INTRODUCTION

The conservation of historical monuments 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, administrative), intertwining in inextricable patterns. In particular, 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 the 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.

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guiding the behaviour of the actors involved as the Mechanics does with the structural engineer. These problems are exemplified by means of a couple of case histories.

2 TOWER OF PISA

2.1 Introduction

The Leaning Tower of Pisa (Fig. 1) is founded on weak, highly compressible soils and records indicate that it started leaning since its construction. The movement went on over the centuries and in 1990 the overhang had reached the worrying value of 4.7 m and was increasing at a rate of 1.5 mm per year.

A reliable clue on the history of the tilt lies in the adjustments made to the masonry layers during construction and in the resulting shape of the axis of the Tower. Based on this shape and a hypothesis on the manner in which the masons corrected for the progressive lean of the tower, the history of inclination of the foundation of the tower reported in Fig. 2 may be deduced. During the first phase of construction to just above the third cornice (1173 to 1178), the tower inclined slightly to the north. The construction stopped for almost a century, and when it recommenced in about 1272 the tower began to move towards the south. Work again ceased when the construction reached the seventh cornice in about 1278, at which stage the inclination was about 0.6° towards the south. During the next 90 years, the inclination increased to about 1.6°. After the completion of the bell chamber in about 1370, the inclination increased significantly. In 1817, when Cresy and Taylor made the first recorded measurement with a plumb line, the inclination of the tower was about 4.9°. In 1859 Rohault de Fleury carried out another measurement, obtaining a value of the inclination significantly higher than of Cresy and Taylor. In fact, between the two measurements the walkway surrounding the base of the tower (the so called catino) had been excavated to uncover the base of the monument which had sunk into the soil due to a settlement as high as 3 m. Digging the catino seriously threatened the stability of the tower, and caused an increase of inclination of approximately 0.5°.

Figure 1: The Leaning Tower of Pisa
The abrupt increase of the inclination, which is evident in Fig. 2 when a definite value of the height had been attained, is a clear sign of an impending phenomenon of instability of the equilibrium, known as *leaning instability*.

![Figure 2: Inclination of the Tower vs. weight, as deduced by the corrections during construction](image)

Since 1911 the rotation of the tower has been monitored by different means. It increases more than the rotation of the foundation (Fig. 3), implying a steady deformation of the tower body. The long term steady trend is marked by two major perturbations: one in 1935 and another one in the early 1970’s. The first one has been caused by cement grouting into the foundation body and the soil surrounding the catino, carried out to prevent the inflow of water. The second perturbation has been related to the pumping of water from deep aquifers, inducing subsidence all over the Pisa plain. The closure of a number of wells in the vicinity of the tower stopped the increase of the rate of tilt.

In any case, even correcting for the anomalous increments occurred in 1935, 1970-73 and some further minor perturbation, it appears that the rate of tilt is steadily increasing and has nearly doubled from 1938 to 1993. In the early 1990 the inclination was about 5.5°.

### 2.2 Studies and investigations from 1902 to 1973

The first Commission on the tower of Pisa installed by the Italian Government was a consequence of the worries induced in the public opinion by the collapse of the S. Marco bell tower in Venice, 1902. The Commission carried out a number of investigations, and presented the results in a broad and valuable report, issued in 1912.
Figure 3 : Increase of the inclination since 1911

A second Commission was installed in the same year with the task of studying the possible means of stabilising the tower, but did not conclude because of World War 1st. A new Commission with the same task was nominated in 1924; it included a number of experienced engineers, and developed a solution consisting in widening the foundation of the tower by filling the catino with concrete. The proposal met a strong opposition in Pisa, and another alternative Commission was appointed by the local authorities, to develop different and less intrusive solutions.

In 1927 the Government succeeded in unifying the two Commissions in a new one, which came to the conclusion that the most urgent need is that of sealing the catino. In fact, being the bottom of the catino well below the ground water table, since 1838 it was kept dry by continuous pumping; it was believed that pumping was responsible for the continuing inclination.

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In the years 1934-35 the tower foundation and the soil surrounding the catino were made watertight by injecting 100 t of cement grout into the foundation masonry and 21 m³ of chemical grout into the soil. The intervention was successful, in the sense that the water inflow into the catino was effectively stopped. The price for this success, however, was a sudden and marked increase of the inclination of the tower. About 100 years after the excavation of the catino, again an intervention carried out with wishful thinking to stabilise the tower has strongly threatened it.

After the World War 2nd, it became clear that the tower was still moving, in spite of the intervention carried out in 1935. A permanent Commission was thus appointed in 1949, and among other tasks it had to examine and evaluate a number of design schemes. Though proposed by renowned engineers, all of them were intrusive and not respectful of the material integrity of the monument; with hindsight, it appears very lucky that the Commission did not recommend any of these solutions. Though being “permanent”, the Commission was dismantled in 1957; only the inclination measurements were continued. Further solutions were proposed in the following years (Fig. 4); it is noteworthy that one of the most intrusive was suggested by the architect N. Benporad, Superintendent of Monuments of Pisa! None of these proposals was taken into consideration.

In 1964 a new and very important Commission was appointed, with the task of preparing the documents of an international competition for the design and implementation of stabilising works. The Commission was chaired by Prof. G. Polvani, and for the first time it included a geotechnical group: C. Cestelli Guidi, A. Croce, E. Schultze, A.W. Skempton. To make available a complete documentation, the Polvani Commission carried out a number of investigations and collected an impressive amount of knowledge.
2.3 The tender of 1973

The call for tender was issued in 1973. There was the participation of 22 groups, and 11 among them were admitted to the competition. Prof. Polvani passed in 1970, but the Commission, with minor modifications, was charged of judging the competition. The proposals by: Fondedile (Fig. 5), Fondisa (Fig. 5), Geosonda (Fig. 6), Konoike and Impresit-Gambogi-Rodio (Fig. 6) were judged worth of mention, but no contract was awarded. At that time, it was discovered that the Piazza dei Miracoli was affected by a subsidence process, induced by water pumping from deep wells. This factor was not properly considered in the tender, and it is probably one of the reasons why the contract was not given. Three of the groups which had been mentioned joined together in a Consorzio, and developed a common solution working in connection with the Commission, but eventually nothing was done.
2.4 From 1975 to 1990

In 1983 a Design Group was charged by the Ministry of Public Works of designing the stabilisation work; the resulting solution was still rather intrusive (Fig. 7), and was not definitively approved by the Council of Public Works. In 1988 a technical Committee, entrusted by the Government to study the problem, focuses the attention on the risk of brittle failure of the heavily stressed masonry, in addition to the risk of a foundation failure. A failure of the masonry would be sudden, without forewarnings.

In 1989 another spectacular tower collapse occurs: that of the Civic Tower of Pavia, with five casualties. As a result, the attention to the safety of the Tower of Pisa increases, and the
Government prohibits the access of visitors, following a recommendation of the Study Committee.

The closure of the Tower results in a strong pressure of the public opinion for a rapid reopening, but the restoration experts warn against hasty and not sufficiently pondered solutions. The Government decides to install a further Commission, chaired by Prof. M.B. Jamiołkowski (a geotechnical engineer) and formed by art historians, restorer, structural engineers and geotechnical engineers; a truly interdisciplinary body. It has the task of conceiving, designing and implementing the necessary stabilisation works.

2.5 Investigations and interventions by the International Committee

A careful study of the behaviour of the tower led to the conclusion that it was affected by a phenomenon of instability of the equilibrium, known as leaning instability, depending on the stiffness and not on the strength of the foundation soils.

To demonstrate leaning instability, the simple conceptual model of inverted pendulum may be used. It is a rigid vertical pole (Fig. 8) with a concentrated mass at the top and hinged at the base to a constraint that reacts to a rotation with a stabilising moment. On the other hand, the rotation induces an offset of the mass and hence an overturning moment. In the vertical position the system is in equilibrium. Let us imagine that a rotation occurs. If the stabilising moment is larger than the overturning one, the equilibrium is stable; the system returns to the vertical configuration. If the contrary occurs, the equilibrium is unstable; the system collapses. If the two moments are equal, the equilibrium is neutral; the system stays in the displaced configuration. The stability of the equilibrium may be characterised by the ratio \( \frac{M_{stab}}{M_{ov}} \) between the stabilising and the overturning moment.

In the case of the tower of Pisa, even this simplistic model allows an important practical conclusion: the tower is in a state of neutral equilibrium. The continuing movement, made possible by the state of neutral equilibrium, is controlled by cyclic actions as the fluctuations of water table in Horizon A. Of course, creep has also some effects on the process.

The leaning instability of the Tower has been investigated by a number of different approaches, including small scale physical tests at natural gravity and in the centrifuge, and several Finite Element analyses based on different constitutive models of the subsoil. The analyses led to the conclusion that the gradual increase of the inclination would have ended in a collapse. Another very significant conclusion was that a decrease of the inclination, even a relatively minor one, results in a substantial increase in the safety against leaning instability.

\[
M_{ov} = W \cdot h \cdot \sin \alpha \\
M_{stab} = k \cdot \alpha \\
FS = \frac{M_{stab}}{M_{ov}} = \frac{k}{W \cdot h}
\]

Figure 8: The inverted pendulum: a simple model of leaning instability

Fully aware that a long time was needed to conceive, design and implement the permanent stabilization measures, the Committee took an early decision to implement temporary and fully reversible interventions to slightly improve the safety against overturning, and to gain the time to properly devise, design and implement the permanent solution. A total of 6.9 MN of lead ingots were installed between May 1993 and February 1994 on the north edge of the base of the
Tower. They induced a change of inclination of 33" by February 1994; by the end of July it had increased to 48". On February 1994 the average additional settlement of the tower relative to the surrounding ground was about 2.5 mm. The settlement and rotation produced by the counterweight had been predicted by the finite element model; the agreement between prediction and observation was satisfactory, increasing the confidence in the model. An event of the utmost importance is that the progressive southward inclination of the Tower has come to a standstill.

The Committee had developed a deep insight of the behaviour of the tower, through the interpretation of its history, the scrutiny of the measurements taken in the last century and the analysis of the phenomenon of leaning instability. After a comprehensive discussion, it has been concluded that a decrease of the inclination of the Tower by half a degree (1800 arc seconds, i.e. around 10% of the inclination in 1990) would have been sufficient to stop the progressive increase of inclination and to substantially improve the stability conditions. The decrease had to be obtained by inducing a differential settlement of the tower opposite to the existing one, by acting on the foundation soil and not on the tower. Among other advantages, such a solution is perfectly respectful of the formal, historic and material integrity of the monument.

The Committee studied in detail three possible means to achieve the decrease of the inclination: (i) the construction of a ground pressing slab to the north of the tower; (ii) the consolidation of the Pancone clay north of the Tower by electro-osmosis, and (iii) the controlled removal of small volumes of soil beneath the north side of the foundation (underexcavation). All three approaches have been the subject of intense investigation, and eventually underexcavation was selected.

Small scale model tests at natural gravity and in the centrifuge and numerical analyses gave a favourable response, encouraging the Committee to undertake a large scale experiment, to develop the field equipment and explore the operational procedures. For this purpose a 7 m diameter eccentrically loaded instrumented footing was constructed in the Piazza and subjected to underexcavation. The trial was very successful.

The Committee was aware that all the investigations carried out might be not completely representative of the possible response of a tower affected by leaning instability; therefore it was decided to implement a preliminary and limited ground extraction beneath the Tower itself, to observe its response. To prevent any unexpected adverse movement of the monument, a safeguard structure was necessary. It consisted of two sub-horizontal steel stays (Fig. 9), connected to the Tower at the level of the third order and to two anchoring frames located some 100 m apart; it was capable of applying to the Tower a stabilising moment, but only if needed. The safeguard structure was installed in December 1998. The preliminary underexcavation experiment has been carried out between February and June, 1999, operating with 12 inclined drill holes and removing a total of 7 m³ of soil, 71% of which north of the tower and 29% from beneath the foundation. The tower rotated northward by 90 seconds of arc till June 1999, when the operation ceased; by mid September the rotation had increased to 130". At that time three of the 97 lead ingots were removed, and since then the tower exhibited negligible further movements.

After the very positive results of the preliminary underexcavation, the Committee went on steadily to the full underexcavation. It was carried out between February 21, 2000 and June 6, 2001, with 41 holes, removing a total of 38 m³ of soil (70% below the catino, i.e. outside the perimeter of the foundation). In the same period all the lead ingots have been removed. In June 2001 the steel cable stays have been dismantled, without having been ever operated.
The goal of reducing the inclination of the tower by half a degree has been fully attained (Fig. 10). The intervention brought the tower back to the position it had at the beginning of the XIX century, just before the excavation of the catino (Fig. 11). It can be seen as reparation to the utious undertaking of the architect Gherardesca, and there is a kind of poetic justice in repairing the negative effect of an imprudent excavation with another well conceived and conducted excavation!

After underexcavation and other minor interventions, at present the Tower is motionless, except for the small cyclic movements connected to environmental actions.
3 THE ROMAN TUNNEL BY COCCEIUS

The conception of the role of an architect in the Roman civilisation was completely different from the present one. He was not distinct from the engineer and, in any case, was not credited as the principal responsible of a work (a building, a monument, a bridge). In fact, the principal responsible was the *promotor*, the second the agent or contractor; the architect, if any, came only after these. They said: Caesar constructed that bridge. Only many centuries later they said: Perronet, or Brunel, or Navier constructed that bridge. This is the main reason why we know very little about the social status and the role of the architects at the Roman times. The Greek – Campanian architect Lucius Cocceius Aucto is a notable exception. Cocceius was formerly the freedman of Lucius Cocceius Nerva, a rich and influential patrician belonging to the circle of Octavianus, later the emperor Augustus. It was Nerva to obtain the first important assignments to his freedman. He introduced him into the narrow group of people involved in the great program of public works that had been started by Marcus Vipsanius Agrippa, deputy and son in law of Octavianus. At the death of Nerva, Cocceius, with some associates as Postumius Pollio, formed an outstanding group of designers and agents. They represent a fine example of social success, certainly connected to political support and to the availability of large capitals, but mostly to an outstanding practice of all the architectural and engineering specialities, making them capable of satisfying any kind of request.

The region west of Napoli, the so called Phlegrean Fields, is universally known and admired for the beauty of the landscape but also for the strong suggestion of legendary events and mythical personages and for the abundance of monuments and ruins. The tunnels located in this area are renowned since the Middle Ages. They were called *grotte*, that means caves, a term used at that times to indicate both natural caves and man made cavities. This term has survived in the modern tradition to indicate the three most important existing Roman road tunnels. They are. (i) the *Crypta Neapolitana*, linking Naples to Puteolis; (ii) the *Grotta di Seiano*, bringing to the villa of Vedius Pollio to the bay of Puteolis, and (iii) the *Grotta di Cocceio*, between the lake of Averno and Cumae. All these tunnels have been excavated in few years, starting in 39 B.C. At
that times Octavianus and Agrippa encouraged an intense renewal in every field of culture and technology. The road tunnels have been practically "invented" by Octavianus and Agrippa; but it was Lucius Cocceius Aucto to put their programs in tangible form.

The Grotta di Cocceio, the longest of the three tunnels, belongs to an impressive complex of works realised by Agrippa in the framework of the naval war against Sextus Pompeius, son of Pompey the Great, who had held for years the Sicily with a powerful fleet.

The lake of Averno and the lake of Lucrino were the seat respectively of the shipyard and the harbour (Portus Julius) of the military fleet, while Cumae was the Octavianus' stronghold. To connect these military installations, Agrippa excavated two large navigable channels, one between Averno and Lucrino and another between Lucrino and the sea, and three large road tunnels (Fig. 12). The Grotta di Cocceio is the central and most important one. It crosses the Monte Grillo with a length of almost 1 km and a maximum cover of about 100 m. In the central stretch there are six ventilation and lighting shafts, vertical and inclined (Fig. 13). The cross section of the tunnel is 4.5 m wide and 5 to 8 m high, with cylindrical vault and vertical walls.

Figure 12: The Averno and Lucrino lakes at the times of Augustus emperor

During World War 2nd the tunnel has been used for the storage of explosives. In 1944 the retreating German army blasted the explosives stored at the centre of the tunnel, producing a huge cavity with a height of 37 m (Fig. 14). Charged of the obscure suggestion of its origin, it represents a further attraction for the visitors.

At present, the tunnel is perfectly stable and can be travelled over its whole length. In spite of this, it is closed to the public because the explosion cavity is unsafe due to the possible occurrence of unexploded weapons and the fall of blocks and risk of collapse of the vault. An investigation of the stability has shown that the cavity is globally stable, but a progressive failure of the vault is likely to occur in the future, following the fall of blocks and eventually evolving in a small sinkhole.
On behalf of the office in charge of the Archaeological Heritage, the University of Naples developed a proposal implying hindering the passage in the cavity but revolting it by a small pedestrian tunnel. From the intersections between the Roman tunnel and the great explosion cavity it would have been possible to see the latter. The vault of the cavity would have been left free to collapse, producing a further ventilation shaft and reproducing the amazing view of the sun beams entering the nearby Piscina Mirabilis (Fig. 15).

Unfortunately, because of the occurrence of some buildings without authorization above the cavity, it is probable that this solution will be abandoned and that the whole cavity will be filled.
4 CONCLUDING REMARKS

The two case histories reported exemplify the variety of problems that can be encountered in the conservation of ancient monuments; in practice, the solution has to be searched in each particular case trying to blend at best different and sometimes conflicting requirements.

In the case of the Leaning Tower of Pisa the importance of the monument and the huge amount of investigations and studies carried out by a number of Commissions allowed finding the equilibrium at a satisfactory level. The achievement of the International Committee has thus to be seen as the final stage of an effort carried out within the arc of a century. The diagnosis of leaning instability, obtained from the history of the tower, and the choice of a very soft solution fully consistent with the principles of restoration, have been made possible by the multidisciplinary nature of the Committee. It made the discussions very difficult and the decisions perhaps slower than strictly necessary, but eventually revealed very stimulating and fruitful.

On the contrary, in the case of the Roman tunnel known as *Grotta di Cocceio*, there is the risk that the requirements of conservation be sacrificed to the safety of few unauthorised cottages.

In the opinion of the author, the possibility of finding in practice an acceptable equilibrium is inexorably linked to the development of a shared culture. The International Society of Soil Mechanics and Geotechnical Engineering contributed to this development by an ad hoc Committee (TC 19 – Conservation of Monuments and Historic Sites), that has been promoted over 25 years ago by French and Italian engineers (Jean Kerisel, Arrigo Croce). At present, a Joint Committee is being formed on the matter by ISSMGE and the sister Societies of Rock Mechanics ISRM and Engineering Geology IAEG.