The Leaning Tower of Pisa

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ABSTRACT: The Leaning Tower of Pisa is one of the world's best known and most treasured monuments. It was erected in the Middle Ages, at the time of maximum power of Pisa. The Tower is founded on highly compressible soils and started leaning from commencement of its construction. In the 1990s the overhang had reached the value of 4.7 m and was increasing at a rate of 1.5 mm per year; an analysis of the situation showed that a collapse was to be expected within some decades.
After having described the monument and its subsoil, the paper reviews its history and all the data available on the progress of its inclination. Studies and investigations carried out since the early XX century are recalled, and finally the activity of the International Committee appointed in 1990 is reported. After the underexcavation carried out by the Committee, and the decrease of the overhang by about 0,4 m, at present the tower is practically motionless. In conclusion, the possible future scenarios are briefly addressed.

1 INTRODUCTION

The monuments of the Piazza dei Miracoli in Pisa (consisting of the Tower, the Cathedral, the Baptistery and the Monumental Camposanto) were erected in the Middle Ages, in the period of maximum splendour and power of the Pisa Republic. Piazza dei Miracoli is the wonderful symbol of the profound unity prevailing at those times among the religious, spiritual and political powers. The history of Art and the civil history intertwine in the monuments enhancing it, giving them an outstanding character of sign and symbol of the city.
The Leaning Tower (Fig. 1) is one of the best known and most treasured monuments of the world.
Construction is in the form of a hollow cylinder surrounded by six loggias with columns and vaults merging from the base cylinder and surmounted by a belfry. The structure is thus subdivided into eight segments, called "orders".
The external surfaces are faced with masonry of cut stones, the outer one of S.Giuliano marble while the inner one is of various materials. The annulus between the facings is filled with rubble and mortar within which extensive voids have been found. A spiral staircase winds up within the annulus till the 6th order, while two shorter winding staircases lead to the floor and top of the belfry.
The staircase forms a large opening on the south side just above the level of the first cornice, where the cross section of the masonry suddenly decreases. The high stress within this region was a major cause of concern since it could give rise to an abrupt brittle failure of the masonry.
The Tower 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 at the end of the first millennium the overhang had reached the worrying value of 4.7 m and was increasing at a rate of 1.5 mm per year.

2 THE SUBSOIL

The ground profile underlying the tower is shown in Fig. 2. It consists of three distinct horizons. Horizon A is about 10 m thick and primarily consists of estuarine deposits, laid down under tidal conditions; as a consequence, a rather erratic succession of sandy and clayey silt layers are found. At the bottom of horizon A there is a 2 m thick medium dense fine sand layer, the so called upper sand.

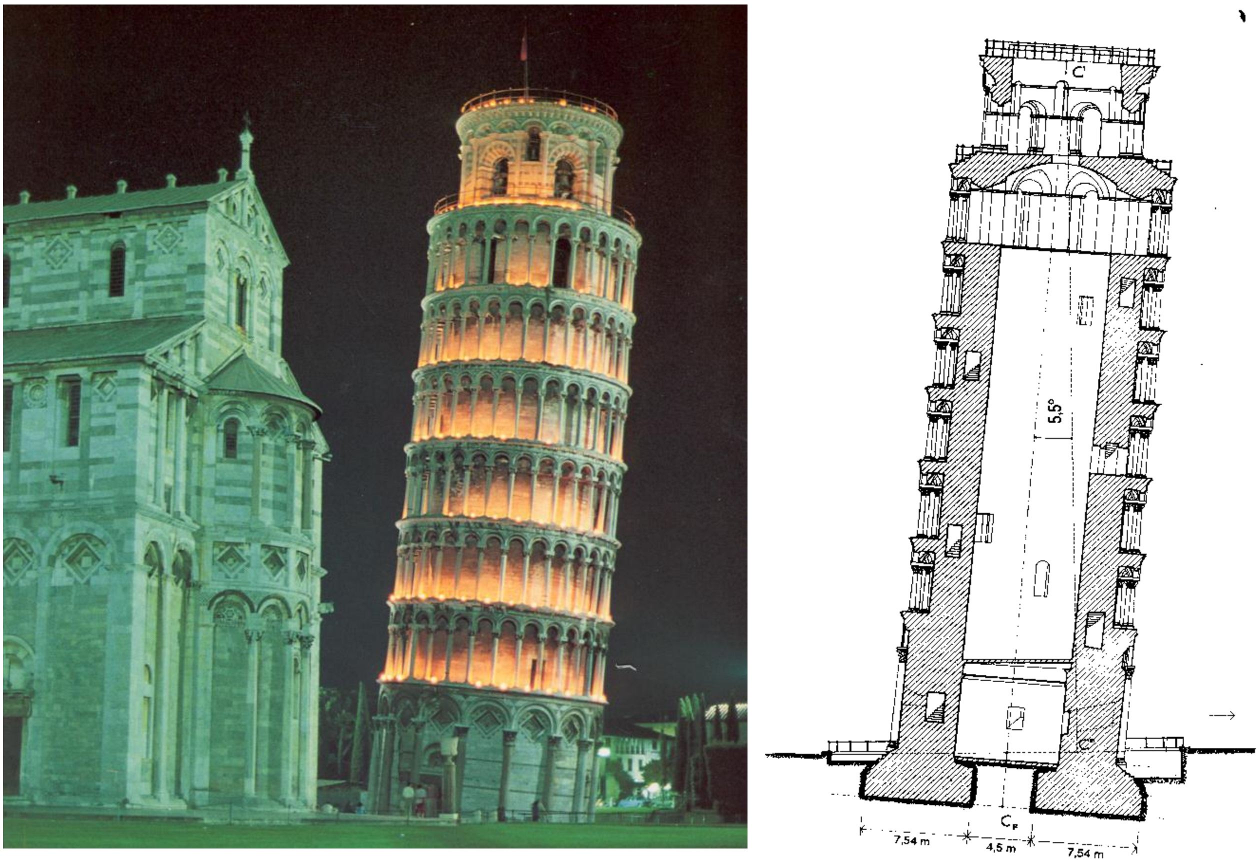


Fig. 1. The Leaning Tower of Pisa

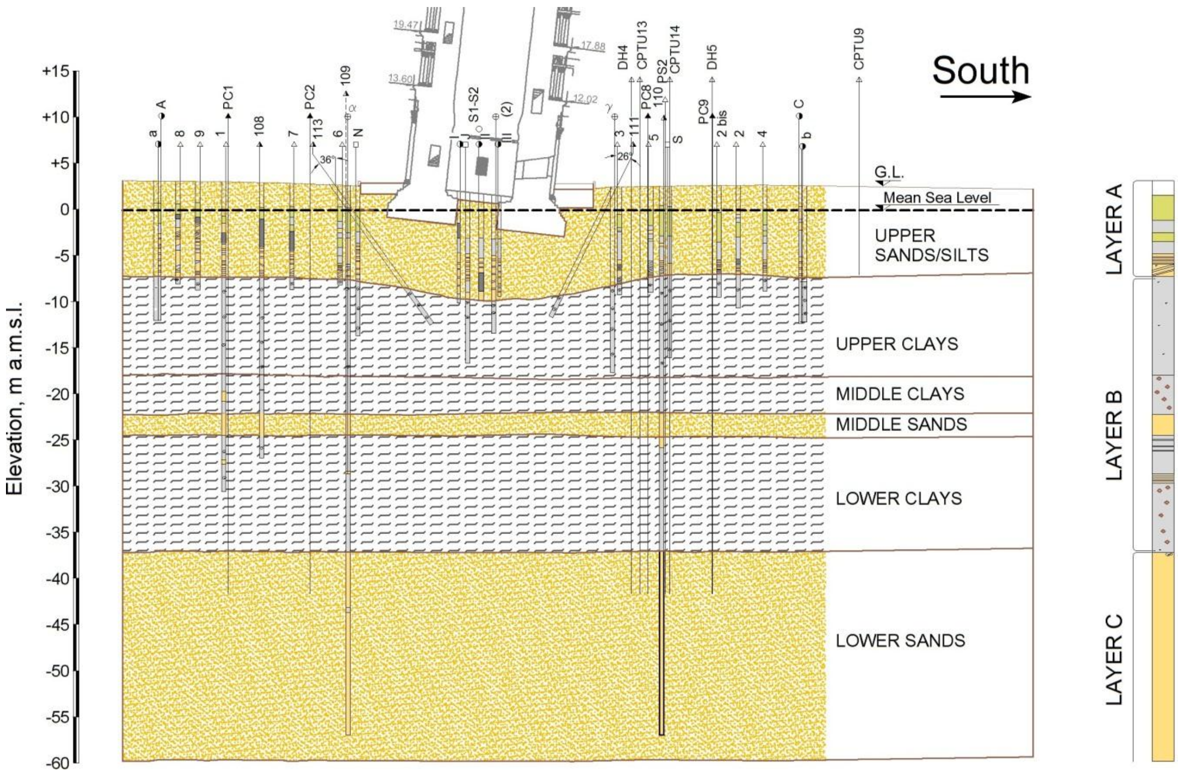


Fig. 1. The subsoil of the Tower

Horizon B consists primarily of marine clay which extends to a depth of about 40 m. It is subdivided into four distinct layers. The upper layer is a soft sensitive clay, locally known as the Pancone. It is underlain by an intermediate layer of stiffer clay, which in turn overlies a sand layer (the intermediate sand). The bottom layer of horizon B is a normally consolidated clay known as the lower clay. Horizon B is very uniform laterally in the vicinity of the tower.

Horizon C is a dense sand (the lower sand) which extends to considerable depth.

From the geological viewpoint, the lower sands are marine sediments deposited during the Flandrian transgression. The horizon B is formed by Quaternary deposits of marine origin, dominantly clayey, formed at the time of rapid eustatic rise. During the last 10,000 years or so the rate of eustatic rise decreased and the sediments became increasingly estuarine in character. The more recent sediments of horizon A mainly comprise sandy and clayey silt; typically of estuarine deposits, there are significant variations over short horizontal distances. Based on sample descriptions and piezocone tests, the materials to the south of the tower appear to be more silty and clayey than to the north, and the upper sand layer is locally thinner. This is believed to be instigator of the southward inclination of the Tower.

The water table in horizon A is found at a depth between 1 m and 2 m below the ground surface; the latter has an average elevation of 3 m above mean sea level. Pumping from the lower sand has resulted in downward seepage from horizon A with a pore pressure distribution with depth which is slightly below hydrostatic (fig. 3).

The many borings beneath and around the tower show that the surface of the Pancone clay is dished beneath the tower, from which it can be deduced that the average settlement of the monument is not less than 3 m.

Figs. 4 to 8 reports some data on the physical and mechanical properties of the soils, as determined by site and laboratory investigations carried out from 1965 to 1993.

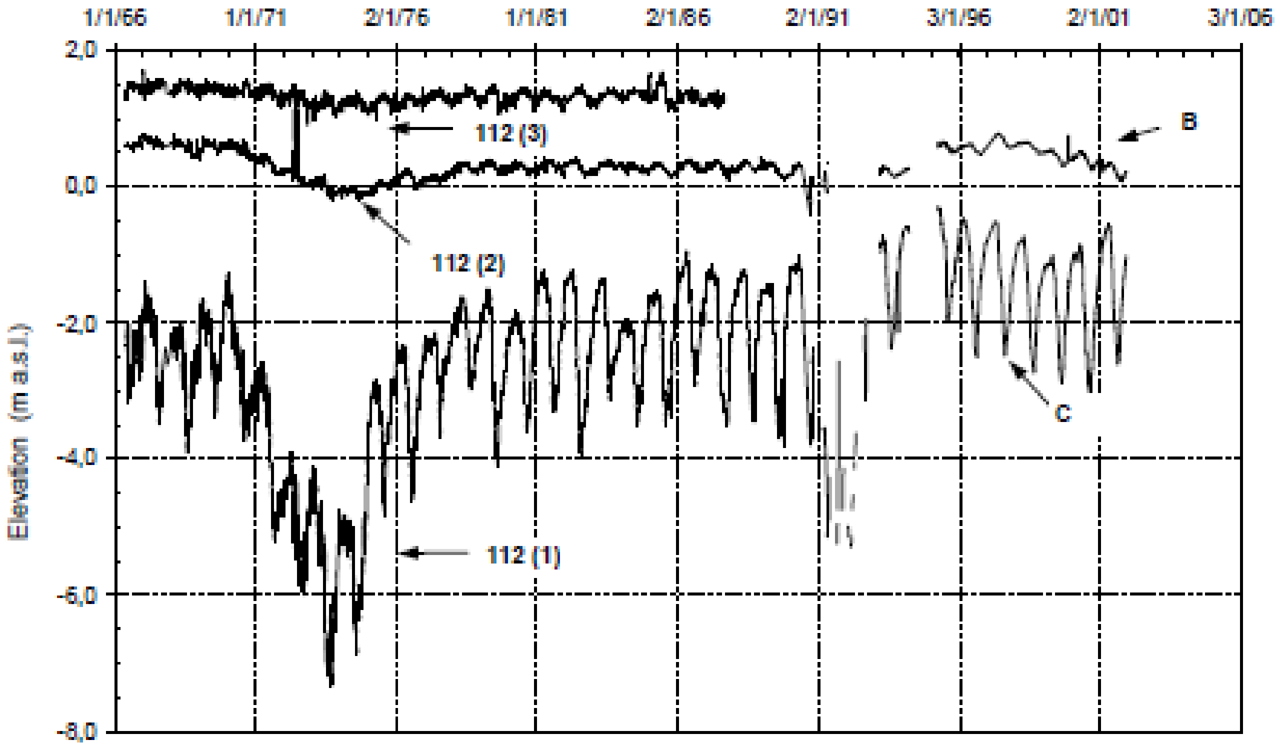


Fig. 3. Ground water regime in the subsoil of the Tower

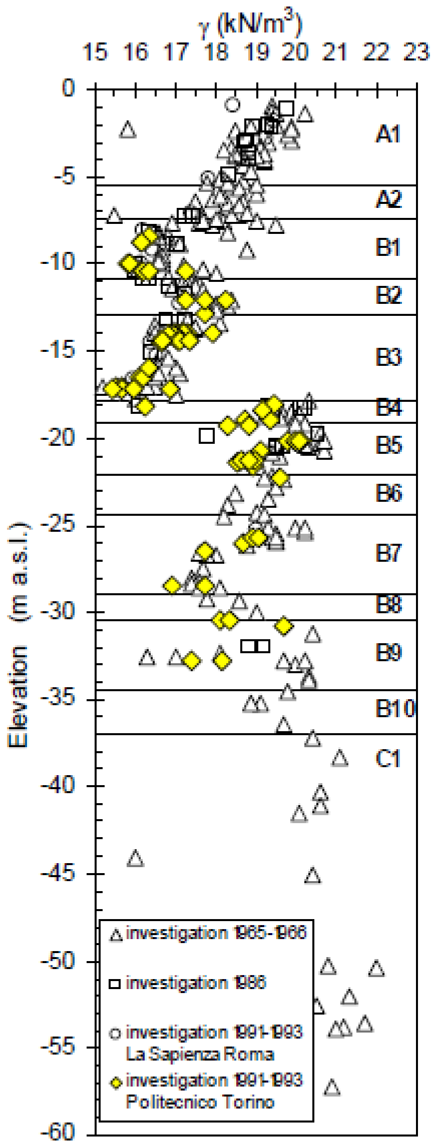


Fig. 4. Unit weight

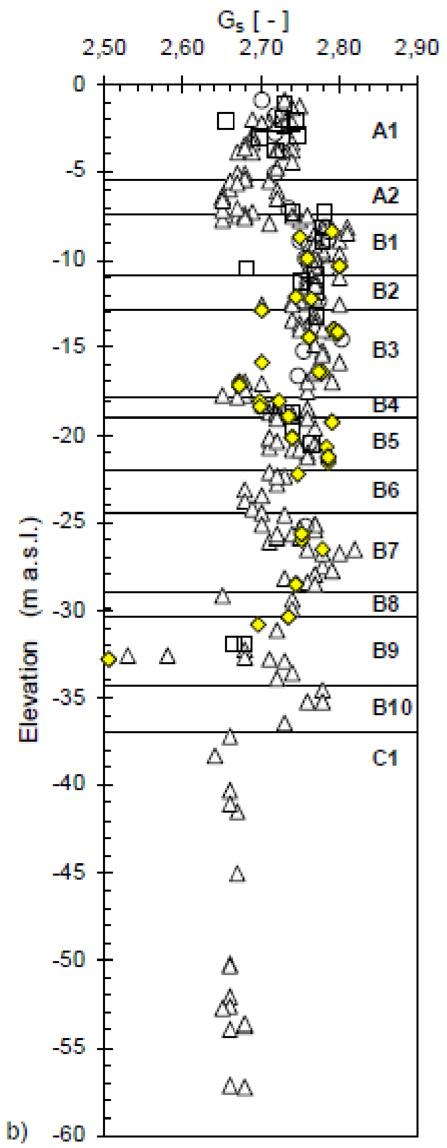


Fig. 5. Specific gravity of solid particles

3. HISTORY OF THE CONSTRUCTION

Work on the tower began in 1173 (Fig. 9). Construction had progressed to about one third of the way up the 4th order by 1178, when the work was interrupted. The reason for stoppage is not known, but had it continued much further, the foundations would have experienced an undrained bearing capacity failure. As a matter of fact, in 1178 the weight of the tower was around 90 MN, with an average pressure of around 315 KPa on the foundation; under undrained conditions, the bearing capacity of the foundation was of the same order (with an average c_u =5.5 KPa, $q_{lim} \approx 6c_u$ = 330 KPa)

Work recommenced in 1272, after a pause of nearly 100 years, by which time the strength of the ground had increased due to consolidation under the weight of the structure. By about 1278, construction had reached the 7th cornice when work again stopped. Once again, had the work continued, the tower would have fallen over. In about 1360 work on the bell chamber was commenced and was completed in about 1370, two centuries after the start of the work. It is known that the tower must have been tilting to the south when work on the bell chamber began, as it is noticeably more vertical than the remainder of the tower. Indeed on the north side there are four steps from the seventh cornice up to the floor of the bell chamber, while on the south side there are six steps (Fig. 10).

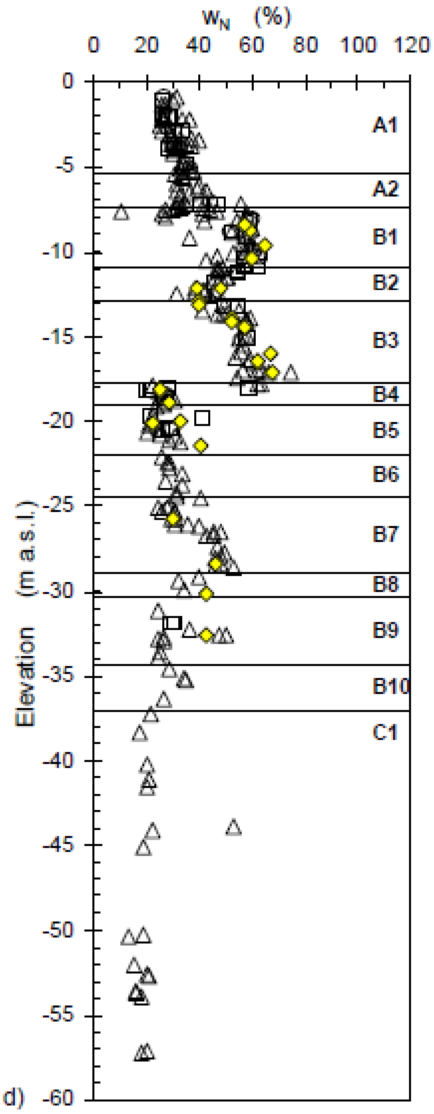


Fig. 6. Natural water content

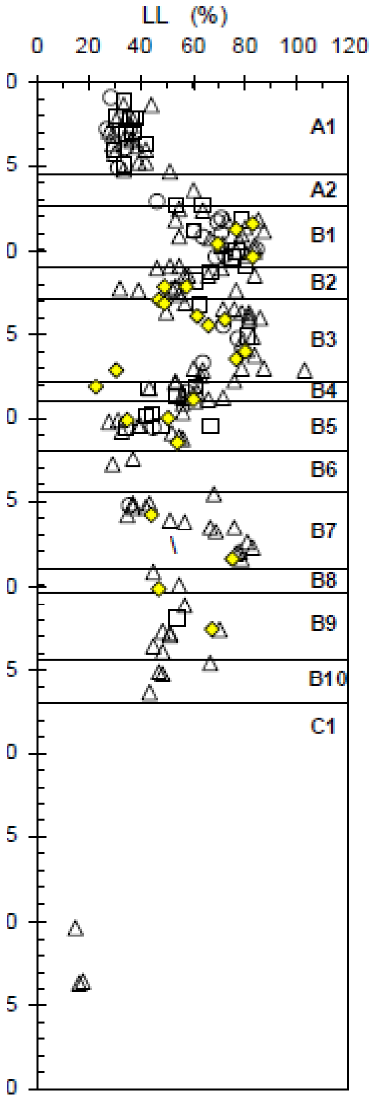


Fig. 7. Liquid limit

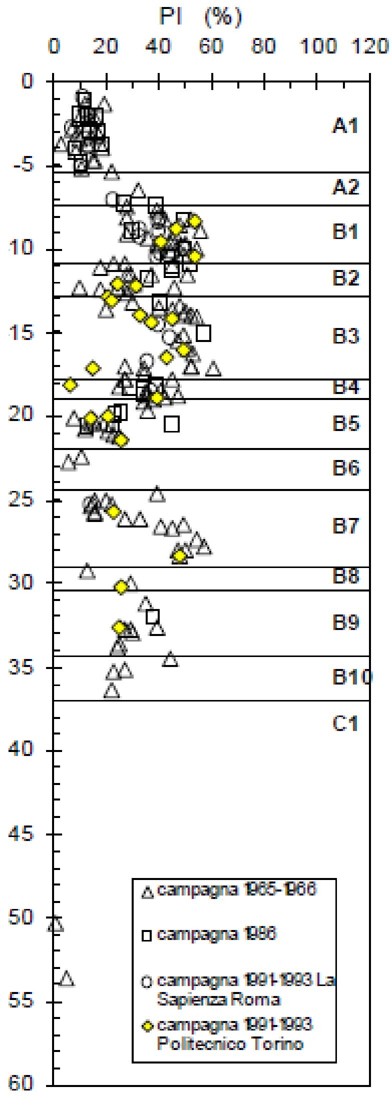


Fig. 8. Plasticity index

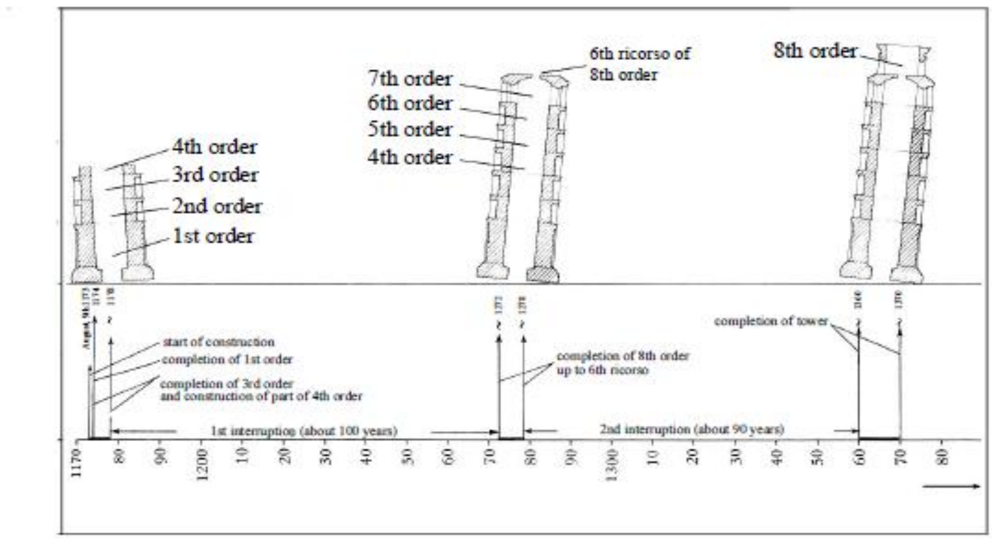


Fig. 9.History of the construction of the Tower

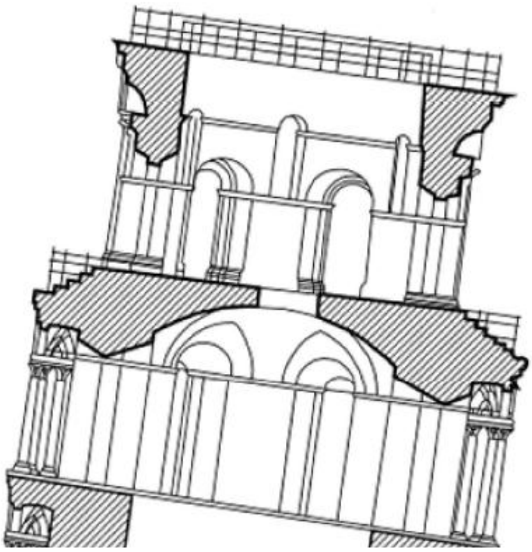


Fig. 10. The last correction: at the top of the seventh order there are six steps at south and only four steps at north

Another important detail of the history of the tower is that in 1838 a walkway was excavated around the foundation. This is known as the *catino*, and its purpose was to expose the column plinths and foundation steps for all to see as it was originally intended. The operation resulted in an inflow of water, the bottom of the catino being well below the ground water table. As a consequence, since 1838 the catino had been kept dry by continuous pumping.

In the belief that pumping could be dangerous for the stability of the tower, in the years 1934-35 the tower foundation and the soil surrounding the catino were made watertight by injecting cement grout into the foundation masonry and chemical grout into the soil. The intervention succeeded in effectively stopping the water inflow, and since then pumping was consequently interrupted.

3 HISTORY OF THE INCLINATION

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 Figure 11 may be deduced. During thefirst 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. When the construction reached the seventh cornice in about 1278, the inclination was about 0.6° towards the south. During the next 90 years the construction was again interrupted and the inclination increased to about 1,6°. After the completion of the bell chamber in about 1370, the inclination went on increasing. Some information on its trend may be obtained by pictures or documents; among them, the value of the inclination

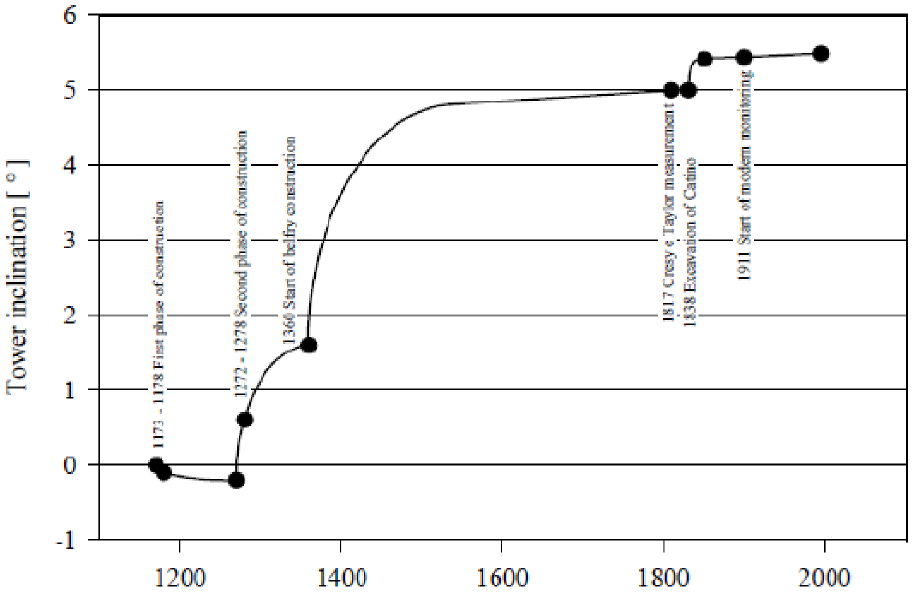


Fig. 11. History of the inclination of the Tower. From 1273 to 1370 the inclination is deduced from the shape of the axis; from 1370 to 1817 from documents and pictures; since 1817, from direct measurements.

deduced by a fresco painted in 1385 by Antonio Veneziano in the Camposanto and the value reported by Giorgio Vasari in 1550. 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, finding a value of the inclination significantly higher than that 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 3.5 m. Digging the catino seriously threatened the stability of the tower, and caused an increase of inclination of approximately 0.5°; furthermore, the rate of inclination increased and the motion changed from retarded to accelerated.

Since 1911 the inclination of the tower has been monitored by different means. It increases slightly more than the rotation of the foundation (fig. 12), implying a steady deformation of the tower body. The long term steady trend is punctuated by two major perturbations: one in 1935 and another one in the early 1970's. The first one was caused by the above mentioned cement grouting into the foundation body and the soil surrounding the catino, carried out to prevent the inflow of water. The second perturbation is 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.

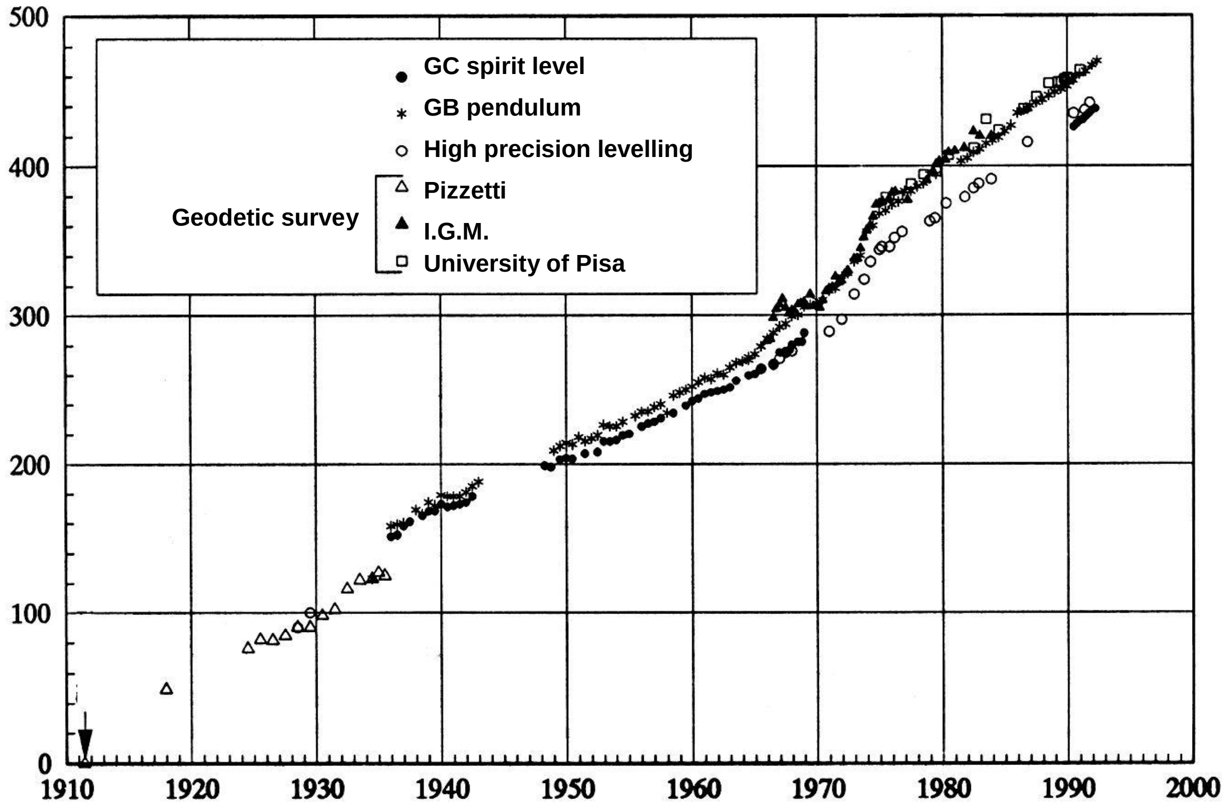


Fig. 12. Increase of the inclination since 1911. GB inclinometer and geodetic measurements include the deformation of the Tower body; GC level and optical levelling are representative of the rotation of the foundation

In any case, even correcting for the anomalous increments occurred in 1935, 1970-73 and some further minor perturbation (fig. 13), it appears that the rate of tilt was steadily increasing and had nearly doubled from 1938 to 1993. In the early 1990s' the inclination was about 5.5°.

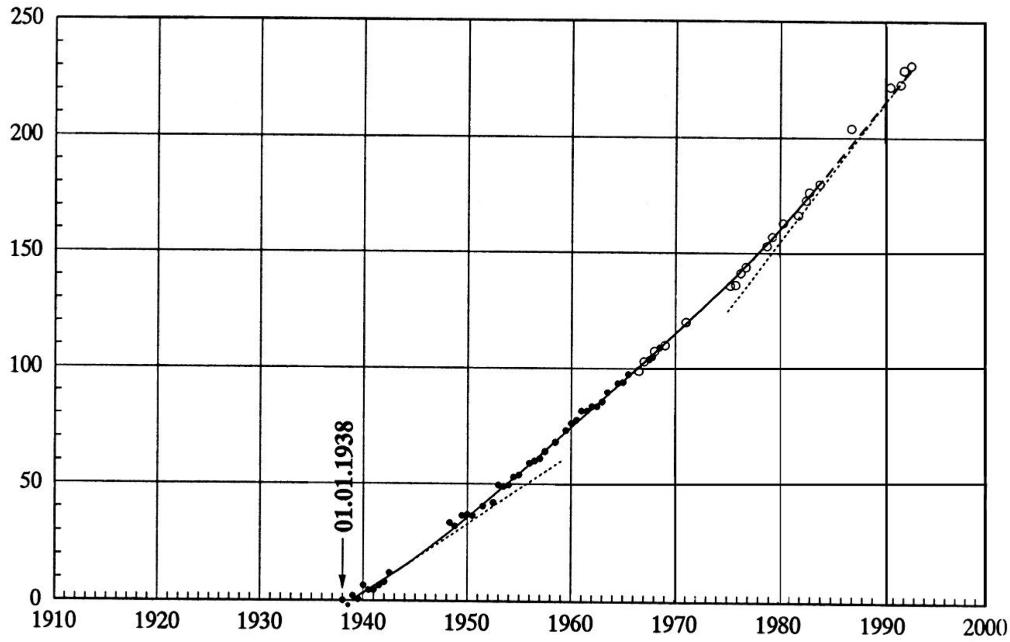


Fig. 13. The increase of inclination after subtracting the effect of the perturbations

4. PREVIOUS STUDIES AND INVESTIGATIONS

4.1. From 1902 to 1973

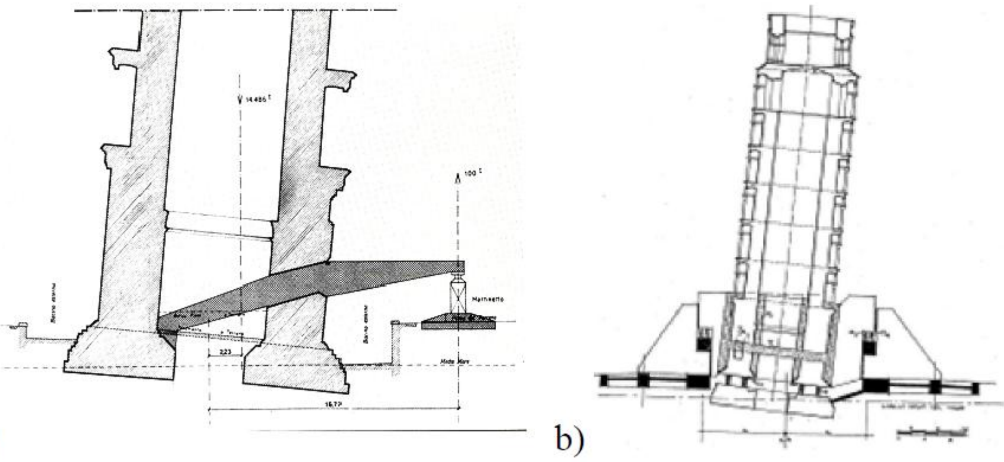
The first Commission on the tower of Pisa appointed by the Italian Government was a consequence of the worries induced in the public opinion by the collapse of the S. Marco bell tower in Venice, 1902. The Commission carried out a number of investigations, and presented the results in a broad and valuable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

A second Commission was appointed in the same year with the task of studying the possible means of stabilising the tower, but did not conclude its work because of the first World War . 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 with 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 was that of sealing the catino. As mentioned before, since 1838 the walkway was kept dry by continuous pumping.

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 m^3 of chemical grout into the soil. As already reported, the intervention stopped the water inflow into the catino; the price for this success, however, was a new sudden and marked increase of the inclination of the tower. About 100 years after the excavation of the catino, another intervention carried out with wishful thinking to stabilise the tower again strongly threatened it; this confirms that the way to hell is paved with good intentions!

After the second World War , it became clear that the tower was still moving, in spite of the works 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 historical and 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. 14); 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 were considered further.



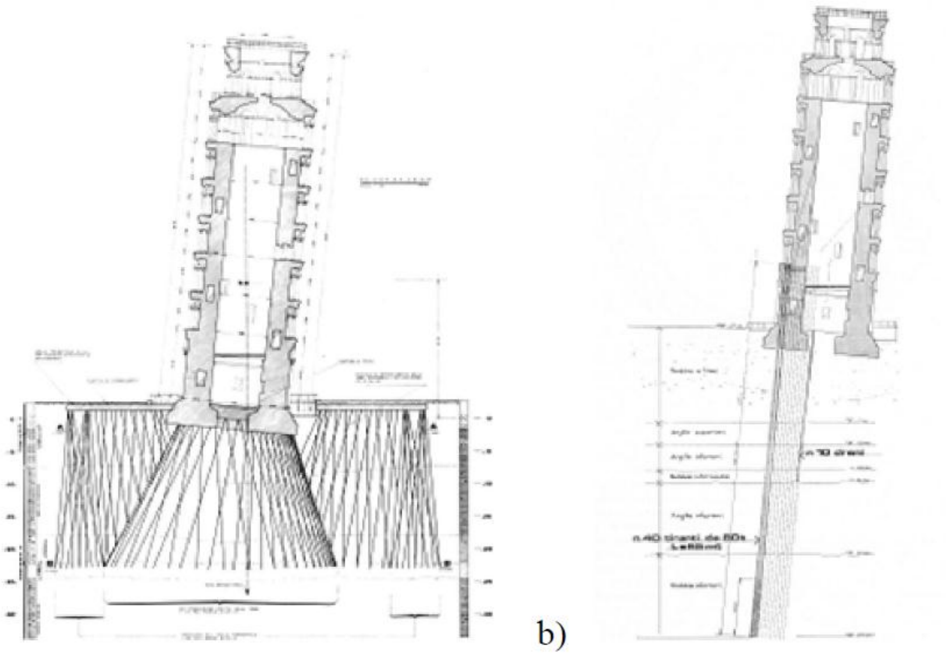
a) b)

Fig. 14. a) Proposal by Colonnetti (1963); b) Proposal by Benporad and Vannucci (1963)

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 Polvani Commission, as it is named because of its chairman, included for the first time a group of geotechnical engineers: 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.

4.2. 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 died in 1970, but the Commission, with minor modifications, was charged with judging the competition. The proposals by: Fondedile, Fondisa (fig. 15), Geosonda, Impresit-Gambogi-Rodio (fig. 16) and Konoike (the latter was based on jet-groting the foundation soil) were judged worthy 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 this was one of the reasons why the contract was not awarded. 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.



a) b)

Fig. 15. International tender, 1973. The proposals by Fondedile (a) and Fondisa (b)

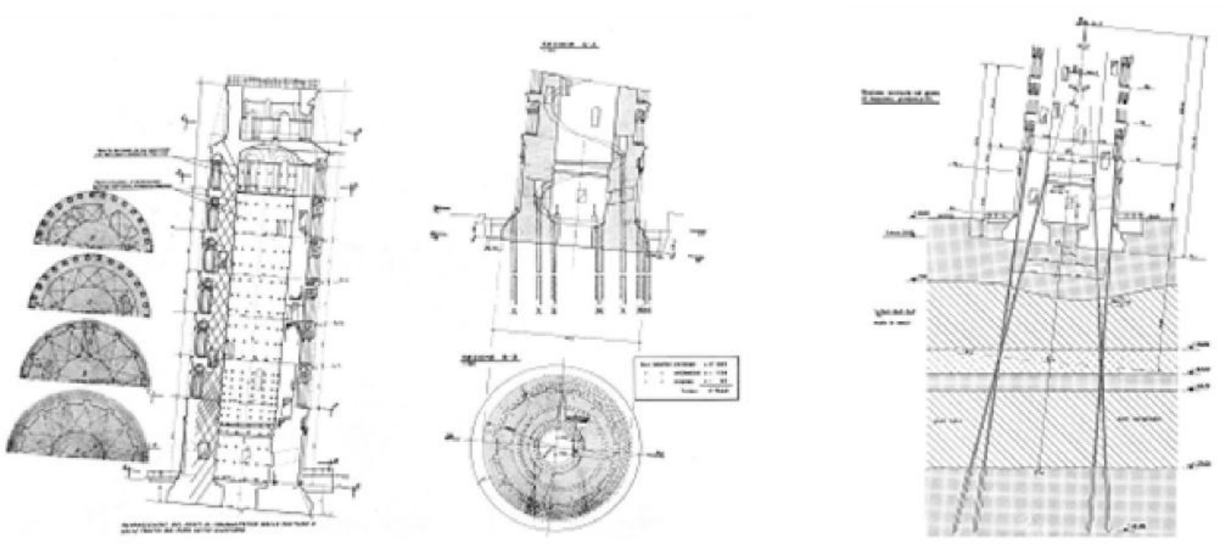


Fig. 16. International tender, 1973. The proposals by Geosonda (left) and Impresit Gambogi Rodio (right)

4.3. From 1975 to 1990

In 1983 a Design Group was commissioned by the Ministry of Public Works to design the stabilisation work; they produced a very sophisticated but still rather intrusive solution (fig. 17), that was not definitively approved by the Council of Public Works. In 1988 a technical Committee, entrusted by the Government to study the problem, focused attention on the risk of a 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, and therefore potentially very dangerous.
In 1989 another spectacular tower collapse occurred in Italy: that of the Civic Tower of Pavia, with five casualties. As a result, the attention to the safety of the Tower of Pisa increased, and the Government prohibited the access of visitors, following a recommendation of the technical Committee.

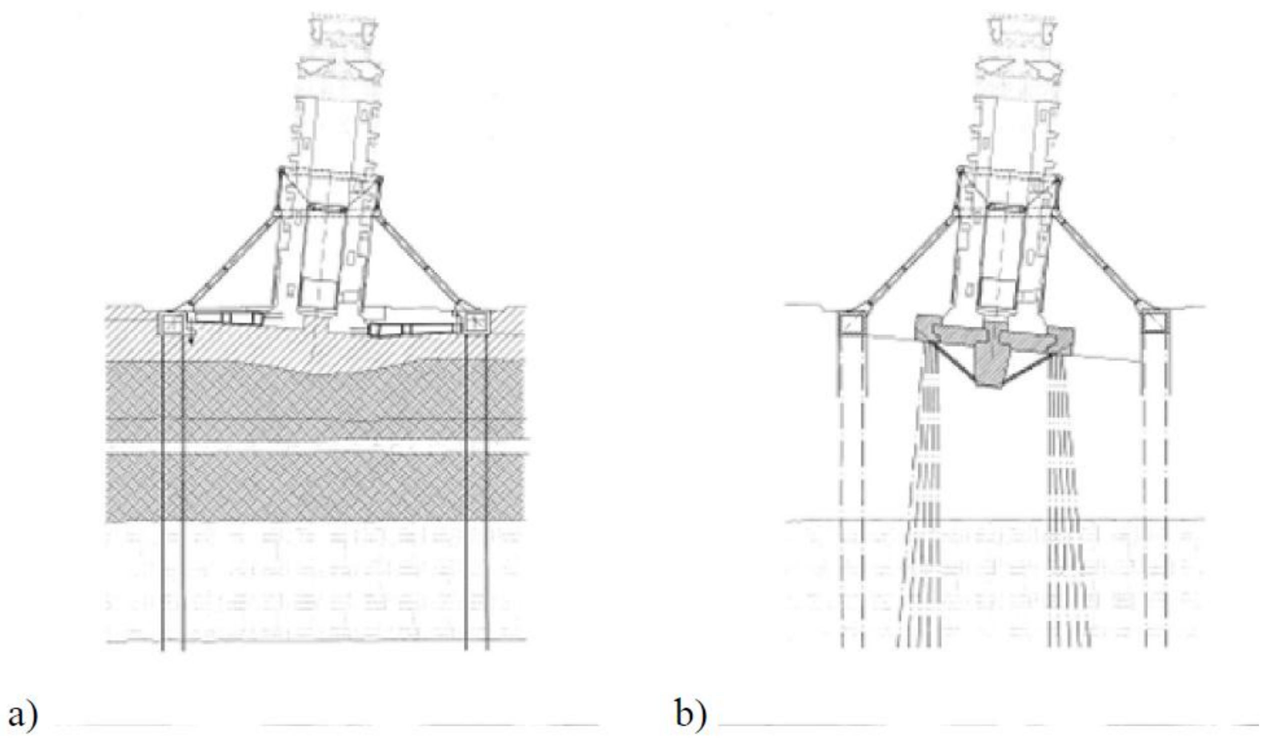


Fig. 17. The solution by the Design Group, 1983. a) *soft* solution; b) *hard* solution

The closure of the Tower resulted in a strong public pressure for a rapid reopening, but the restoration experts warned against hasty and insufficiently considered solutions. The Italian Government decided to appoint a further Commission, a truly interdisciplinary International Committee chaired by a geotechnical engineer and formed by art historians, restorers, structural engineers and geotechnical engineers, among whom are the authors of this paper. It had the task of conceiving, designing and implementing the necessary stabilisation works.

5. INVESTIGATIONS AND INTERVENTIONS BY THE INTERNATIONAL COMMITTEE (1990 – 2001)

5.1. Analysis of the statics of the tower-subsoil system

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 soil. To demonstrate leaning instability, the simple conceptual model of an inverted pendulum may be used. It is a rigid vertical pole (Fig. 18) with a concentrated mass at the top and hinged at the base to a constraint that reacts to a rotation with a stabilising moment M_s proportional to the rotation. On the other hand, the rotation induces an offset of the mass and hence an overturning moment M. In the vertical position the system is in equilibrium. Let us now perturb the equilibrium with a small rotation of the pole. 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 $FS = M_s/M$ between the stabilising and the overturning moment.

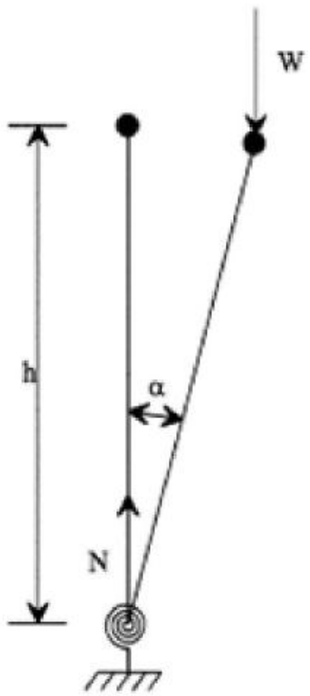


Fig. 18. The inverted pendulum: a simple model of leaning instability

Modelling the tower as an inverted pendulum, the restraint exerted by the foundation may be evaluated by representing the foundation as a circular plate of diameter D resting on an elastic half space of constants E, ν. Defining W and $M = We$ the vertical load and the overturning moment respectively and ρ, α the settlement and the rotation of the foundation respectively (Fig. 19), it may be shown that:

$$\begin{Bmatrix} \rho \\ \alpha \end{Bmatrix} = \begin{vmatrix} \frac{1}{k_\rho} & 0 \\ 0 & \frac{1}{k_\alpha} \end{vmatrix} \begin{Bmatrix} W \\ M \end{Bmatrix}$$

with:

$$k_\rho = \frac{ED}{i - \nu^2}; \qquad k_\rho = \frac{ED^3}{6\left(1 - \nu^2\right)}$$

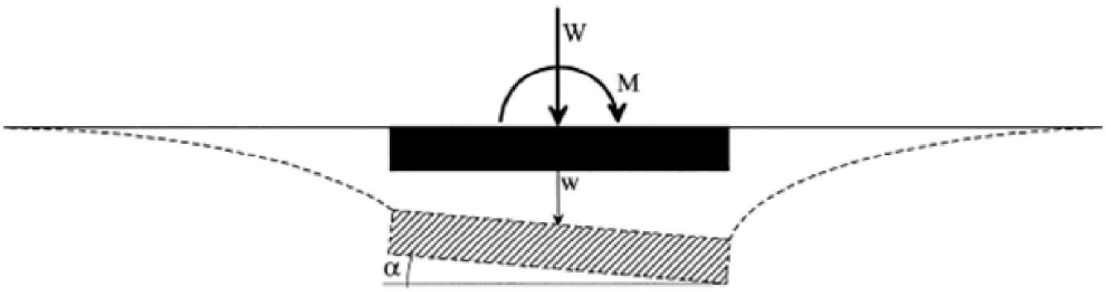


Fig. 19. Eccentrically loaded rigid circular plate resting on an elastic half space

In this simple linear model there is no coupling between settlement and rotation, and the stability of the equilibrium is an intrinsic property of the ground – monument system. It may be characterized by the ratio *FS* between the stabilizing and the overturning moment:

$$FS = \frac{k_\alpha \alpha}{Wh \sin\alpha} = \frac{ED^3}{6\left(1-\nu^2\right)} \frac{1}{Wh}$$

In the case of the tower of Pisa an evaluation of *FS* may be obtained by the knowledge of the settlement of the tower, $\rho \geq 3$ m. Being $k_\rho = W/\rho$, one gets $E/(1-\nu^2) \leq$ 2.85 MN/m^2. Accordingly, with h = 22.6 m (height of the centre of gravity of the tower) and W = 141.8 MN (weight of the tower), $FS \leq 1.12$. Even this simplistic linearly elastic subsoil model allows the important conclusion that the tower is very near to a state of neutral equilibrium. The continuing movement, made possible by the state of neutral equilibrium, is controlled by ratchetting following cyclic actions such as the fluctuations of water table in Horizon A. Of course, creep has also some influence on the process.

The relationship between the stabilising moment $M_s = k_\alpha \alpha$ and the rotation α may be linearized over a short interval, but it is certainly non linear and approaches asymptotically a limiting value of M_s. In a case such as that of the Leaning Tower, that is on the verge of instability, consideration of non linearity appears mandatory. As a matter of fact, centrifuge experiments by Cheney *et al*. (1991) (fig. 20) show coupling between settlement and rotation, non linearity and strain hardening plasticity.

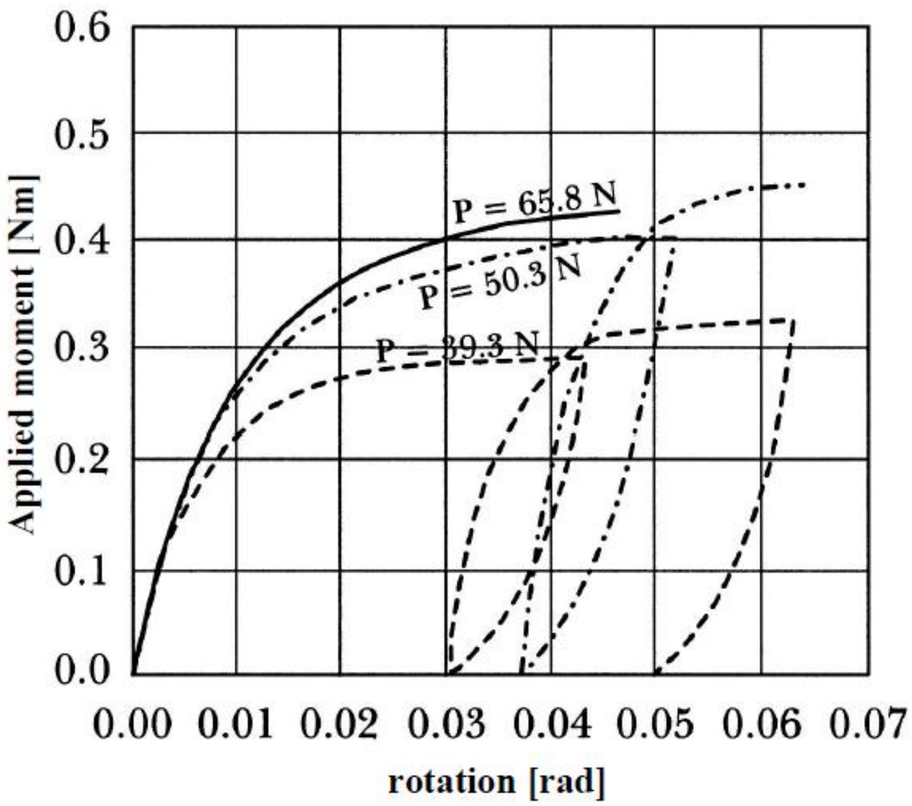


Fig. 20. Centrifuge experiments on the behaviour of an eccentrically loaded circular plate on clayey subsoil (Cheney *et al.*, 1991)

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 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.

To clarify this conclusion, reference may be made again to the inverted pendulum model. In a non linear mode, the relation between loads and displacements has to be expressed in incremental form:

$$\begin{Bmatrix} \partial\rho \\ \partial\alpha \end{Bmatrix} = \begin{vmatrix} \frac{1}{k_\rho} & \frac{1}{k_{\rho\alpha}} \\ \frac{1}{k_{\alpha\rho}} & \frac{1}{k_\alpha} \end{vmatrix} \begin{Bmatrix} \partial W \\ \partial M \end{Bmatrix}$$

The increments of displacement depend on the load increments, the current state of load and the load history. Hence the factor of safety depends on the current state of stress and stress history.

It may be seen in fig. 20 that a decrease of the inclination, which involves the unloading branch of the curve, strongly increases the stiffness of the ground – foundation system, and hence the stability. This generated the idea that a decrease of inclination could be used to stabilize the tower.

5.2. Temporary interventions: lead counterweights

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 (fig. 21). They induced a change of inclination of 33" by February 1994; by the end of July it had increased to 48" and eventually to 53”. By 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 came to a standstill.

These observations allow an important experimental confirmation of the intended stabilization approach. The tower reacted to the application of the lead weights with a rotational stiffness:

$$k_\alpha = \frac{43.5MNm}{52''} = 172{,}548MNm$$

The factor of safety therefore increased to:

$$FS = \frac{k_\alpha}{Wh} = \frac{172{,}548}{141.8x22.6} = 54$$

As a matter of fact, after the application of the counterweight the tower remained essentially motionless for over three years, apart from the seasonal cyclic movements.

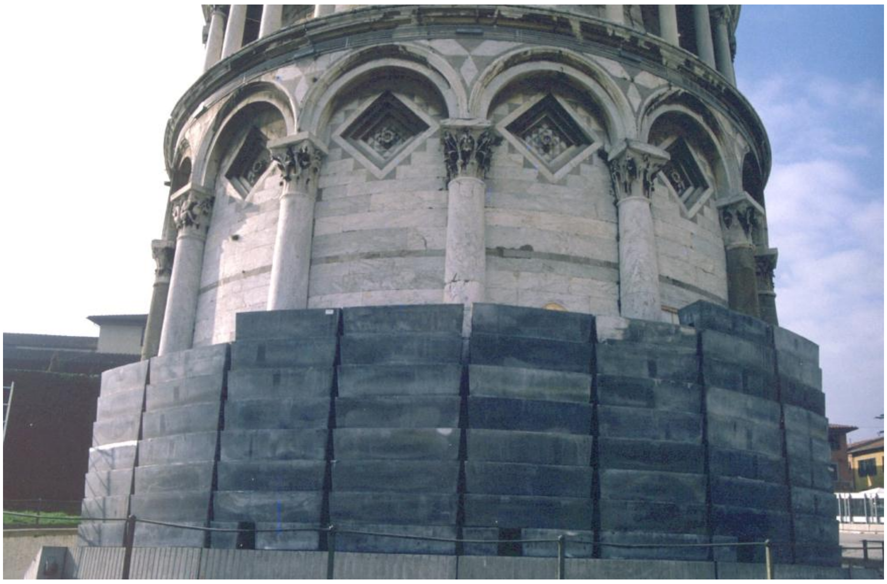


Fig. 21. The provisional intervention by lead ingots counterweight

5.3. Temporary interventions: ground anchors

The administrative life of the International Committee was somewhat difficult; for various reasons its continuation was repeatedly in doubt and its activity was repeatedly interrupted for periods up to many months. In these conditions there was a widespread fear that the Committee could dissolve, as all the preceding Commission had done, but this time leaving the stack of lead ingots on the tower for a period difficult to foresee, but certainly of some years or even decades. Essentially for this reason, a medium term temporary scheme was developed to replace the lead weights with ten tensioned steel cables anchored in the lower sands at a depth of over 40 m (fig. 22). Apart from the advantage of being invisible, an additional benefits of this scheme was the increased lever arm that would give a stabilizing moment larger than the lead ingots. The major problem of the ten anchors solution was that the anchors had to be connected to the Tower foundation through a ring beam to be constructed below the floor of the catino, and this involved an excavation around the tower below ground water level, an operation of the utmost delicacy. After a careful comparison of different possibilities, it was decided to employ local ground freezing immediately below the catino floor but well above the Tower foundation level. Following investigations by drill cores, it was discovered that below the catino floor there is a concrete bed of 1 m thickness, set in place partly in 1837 and partly in 1935. Some cracks at the interface between the concrete and the tower foundation, led to the conclusion that the two bodies were not connected; as a consequence, the volume variations of the frozen soil during freezing and thawing were expected not to influence the tower.

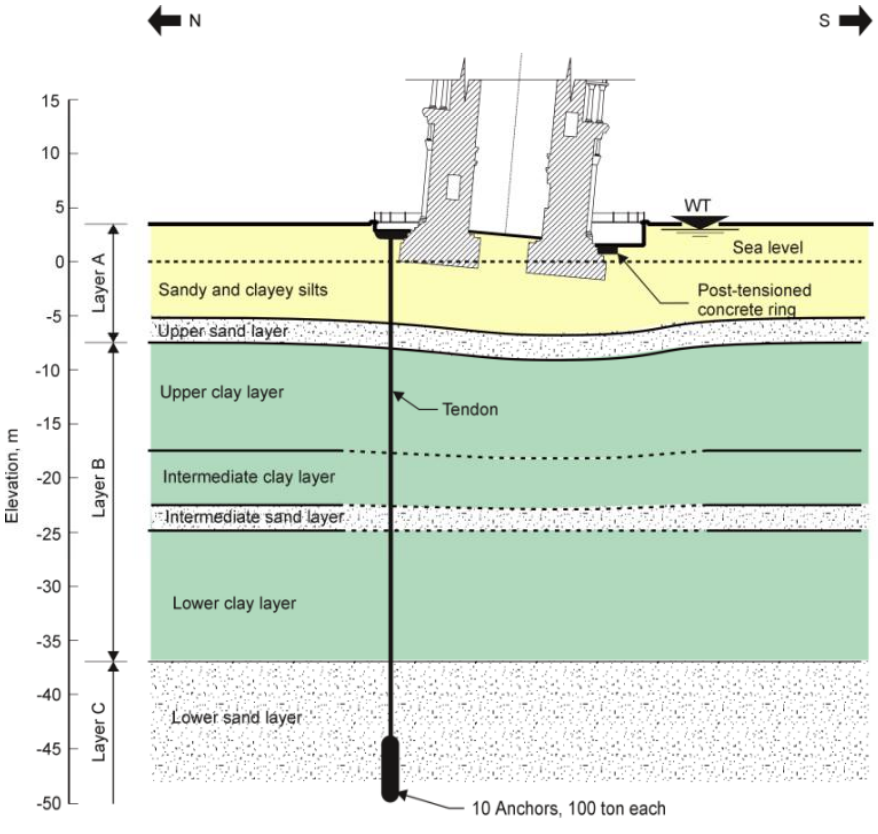


Fig. 22. The medium term solution of ten anchors

Without going into the details of the operation, it can be reported that freezing was commenced on the North side and the northern sections of the ring beam were successfully installed. They were connected to the foundation by means of stainless steel rods, cemented in the foundation masonry. During these operations, the water tightness of the catino was partly destroyed and two pumps had to be installed to prevent the flooding; since a sand layer was provided below the ring beam sections, the system worked as a ground water level control.

During the excavation, a number of short steel tubes of the diameter of 50 mm emerging from the tower foundation were discovered. They represent the intake of the injection holes executed in 1934-35 to make

watertight the foundation, and left in place. In spite of their short length (about 0.5 m, half cemented in the masonry and half protruding), they represent a connection between the catino and the tower.
In September 1995 freezing was commenced on the south-west and south east sides, and the Tower began to rotate southward; the movement was also affected by an attempt of installing some micropiles at the south boundary of the catino. After some attempts of controlling the rotation by the application of further lead weights at north, the operation was abandoned.

5.4. Final intervention

The Committee had developed a deep insight into 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 was 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 be sufficient to stop the progressive increase of inclination and to substantially improve the stability conditions. At the same time, such a reduction was considered small enough not to be perceived at a first glance. 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 were the subject of extensive numerical modelling.

A large field experiment of electro-osmosis (Squeglia, Viggiani, 2003) showed that the process cannot be completely controlled, and dangerous phenomena such as pore pressure increase may occur. For this reason the use of electro-osmosis was ruled out.

Small scale model tests of underexcavation at natural gravity and in the centrifuge, in addition to 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 (fig. 23).

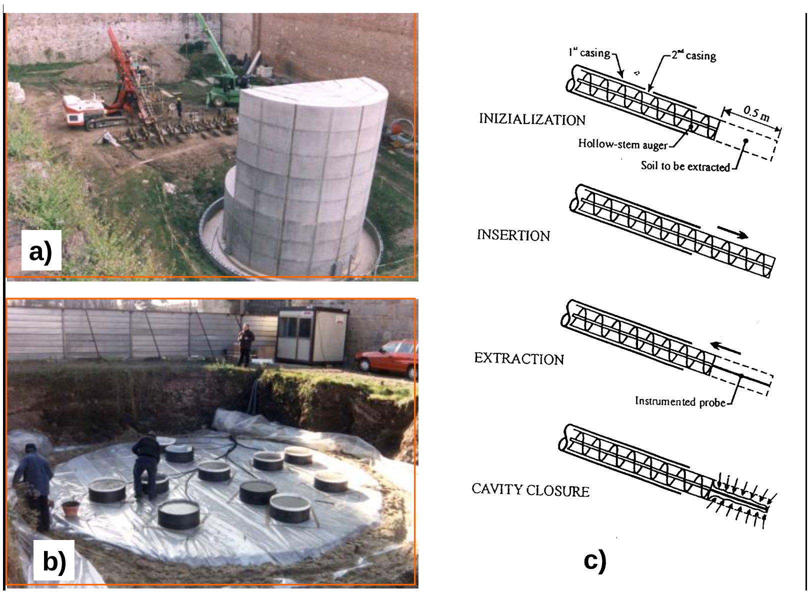


Fig. 23. a) The underexcavation trial field. b) Installation of pressure cells on the foundation plane. c) The underexcavation procedure finally developed

The trial was very successful; it proved that it was possible to steer the footing and act on the rate of rotation by varying the position and the intensity of soil extraction. The numerical modelling and the centrifuge tests had revealed the existence of a critical line beyond which the effect of the underexcavation is detrimental; in fact, during the field trial, an overenthusiastic excavation beyond that line actually produced an increment of the inclination thus confirming the prediction.

The Committee was aware that all the investigations carried out might be not be 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. 24), 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.

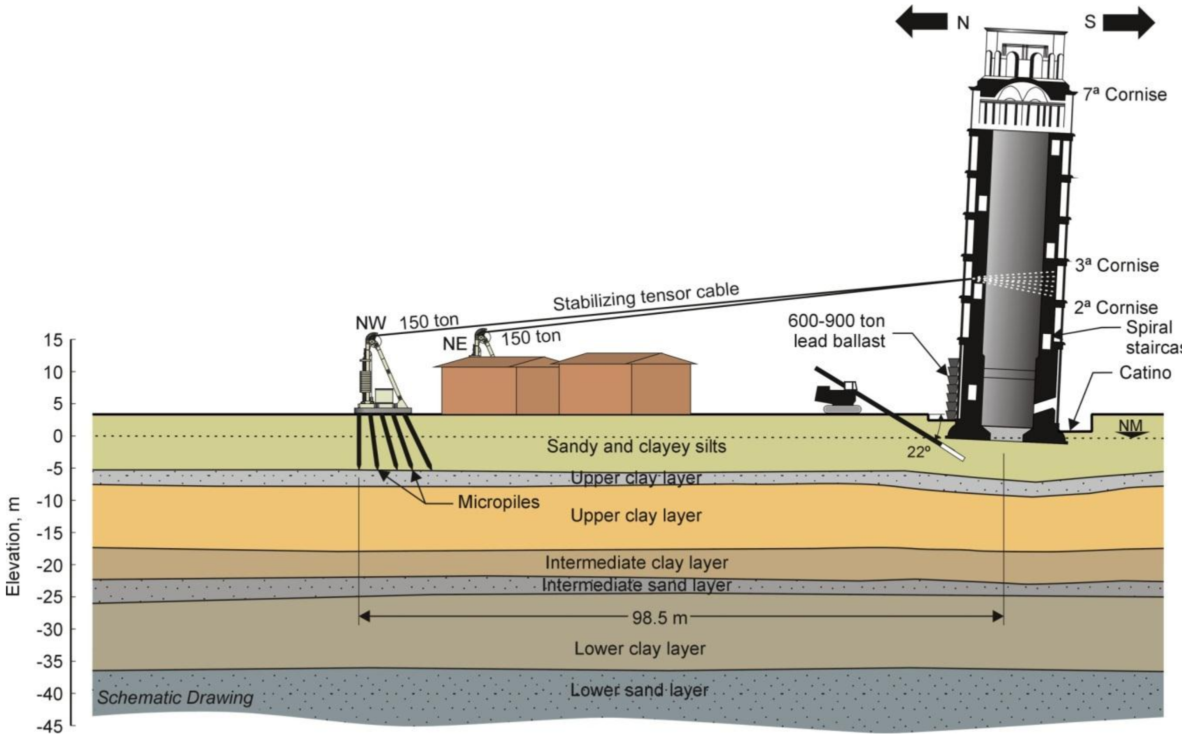


Fig. 24. Scheme of the safeguard structure with steel stays

The preliminary underexcavation intervention was carried out between February and June, 1999, operating with 12 inclined drill holes and removing a total of 7 m^3 of soil, 71% of which was north of the tower and 29% from beneath the foundation. The extraction of soil was very gradual, with the removal of only 22 dm^3 in each single underexcavation. The movements of the tower were monitored by a comprehensive system of geodetic survey and transducers, allowing the acquisition and processing of the data in real time. An observational approach was adopted; the program of soil extraction was decided daily on the basis of the observed movements of the previous day.

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 (fig. 25). It was carried out between February 21, 2000 and June 6, 2001, with 41 holes, removing a total of 38 m^3 of soil (70% below the catino, *i.e.* outside the perimeter of the foundation) involving 1737 single extractions. In the same period all the lead ingots were progressively removed. In June 2001 the steel cable stays were dismantled, without ever having been operated.

The goal of reducing the inclination of the tower by half a degree has been fully attained (fig. 26).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. 27). It can be seen as a reparation to the incautious 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 carefully conducted excavation.

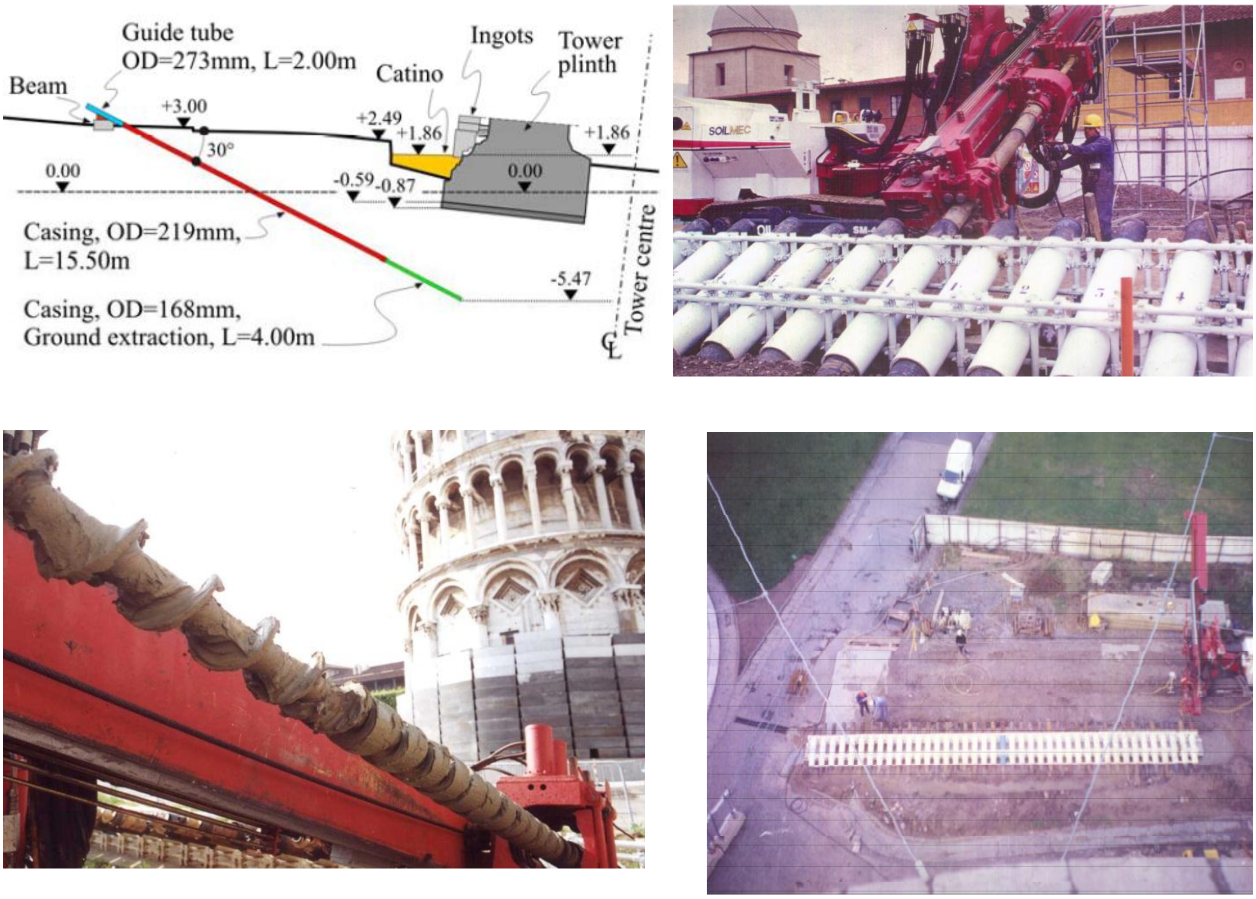


Fig. 25. The underexcavation

Fig. 26. Rotation of the Tower foundation since December 1998

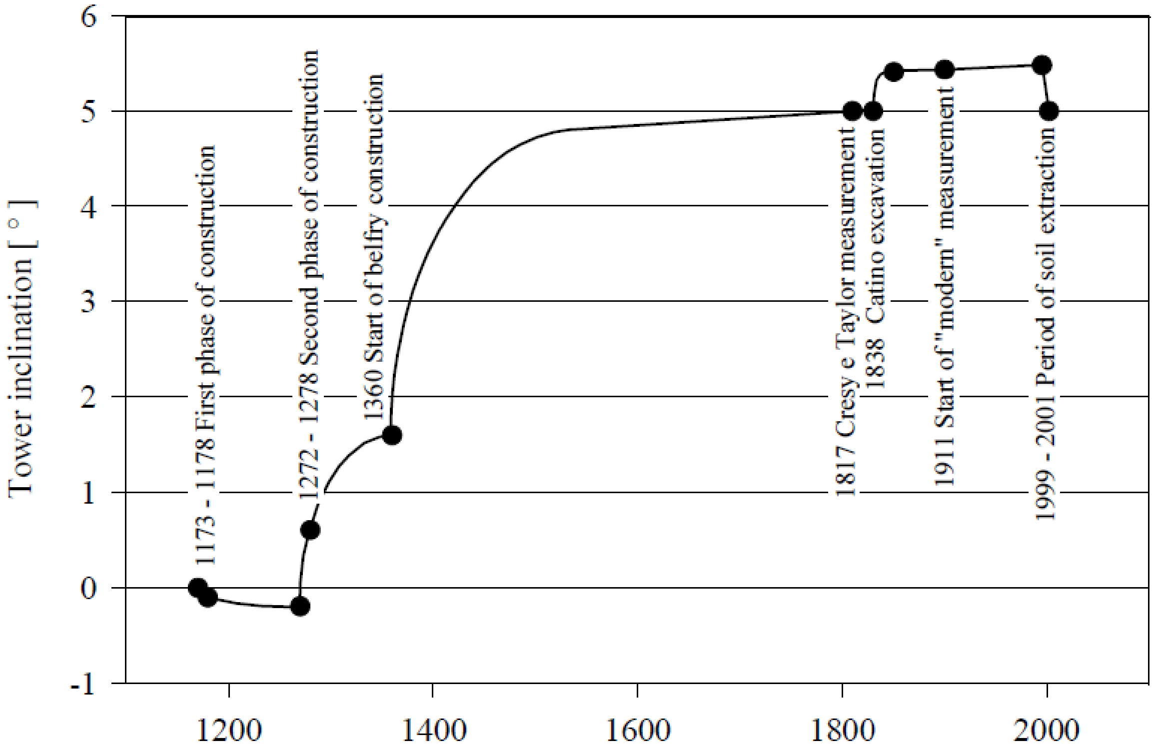


Fig.27. History of the rotation of the tower from the time of its construction

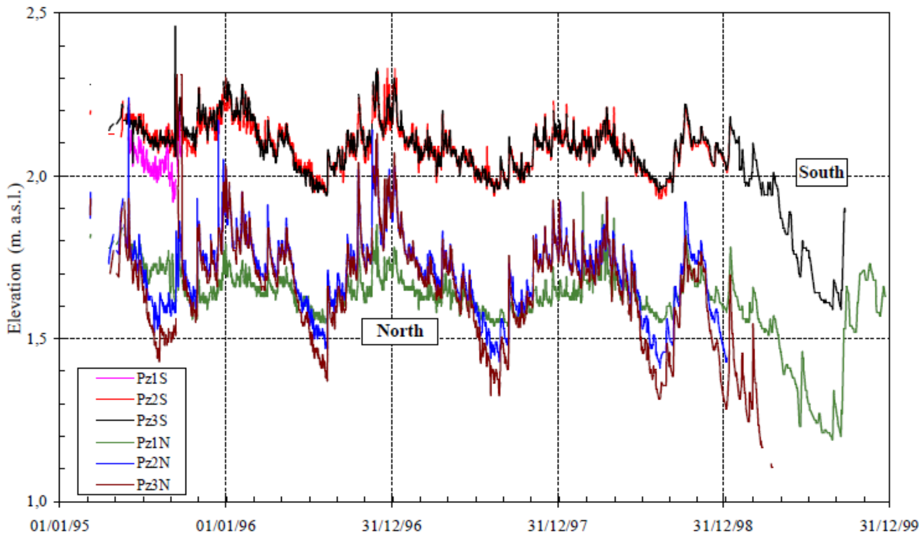


Fig. 28. Groundwater elevation in Horizon A

It is important to add that the study of the movements of the Tower revealed that the oscillations of the ground water table consequent to heavy rainfalls exerted a small negative influence on the monument. As a matter of fact, the ground water table at south of the foundation is around 0.4 m higher than that at north, so that the net result of the underpressure on the Tower is a small stabilizing moment. During intense rainfall events the two levels tend to equalize (fig. 28), thus producing a small overturning moment on the monument; it is believed that the cumulative effects by ratchetting of these repeated impulses has been one of the factors producing the steady increase of inclination in the long term.

As a final intervention, a drainage system was thus installed in April 2001 at north of the Tower (fig. 29), essentially aimed at stabilizing the groundwater level in the vicinity of the Tower. It produced a further reduction of the inclination of around 60 seconds of arc, that can be clearly detected in fig. 26. After underexcavation and drainage, at present the Tower shows small cyclic movements connected to environmental actions, and there may be still a very slow movement northwards.

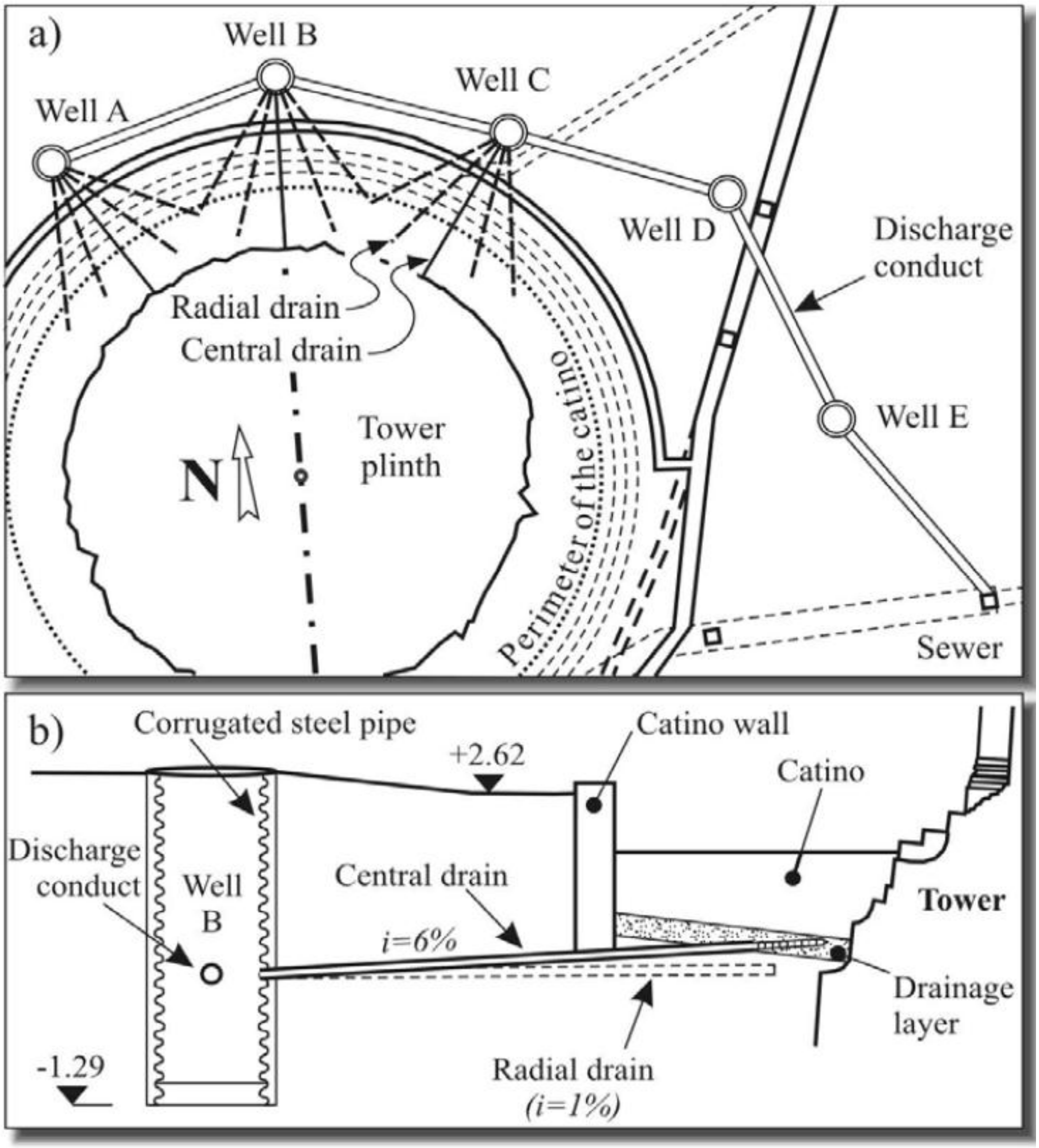


Fig. 29. Drainage system to control the ground water table in Horizon A

5.5. Future scenarios

More than ten years have elapsed since the end of underexcavation and the installation of the drainage system, and as mentioned above the tower is still moving northwards. In spite of this very satisfactory situation, a prediction of the future behaviour is not simple, because of the complexity of the phenomena controlling it. Two possible scenarios may be envisaged: an optimistic and a pessimistic one (fig. 30).

In the optimistic scenario the progressive increase of the inclination, affecting the tower since the construction, has been definitively stopped and the monument keeps motionless, apart from the cyclic movements connected to the environmental action, such as the daily sun irradiation and the seasonal groundwater table fluctuation. If in future the drainage system is kept effective by proper maintenance, the main cyclic action – the fluctuations of the water table – will be strongly attenuated if not eliminated.

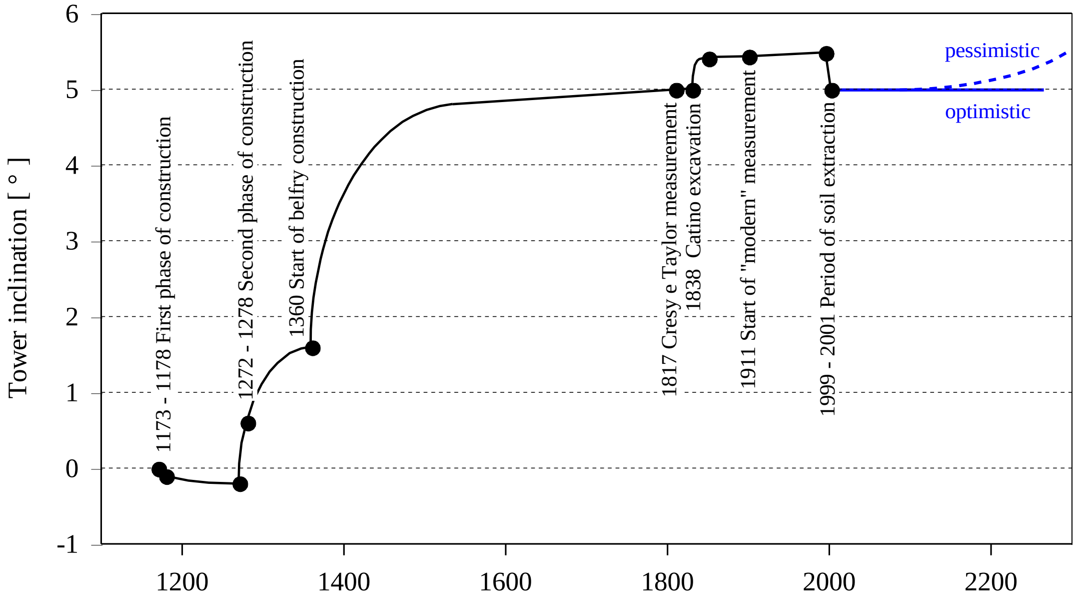


Fig. 30. Possible scenarios of the future behaviour of the Tower

The pessimistic scenario sees the tower staying motionless for a period, the honeymoon, of some decades, followed by a resumption of the southward rotation with a steadily increasing rate, and approaching after a long time the value it had experienced at the end of XX century. It is worth pointing out that, should the pessimistic scenario actually occur, the tower would reach the inclination it had before underexcavation in a time of the order of 300 years; this leaves ample margin for further interventions, if needed, possibly repeating the underexcavation.

In order to provide a reference in the debate about future scenarios, a rather sophisticated numerical analysis of the tower-subsoil system is being carried out. The analysis takes into account the three dimensional geometry, the history of construction and all the details of the interventions carried out since the XIX century; the constitutive model employed includes volumetric (but not deviatoric) creep.

The first results obtained support qualitatively the pessimistic scenario, in the sense that a honeymoon period followed by a resumption of the southward movement is foreseen. In any case, at the present time a comparison with the actual observations of the tower behaviour seems to indicate that the prediction is rather conservative.

6. CONCLUDING REMARKS

The stabilisation of the Tower of Pisa has been a very difficult challenge for geotechnical engineering. The tower is founded on weak, highly compressible soils and its inclination had been increasing inexorably over the years to the point at which it was about to reach leaning instability. Any disturbance to the ground beneath the south side of the foundation is very dangerous. Therefore the use of conventional geotechnical processes at the south side, such as underpinning, grouting, etc., involved unacceptable risk.

The internationally accepted conventions for the conservation and preservation of valuable historic buildings, of which the Pisa Tower is one of the best known and most treasured, require that their essential character should be preserved, with their history, craftsmanship and enigmas. Thus any intrusive interventions on the tower had to be kept to an absolute minimum and permanent stabilisation schemes involving propping or visible support were unacceptable and in any case could have triggered the collapse of the fragile masonry.

The technique of underexcavation provided an ultra soft method of increasing the stability of the tower, which is completely consistent with the requirements of architectural conservation. Different physical and numerical models have been employed to predict the effects of soil removal on the stability. It is interesting to point out that some mechanisms (as, for instance, the occurrence of a critical line beyond which the underexcavation becomes dangerous) are predicted by physical modelling and by the FEM analyses, while these are missed by the simplified Winkler type models.

The preliminary underexcavation intervention, only undertaken once the Commission were satisfied by comprehensive numerical and physical modelling together with a large scale trial, has demonstrated that the Tower responds very positively to soil extraction. The final underexcavation has attained the target of reducing the tilt of the Tower by half a degree.

It is believed that the geotechnical stabilisation has been finally attained; monitoring the behaviour of the monuments for the forthcoming few years will confirm it.

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