Kerisel Lecture
The role of Geotechnical Engineers in saving monuments and historic sites.

Conférence Kerisel
Le rôle des ingénieurs géotechniciens dans la sauvegarde des monuments et des sites historiques.

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ABSTRACT: There are many interesting ways for geotechnical engineers to contribute to conservation issues. Firstly they can give a substantial contribution to the knowledge of the monuments and of their history. Then by assuming a broader, more comprehensive approach to the conservation issues, based on historical studies, possibly with the cooperation of scholars of different disciplines, they are often able to identify the nature, characteristics and evolution of the deterioration phenomena and to ascertain the necessity or opportunity of removing them. Eventually they can propose the less invasive solutions to save the monument and its material components that bear witness of its origin and history. The paper shows that in some cases this approach can be successfully applied to save historic buildings, while in others the origin of very slow soil movements, which increase the damage, can be very difficult to identify and furthermore costly investigations are required. However it is worthwhile to do any effort to achieve a convincing explanation of the distress causes and to propose interventions that are safe and respectful of the history of the monument.

RÉSUMÉ : Les ingénieurs géotechniciens peuvent contribuer à la sauvegarde des anciens bâtiments et sites historiques de plusieurs façons. Premièrement, ils peuvent apporter une contribution importante à la connaissance des monuments et de leur histoire. Ensuite, avec une approche globale des questions de conservation, basée sur des études historiques, et éventuellement en coopération avec des chercheurs de différentes disciplines, ils peuvent souvent identifier la nature, les caractéristiques et l'évolution des phénomènes de dégradation et déterminer la nécessité ou la possibilité de les éliminer. Finalement, ils peuvent proposer les solutions les moins invasives pour sauver le monument et les matériaux qui le composent, témoins de son origine et de son histoire. Dans certains cas, cette approche peut être appliquée avec succès pour sauver les bâtiments historiques, tandis que dans d'autres, l'origine des mouvements du sol très lents peut être très difficile à identifier et les études nécessaires pour poursuivre les recherches deviennent très coûteuses. Néanmoins, il est justifié de faire tous les efforts possibles visant à parvenir à une explication convaincante des causes des désordres et de proposer des interventions qui soient sûres et respectueuses de l'histoire du monument.

KEYWORDS: Geotechnical engineering, monuments, historic sites, conservation criteria, saving approach, underpinning, micropiles.

1 INTRODUCTION

Since the time when J. Kerisel (Kerisel 1975, 1987, 1997, 2004. Viggiani 1997, Isnard 1980) and Arrigo Croce (Croce 1980, 1985, Jappelli 1997) raised this issue, the theme of saving monuments and Historic Sites has gained interest and has seen an increasing involvement by geotechnical engineers. A contribution to this heightened interest has also come from the establishment and the activity of the ISSMGE Technical Committee (Tsatsanifos and Psarropoulos 2009) and from the impact of the debate that accompanied the search for solutions and the implementation of difficult interventions in the case of very famous monuments like the Tower of Pisa and the Cathedral of Mexico City. The theme is now a topical one in all Countries and often involves Geotechnical Engineers, but the close relationship between Geotechnics, history and evolution of engineering and architecture is particularly evident in Italy where towns, buildings and monuments built over a time period spanning thirty centuries, that are concrete evidence of how civilization has evolved in the Mediterranean, pose daily problems to restorers and conservation experts.

In Italy, almost all buildings, monuments and historic sites have undergone successive changes throughout the centuries. Their history bears witness to the succession of events, interests, artistic trends, visions and to the evolution of construction techniques that have occurred over time. Their conservation demands contributions not only by the scholars of the Arts and Humanities, but also by technical experts who are capable of ensuring such conservation. The complexity of the history and of the static and conservation conditions of historic buildings often generates problems in choosing the right intervention because of the presence of technical difficulties or because of differences in conservation criteria.

All of this experience deserves being highlighted by promoting a critical discussion on the role of Geotechnical Engineers in saving monuments and historic buildings.

2 THE TECHNOLOGICAL PROGRESS OF GEOTECHNICAL ENGINEERING

It is self-evident that since all buildings interact with the ground on which they rise and are conditioned by its behaviour, their state of conservation is affected by any deformation of the soil and by any changes in its properties occurring naturally over time or caused by variations in environmental conditions. A monument, its foundation and the supporting ground should be considered as parts of a comprehensive complex system, that any saving proposal should take into account, but the soil is generally more sensitive than construction materials to stress variations and weathering; hence it is only natural that Geotechnics should be involved in discussions on saving and restoration problems since it is the discipline that more than any other investigates the nature and causes of soil displacements, and is therefore the best suited to finding ways of preserving ancient buildings and monuments.

The possibilities offered in this field by technological progress in Geotechnical Engineering in recent years have stimulated these activities all over the world, as is shown by the reports published in journals and in conference proceedings. Of course the potential of the new technologies opens up fascinating prospects in this sector; suffice it to think of the possibilities of introducing structural elements of any size into the soil or of mixing the soil with cement to turn it into a new coherent material that is very similar to concrete, or of injecting hardening materials that replace pore pressure fluids in predetermined points of the subsoil, using probes of all lengths that can travel in any direction, even along predetermined and controlled, curved lines.

Actually, scientific progress and the great potential and flexibility of Geotechnical Engineering technology have allowed for the conservation and protection of important historic sites threatened by instability, landslides and weathering of the soils on which they rise.

Suffice it to mention the measures taken to protect Orvieto, Italy (Fig. 1), that took more than a decade, with the anchoring of the high cliff faces made of soft pyroclastic rock (tuff) whose stability had been undermined by the slow softening of the Pliocene overconsolidated clays, present at their base (Manfredini et al. 1980, Martinetti 1981, Lembo Fazio et al. 1984, Tommasi et al. 1997, Tommasi and Ribacchi 1997, Pane and Martini 1997, Tommasi et al. 2005, Soccodato et al. 2013)

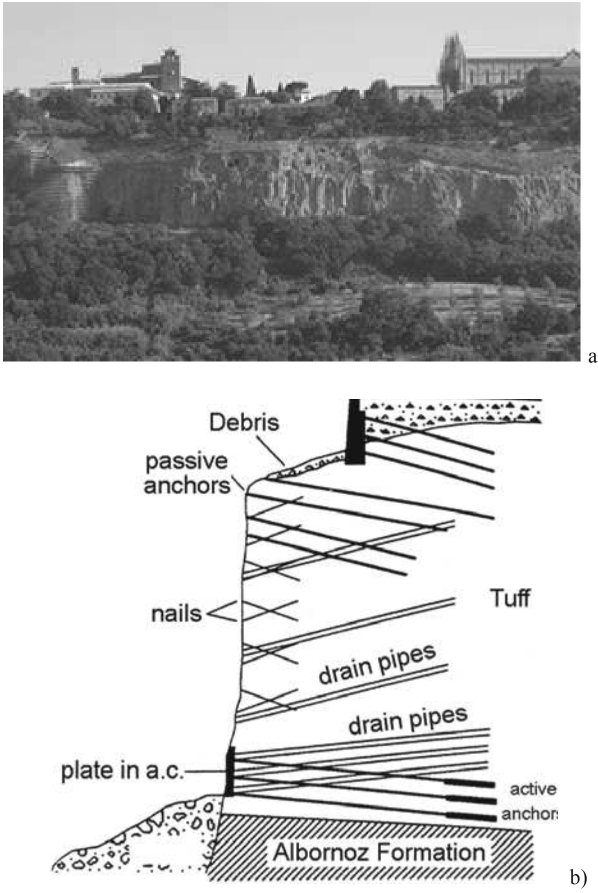


Figure 1. Orvieto: the tuff high cliff (a) consolidated by means of passive anchors, nails and drain pipes (b). Scheme of the strengthening works along the edge of the Rock (Cencetti et al., 2005).

Not as extensive but not less important are the anchorage works on another cliff face overlooking Lake Maggiore thanks to which the historic hermitage of Santa Caterina del Sasso (Fig. 2) has been saved (Balossi Restelli 2009). More recently, a set of fiberglass tie-rods and a masonry underpinning have stopped the collapse of large tuff blocks from the NW face of the Palatine Hill. This measure not only made it possible to stop the progressive instability caused by the erosion of the sand levels and by the excavations made during the Middle Ages, but also to free the stone face from the debris produced by the collapsed rock and discover the unsuspected presence of Hypogeums (Tomei and Filetici 2011).

New intervention arose also from the progress achieved in the last decades in the knowledge of the behaviour of unsaturated soils and in the measurement of soil suction. Actually many old buildings with shallow footings suffer the effects of the shrinkage and swelling of unsaturated cohesive soils. The climate changes which occur in some world areas or the water level decrease produced by intense pumping lead often to new unattended settlements. However, as it has been recently proposed and implemented, control system of the saturation degree of the foundation soil can be carried out by means of subsurface porous water pipes, to be driven according to prearranged profiles (Carbonella et. al 2011).

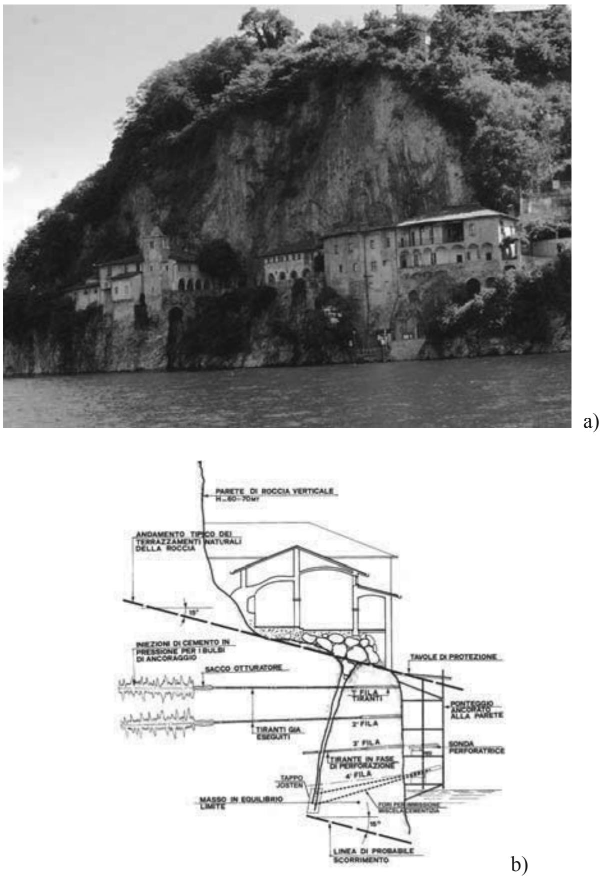


Figure 2. a) The limestone cliff over the hermitage of Santa Caterina del Sasso. b) The anchoring consolidation works.

3 A MORE RESPECTFUL APPROACH: PRESERVING THE KNOWLEDGE OF THE PAST

Quite often, for most engineers, the interaction between Geotechnics and the protection of ancient buildings is seen only from the standpoint of the design and execution of consolidation measures. First of all it has been noticed that measures taken to improve the static behaviour or seismic resistance of ancient buildings have not always had lasting effects, but on the contrary they have often produced even greater and irreversible damages. One example speaks for all: the Minaret of Mosul, Iraq, UNESCO Heritage monument (Fig. 3). The heavy, invasive, structural consolidation (by means of iron nails) and underpinning (micropiles) carried out in the 1981 (Lizzi, 1982, 1997) have not protected the monument from a further worsening of its static conditions, so much so that new measures are most urgent, but it is extremely difficult and problematic to decide on how to go about such measures.

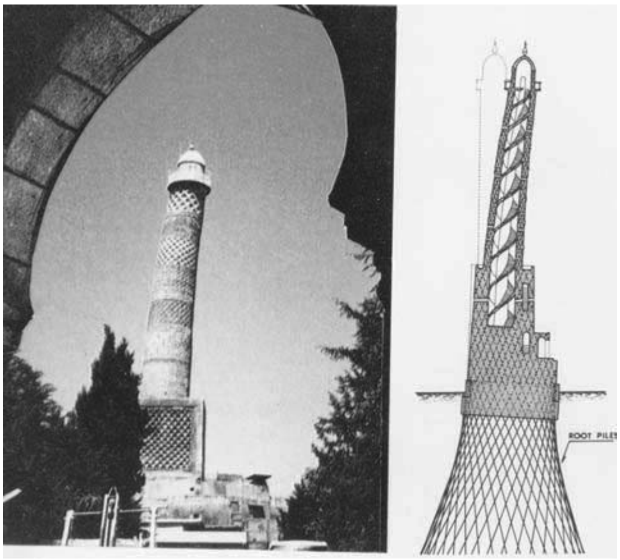


Figure 3. The Minaret of Mosul, underpinned micropiles and structurally strengthened in 1981 (Lizzi 1982, 1997).

The role of Geotechnical Engineers in the conservation of historic towns and monuments could be much broader and multifaceted and even more attractive in cultural terms than what is generally believed. The general perception of geotechnical engineering only as a means for intervening in a historic structure from the static standpoint is restrictive and far from the present view of thinking about monument conservation. Indeed it is now common thinking that the replacement or substantial modification of a structure or of a foundation alters or even eliminates forever an historically essential feature of a monument, the idea being that even its non visible parts, like the foundations, must also be preserved as a material token of its history.

A self evident example of the changing of mind that occurred in the course of a few decades is provided by the Leaning Tower of Pisa: for a long time, faced with the objective difficulty in interpreting the phenomena that were causing the progressive inclination of the Tower, technological solutions were offered that were intended to make the Tower independent of the behaviour of its foundation soil. In 1962, F. Terracina, a geotechnical engineer who was a passionate scholar of the Tower, published a proposal (Fig. 4) that simply envisaged the removal of soil from the uphill section (anticipating the solution adopted 40 years later) (Terracina 1962), but its suggestion remained unattended.

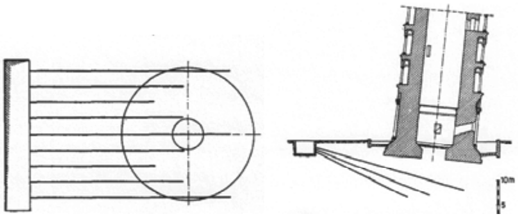


Figure 4. Layout of the underexcavation proposed by Terracina (1962).

Geotechnical Engineering had made great progress (with the development of micropiles and consolidation techniques) and the call for projects launched to save the Tower in 1973, after the completion of the studies on its subsoil (Cestelli Guidi et al. 1971) attracted only projects that aimed at creating a deep-seated underpinning (Fig. 5), across soils that were more or less deformable (Burland et al. 2013).

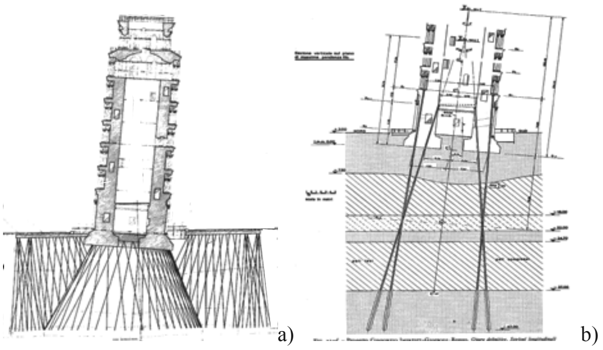


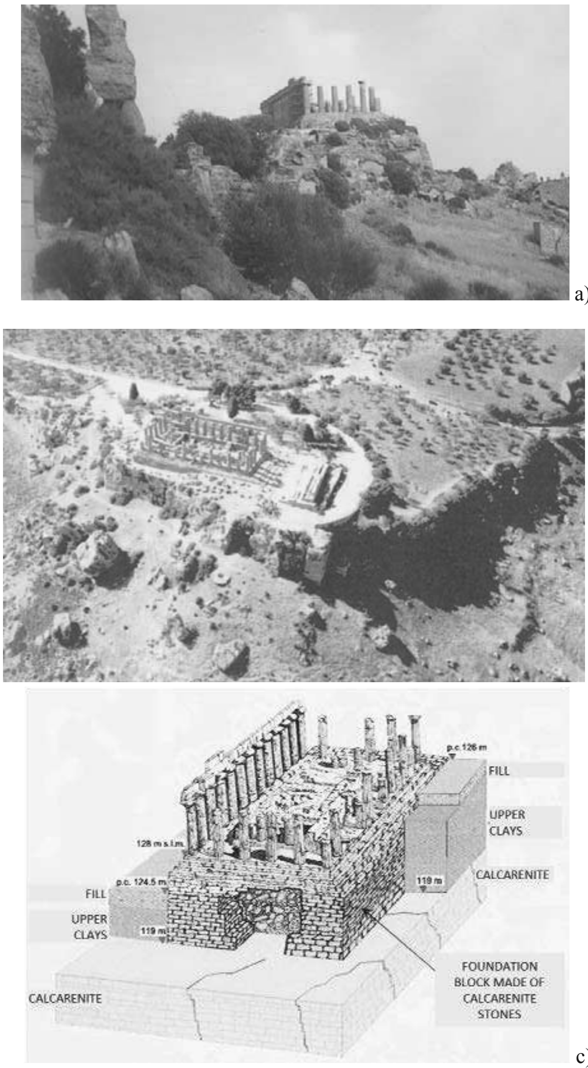
Figure 5. Some of the intervention measures proposed to save the Tower of Pisa at the 1973 call for projects (Burland et al. 2013): a) Fondedile proposal; b) Impredit-Gambogi-Rodio proposal.

Actually until the early 1990s, the concept that the conservation of a monument involves also saving its construction components, even those that are not visible had not yet gained ground; the idea that the Tower of Pisa, once it were to be transferred onto a new foundation built using the technologies of the 20th century, would become a fake, only a pure icon of the monument, was not understood (Calabresi and Cestelli Guidi 1990, Calabresi 2011). The new way of thinking made its way gradually and radically changed the cultural approach to the consolidation of ancient buildings, and in the case of the Tower of Pisa, it led to the solution that was finally and happily adopted for its stabilization (Burland et al. 2000).

4 THE NEED OF MULTIDISCIPLINARY STUDIES

If the protection of a historic and monumental building has the aim of maintaining and spreading the knowledge of past eras and civilizations, then the study of the interaction between buildings and the environment, and in particular their foundation soils, brings a substantial contribution to it; it may help understand the choices made by the designers at the time of construction, the changes that occurred over the years, the causes of damages, and the techniques and materials used and relate them to the natural and artificial materials available, to the machines and to the historic context. All this helps deepen our knowledge of remote times. In this setting the contribution offered by Geotechnics, alongside that offered by structural engineers, geologists, seismologists, architects, art historians and construction historians may play an extremely important role. The examples of activities carried out with this spirit are now a great many and have been quite successful with at times unexpected and surprising results. More than thirty years ago the archaeologist Gullini had already presented a fascinating picture of the results achieved through cooperation between geotechnical engineers, archaeologists and historians in studying the developments in construction techniques and design in antiquity (Gullini 1980). They studied the foundations of ancient monuments and archaeological settlements in Mesopotamia and in the Mediterranean area from the 4th millennium B.C. to the late Roman Empire. Today there are many conservation projects sponsored by UNESCO which have a multidisciplinary approach in which Geology and Geotechnics play an essential role: for instance mention can be made of the set of measures proposed for Greece presented by IAEG (Christaras 2003).

An Italian example is the Valley of the Temples in Agrigento (Croce et al. 1980.): studies carried out on the slope stability of the area where the temples rise have contributed to a better understanding of the history of Magna Greece and of the technical culture of its inhabitants between the 6th and 5th centuries B.C. within the frame of our knowledge of ancient Greece architecture (Dinsmoor 1975).


a)

b)

c)

Figure 6. The Temple of Juno at Akragas (Agrigento). a) The calcarenite cliff; b) An aerial view; c) An outline of its foundations Cotecchia et al. 2000).

The rational layout of the Greek town, Akragas, is only one of the many discoveries made (Fig. 6). Actually it is clear that the designers took into account the geomorphological characteristics of the area and they adopted solutions for the foundations that contemplated the properties of the soils and the seismic nature of the area (Cotecchia 1997, Cotecchia et al. 2000). Indeed, the foundations of the structural elements of all the temples, consisting of large calcarenite blocks were placed on the rigid and resistant calcarenite layer located at several metres depth, underneath the Pliocene outcrop of a medium hard clay: the foundation of the temple of Hera Lacinia is located at more than 7 metres below ground surface. Does this mean that the Greeks knew about the local amplification of seismic action induced by the clay layer? The ruins of Jupiter's Temple, that had been built previously and that had collapsed before its completion, suggest that this may be the case.

Being acquainted with all the details of a monument's history is essential in studying how to conserve it and in finding the best measures to ensure its conservation without undermining its original characteristics.

The recent study of the static condition of the leaning tower Ghirlandina in Modena (Figs. 7, 9) is a beautiful, outstanding exemplary demonstration of the importance of deep historic knowledge for explaining the nature and origin of the damages and of the effective contribution offered by a thorough geotechnical investigation. The Ghirlandina, that was designed by Lanfranco, a famous medieval architect, and built from 1099 to 1319, has a total height of 89 m; presently its axis has an inclination of 1°16' against the vertical, that is not increasing. In recent years there has been a widespread concern about the possible seismic vulnerability of the tower and an in-depth research has been carried out on its static and dynamic equilibrium conditions (Lancellotta, 2007, 2013). The main problem was whether the tower had a sufficient stability factor against a seismic action of assumed intensity.

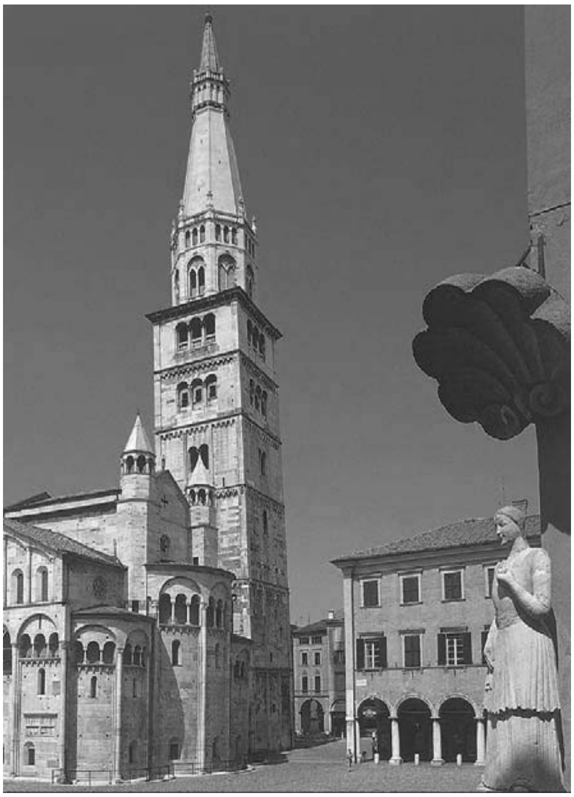


Figure 7. The Cathedral and the Ghirlandina tower at Modena. A view of the leaning tower and the Cathedral apse.

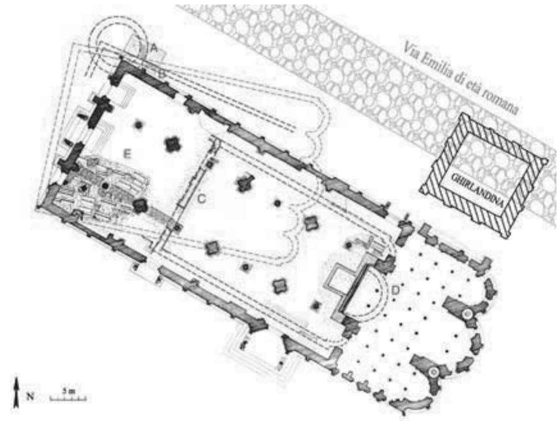


Figure 8. The planimetric positon of the various historic buildings and of the ancient Roman road Aemilia (Lancellotta 2013).

The geotechnical characteristics of the site are very complex. Actually the foundation soil is a succession of geologically recent alluvial deposits, covered by a thick (more than 6 m) layer of ancient, man made heterogeneous landfills. The upper horizons down to about 22 m are formed by medium to high plasticity inorganic clays, with an abundance of thin laminae of sand and peat. The geological, geotechnical and geophysical investigations showed that various periods of emersion during the deposition of the thick alluvial deposit generated a series of layers overconsolidated by desiccation.

A detailed history of the tower and the nearby Cathedral (Labate 2009), their original design and subsequent modifications, was obtained from the study of many archive documents and was checked against the comparison of the material and stylistic characteristics of the various masonry levels of both buildings. In addition, on the basis of archeological escavations made in 1913 (Sandonnini, 1983) and more recent investigations (Labate, 2009), it was possible to identify the position of the late medieval cathedral, the pre-Lanfranco cathedral and the actual Lanfranco cathedral (Fig. 8).

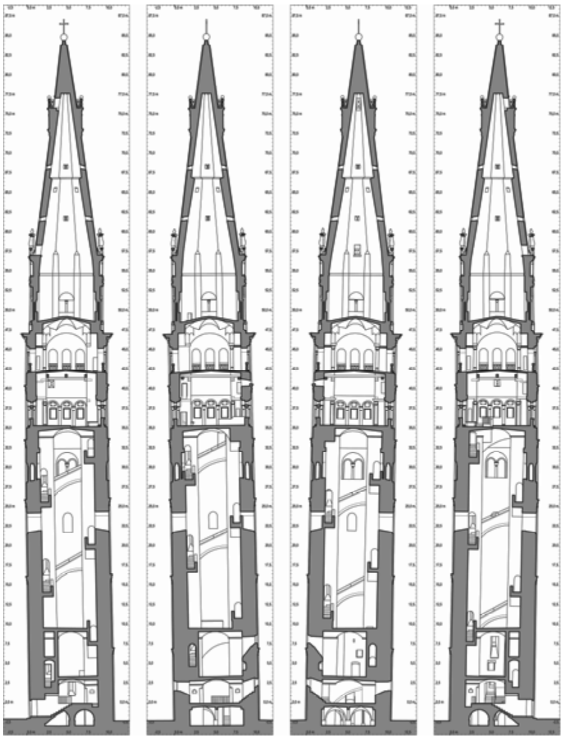


Figure 9. Vertical sections of Ghirlandina tower: from the left, view towards West, view towards North, view towards South, view towards East (Lancellotta 2013).

Since the foundation soil has "memory" of the previous loading history, this detailed reconstruction was the key to explain the differential settlements, suffered by the cathedral and in particular the tilt of its apse towards East and not only towards the Ghirlandina tower.

Additional borings allowed to identify a detailed profile of the soil upper layer and to find the remains of the ancient Roman road Via Aemilia at a depth of about 7 m. By comparing the different elevations of its pavement below the tower and outside, it became possible to deduce the settlements of the tower and the compressibility of its foundation soil. In order to explore the stability equilibrium of the leaning tower (Cheney et al. 1991, Di Tommaso et al. 2012) the inverted pendulum model has been adopted. Its parameters were derived from the soil investigations and from an experimental identification analysis of the tower dynamic behaviour in the presence of ambient vibration. The model parameters were chosen according to the time histories of the tower vibration, collected by means of a set of accelerometers at different heights; then a thorough analysis of soil-structure interaction was carried out in order to get a reliable estimate of the rotational stiffness and of the dynamic response of the tower foundation. The results gave reason for the good performance of the tower during the past seismic events and showed that there is no need for underpinning interventions. Furthermore it appeared that if the tower had been underpinned on micropiles, following the dogmatic trend of 20-30 years ago, the decrease of the fundamental period of the structure would have increased its seismic vulnerability.

In this connection another emblematic and famous case is the Cathedral of Mexico City (Ovando-Shelley et al. 1997, Tamez et al. 1997, Santoyo and Ovando-Shelley 2000, Ovando-Shelley and Santoyo 2001). Historic information made it possible to identify the origin of the differential settlements of the foundation soil, part of which had been consolidated by pre-Columbian works, and to design sub-excavation and soil consolidation measures to offset the differential settlements (Fig. 10). On the other hand, the studies on foundations have contributed to a thorough understanding of the historic events of the Cathedral and of the surrounding area.

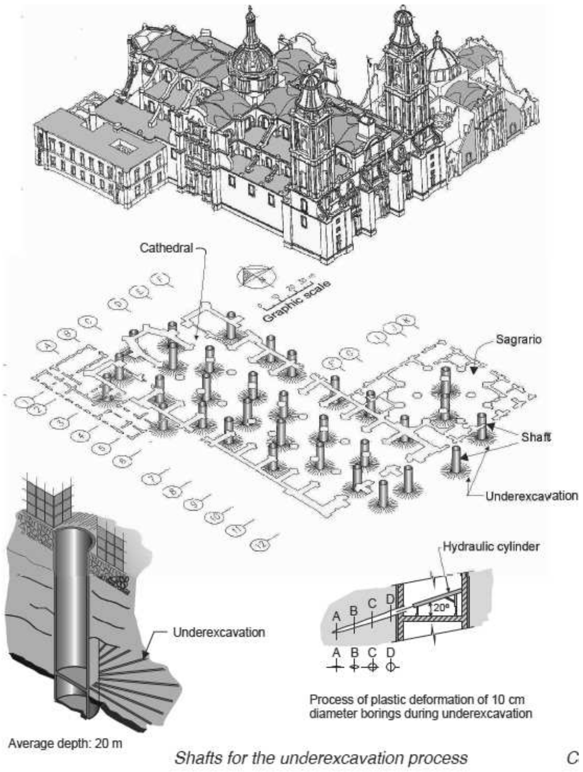


Figure 10. Underexcavation at the Cathedral of Mexico City (Santoyo and Ovando-Shelley, 2000).

5 CRITICAL CASES

There is a long list of monumental buildings that, owing to the slow or very slow displacements in the foundation planes, suffer progressive instability. In these cases a conflict sets in between the purely technological approach (aimed at reinstating the safety of the monument with structural interventions which, while ensuring that the external aspects are preserved, modify the original structural design), and a softer approach, on the other hand, that begins with a study of the phenomena underlying the instability and makes a long and perhaps uneventful search of the causes that need to be removed to stop the instability and if possible save the monument without substantial alterations so as to respect its historic integrity. It is worth recalling that the search for the causes is always a time-consuming exercise that is often much more expensive than ordinary, obvious structural and geotechnical engineering interventions. A systematic study of the saving projects carried out in Italy until 1995, including buildings of different kinds (Table 1), has shown that pure underpinning by micropiles was the largely predominant type of measure (Fig. 11) which in many cases was probably unnecessary or unsuited.

TIPO	MONUMENTO	PLACE
CASTLE	Forte di S.Andrea	Venezia
	Fortezza da Basso	Firenze
	Castello di Caccamo	Caccamo (Palermo)
	Castello Colonna	Genazzano (Roma)
CHURCH	Duomo di Agrigento	Agrigento
	Monastero di S.Apollonia	Venezia
	Chiesa di S.Andrea delle Fratte	Roma
	Monastero di S.Caterina dal Sasso	Leggiuno (Varese)
	Chiesa di S.Chiara	Cagliari
	Basilica di S. Francesco	Assisi (Perugia)
	Chiesa di S. Francesco al Prato	Perugia
	Chiesa di S.Maria Assunta dei Gesuiti	Venezia
	Chiesa di S. Maria della Consolazione	Todi (Perugia)
	Basilica di S.S. Maria e Donato	Murano (Venezia)
	Cattedrale di S. Maria del Fiore	Firenze
	Chiesa di S. Maria della Piazza	Ancona
	Duomo di Milano	Milano
	Duomo di Nicosia	Nicosia (Enna)
	Duomo di Orvieto	Orvieto (Terni)
	Chiesa Parrochiale di Piovà Massaia	Piovà Massaia (Asti)
	Duomo di Pienza	Pienza (Siena)
	Chiesa di S.Pietro in Portovenere	Portovenere (La Spezia)
	Basilica di S. Vitale	Ravenna
PALAZZO	Palazzo Ducale di Modena	Modena
	Palazzo di Giustizia di roma	Roma
	Palazzo della Regione di Milano	Milano
	Domus Tiberii	Roma
TOWER	Torre degli Alberti	Firenze
	Campanile di Aquileia	Aquileia (Udine)
	Campanile di Burano	Burano (Venezia)
	Campanile di Concordia Sagittaria	Concordia Sagittaria (Venezia)
	Campanile di S. Marco	Venezia
	Torre di Pisa	Pisa
OTHER	Antico magazzionodel sale	Cervia (Ravenna)

Table 1. Monuments types subjected to systematic study (from Cecconi et al. 1997).

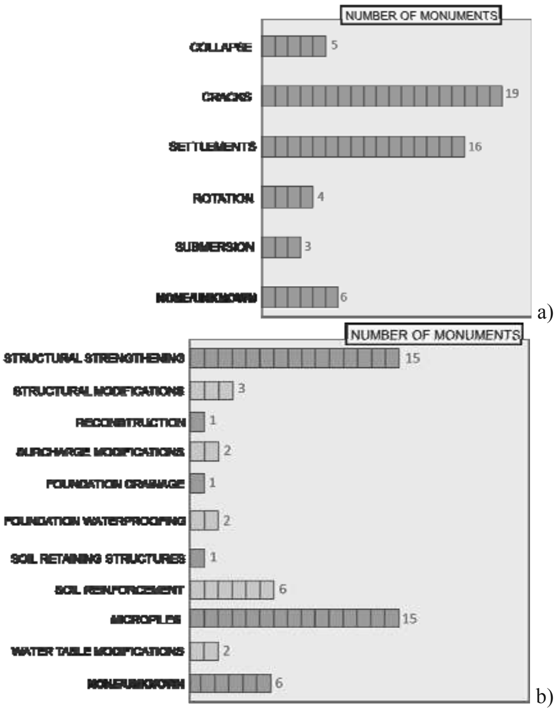


Figure 11. An analysis of some Italian monuments (modified from Cecconi et al. 1997): a) damage types; b) preservation measures.

However sometimes the causes of the instability are not clear and the possibility of removing them remains at best uncertain. This is the case of two Italian monuments of great value for which, after years of investigations, the causes of their instability still have not been found and for which there are only mere hypotheses: the Basilica of St. Angelo in Formis and the Pienza Cathedral.

St. Angelo in Formis

St. Angelo in Formis is a Benedictine basilica near Capua which rises on the slopes of a rock hill (Fig. 12); it was built in the 6th century A.D. on the ruins of a Roman temple whose origins date back to the 5th century B.C (Cammarota, 2013). The basilica, which has three naves, presents traces of the changes it underwent in time. In particular the bell tower and the portico probably collapsed and were rebuilt in the 13th century. The foundations of the apse, most of the external walls and the pillars of the naves are rather shallow and rest on a fractured dolomite mass, whereas the foundations of the facade, the portico and a small proportion of the side walls rest on debris deposits and backfill.

The geology of the area is complex because the dolomite mass overlies more recent Oligocene and Myocene deposits and there are major fractures of tectonic origin (Fig. 13). There is knowledge of relevant repair and consolidation measures adopted in 1732 and in 1930 after seismic damages. Of the more recent earthquakes of 1962, 1970 and 1980, only the last one caused some slight damages. From the end of the 1960s some cracks of static origin appeared in the walls of the naves lying over the pillars and with their slow progression they have caused quite some alarm and have required underpinning props.

Figure 12. The Benedictine Basilica of St. Angelo in Formis.

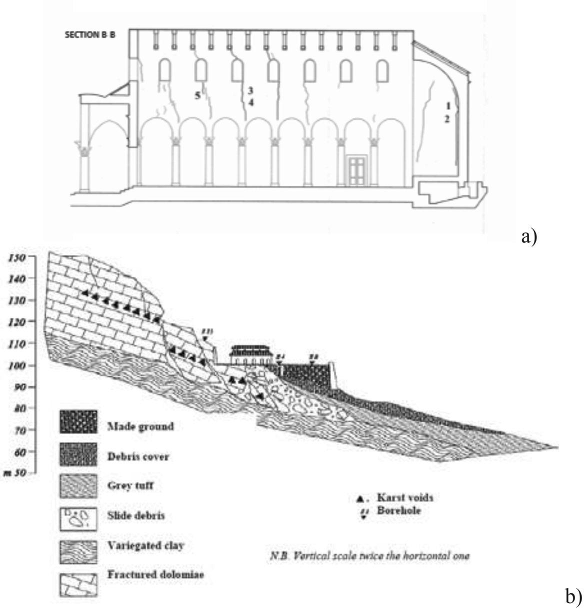


Figure 13. St Angelo in Formis. a) The main fissures; b) Geologic section of the foundation soil (Cammarota et al. 2013).

The geological and geotechnical investigations performed so far in different stages have not helped to identify the causes of the settlements of the foundation soil. A first hypothesis attributed the instability to the mining activities carried out using explosives in a nearby quarry, but even after the mining activities stopped in 1981 the cracks and fissures continued to widen.

The origin of the distress remains unclear so that further geotechnical investigations and more extended studies are necessary. The safety of the fissured masonry structures – arches and vaults – is currently ensured by provisional and removable props, but while it is increasingly difficult to obtain public economic support to carry out research into the causes of the on-going phenomena, the proposals of consolidating the masonry walls of the basilica by means of important structural measures are bound to increase.

The Pienza Cathedral

The Pienza Cathedral (Fig. 14) is perhaps less famous than the Tower of Pisa, but it is just as problematic and intriguing.

Figure 14. Cathedral of Pienza and Piccolomini Palace from the square.

Perhaps there is no other monument that, in its lifetime, has been subjected to so many consolidation and strengthening measures as the Pienza Cathedral, because of the very slow, but continuous settlements of the foundation soil underneath its apse (Forlani Conti 1986).

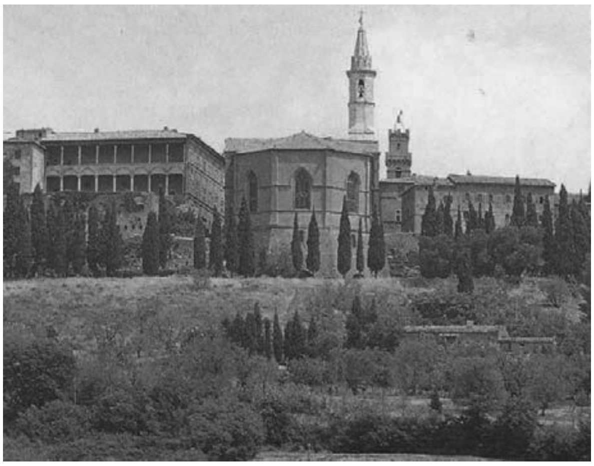


Figure 15. The Piccolomini Palace and the Pienza Cathedral apse seen from the rock scarp downhill.

In 1459 Enea Silvio Piccolomini, newly elected pope with the name of Pius II, decided to raise the status of his birth town with the construction of a Cathedral and some noble palaces. Works for the construction of the new cathedral started in 1459 and were completed in only three years. In order to make sure that the cathedral would be of appropriate proportions without restricting the size of the main square, situated symbolically between the Cathedral and the City Hall, the architect, Bernardo Rossellino extended its layout beyond the walls of the village and the sandstone scarp that delimits it towards the Orcia Valley (Fig. 17): the apse, with its underlying crypt, had its foundations downhill from the scarp where the level of the ground is about 15 m lower (Fig. 15).

The construction of the apse ran into considerable and unexpected difficulties. In his memoirs the Pope wrote that the foundation plane rested on rock masses crossed by large fissures and that large arches were built across them to support the foundations. Some fissures appeared in the walls of the apse before the completion of the construction works, but Rossellino attributed them to the setting of the mortar (Piccolomini 2008).

The church was inaugurated on 29 August 1462. New cracks appeared soon after between the nave and the apse and in the underlying crypt. Since then, for five centuries, there has been an uninterrupted succession of instability phenomena and consolidation works under the foundations; drifts and deep drainage wells have been driven, reinforcement buttresses have been built to uphold the apse, repairs and restructuring measures have been adopted for the side walls, the crypt under the apse, the vaults and the roof (Di Pasquale 1992).

All these measures were made necessary by the constant lowering of the apse foundation downhill from the rock scarp: there is proof that between 1520 and 1530 the floor of the apse was al-ready lower than that of the nave by about 27 centimetres. A sudden settlement of about 0.3 m of the soil downhill from the scarp occurred on the night of 26 November 1545 and caused the partial collapse of the apse and of the bell tower. The event, described in the memoirs of a citizen of Pienza is defined *Terrae motus* (literally a movement of the earth), but there are doubts about it being an earthquake or a sudden slope instability phenomenon, perhaps triggered by a seismic quake. At present the overall difference in level of the apse with respect to the nave is about one metre, as it can be seen from the relative displacement of the cornice in Figure 16.

Figure 16. The cornice displacement shows the apse settlement.

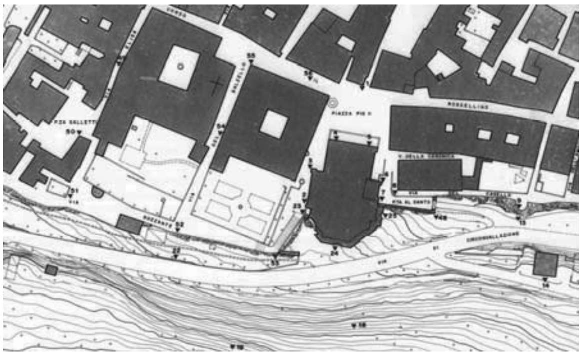
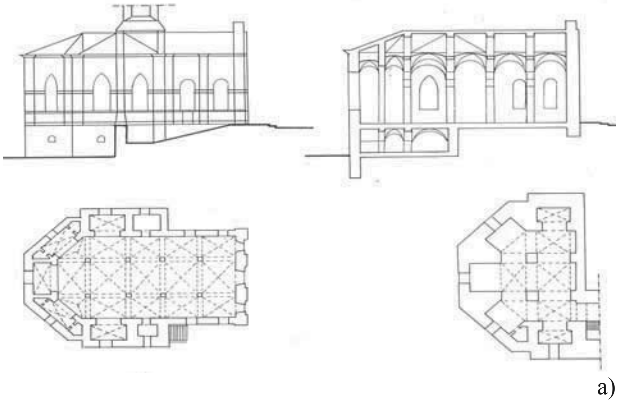


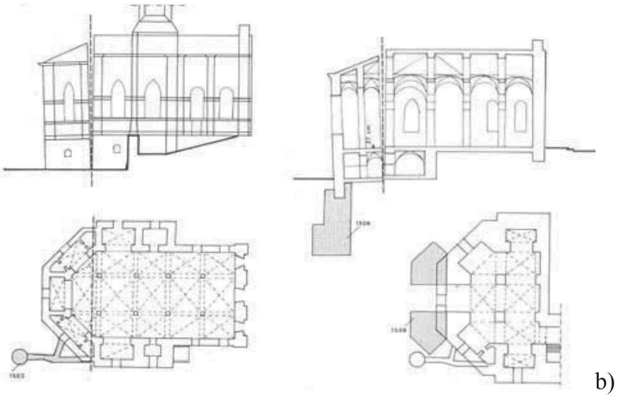
Figure 17. Planimetric position of the Cathedral.

Main events in the Cathedral history (Fig. 18)

1458, Enea Silvio Piccolomini is elected pope (Pius II) and begins to rebuild his home town.
1459, The construction of the Cathedral is initiated by Bernardo Rossellino. Some problems arise in the apse foundation.
1462, At the end of the works some fissures appear close to the first choir chapel. Their openings increase towards the vaults. (a)
1462, Aug. 29, Solemn opening of the Cathedral.
1490, The apse begins to settle.
1500, The settlement of the apse reaches about 0.3 m.
1503, A tunnel is built to drain water from under the crypt.
1508, Two buttress piers are built against the apse to sustain it.(b)
1514, A wall is built around the apse. The settlement reaches 0.45 m
1545, Nov. 25, An earthquake (?) causes a large settlement of the apse and the collapse of the belfry; a crack appears along the natural scarp, SW of the town. (c)
1570, Repair works of the earthquake damages are completed. The collapsed vaults of the transept are substituted by false vaults
1596, The crypt arches and the external walls are streightened.
1604, A. Sandrini, architect, states that the damages are due to the slope movement, so that underpinning the apse is useless. (d)
1650 - 1760, Repeated repair works. The apse is more than 25 cm out of the plumb line.
1750 - 1770, A proposal of demolishing the apse and shortening the church is considered, but happily not carried out.
1888 - 1895, Collapsing vaults are replaced by false works. The pillars are connected by steel tendons. The apse has settled 0.85 m and has increased its detachment from the nave. (e)
1911 - 1925, Underpinning of the apse with masonry pillars, which bypass the sandstone layer to reach the marly clay. (f)
1926 - 1929, Various repair works are carried on, the apse walls are strengthened. The transept is underpinned.
1930 - 1933, The apse and crypt vaults are rebuilt. (g)
1958 - 1962, Underpinning of nave and aisle pillars with root piles. A hydraulic diaphragm is built around the front. (h)



a)



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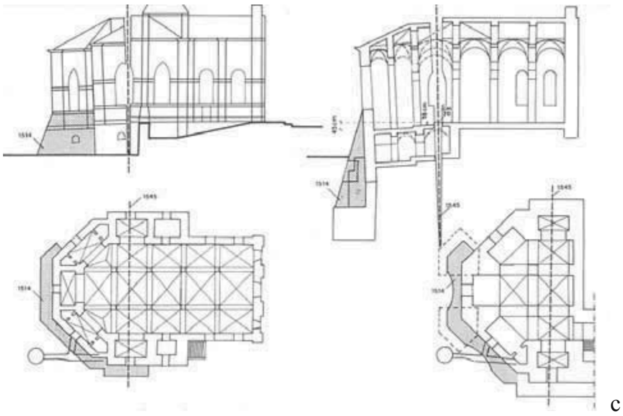

c
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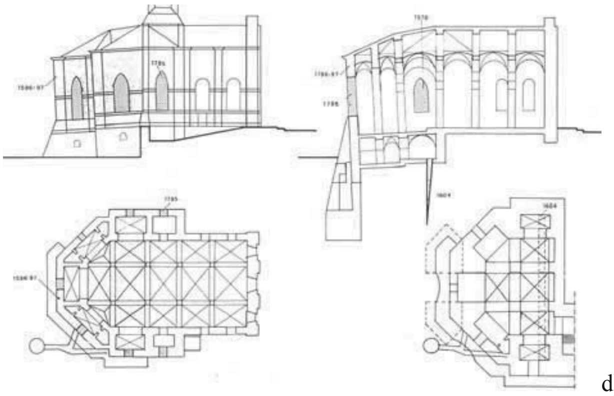
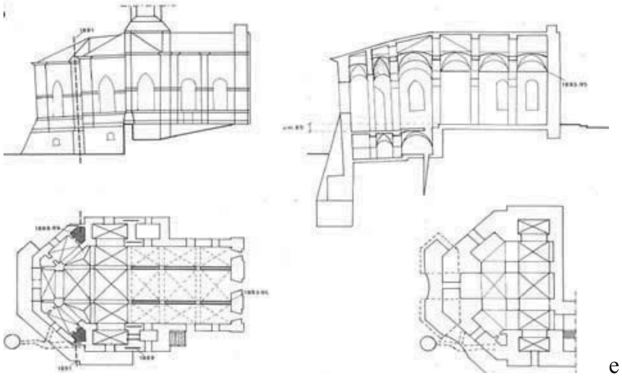


d)



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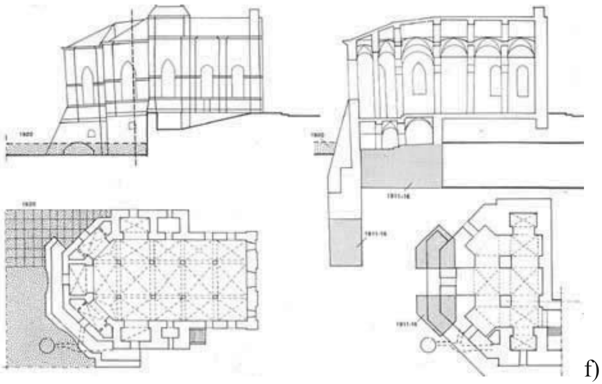
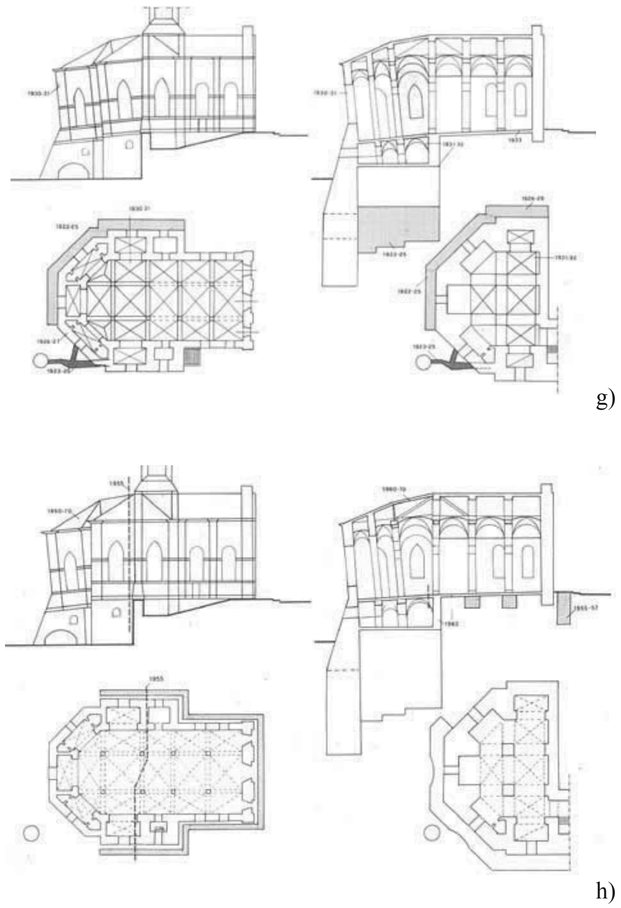


f)


g)

h)

Figure 18. Main events in the Pienza Cathedral history: a) 1462; b) 1503-1508; c) 1514-1545; d) 1570-179e) 1888-1895; f) 1908-1920; g) 1922 -1933; h) 1955 - 1979 (Di Pasquale 1992).

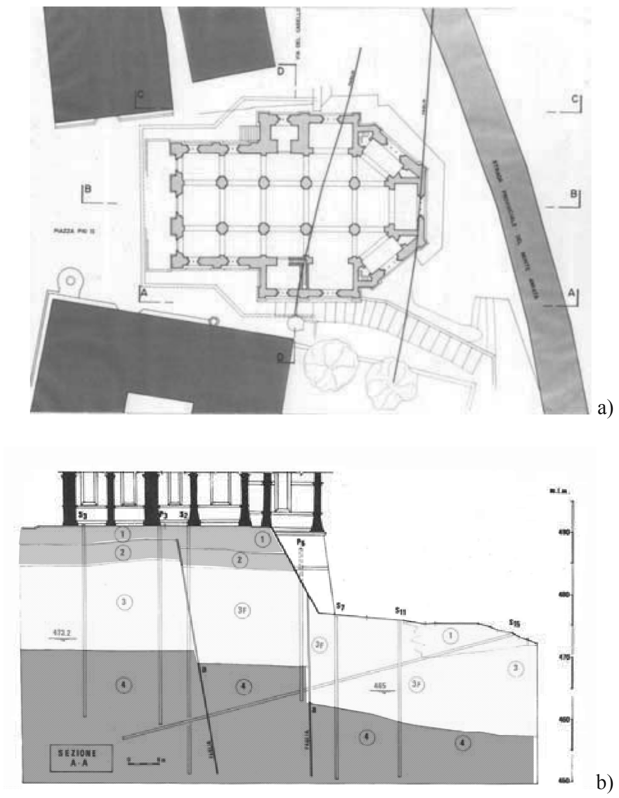
The phenomenon has always been attributed to the poor quality of the foundation soil, to its many fissures and to the effects of underground water. The sole exception is a report on instability dated 1604, in which an architect, A. Sandrini, having noticed that the earth surface fissures caused by the 1545 displacements were aligned with the scarp and extended throughout the whole southern side of the village, stated that the apse settlement was due to the movement of the slope; this interpretation of the phenomenon has been systematically ignored.

In about 1750, as the instability in the area of the apse continued, suggestions were made to demolish that part and restrict the Cathedral to the part rising on the uphill part of the scarp. Luckily the proposal was not followed up and further measures were taken to consolidate the walls and foundations of the apse.

In 1911, as concerns grew for the stability of the Cathedral, a lively debate occurred between those who suggested underpinning the apse and those who, following the example of what had just be done for the Spina Church in Pisa, suggested dismantling the apse to build a new foundation. In any case everyone was persuaded that the settlement of the apse was due to the poor quality of the foundation soil. Luckily the first position prevailed and between 1911 and 1929, by means of sample excavations through the sandstones to the underlying marly clays, stone and brick pillars were built under the apse down to more than 20 m from ground level downhill from the scarp. It was deemed that the apse, provided with a rigid monolithic foundation resting on the layer of marly clays, was finally consolidated. However, cracks causing detachment of the apse from the nave occurred again quite soon and in 1956 a new study committee was appointed including a geologist engineer who identified two traces of a vicarious fault, practically aligned with the cracks in the walls, having a total throw of about 15 m. Quite surprisingly the new structural consolidation measures adopted a few years later did not take this fact into any account.

Later, between 1979 and 1984 a more thorough survey was made of the structures and of the relevant instability and geological and geotechnical investigations were carried out to define the bedding and mechanical characteristics of the foundation soils.

The following figures (Figs. 19, 20) show two stratigraphic sections and their positions in the plan view. Under the square and the nave of the Cathedral a limestone layer 3 to 4 m thick over-laps the weakly cemented sand and fissured sandstone layer, having a thickness of 12-15 metres, which can be seen in the scarp on the sides of the apse (Lazzarotto and Micheluccini 1986, Calabresi et al. 1988, Calabresi et al. 1998).



a)

b)

Figure 19. a) The Cathedral plan and the traces of the fault traces; b) Geologic section AA, parallel to the church axis;

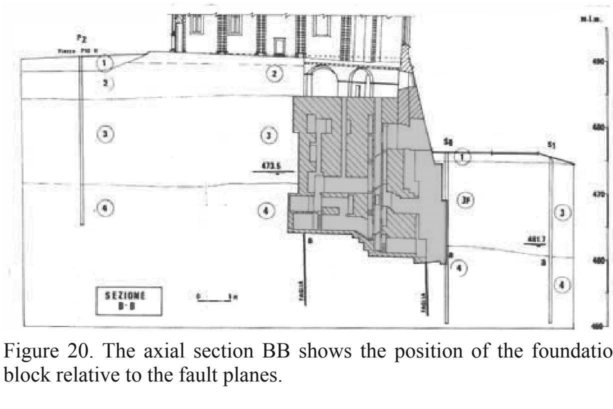


Figure 20. The axial section BB shows the position of the foundation block relative to the fault planes.

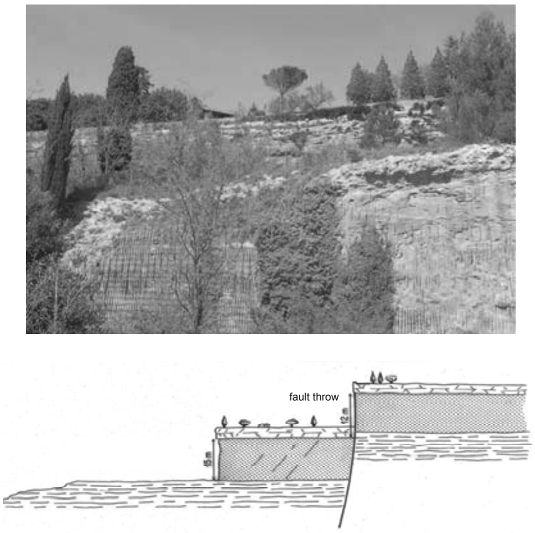


Figure 21. The main fault surface about 400 m N-W of the Cathedral

It lies on a Pliocene formation of strongly overconsolidated marly clays whose thickness is about 100 m at the centre of Pienza and increases to over 800 m southwards (Brogi et al. 2005). The substrate of the Pliocene sediments consists of Mesozoic, carbonate-siliceous formations of the "Tuscan Series". The discontinuities that border the scarp, already identified in 1956, are a set of locally vicarious faults having a WNW-ESE direction and southward dip. They are crossed by minor, approximately perpendicular discontinuities.

The geotechnical investigations showed that both the sandstones and the underlying marly clays have high strength and negligible compressibility.

In 1983 a periodical levelling was started by installing many benchmarks, uphill and downhill from the scarp and from the set of faults (Fig. 22). The measurements, repeated every year until 1992 (Guidi 1986) then at various intervals between 1994 and 1999 and resumed recently, show that the whole area covered by the bench-marks downhill from the scarp has a constant non uniform settlement of between 1 and 2 mm per year (Figs. 23, 24). Minor effects of this phenomenon are visible in other buildings in the same area (Costantini and Lazzarotto 2010). The lack of uniformity of the settlement rate shows that the Pliocene marly clay is split by the sets of discontinuities; the main vicarious fault is the main, but not the only source, of the soil displacement downhill from the scarp.

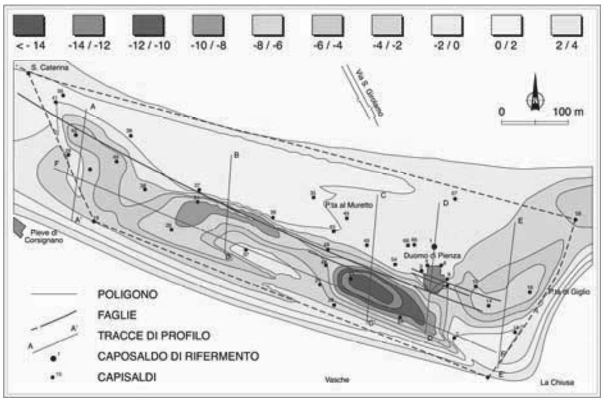
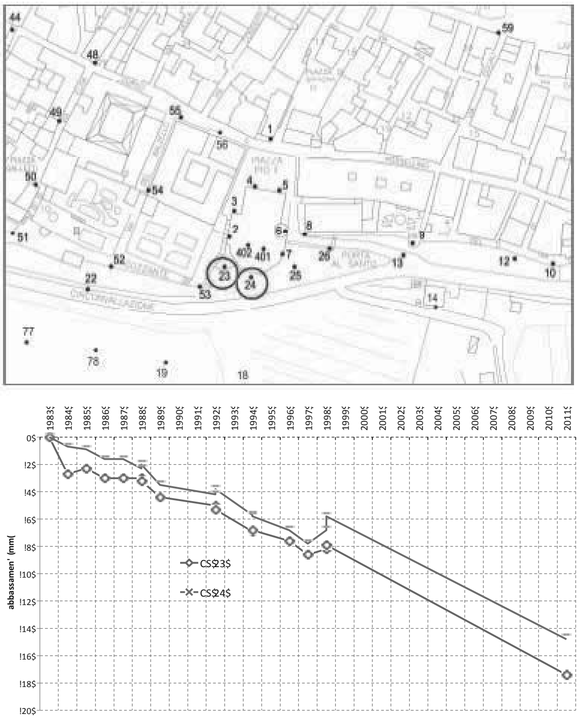


Figure 22. Ground settlement contours from June 1983 to January 1992.

Horizontal displacements are null or non measurable. The steady and extremely small rate of the movement, detectable only by a high precision levelling over a long term campaign explains why the phenomenon was never detected in the past.

Then it was finally stated that the apse settlement is not due to the deformation of the foundation soil but to the constant lowering of the area downhill from the set of faults.



a)

b)

Figure 23. Settlements of two significant points close to the Cathedral apse: a) plan view; b) settlements *vs.* time

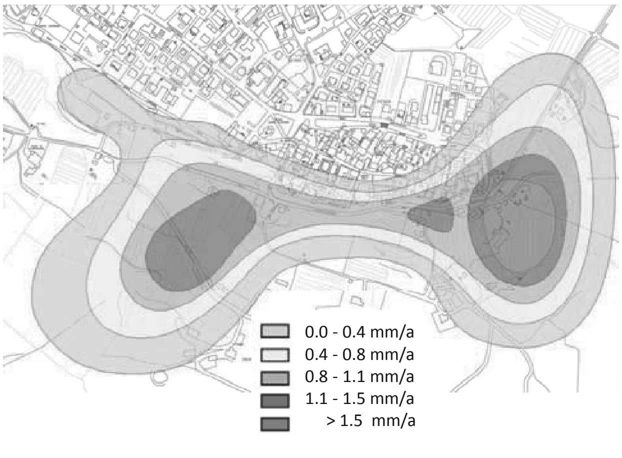


Figure 24. Settlement rate contours in the area south of the Cathedral.

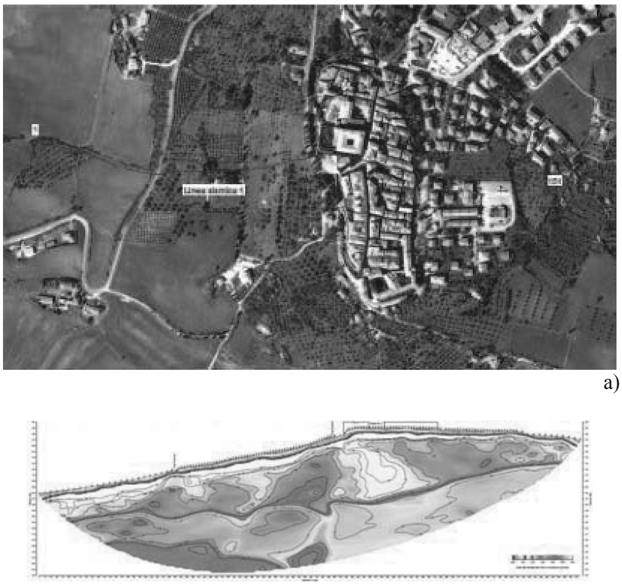
At the present time the masonry block constituting the underpinning of the apse built at the beginning of last century, whose internal edge lies uphill from a fault plane, while the external part is downhill, has a rigid downhill rotation which involves the overlying apse. Since the existence of an active fault should be ruled out, the only hypothesis that would account for the continuous settlement is a deep seated gravitational slope deformation within the marly clay formation, influenced by the shape of its bed and by the discontinuity surfaces (Genevois and Tecca, 1984, Calabresi 1992, Calabresi et al. 1995, Calabresi et al. 1988, Sciotti and Calabresi 2004).

A recent seismic investigation along a longitudinal section measuring more than 1000 metres has highlighted a significant anomaly in the P-wave velocity contours under the Cathedral apse and a depression in the bed of the Pliocene deposits in the zone where the surface movements are largest, thus confirming that the faults detected at the surface involve also the underlying

Mesozoic formation (Fig. 25). The lines of larger V_p gradient obtained from the seismic reflection investigation (Fig. 26) show the main units of the stratigraphic section and the probable traces of the discontinuity surfaces (Brogi et al. 2003).

A likely hypothesis is that the sinking of a dihedral mass between two convergent fault planes is made possible by a horizontal displacement rate of the downhill zone too small to be topographically detectable. While it is evident that the faults, along whose surface the clay shear strength has a residual value, and the sets of minor discontinuities have a critical influence on the equilibrium conditions of the slope, their geometric characteristics and the cleft water pressures (Calabresi and Manfredini 1973, Sciotti and Calabresi 2004) have not yet been sufficiently defined to get a convincing explanation of the phenomenon.

The project of a deeper geostructural and geotechnical research has been recently submitted to the study committee recently charged of carrying out an updated analysis of the Cathedral conditions, but its implementation has been delayed by economic problems. However the fundamental question still remains: assuming that the above explanation be correct, could a geotechnical measure, such as a decrease of the piezometric head, be designed to slow down the movement?



a)

b)

Figure 25. Seismic refraction tomography. a) The section trace; b) P-wave velocity contours.

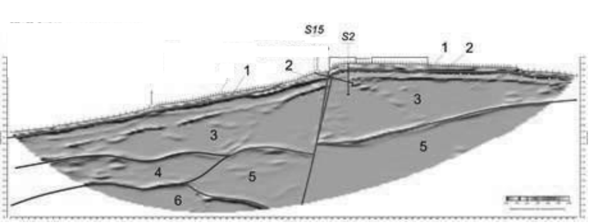


Figure 26. Wave P velocity gradients from the seismic reflection measurements. 1. Remoulded superficial soil; 2. Limestone and Sandstone (Pliocene); 3. Over-consolidated marly clays (Pliocene); 4, 5 carbonate-siliceous formations "Tuscan Series" (Mesozoic); 6 Anhydrite (Trias).

Consolidation measures of the Cathedral of an entirely different approach, aimed at supporting the apse area with new reinforced concrete structures hinged to the ground uphill from the fault, are repeatedly being submitted by groups with different opinions. Some structural solutions were presented and discussed at a special conference (Mascardi 1992, Migliacci 1992), where however the concept of protecting the monument and its history also from a material point of view, without modifying its original design with inappropriate changes, largely prevailed. Luckily the rates of subsidence and rotation of the apse are very small and leave time for geotechnical engineers to look for a possible soft solution. There is a hope that they may win the challenge as it has happened for the Tower of Pisa.

CONCLUSIONS

Geotechnics may offer a significant contribution to the knowledge of ancient designs and construction techniques and to the interpretation of the causes of instability. The effects of deformations in foundation soils that occurred in ancient times, or that are difficult to trace back to any specific cause, can often be observed in ancient buildings. An ancient building or historic site is interesting in and of itself for geotechnical engineers, since it constitutes a monitoring instrument of the long term behaviour of the soil that influences them.

The progress of geotechnical engineering and of the specialized technologies offer the means to perform complex and efficient interventions to save monuments, historic buildings and old towns. However too often in the last decades the new opportunities offered by this progress and the cooperation of geotechnical engineers has been utilized inappropriately by applying new deep foundations and structural modifications, that overcome the ancient building distress in a simplistic way, that ignores the history of the object of the intervention, from its initial building to our time, and the witness value of the technical solutions adopted by our predecessors and of their expertise.

The great challenge is how to save monuments and historic buildings together with the physical token of their conception, their original construction techniques and their historic modifications, that are tangible witnesses of the history of mankind.

The problems posed by slow, continuous settlements induced by deep seated deformations, which require long, in-depth and expensive investigations, are among the most difficult to be understood and explained. However the geotechnical engineers should feel themselves engaged in exploiting their knowledge of soil mechanics and applied geology to look for a way, if it exists, to save monuments and historic sites by removing the cause of distress and avoiding heavy structural interventions that distort their substantial characters.

The cooperation of architects, historians, archaeologists, structural and geotechnical engineers is the necessary precondition for a respectful attitude towards conservation problems.

In this context the geotechnical engineers have also the opportunity of actively contributing to the knowledge of the history of architecture and engineering, by following the unforgettable example and the footsteps of our great colleague Jean Kerisel.

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