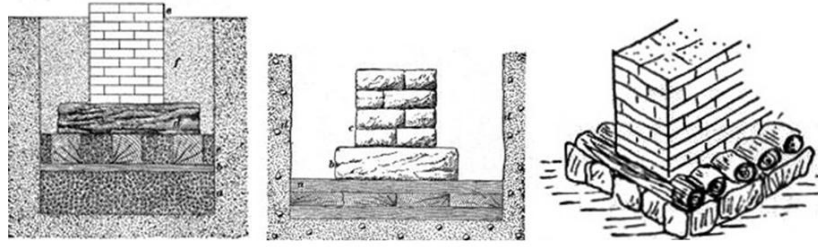


Figure 4. Wood foundation base [AE Report, 2007; Nauman, 1991; Colliery Engineer, 1899]

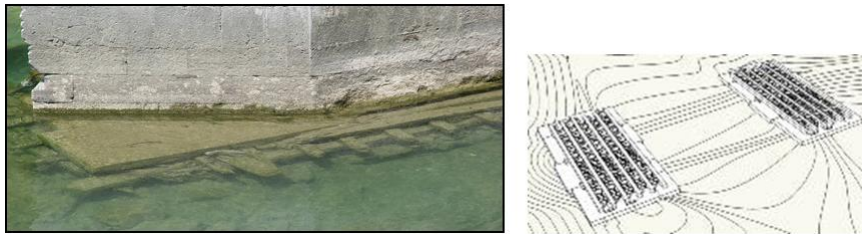
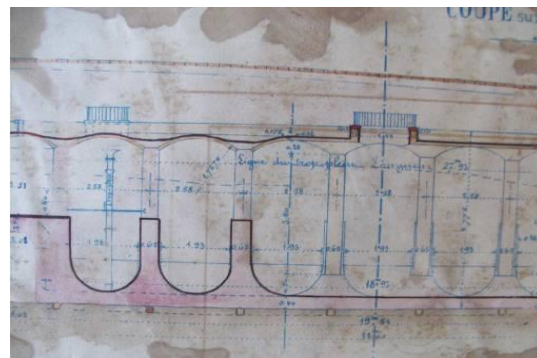


Figure 5. Round wood foundation base of Konjic Bridge [Sert, 2007]



Figure 6. Wooden grillage of a Üsküdar and Sirkeci Byzantine chapels in Istanbul



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Figure 7. Wooden grillage under the inverted vault foundation of Edirnekapı Cistern

If the rock bed was on the surface, the rock was carved in the form of trough so that each stone of the foundation wall could be placed in the rock as if resting in a cradle [AE Report, 2007, Nauman, 1991] (Figure 8). Here the big, dressed stones of the wall rested on the high edges of the trough, not inside [Ousterhoud, 1999, AE Report, 2007, Nauman, 1991]. In between the rock and the foundation stone briar, pieces of coal or animal skin were placed [Philemon, 1601]. The rock foundations in the form of trough were met in Boğazköy, Temple of Diana at Ephesus in Turkey.].



Figure 8. The rock foundations in the form of trough [Nauman, Arun, 2013]

Octagonal buildings, especially octagonal tombs rested on rectangular foundation systems for octagonal is not an adequate form in EQ areas. The foundation of semihexagonal apsis Küçük Ayasofya Mosque, former church of Sts. Sergius and Bachus was three layers of stone constructed as zigzag (Figure 9). Another different foundation system practice was met at the 16th century octagonal tomb foundation of Yavuz Selim Mosque complex. Around 4m distance away from the octagonal tomb, 2m thick, 6m high buried stone wall in the same octagonal form was found. Since octagonal is not an adequate form in EQ areas was this wall might be constructed as a retaining wall to absorb the first shock of earthquake forces (Figure 10).

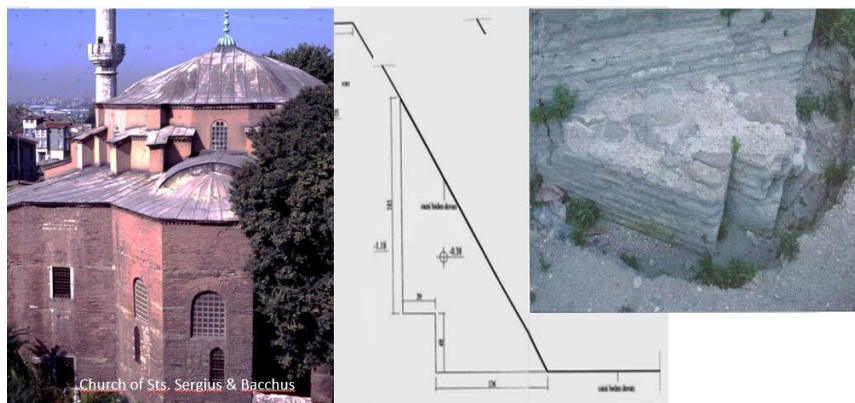


Figure 9. Foundation of the Apsis of Küçük Ayasofya Mosque, the Church of Sts. Sergius and Bachus



Figure 10. Retaining wall of the tomb at Yavuz Selim Mosque

UNDERGROUND AND SURFACE WATER CONTROL SYSTEM

Development of civilization was linked with water management. In archaeological excavations, it is seen that water management and conservation was given high priority during its design and construction for master builders. Ancient builders were aware that in regions with both high and low earthquake risk, water could damage walls and floors by eroding them and reducing their strength. To prevent weakening instability of the building through humidity resulting from water, they designed an effective system of wells, cisterns, and channels to collect and drain the surface and underground water.

In Egypt, the foundation rituals for temples, palaces, tombs, and forts consisted of marking the corners of the building, cutting the earth in the building site through to the water god which represented the upper limit of the water table. Then they constructed a well with galleries or channels to the ground level before starting the foundation wall construction [Montet, 1964]. This construction system, constructing a well in the building, was practiced till late 19th century in important buildings (Figure 11). Here the aim is not to discharge the underground water. Connection of two or more wells provided circulation of underground water between the wells without causing land subsidence. This system is important for controlling overflow during earthquakes or floods. The main components of the drainage system used to drain interior floor surfaces of a building were wells or cisterns in the basement, galleries or channels that discharge the water out of the building, and gates for ventilation to the outside of the building. In settlements, the channels of the wells, penetrating the walls, generally continued to the other building's drainage system. Excessive water was then discharged to a channel along a main road or to a cistern or to a fountain tank.

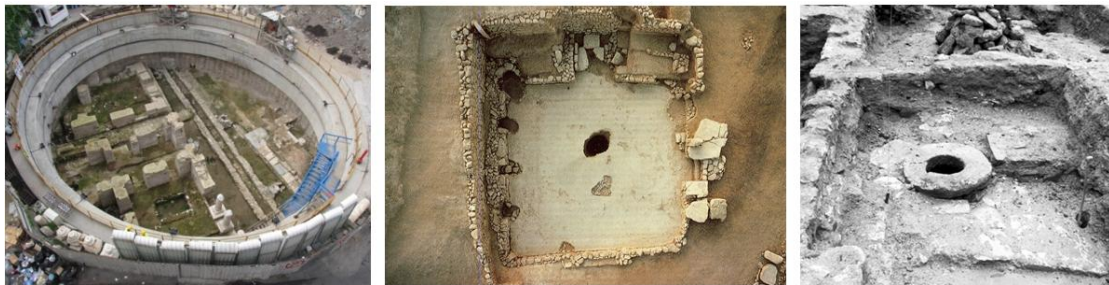


Figure 11. Wells in Antique Buildings

Ottoman culture preferred discharging the wells to a nearby fountain tank. In most of the Byzantium buildings in and around Istanbul, the underground water was discharged to a nearby cistern or the foundation of the buildings included cistern [AE Report, 2007]. In the area of Topkapı Palace, more than forty cisterns were found within the substructures of buildings [Tezcan, 1989]. The twelfth-century church of Pammakaristos includes a large colonnaded and vaulted cistern that extends under the naos and parts of the ambulatory, now filled with soil. There is also a cistern near the Fatih Mosque. Yavuz Selim Mosque in Fatih district and Nur-u Osmaniye Mosque in Bayezid district include large gallery heading toward a cistern that is blocked by the foundation of the mosque.



Figure 12. Discharge of underground water

The size of the galleries or channels connecting wells to each other or discharging water away from the building varies from 30-40cm to 1.0-2.5m depending on the size of the building. These are generally

constructed of stones or bricks bound by mortar [Ousterhoud, 1999] (Figure 12). Often, the galleries or channels were constructed within the foundations, just below the foot touch [Bayraktar et al, 2007]. These tunnels served to keep the structure warm in the winter and cold in the summer while removing the moisture from underground water. The size and length of these gates varied according to the need and size of structure and air ventilation of structure. Because this practice is completely forgotten, while constructing new buildings close to historic buildings, the drainage system is often demolished and cause partial settlement of the structure (Figure 13).



Figure 13. New construction beside a masonry building

Several lined masonry houses in Galata district of Istanbul, suffering of moisture and tilting due to the soil settlement, had wells in their basement connected to each other by a channel system through all the settlement. The newly built RC building in between them had blocked the subsurface water control system and water started to rise to the building softening the soil that had led to the building settlement. Inspection of the subsurface drainage works under the district provided important information for the damage evaluation of these historical masonry buildings.



Figure 14. Küçük Ayasofya Mosque after a heavy rain

Similarly, the Küçük Ayasofya Mosque, former church of Sts. Sergius and Bachus constructed near South Sea walls of Constantinople had a well underneath its naos. Construction of highway filling the sea in front of the building must have demolished the underground water discharge system that the building was suffering of moisture and partial settlement before its recent restoration. During the building's restoration in 2001, today's master builders decided that this well is of no use today and closed the system filling with concrete. Today, after every heavy rain, the building is suffering from overflow (Figure 14).

CONCLUSIONS

Ancient building masters, with accumulation of knowledge from previous cultures and their trial and error had introduced special techniques to make the structure withstand the lateral forces and to control the underground and surface water movement.

To provide the lateral stability of structures in seismic areas, building masters

- Provided seismic joints by not connecting the foundations of different weighing components of a building
- Changed the natural frequency of soil by placing a pillow layer of sand or gravel under the foundations,
- Provided flexible base by placing round wood at the foundation base or by carving the rock in the form of a trough and placing the foundation stone on a flexible layer in the trough.

To control the underground and surface water, they constructed an effective drainage system with wells or cisterns in the basement, galleries or channels that discharge the water out of the building, and gates for ventilation out of the building so that the building doesn't get moisture from the ground.

The engineering systems of past are different than modern structures. It is necessary to investigate heritage buildings according to their construction time with their engineering point when diagnosing the problems. The ignorance of the accumulation of master builder's knowledge and construction technique of their time may lead to incorrect intervention and long-term harmful effects on the structure.

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