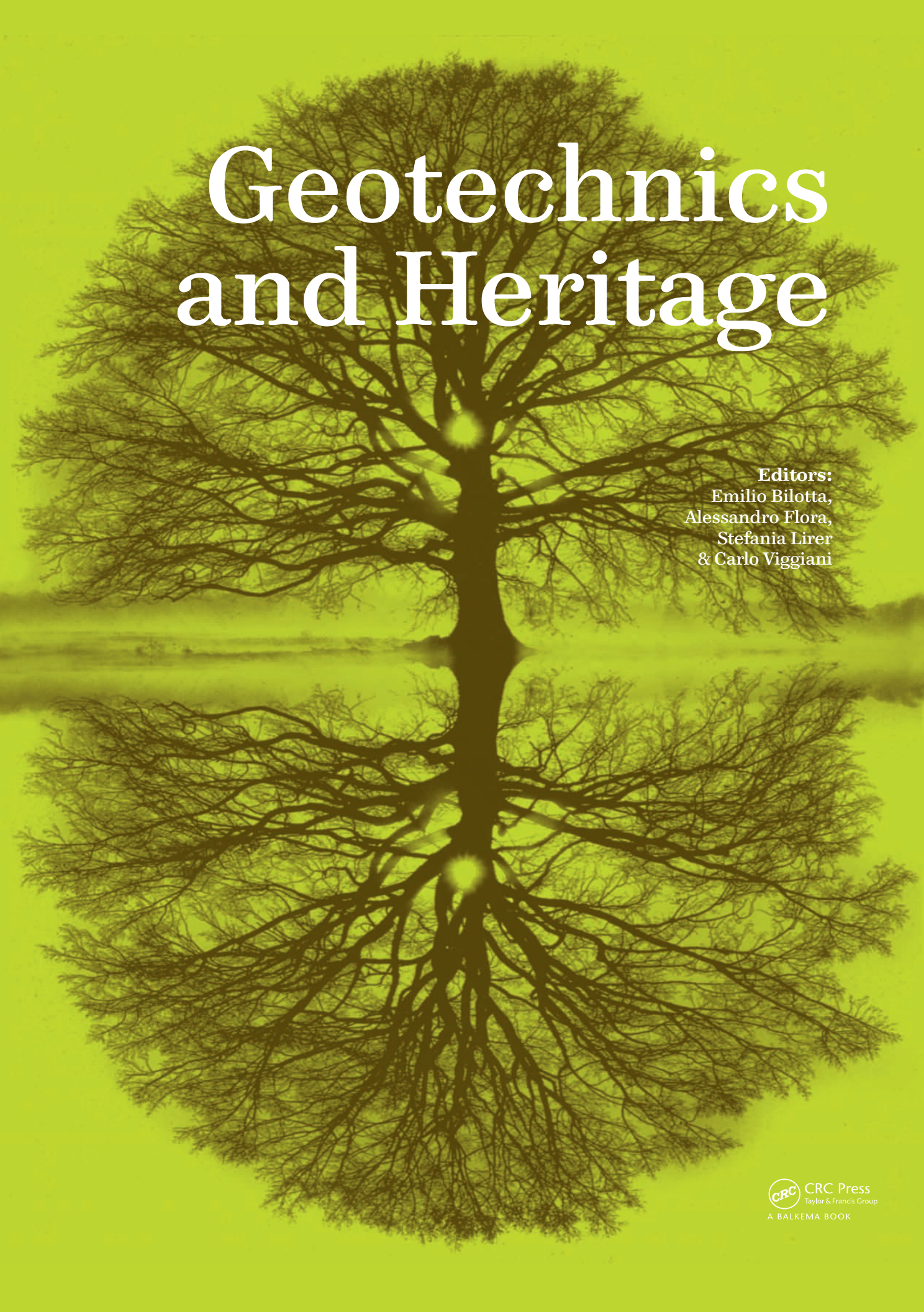
Geotechnics and Heritage

Editors:
Emilio Bilotta,
Alessandro Flora,
Stefania Lirer
& Carlo Viggiani



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Preface

The Technical Committee on Preservation of Monuments and Historic Sites was established by the International Society of Soil Mechanics and Geotechnical Engineering in 1981 with the mark TC19, and renamed TC301 in 2010. The Committee is supported by the Italian Geotechnical Society (AGI); it has been chaired in the past by Jean Kerisel, Arrigo Croce, Ruggiero Jappelli.

Edmund Burke, in his "Reflection on the revolution in France", states as early as in 1790: "*People will not look forward to posterity, who never look backward to their ancestors*". And Lenin writes in the early XX century: "*Citizens, don't touch even a stone. Protect your monuments, the old mansions. They are your history, your pride*". Besides being so important, conservation is also one of the most challenging problems facing modern civilization. It involves a number of factors belonging to different fields (cultural, humanistic, social, technical, economical and administrative), intertwining in inextricable patterns. The complexity of the topic is such that it is difficult to imagine guidelines or recommendations summarizing what should be done and prescribing activities to carry on, intervention techniques, design approaches.

Instead of this ambitious undertaking, the Committee resolved to produce this volume collecting a number of relevant case histories concerning the role of Geotechnical Engineering in the preservation of monuments and historic sites, in addition to the Proceedings of the two International Symposia organized by the Committee in Napoli in 1994 and 2013. It is offered to the geotechnical engineers dealing with monuments and historic sites, as a collection of paradigmatic examples which may suggest an approach rather than a solution.

The lovely picture on the cover of this book illustrates at the best the concept of ground-monument system; it seems to suggest that a majestic tree must be based on a similarly majestic underground structure. It is hence evident that geotechnical engineers may play a significant role in conservation. We hope that this volume will contribute to such an undertaking.

The TC301 of ISSMGE

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Cultural heritage and geotechnical engineering: An introduction

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ABSTRACT: One of the fields of activity of Civil Engineering is the maintenance of existing constructions and infrastructures; among these, the Cultural Heritage. In particular, Geotechnical Engineering plays a significant role in a number of relevant cases.

The conservation of Heritage is one of the most challenging problems facing modern civilization. It involves a number of factors belonging to different fields (cultural, humanistic, social, technical, economical and administrative), intertwining in inextricable patterns.

From the point of view of an engineer, the peculiarity of this type of intervention is the requirement of respecting the integrity, besides guaranteeing the safe use. This requirement is analysed and discussed. It is concluded that the development of a shared culture between engineers and other professionals such as archaeologists, art historians and architects is a necessary condition for a successful conservation. To become sufficient too, the conservation culture should be spread widely and become a common sentiment amongst the majority of people.

1 INTRODUCTION

Geotechnical Engineering is part of Civil Engineering, the oldest branch of Engineering. As early as 30 centuries BC Egyptian engineers conceived and directed large constructions, as the great pyramids, the river Nile regulation and huge irrigation projects.

During the centuries, civil engineers have used the resources of Nature for the progress of mankind. At present, however, they are generally considered to operate in a "mature" sector, where mature is just an euphemism meaning outdated, behind the times, out of the mainstream of modernity. Till a few decades ago, the public perception of civil engineer was the man of progress; at present, this image is gradually changing into that of a cementifier, dangerous for the environment, operating in a routine sector of activity not worthy of investing financial and human resources; these on the contrary are reserved for fields such as aerospace, informatics, biomedicine.

We all know that this picture is utterly in error. According to the American Peoples Encyclopedia, Engineering "… applies scientific knowledge to the practical problems of creating, operating and maintaining structures, devices and services". Civil Engineers have thus still a fundamental role not only (i) in constructing new structures and (ii) in dealing with new problems, but also (iii) in taking care of the existing infrastructures and heritage.

As for new structures, just to quote a few examples, structures such as the Messina Strait suspension bridge, with its 3.3 km span (fig. 1), or skyscrapers such as the Burji Khalifa, with its 830 m height (fig. 2), will continue to require high level knowledge. Less visible (there is no glory in foundations, said Terzaghi), but probably equally demanding and more important and widespread are other works, as for instance the shallow urban tunnels for transportation and other purposes that are being excavated under all the great cities of the world.

New problems are continuously posed to civil engineers by the evolution of Society. For instance, environmental problems were not included in the engineering curricula when I was a student (admittedly, very long ago), in spite of them being described at the best as early as in Shakespeare's Hamlet. "*This goodly frame, the earth, seems to me a sterile promontory, this most excellent canopy, the air, look*

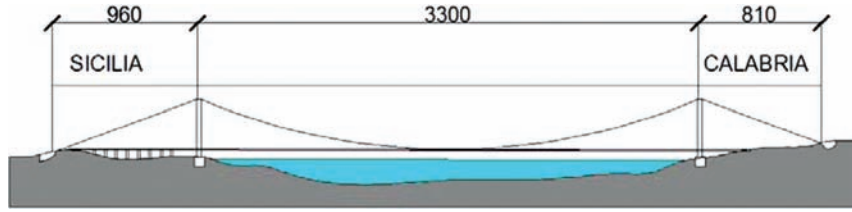

Figure 1. Sketch of the intended suspension bridge across Messina Strait, Italy.

Figure 2. The Burj Khalifa, the tallest building in the world.

you, this brave overhanging firmament, this majestical roof fretted with golden fire, why, it appears no other thing to me than a foul and pestilent congregation of vapours" says Hamlet entering the scene at the beginning of the second act.

We are used to associate sea gulls with blue skies and uncontaminated seas (fig. 3); but nowadays, on the contrary, they often deal with things such as solid urban wastes (fig. 4). Seagulls undertake a dirty job, just as we civil engineers do in addition to conceiving and constructing suspension bridges, skyscrapers, tunnels.

At a first glance, taking care of (maintaining, upgrading, reinforcing) existing structures, devices and services appears a minor field of activity; but there are many arguments proving the contrary. Apart from ordinary maintenance, puzzling problems are posed by new destinations of the existing structures or by more demanding safety requirements (for instance, in connection with the seismic safety of existing dams).

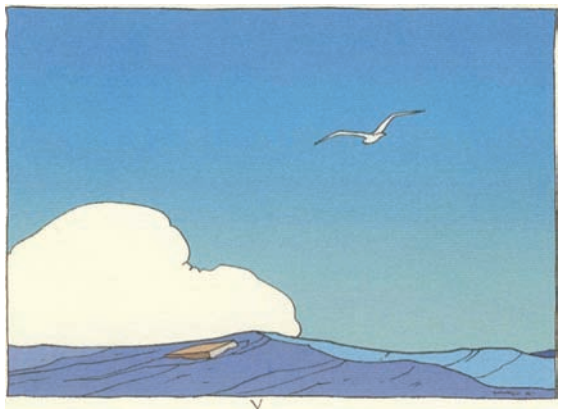

Figure 3. Blue skies and uncontaminated seas.

Figure 4. One of the present jobs of the seagulls.

Within this sector, there is the sub sector of taking care of (maintaining, preserving, conserving, restoring, improving) monuments and historic sites. Again, an apparently minor sub sector, and again, on the contrary, one of the utmost importance—may be the most significant contribution that Civil Engineering can give to mankind in our time.

Edmund Burke, in his famous "Reflection on the revolution in France", states in 1790: "*People will not look forward to posterity, who never look backward to their ancestors*". And Lenin writes: "*Citizens, don't touch even a stone. Protect your monuments, the old mansions. They are your history, your pride*". Both a reactionary and a revolutionary acknowledge the importance of the heritage and, oddly, the revolutionary seems to focus on the past and the reactionary on the future!

2 ITALIANS DO IT BETTER?

Italy has a long history of conservation; there is a widespread belief that the national heritage is very important. Let us examine a few quotations: "*According to UNESCO's estimates, Italy has between 60 and 70 per cent of the world's cultural assets*" (Eurispes Report, 2006). "*72% of Europe's cultural heritage is to be found in Italy and as much as 50% of the world's*" (Berlusconi, press conference held in London on 10 September 2008). According to a Sicilian minister, "*60 per cent of the world's cultural assets are in Italy and of these, 60 per cent are in Magna Grecia and of these last ones 60 per cent are in Sicily*". According to the councilor responsible for culture in the Regione Toscana, "*Italy alone has 60% of the world's cultural assets, but 50% of those Italian cultural assets are concentrated in Tuscany*"; according to the Deputy Mayor of Rome, Rome by itself "*has 30–40% of the world's cultural assets*". If we add all the percentages together, it would appear that Italy somehow manages to encompass more than 100 per cent of the planet's cultural heritage!

Obviously these "UNESCO statistics" do not exist, and the figures, invariably inconsistent with one another, are shamelessly concocted on various occasions; perhaps the symptom of national pride, but certainly of ill-conceived superficiality. Yet Italy does have a very significant position because of its cultural heritage, whose central importance, however, is not based on its quantity but rather on its quality. There are three different reasons for this: first, the time-honored harmony between the city and the wider landscape; second, the spread of this heritage throughout the country and down to the smallest towns and villages; third, the continuity in the use of churches, mansions, statues and paintings. Italian museums only contain a small portion of the country's artistic heritage, which is spread throughout the cities and the countryside: within this context—the product of many centuries of accumulated wealth and civilization—the whole is far more than the sum of its parts.

There is, however, a fourth factor at play, which is no less important: the "Italian model" of conservation of cultural heritage. Long before Italian unification, the Italian states formulated rules and set up public institutions to regulate and engage in this area of activity. Italy (as a state) was the first country

to include the preservation of its landscapes and its cultural heritage amongst the founding principles of its Constitution. Article 9 of the Italian Constitution (which came into effect on January 1st, 1948) states: "The Republic promotes the development of culture and scientific and technical research. It protects the landscape and the Nation's historical and artistic heritage." (in the Italian original: *La Repubblica promuove lo sviluppo della cultura e la ricerca scientifica e tecnica. Tutela il paesaggio e il patrimonio storico e artistico della Nazione*). The Constituent Assembly arrived at this formulation after a long debate and eleven different proposed texts. Members of all parties contributed to the final wording, particularly the communist Concetto Marchesi, a professor of Latin from Sicily who had been rector at the University of Padua, and a very young Christian-democrat, later to be prime minister, Aldo Moro.

3 GEOTECHNICS AND HERITAGE

There are quite a number of monuments, monumental buildings, historical cities and sites affected by geotechnical risks of various types, so that Geotechnical Engineering is called to play a very important role in their safeguard. Just to quote some examples, the village of Terra Murata (Walled Land) in the island of Procida in the bay of Napoli, is a settlement dating back to the X century and includes the Abbey of S. Michele and a number of churches. The Abbey and other churches are exposed to the risk of collapse by the action of the sea, undermining the steep cliffs over which they were erected (fig. 5); a problem of stabilisation of rock slopes. Very frequently, in historical cities there are a number of superimposed remains; in fig. 6 a Roman villa of the imperial age found just below a church in a seaside resort near Napoli is reported. The villa had been buried by the Vesuvius eruption of 69 AD, and the church has been built in the Middle Age on a thin tuff layer covering it. It is evident that the solution of any foundation problem for the church needs the use of sophisticated geotechnics.

The famous Leaning Tower of Pisa is depicted in fig. 7; it has been recently stabilised by slightly decreasing its inclination by underexcavation. The inclination of the Big Ben clock tower (fig. 8) caused by the nearby excavation of the tunnels of the Jubilee Line Extension has been controlled by compensation grouting. Both these case histories are reported in details in two contributions in this volume.

The road tunnels excavated by the Romans in the Phlegrean Fields, east of Napoli, are unprecedented and unequalled masterpieces of ancient geotechnical engineering. Some of them have been in regular use till the XIX century! The so called Grotta di Cocceio, linking the Avernus lake to the citadel of Cumae (fig. 9), includes an enormous explosion cavern caused by the firing of explosives stored there during World War II. The cavern is now inhabited by chiroptera (bats) who are a protected species; their

Figure 5. The village of Terra Murata in the island oProcida. (Left) view from the sea; in the background, at the right of the picture, the Abbey of S. Michele. (Right) bird's eye view.

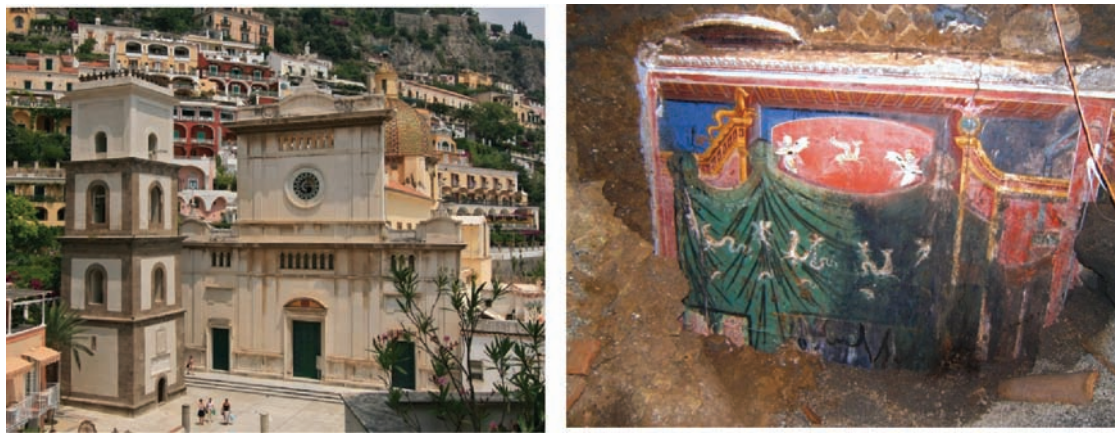

Figure 6. (Left) the Church of S. Maria Assunta at Positano, near Napoli. (Right) the remains of a Roman villa of imperial age found just a couple of meters below the foundation of the church.

Figure 7. The Leaning Tower of Pisa.

Figure 8. The Big Ben Clock Tower.

protection is at present conflicting with the stabilisation of the cavern, epitomizing the complexity and variety of conservation problems.

Many other examples could be quoted, that are omitted here for space reasons.

4 INTEGRITY

The conservation of monuments and historical sites is one of the most challenging problems facing modern civilization. It involves a number of factors belonging to different fields (cultural, humanistic, social, technical, economical and administrative), intertwining in inextricable patterns.

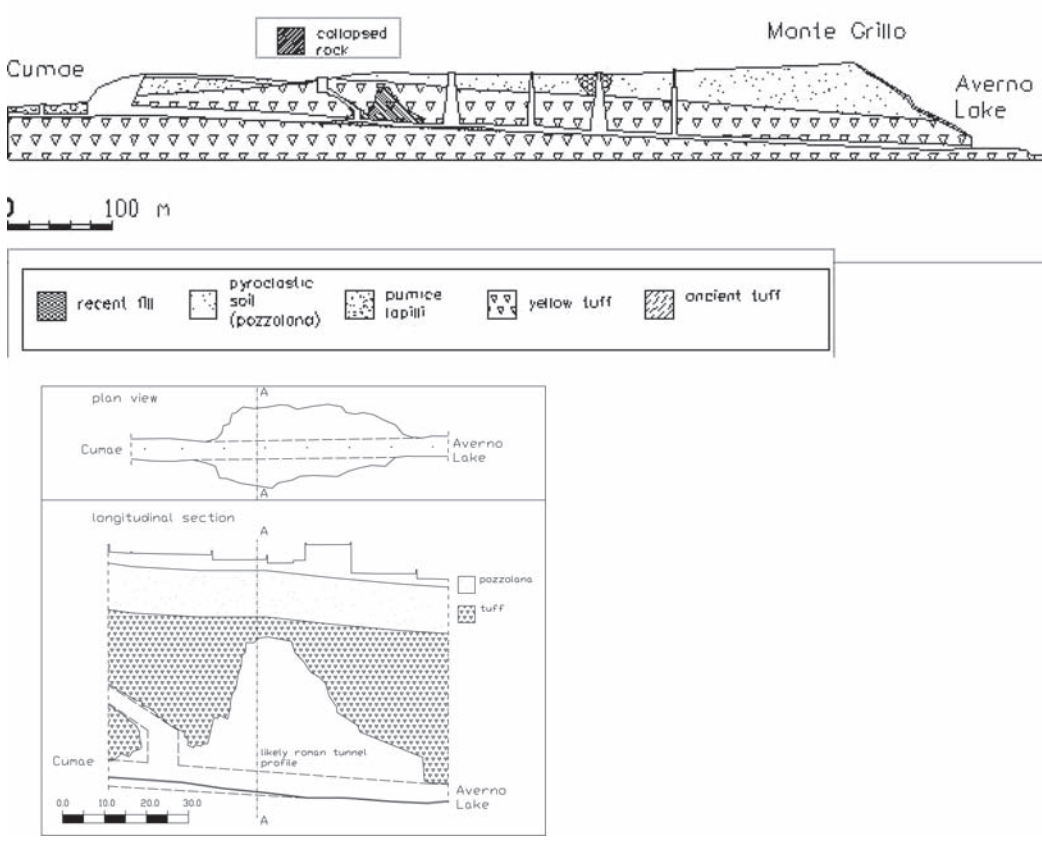

Figure 9. The grotta di Cocceio, a Roman tunnel in the Phlegrean Fields east of Naples. (Above) longitudinal profile of the tunnel. (Left) the explosion cavern in the mid of the tunnel.

From the point of view of an engineer, the peculiarity of this type of intervention is the requirement of respecting the integrity, besides guaranteeing the safe use. The latter requirement is relatively straightforward for a well trained and experienced engineer. The former one, on the contrary, is worth of some discussion.

A prerequisite is the comprehension of the concept of integrity; one soon discovers that it has many facets and is rather elusive. Formal or iconic integrity is the first and most obvious facet; the external aspect, the original form should not be altered by the engineering intervention. Let us imagine an old, experienced civil engineer contemplating Leonardo's Mona Lisa, in the Museum of Louvre in Paris. Let us also imagine that his expert eye discovers that the wall hook to which the picture is hanging is near to collapse, with the risk of the masterpiece falling on the floor and possibly being damaged. What horror! The expert engineer takes a new large nail, plants it in the forehead of the lady and knocks it into the wall (fig. 10). "Now it is safe", he concludes with a legitimate satisfaction; but the visitors of the Museum would probably be much less satisfied.

Unfortunately formal integrity, though being very important, is not all, otherwise a copy would have the same value as the original. Another important facet of integrity is historical integrity; it can be best illustrated by an example, taken from the history of Napoli. The church of Santa Chiara was founded in 1310 by Robert the Wise and Sancia of Mallorca as a double convent for the Poor Clares and Franciscans.

The church exceeded in scale any other church in the kingdom; it loomed over medieval Naples and still presides over the modern city (fig. 11). It was intended not only to host the tombs of the royal family but probably as part of a program to propose a Franciscan alternative to the authority of the papacy, by this time displaced to Avignon. The project of Santa Chiara, initiated soon after the arrival of Robert and Sancia in Napoli, reflected a new trend in the spiritual life of the kingdom, now strongly inclined towards the Franciscan and in particular towards the Spirituals. According to some historians,

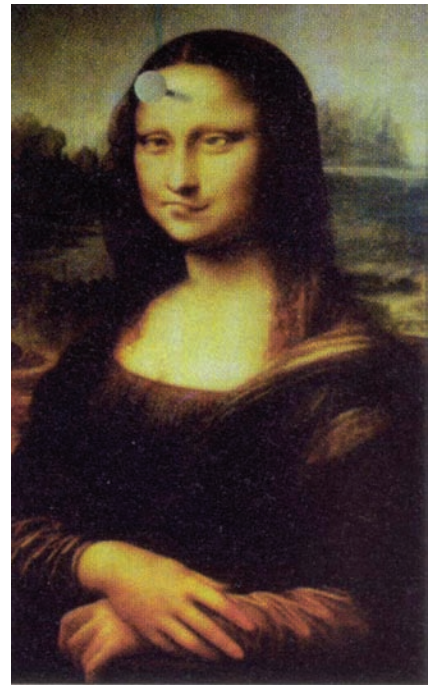

Figure 10. Mona Lisa stabilised.

Figure 11. The Angevin church of Santa Chiara in Napoli.

Santa Chiara was perhaps nothing less than the setting for a brave and doomed attempt to reform the Church.

Before 1943, the medieval interior of Santa Chiara was actually invisible, encased in a sumptuous baroque decoration designed by Domenico Antonio Vaccaro in 1744 and executed by Giovanni del Gaizo and others (fig. 12). It perfectly epitomized the defeat of the Franciscan party and the historical victory of the Rome papacy.

Figure 12. The interior of Santa Chiara in 1942.

Figure 13. Santa Chiara in August 1943.

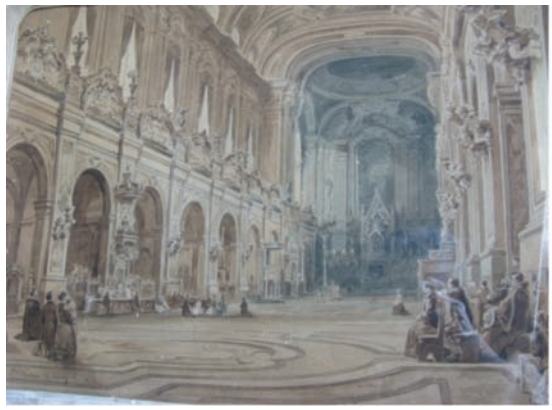

Figure 14. Has the historical integrity been respected?

The original structure underneath the baroque decoration was revealed to modern eyes only on 4 August 1943, after American incendiary bombs caused a fire that burned continuously for 36 hours. The eighteenth century stucco was entirely destroyed and the medieval walls behind severely calcinated (fig. 13). In keeping with the post-war preferences for streamlined design, and principally because of the cost and complexity of re-creating the splendors of the baroque interiors, the church was reconstructed instead to an austere medieval shell, a loss still lamented by most Neapolitans lovers of the Baroque. Has the historical integrity been respected? (fig. 14).

A further facet of the integrity is the material integrity. It is at present acknowledged that the materials, the construction techniques, the structural scheme are original features of the monument as significant as its appearance and history. An arch should not be transformed into a garland of stones hanging from a hidden beam; a direct foundation should not be transformed into a piled one, unless this is the only way to save it, and in any case at the price of a defeat.

Fig. 15 shows one of the solutions proposed in the 1970's to stabilize the leaning tower of Pisa; while completely exhaustive from a merely technical viewpoint, it would have deprived the visitors of the tower of the subtle sensation of risk when climbing the spiral stairs!

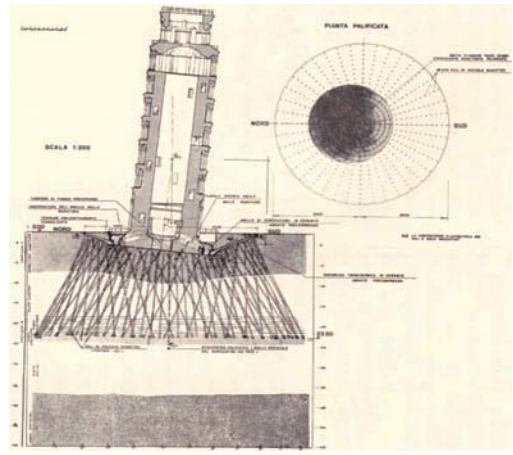

Figure 15. One of the solution proposed in the 1970's for the stabilization of the Tower of Pisa.

Figure 16. Pienza.

Finally, we have already mentioned the harmony between the city and the wider landscape that is one of the factors making Italy so important from the point of view of cultural heritage. Fig. 16 shows a quintessentially Italian landscape: Pienza in Tuscany, a small city founded by Pope Pius II in 1462 and still gloriously emerging from the surrounding landscape on top of a hill, in the Senese Val d'Orcia. The balance of countryside and cityscape is so admirably preserved that in 2004 the entire Val d'Orcia was included among the UNESCO sites.

Geotechnical interventions may significantly affect the landscape; this is another important facet of integrity to take into account. The cliff in the island of Procida below Terra Murata mentioned above, for instance, could be protected from the sea action lining it by reinforced concrete, but this would be an irreparable wound to the landscape.

5 SHARED CULTURE

The requirements of safety and use, in the majority of cases the Author has experienced, appear (and often actually are) in conflict with the respect of the iconic, historical and material integrity of the monuments. In almost all countries of the world conservation is looked after by an official trained in Art History or Archaeology. Generally (e.g., this is the case in Italy) he has an absolute control on any action to be undertaken, and imposes constraints and limitations that sometimes appear unreasonable to the engineer. The engineer, in turn, tends to achieve safety by means of solutions which appear unacceptable to the official in charge of conservation, sometimes mechanically applying procedures and regulations conceived for new structures. With a misused word, he tends to cementify.

It is evident that some equilibrium has to be found. Conservation requires on one hand the safeguard of the formal, material and historical integrity of the monument, while on the other its survival and safe fruition. The difficulty of the problem is increased by the lack of a general theory, guiding the behaviour of the various actors involved as Mechanics does with the structural engineer. The lack of unicity of the solution of preservation and conservation problems, vividly exemplified by the case of Santa Chiara, is in particular rather disturbing for us engineers.

It is a deep belief of the author that a satisfactory equilibrium between safety and conservation, between engineers and restorers, may be found only in the development of a shared culture. In the last decades, significant advancements have been actually registered in this direction between the realm of conservation ant that of engineering, and a number of associations, conferences, seminars have contributed to these advancements. ISSMGE is pursuing this goal in different ways; among them, the institution of a Technical Committee on Geotechnical Engineering for the Preservation of Monuments and Historic Sites (TC301, formerly TC29), started many years ago by Jean Kerisel and Arrigo Croce and sponsored by the Italian Geotechnical Society. This volume is intended as a contribution to the effort.

6 NECESSITY AND SUFFICIENCE

Unfortunately, the development of a shared culture of conservation is a necessary, but far from sufficient condition. Immediately after the inclusion among the UNESCO sites, the area around Pienza was involved in a real estate project (fig. 17). The new settlement, the *Casali di Monticchiello*, were advertised as "your new home in a Unesco site". In other words, the UNESCO label, that the Val d'Orcia earned for its preservation, was immediately exploited for commercial reasons.

The eighteen-year-old king Charles of Bourbon, who entered Naples to great celebrations in 1734, inaugurated a new era in the history of the Kingdom which was now once more independent after centuries of being a Spanish viceroyalty. He initiated the digs in Herculaneum (from 1738) and Pompeii (from 1748), which produced an enormous quantity of new antiquities. This situation gave rise to Neapolitan legislation to protect the cultural heritage (1755), expressing the King's "profound regret" over the past export of antiquities from the Kingdom and establishing new rules to prevent it to happen again in the future.

Indeed, when Charles III became King of Spain (1759), in his new capacity he did not issue any provisions to safeguard artifacts there. Had his "profound regret" over the lack of protection for works of

Figure 17. Commercial exploitation of Val d'Orcia near Pienza.

art in Naples vanished once he got to Madrid? No. In both cases, the monarch had not been writing the legislation personally, but expressing through it the civic and juridical traditions and practice of the place in which he was ruler.

In Italy, there is a sharp contrast between a long history of preservation and its decline over the last few years. The roots of the civic, cultural and juridical aptitude to preservation are to be found in the spirit and tradition of the Italian cities, which, at least from the twelfth century on, had been developing a deeply held and highly sophisticated concept of citizenship, in which the monuments were the basis for civic pride and identity and a sense of belonging which were closely linked to the very idea of a well governed community. In this connection, it is interesting to quote two documents:

i. the Commune of Rome (1162), concerning Trajan's Column (fig.18), states: "In order that the public honor of the City of Rome is preserved, the Column shall never be damaged or knocked down, but must remain as it is for eternity, intact and unspoiled for as long as the world shall exist. Should anyone inflict or attempt to inflict damage on it, they shall be condemned to death and their assets confiscated by the treasury";
ii. the Constitution of the Commune of Siena (1309) says that "those who govern the city must above all ensure its beauty and ornament (fig. 19), which is essential for the delight and amusement of foreigners, but also for the honor and prosperity of the Sienese themselves".

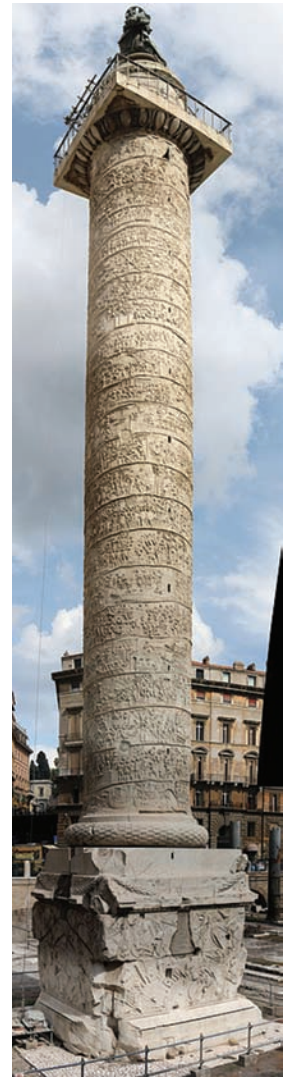

Figure 18. Rome, Trajan column.

Figure 19. Siena.

Very similar principles are found in hundreds of documents: beauty, decorum, suitability, public honor, the common good or *public benefit*, for which the classical Roman formula *publica utilitas* was often employed. There is a perfect continuity between the conservationist laws of Italy's liberal governments, the two laws passed by Mussolini's regime and finally Article 9 of the Republic's Constitution; this come as a surprise only to those who think in terms of labels and affiliations, and fail to enter into the complexities of the history of ideas. What might be even more surprising is the evident continuity between the conservationist legislation of the Italian states of the *Ancien Régime* (for instance, papal Rome and Bourbon Naples) and the heritage and conservation culture that spread around Europe after the French Revolution. The latter was definitely not a "restoration" of previous laws, but a radical rethinking of the language and rules of the *Ancien Régime* in the light of new guiding principles, such as the concepts of nation, of popular sovereignty and of citizenship, which the events of the French Revolution had changed forever, while giving new meaning to the notion of the "common good" and encapsulating it, among other things, also in historical monuments.

However, this complex system is operating in an increasingly ineffective manner. The devastation of the landscape in Italy has become dramatic. The harmonious relationship between the Italian cities and their countryside, established over many centuries, is giving way to an uncontrolled urban sprawl, which is now home to a large proportion of the population. Although the conservationist laws remain in force and indeed are constantly improved (on paper), "derogations", "exceptions" and even "amnesties" (*condoni*) for the infringement of building regulations are continuously enacted. At the same time, conservation of the cultural heritage is undergoing a deep crisis caused by a lack of human and financial resources.

I have a dream. The international geotechnical community, besides contributing to the development of a shared culture of conservation, plays an active role in the re-establishment of these principles in the common sentiment of people in Italy and all over the world.

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The author owes a deep debt for their teaching and for stimulating discussions over the years to masters as Arrigo Croce, Ruggiero Jappelli, Jean Kerisel and to friends as Giovanni Calabresi, Salvatore D'Agostino and Salvatore Settis; their inspiration is gratefully acknowledged.

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Geotechnical issues of the Athenian Acropolis

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ABSTRACT: The monuments of the Acropolis survived until today, through centuries of perils and changes in use and in form, wounded but still standing. Their continuous exposure in the action of damaging factors (natural or man made) during their long history has provoked major or minor failures, related to geometry and/or mechanical strength of their structure and materials. Those damages had to be confronted and thus an integrated restoration project began in 1975 and is continued until today. This paper, giving an insight to the restoration programme, focuses on the geotechnical issues of the monumental complex. It presents the geotechnical data collected as well as the most significant studies and interventions already conducted. Moreover, the seismotectonic regime of the area is presented with a commentary review of literature for the historical and recent seismicity of the broader area, as well as a quotation of earthquake effects on Acropolis hill and monuments. Specific macroseismic observations of strong earthquakes of different source properties are mentioned. Finally, a brief description of the strong motion array deployed on the Acropolis hill and some conclusions from the accelerographic records are presented.

1 INTRODUCTION—THE ACROPOLIS MONUMENTS

The Acropolis of Athens is the most striking and complete ancient Greek monumental complex still existing in our times; an architectural treasure that belongs not only to the Greek patrimony but also to the worldwide cultural heritage (Fig. 1). It is situated on a medium high hill (altitude 157 m) that rises in the basin of Athens. Its overall dimensions are approximately 170 × 350 m. The hill is rocky and sheer on all sides except for the west, and has an extensive—nearly—flat top covering an area of about 30.000 m^2.

Strong fortification walls have surrounded the summit of the Acropolis for more than 3.300 years. The first fortification wall was built during the 13th century BC (Fig. 2), enclosing the residence of the local Mycenaean ruler. In the 8th century BC, the Acropolis gradually acquired a religious character with the establishment of the cult of Athena, the city's patron goddess. The sanctuary reached its peak in the archaic period (mid 6th century-early 5th century BC).

In the 5th century BC, the Athenians, empowered from their victory over the Persians, built a new circuit wall and under the leadership of the great statesman Perikles they carried out an ambitious building programme comprising a large number of monuments that transformed the rocky hill into a unique complex, which proclaimed the ascendancy of classical Greek thought and art. These monuments include: the Parthenon, a temple of Doric order, of particularly large proportions, that dominates the summit of the Acropolis rock (Fig. 3); the Erechtheion, a temple of Ionic order, of curious shape, with rich sculptural decoration and the emblematic feature of the Porch of the Caryatides

Figure 1. The Acropolis of Athens.

Figure 2. Part of the Mycenaean fortification wall preserved on the Acropolis hill.

Figure 3. The Parthenon (right) and the Erechtheion (left).

(Fig. 3); the Propylaia, the monumental entrance building to the sanctuary, famous for its impressive coffered ceilings (Fig. 4); the temple of Athena Nike, a small temple of the Ionic order (Fig. 5), notable for its elegance and grace (Brouskari 1997, Ioannidou et al., 2008). These buildings, characterized by ingenious planning and flawless construction, were built with dry masonry consisting of white pentelic marble. Only the foundations were of poros stone.

Smaller buildings, a plethora of votive offerings and inscriptions, fill the picture of a living and active sanctuary that remained as such until the 4th century A.D. From the end of the 3rd century A.D., however, the west side of the Acropolis is fortified (Ioannidou et al., 2008). With the establishment of the new religion—Christianity—the process of decay began. The sanctuary was stripped of its artistic wealth, some of the smaller buildings were destroyed and significant changes were made to the larger ones that survived: the Parthenon was converted into a church of the Holy Wisdom, popularly known as the church of the Virgin Athiniotissa, the Erechtheion was transformed into a Christian basilica dedicated to the Virgin. A church was built in the south-west wing of the Propylaia in the 6th century A.D., and in the 10th century the main part of the monument was converted into a church of the Archangels (Brouskari 1997).

Figure 4. The coffered ceiling of the Propylaia. Restored.

Figure 5. The temple of Athena Nike after its restoration.

Figure 6. The Acropolis in the mid-15th century.

Figure 7. General view of the Acropolis at the begining of the 19th century. E. Dodwell (1804–1806).

During the Latin domination (1204–1458) extensive fortification works were carried out (Fig. 6) and the Propylaia was transformed into a fortified residence for the ruler of Athens. During the Ottoman domination (1438–1833) the Parthenon becomes a mosque and the Erechtheion the residence of the local ruler, the disdar (until the 18th century). Parthenon was severely damaged in 1687, when it was bombarded by the Venetians. The explosion of the gunpowder stored in the building transformed it to a ruin (Brouskari 1997) (Fig. 7).

After the end of the Greek War for Independence, during which the Acropolis was found in the centre of the events, and the creation of an independent state (1833), the Acropolis was proclaimed an archaeological site (Ioannidou et al., 2008).

Since then works began on cleaning the ruins and restoring the monuments that have survived for almost twenty-five centuries through wars, explosions, bombardments, fires, earthquakes, thefts and interventions as well as alterations connected with different usage.

The extensive restorations carried out, throughout the 19th and at the beginning of 20th century, together with the still ongoing restoration programme that began in 1975, gave the Acropolis monuments the appearance they have today.

2 GEOTECHNICAL DESIGN AND PATHOLOGY OF THE ACROPOLIS MONUMENTS

2.1 *Geology of the Acropolis hill*

The Acropolis hill is a trapezoidal-shaped block of Late Cretaceous grey limestone (thick platy or unbedded) resting on the marls and sandstones of the Athens Schist rock series, encountered either as marly schist, or sandstone marl (Fig. 8).

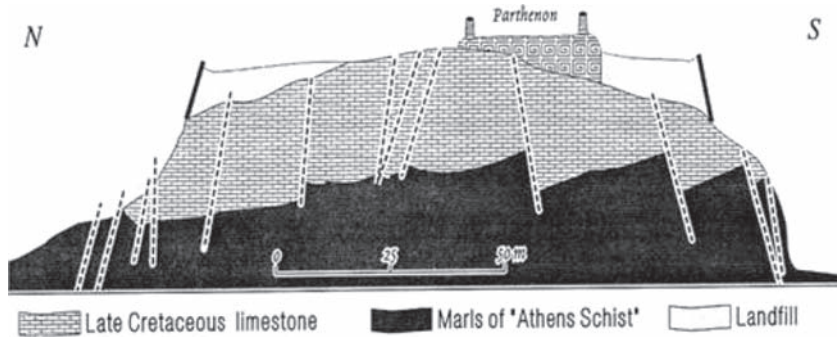

Figure 8. Geological section of the rockhill (N-S direction). From Higgins and Higgins 1996.

Between the limestone mass and the underlying bedrock a rather thin layer of conglomerate is interjected. Locally, in the upper surface of the bedrock conglomerate horizons are met. Superficially the bedrock is covered at places with an eluvial soil cover of small thickness, coming from the weathering of the schist bedrock.

The grey limestone is well exposed on the top of the hill. It has closely spaced joints and some of the older fissures have been filled with red marl or coarse calcite crystals. The top of the hill has been leveled with artificial fill up to 17 m thick which is retained by the Circuit Wall (see paragraph 2.3). The artificial fill that forms the plateau where the monuments stand has a varying composition. This fact is mainly attributed to the different historic stages of backfill construction.

The prevailing theory for the creation of the Acropolis rock hill considers an initial unified large formation of limestone mass including all the neighboring hills (Areios Pagos, Filopappos hill, Pnyx etc). As a result of the strong erosive action of the environment, the initial mass has been divided into several hill formations that exist nowadays.

The rock mass quality shows significant local differentiations. The summit and the inner part of the hill consist mainly from compact to thick platy limestone and show a rather low degree of weathering with sparse closed discontinuities and favorable tectonic characteristics. On the other hand the slopes show clearly a higher degree of weathering (leading to systematically jointed rock mass). This is especially clear in the case of the east and the north slope, where the intense karstic effects, the usually intensely fractured rock mass, the unfavorable orientation of the discontinuities and the increased action of the environmental agents, lead to the development of local instabilities and rock falling as well as to the formation of caves and clefts. Such caves can be seen in the slopes of the hill. According to Higgins and Higgins (1996), other caves, probably mostly choked with debris, exist in the interior of the hill.

The discontinuities of the permeable limestone formation allow for a regular drainage of the hill. The water from the rainfalls, seeping into the faults and fractures on the upper part of the Acropolis, discharges in characteristic springs at the hill base, since the underlying schist bedrock is practically impermeable.

As far as the tectonics of the rock are concerned, 23 micro tectonic diagrams were performed (Andronopoulos and Koukis, 1976): 12 around the slopes and 11 at the summit of the hill. The most unfavorable situations are met in the eastern slope and the eastern crown (5 locations), in the northern slope (3 locations), while in the south slope only 1 location presents unfavorable tectonic characteristics.

The Acropolis hill was not intensely defaced with quarries. Limestone from several of the adjacent hills including the Hill of the Nymphs was used for many of its buildings. Dolomite and marly limestone that came from Piraeus was used for many buildings' foundations and the Circuit Wall. Marble from Mt. Penteli was used for the construction of all the great buildings of the Periclean project. Besides these materials, limestone and conglomerate from Kara, near the base of Mt Hymettos, were also extensively used (Higgins and Higgins 1996).

2.2 *The foundations of the existing monumental structures*

As it was previously mentioned (paragraph 1) a plethora of buildings—small or large—once stood on the Acropolis hill throughout its long history. From those buildings only four remain standing: the Parthenon, the Erechtheion, the Temple of Athena Nike and the Propylaia. However, the foundations of other ancient structures are still—clearly—visible on the Acropolis plateau. Among them are the *Old temple of Athena*, a large Doric temple of the 6th century B.C. that was destroyed by the Persians in 480 B.C., *the Arrephorion*, a small cult building of the 5th century B.C. where the mystery ritual of the Arrephoria took place, the *Chalkotheke*, a rectangular building of the 5th—early 4th century B.C. that housed the metal offerings and dedications to the patron goddess, the *sanctuary of Artemis Brauroneia*, an irregular Π shaped building (in the form of a stoa with two projecting wings), founded by the tyrant Peisistratos in the 6th century B.C., *the sanctuary of Zeus Polieus*, where the ceremony of Diipolia was held, *the temple of Rome and Augustus*, a circular monopteral temple of the late 1st century B.C. and the *monument of Agrippa*, a high pedestal that supported a bronze quadriga (with the statue of Agrippa in it), probably originally erected by Eumenes II in 2nd century B.C. with the statues of himself and his brother Attalos II in the quadriga.

Most of the above buildings were founded directly on the natural rock. But in some cases, mainly due to the irregular geometry of the rock at the location selected for the erection of each monumental structure, typical foundations from poros stones had to be constructed. The cases with foundations of geotechnical interest are the Parthenon, the Propylaia, the temple of Athena Nike, the Arrephorion and the monument of Agrippa.

2.2.1 *The Parthenon*

The Parthenon was preceded on the same site by an earlier temple, of equally large proportions, conventionally known as the Pre-Parthenon. The Pre-Parthenon's foundations (stereobate) were used also for the foundations of the Parthenon of the Periklean era (Brouskari 1997, 153). (Fig. 9a, b).

The preserved temple stands on the top of the rock. Only three quarters of the building possess foundations. The material is poros ashlars quarried especially for the purpose (Bundgaard 1976, 54). For the necessary elevations see Fig. 10.

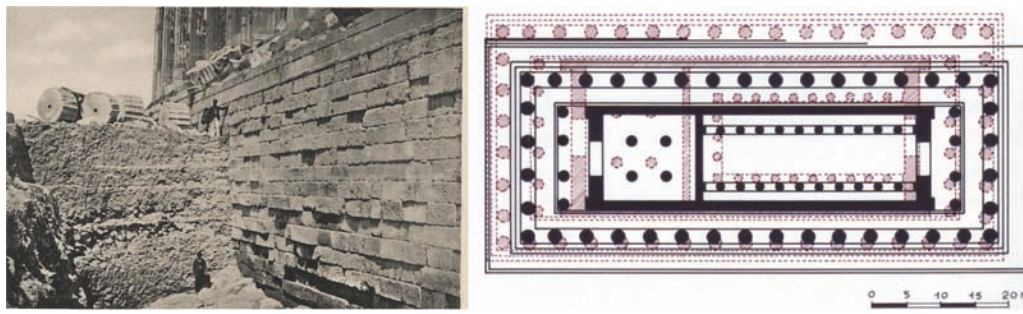

Figure 9. Parthenon foundation a) South side after Cavvadias and Kawerau 1907 and b) plan. (Periklean in red, pre- Periklean in black). After Brouskari 1997, 152.

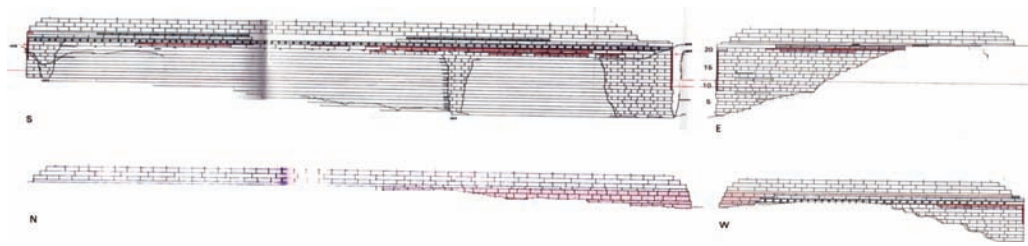

Figure 10. Elevations of the Parthenon's stereobate. (After Bundgaard 1976, t.H)