The leaning tower of Pisa: End of an Odyssey

La tour penchee de Pise: Fin d'une Odyssee

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ABSTRACT: The paper summarises the eleven-year activity of the International Committee for the Safeguard and Stabilisation of the Leaning Tower of Pisa. After a description of the Tower, of its history and of the related subsoil conditions, the paper focuses on the intervention that have been implemented with the aim to stop the progressive increase of the inclination, which was jeopardising the survival of the Tower. The method chosen to stabilise the Tower consisted in highly controlled ground extraction, named underexcavation, which by inducing the settlement of the North edge of the plinth, allowed to reduce the inclination of the Tower by 1800 arc-seconds, one tenth of the maximum tilt, recorded in 1993. This intervention is now leaving the Tower in the same situation of the beginning of XIX Century.

RÉSUMÉ: L'article résume onze années d'activité du Comité International pour la Sauvegarde et la Restauration de la Tour Penchée de Pise. Après une description de la Tour, de son histoire et des conditions du sol dessous, on ce concentre sur le travaux visée à arrêter. L'augmentation progressive d'inclinaison, qui avait amené le Monument près de l'effondrement. La méthode choisie pour stabiliser la Tour consiste à extraire du terrain en dessous de sa fondation, de façon à la faire tasser dans des conditions strictement contrôlées. L'effet a été un redressement de l'axe de la Tour de 1800 secondes, soit un dixième de l'inclinaison en 1993, avant le démarrage des travaux, avec un très faible soulevement du bord sud de la fondation. Ca à ramené la Tour à la situation qu'elle présentait au debout de XIXéme siècle.

1 INTRODUCTION

This paper describes the geotechnical stabilisation of the Leaning Tower of Pisa carried out in the period 1990-2001 by the International Committee for its safeguard and consolidation.

Because of the complexity of the problems related to the conservation and preservation of the Monument, the chapters that follow mainly deal with the permanent stabilisation of the Tower's foundation. A more comprehensive description of the Committee's activities can by found in the works by Jamiolkowski (1999), Burland et al. (1999), Macchi (1997, 2000), Capponi and Vedovello (2001).

2 THE TOWER

As shown in Fig. 1, the Tower is one of the monuments of the medieval Piazza dei Miracoli, which includes also the Cathedral, the Baptistery and the monumental Cemetery.

The tower, whose cross-section is shown in Fig.2 is constructed as a hollow masonry cylinder surrounded by six loggias with columns and vaults merging from the base cylinder.

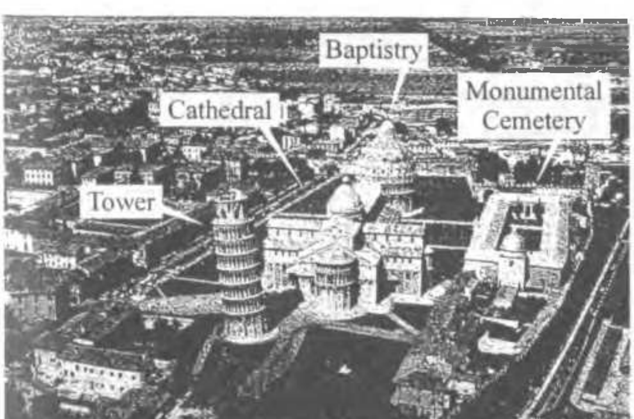


Fig. 1 - Piazza dei Miracoli - Air View.

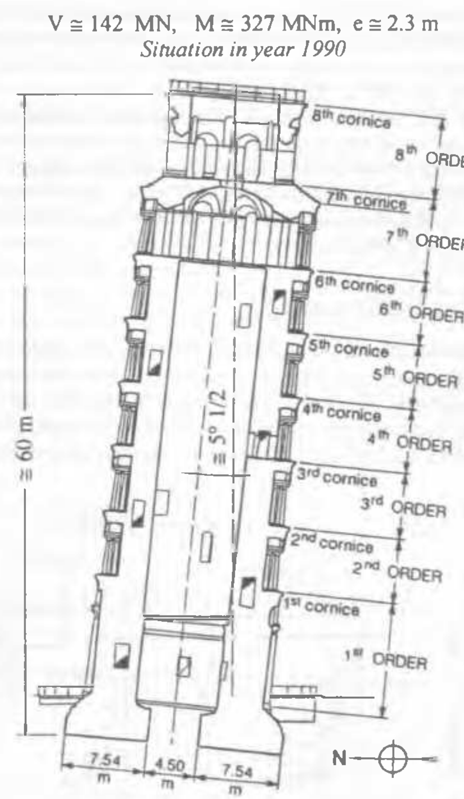


Fig. 2 - Leaning Tower of Pisa - Cross-Section.

The outer and inner walls are faced with San Giuliano marble while the cavity between is filled with rubber and mortar mix.

Inside the masonry annulus a helicoidal staircase leads to the bell chamber located at the top of the monument.

The body of the tower is almost 60 m high and the foundation plinth is 19.6 m in diameter.

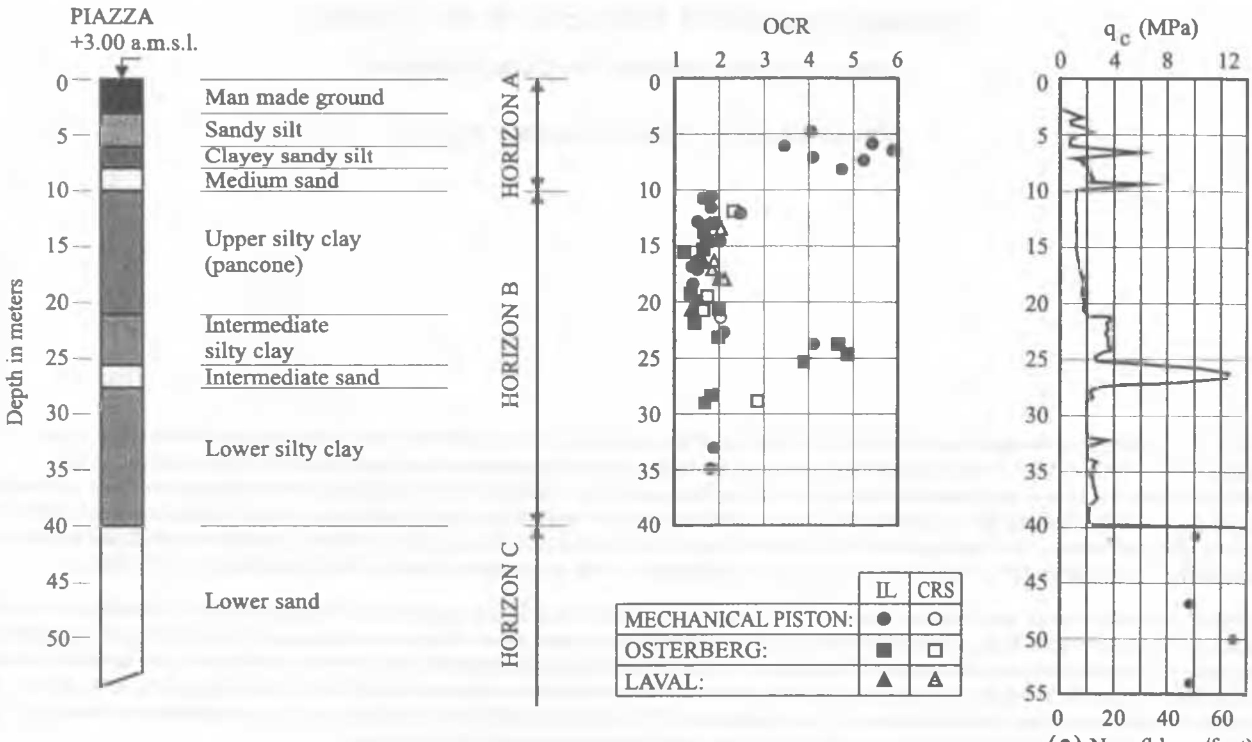


Fig. 3 - Leaning Tower of Pisa - Soil Profile.

As shown in Fig.2 the tower leans Southwards. In 1993, before starting the stabilisation works on the tower, its inclination approached 5° ½ leading to an overhang, with respect to the South edge of the plinth, very close to 4.5 m.

In early 1830's a ditch 3 m wide was excavated around the Tower, so that visitors could observe the basis of the columns and the upper portions of the foundation that had sunk during the centuries.

More detailed information about the Tower can be found also in the report by the Italian Ministry of Public Works, MPW (1971) and in the work by Luchesi (1995).

3 SUBSOIL CONDITIONS

Fig.3 shows the soil profile and a typical CPT profile representative of soil conditions in the proximity of the tower. Three distinct horizons can be recognised: Horizon A, approximately 7 m-thick estuarine deposits, laid down in tidal conditions, of sandy and clayey silts having at the bottom, a 1.5 to 2 m thick layer of fine sand. Based on the samples retrieved from the borings and on piezocone tests results, this sand layer becomes more silty-clayey and thinner from the North to the South edge of the plinth (Fig.4).

The same trend is observed comparing the piezocone data of the western to the eastern edge of the plinth (Fig.5).

The above deposits are covered by a 3 m-thick layer of man-made ground rich of numerous archaeological remainings dated from 3rd century B.C. to the 7th century A.C.

The level of the Piazza corresponds to an elev. of +3 a.m.s.l.

The underlying marine deposits of Horizon B can be subdivided into four distinct layers. The upper layer B-1 of soft sensitive medium to high plasticity clay is named "Pancone".

This layer it is underlain by an intermediate, stiffer clay B-2 of medium plasticity 4.5m-thick, beneath which a 2m-thick layer of intermediate sand B-3 is encountered. The Horizon B ends at a depth of about 40 m with a 11m-thick layer of almost normally consolidated clay B-4. Beyond such depth, a 20 to 25 m thick Horizon C of fine to medium dense sand is present.

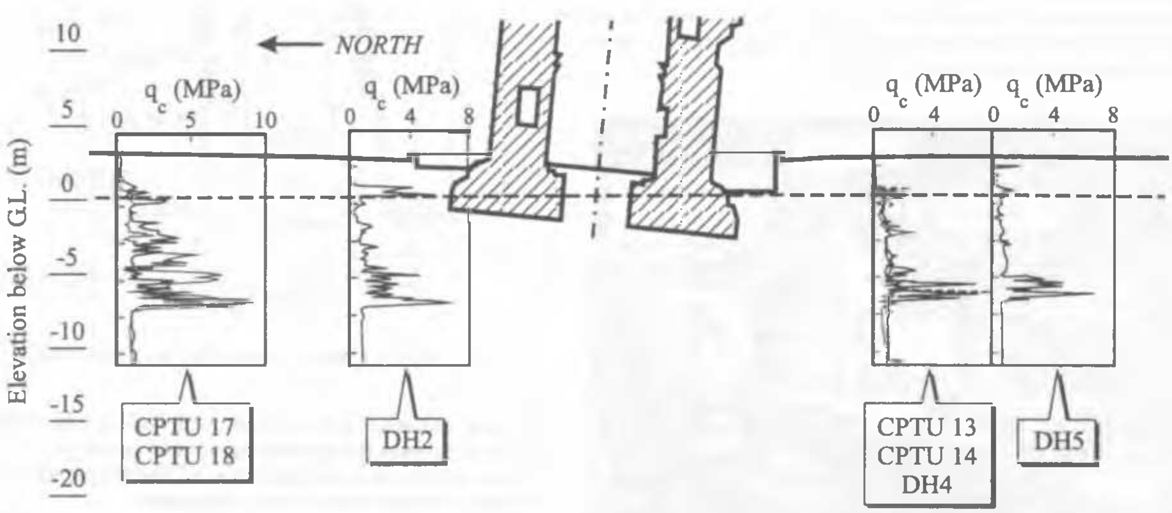


Fig. 4 - Leaning Tower of Pisa - Cone Resistance in horizon A, North-South Cross-section.

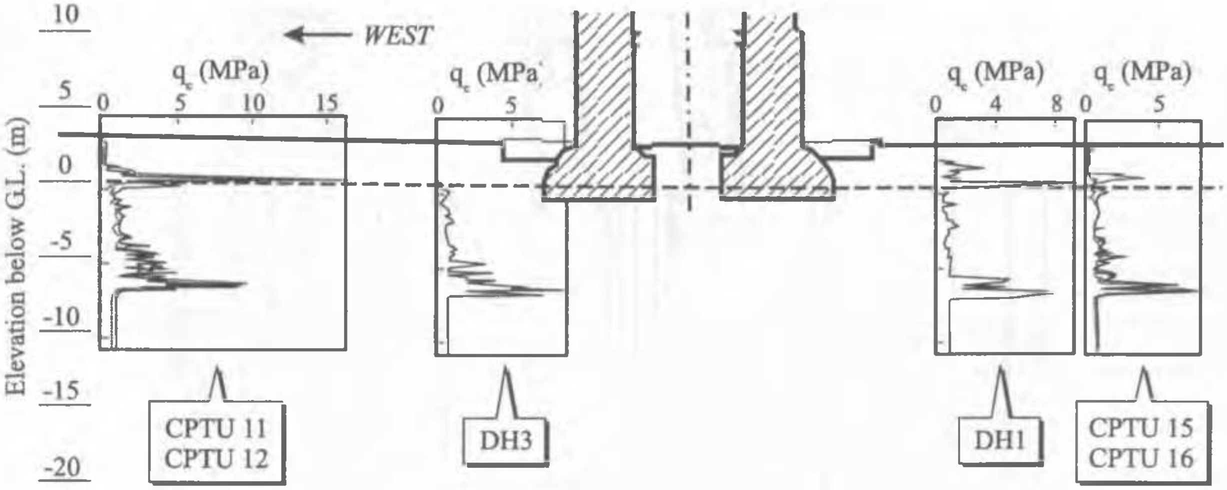


Fig. 5 - Leaning Tower of Pisa - Cone Resistance in horizon A, West-East Cross-section.

The groundwater conditions under the Piazza can be inferred from the Fig.6. The water table in Horizon A oscillates between 1 and 2 m below the ground surface. Intensive and extensive pumping from Horizon C determined that the groundwater table in deep sand dropped down to an elevation varying between -0.5 and -3.0 a.m.s.l. over a period of one year. This drawdown induced the downward water flow responsible for the subsidence of Piazza described in detail by Croce et al. (1981).

In Fig.7 is shown the soil profile beneath the Tower corresponding to the N-S cross-section. It shows that the contact between Horizon A and Pancone clay, which is horizontal under the entire Piazza, under the Tower has a dish-shape depression just beneath the plinth indicating that the average settlement at the contact between the two formations is close to 2.5 m. Moreover, if we take into account the best estimate of what could have been the average settlement of the soils belonging to Horizon A, we end up with an overall average settlement of the Tower around 3.0 m. An upheaval of the Pancone clay with a magnitude of 0.4 m is also evident at the South side (Fig.7), testifying that at some stage during its construction, the Monument approached a situation very close to the bearing capacity failure.

More information about the subsoil and groundwater conditions around the Leaning Tower of Pisa can be found in MPW (1971), Berardi et al. (1991), Callisto and Calabresi (1998) Costanzo (1994), Lancellotta and Pepe (1990), Lancellotta et al. (1994), Jamiolkowski et al. (1994).

4 HISTORICAL BACKGROUND

The construction of the monuments in the Piazza dei Miracoli (Fig.1) started in late 1000 and the Cathedral was built first.

The design of the Tower is ascribed to Bonanno Pisano.

The construction started in August 1173 but approximately five years after building begun, the works were suspended during the construction of the fourth order. The construction was resumed in 1272 under the lead of the architect Giovanni Di Simone who, in six years, brought the Tower almost to completion up to the seventh cornice (Fig.8).

The construction of the Tower was finally completed when architect Tommaso Andrea Pisano added the bell chamber between 1360 and 1370.

It was during the second construction stage that the inclination began to appear, see Fig.9. This reflects the attempts by the masons, charged with the construction works, to compensate against the on- going tilting. The position and the minor inclination of the added bell chamber, testify a further attempt to correct the geometry of the Monument and to balance the effects of the growing inclination. However, because there are few documents recording the history of the Tower, its inclination has been tracked also by looking at paintings and other historical evidences such as:

- the 1384 Fresco by Antonio Veneziano illustrating the funeral of Saint Ranieri;

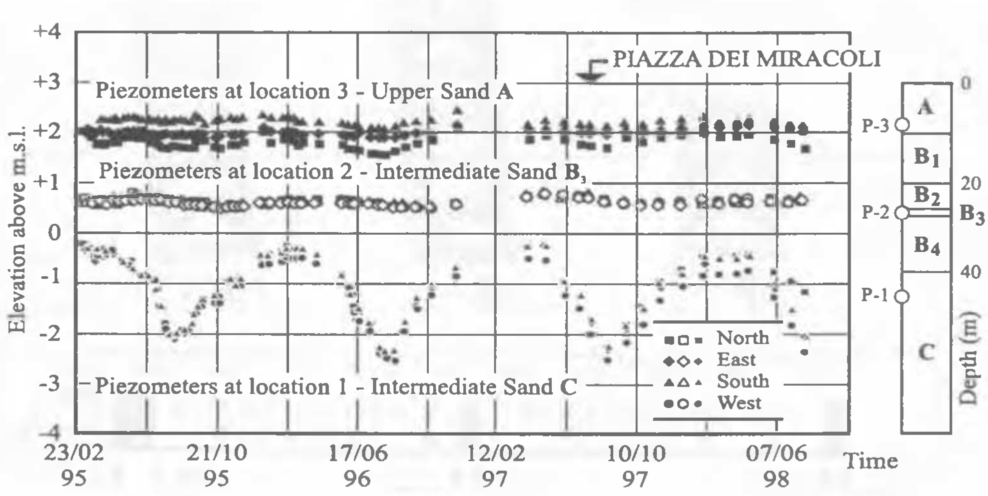


Fig . 6 - Ground water level beneath Piazza dei Miracoli.

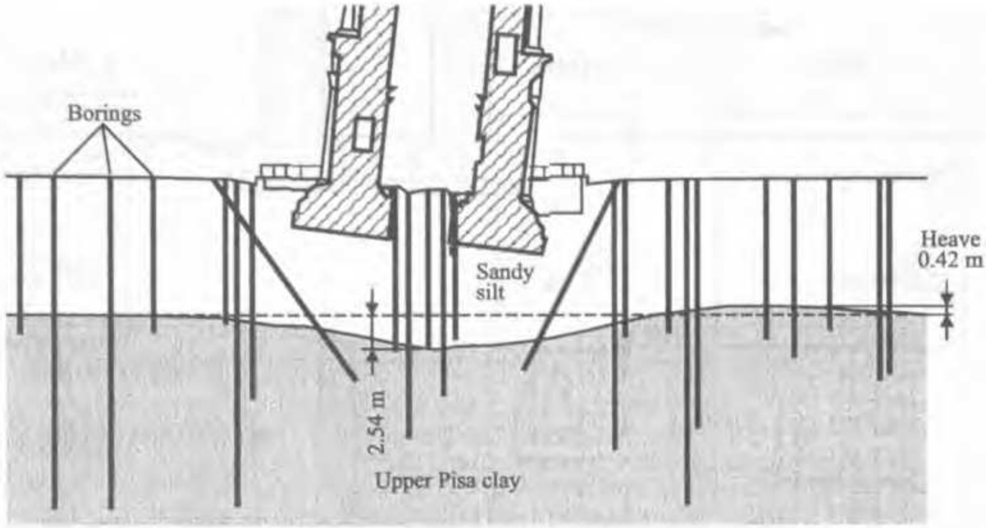


Fig . 7 - Settlement and heave of surface of upper Pisa clay.

- the 1500 work life by Arnolfo Vasari;
- the measurements of the tilt performed in 1818 by two English Architects E. Cresy and G.L. Taylor with the plumb line. Similar measurements were carried out by the French Architect Rouhault De Fleury in 1859 whose results are not known. Moreover, the French Architect mentions an appreciably larger inclination than that recorded by the two English Architects.

The increased rate of inclination after Cresy's and Taylor's measurements is commonly credited to architect Della Gherardesca who in 1838, dug a walkway around the foundations, known as the catino. The excavation itself and the evidence that the catino was below the groundwater table required continuos dewatering, and probably triggered an increase in the inclination rate of the Tower.

Only in 1935 [MPW (1971)] when cement grouting in the tower plinth was performed and a new waterproof catino structure was implemented, the dewatering was definitively stopped.

The modern monitoring of the Tower's inclination started in 1911, see Fig.10. Ever since, the Tower has continued to increase its tilt, at a slightly increasing rate. In fact, according to Burland (1990) who attempted to subtract from the measured inclination the effects of perturbations due to environmental changes and to various anthropic activities performed around the Tower, the rate of inclination per annum increased from 3" in the forties to 5" to 6" in late eighties.

Fig.11 presents an attempt to go back to the beginning of the history of the Tower tilt, considering the corrections made by the masons during the construction and other historical evidences integrated with the modern monitoring data since 1911.

Based on all the gathered information it can be figured out that:

- During the second construction stage the tower was very close to collapse due to the bearing capacity failure.
- The Tower continued to increase its inclination during the centuries reaching in 1993, before starting the stabilisation works, the magnitude of inclination of the tower plinth $\theta = 5° 34' 07"$.
  The terms of reference for the different possible definitions of the Tower inclination can be inferred from Fig.12.
- As shown by the modern monitoring data, the monument resulted extremely sensitive to any change in the environmental condition and to the works performed on or around it.

More detailed information regarding the Tower monitoring can be found in MPW (1971), Burland and Viggiani (1994), Burland (1995).

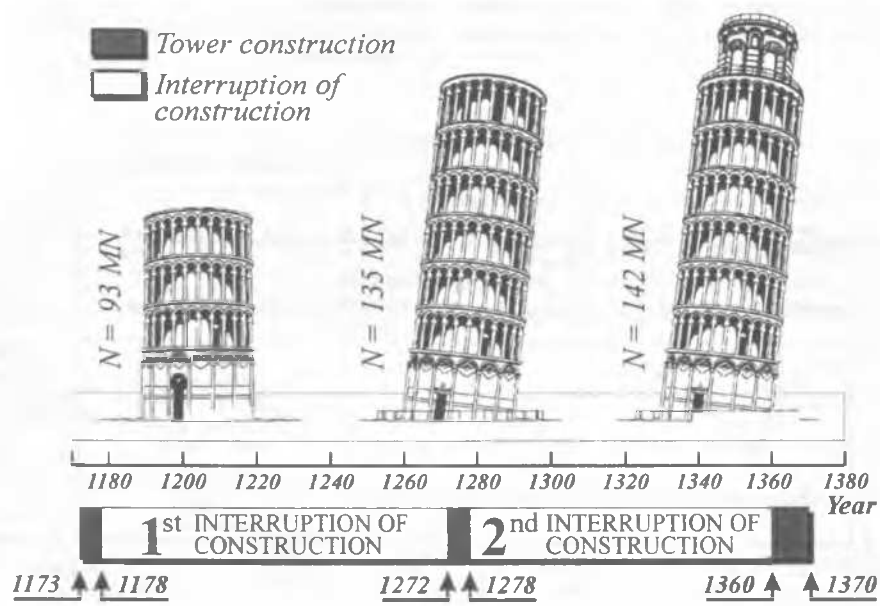


Fig. 8 - Construction History.

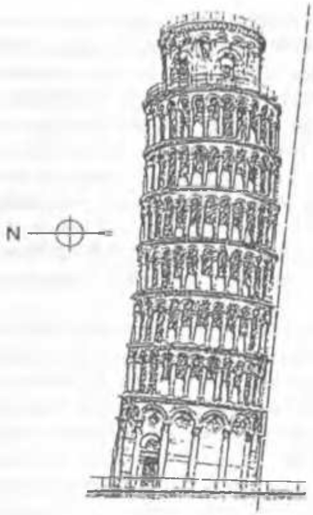


Fig. 9 - Shape of the Tower.

5 LEANING INSTABILITY

The Tower began to lean Southwards during the second construction stage when its weight approached the two third of that of the monument and, as mentioned, the phenomenon continued until 1993 when the temporary intervention on the Tower stopped this trend, averting the risk of toppling.

In the attempt to explain the behaviour of the Tower since the end of construction, the general consensus over the last decade [Hambly (1985), Lancellotta (1993), Desideri and Viggiani (1994), Veneziano et al. (1995), Pepe (1995), Desideri et al. (1997), Lancellotta and Pepe (1998)] has been that its equilibrium is affected by the leaning instability. A phenomenon similar to the one known in structural mechanics under the term of instability of equilibrium, and which threats the stability of tall heavy top structures seated on soft compressible soil. The beginning and the evolution of the leaning instability are a soil-structure interaction phenomenon entirely controlled by the non-linearity of the stiffness of the supporting soil.

In the case of the Tower of Pisa, the leaning instability was triggered by a Southwards inclination occurred during the second construction stage.

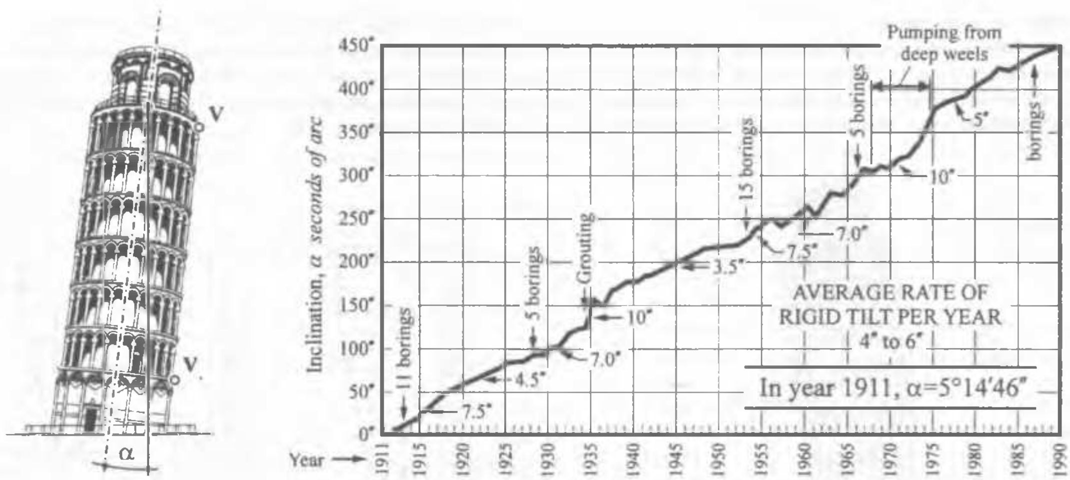


Fig. 10 - Inclination of Leaning Tower of Pisa.

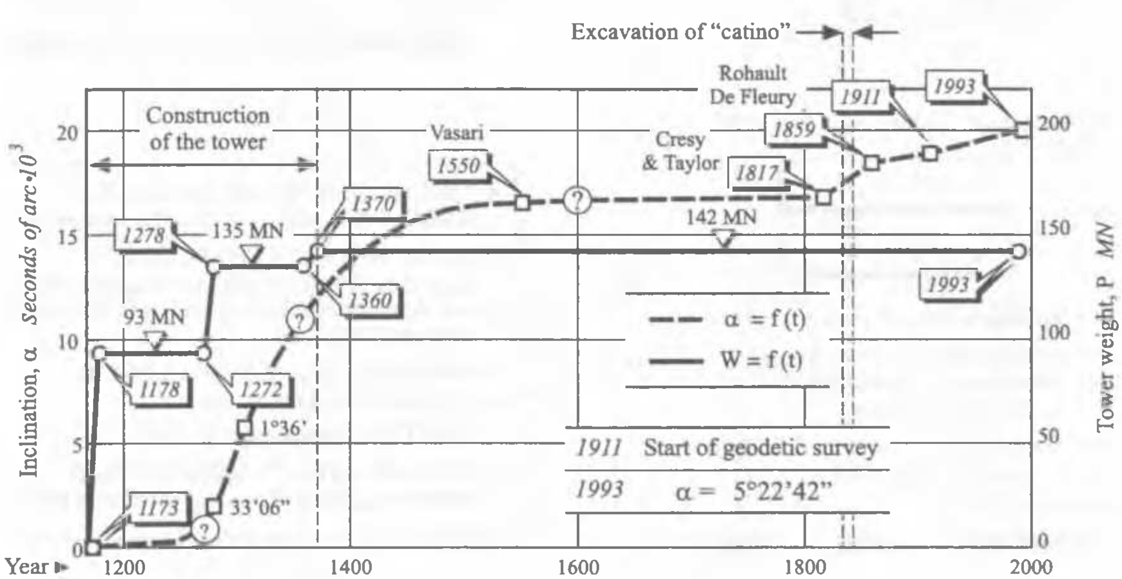


Fig. 11 - Evolution of inclination with time.

Because of the high compressibility and of the pronounced stiffness non-linearity, the resisting moment produced by the reaction of the supporting soil, proved to be unable to balance the progressive increase of the overturning moment generated by the increasing tilt. Therefore, after the manifestation of this initial tilt, a self-driving phenomenon of the leaning instability was activated, responsible for the continuous growth of the Tower's inclination through the centuries.

The reasons for the initial inclination α_o, called hereafter initial geometrical imperfection [e.g.: construction imperfection, differential settlements, etc.) [Abghari (1987), Cheney et al. (1991), Lancellotta (1993)], are matters of controversy. Various hypotheses have been postulated, the most likely are:

- Spatial variability of soil compressibility and permeability [Terzaghi (1934), Mitchell et al. (1977), Croce et al. (1981)].
  Based on the CPT profiles shown in Fig.4 it can be postulated a higher compressibility of Horizon A at the South side than the Northern one.
- Local bearing capacity failure and the resulting confined plastic developed during the second construction stage in the upper Pancone clay B-1, see Fig.6 [Mitchell et al. (1977), Leonards (1979)].

It is very likely that both mechanisms have been responsible for the initial geometrical imperfection of the Tower.

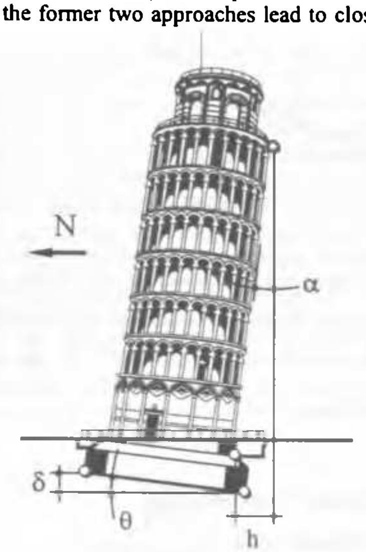
Lancellotta (1993) and Lancellotta and Pepe (1998) have estimated that the initial geometrical imperfection triggering the leaning instability of the Tower, is in the range of 1°.

The leaning instability problem can be investigated referring to different models of soil support i.e.: elastic continuum, Winkler's type subgrade and more realistically elasto-plastic work hardening continuum. While the former two approaches lead to closed-form solutions, the latter requires a much more complex numerical modelling, e.g. Burland and Potts (1994) and Potts and Burland (2000). The most comprehensive investigations on the relationship between the overturning (=external) moment M_e and the Tower's inclination α attempted mainly to assess its margin of safety against toppling and were carried out referring to one and two degree of freedom models simulating the action of the soil restraint by concentrated springs to which different constitutive relationships to model M_e versus α were assigned [Como (1965), Hambly (1985), Abghari (1987), Cheney et al. (1991), Lancellotta (1993), Desideri and Viggiani (1994), Veneziano et al. (1995), Pepe (1995), Desideri et al. (1997), Lancellotta and Pepe (1998)], see Fig.13.

Some of the mentioned authors have supported the results of their analyses with comparisons against multi-g physical model reproducing the instability of equilibrium of the Leaning Tower of Pisa in the centrifuge [Abghari (1987), Cheney et al. (1991), Pepe (1995)].

All the mentioned attempts to model the leaning instability phenomenon, applicable to the Tower of Pisa, have led concordantly to the conclusion that its factor against falling over is very low and falls in the range of 1.07 to 1.15, see examples by Lancellotta (1993), Desideri and Viggiani (1994) and Pepe (1995). Figure 14 shows the relationship between the collapse load P_c and the tilt α as computed by Pepe (1995) referring to the two degree of freedom spring model. In this computation has been adopted a non-linear relationship between the external moment (M_e) and α of hyperbolic type incorporating also the effect of the initial geometrical imperfections α_o.

It results that in 1993 when the α reached $\cong 5° \frac{1}{2}$, the ratio between the P_c and the current weight of the Tower had approached the extremely low value of 1.07.



Inclination and overhanging in May 1993

$\theta = 5° 34' 07"$

$h = 4.31$ m

θ = inclination of Tower Plinth*

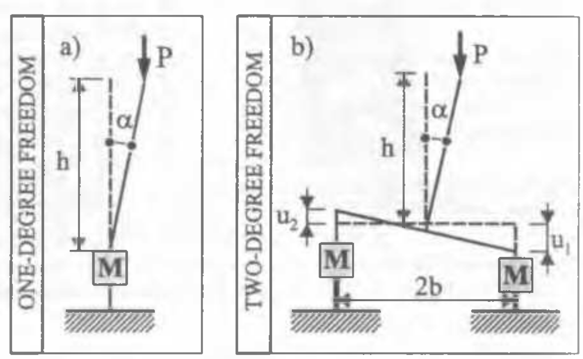
δ = relative settlement of South edge with respect to North edge;
δ (θ=1") $\cong$ 0.095 mm

h = overhanging referred to 7 th "cornice";
h (α = 1") $\cong$ 0.223 mm

$\theta = \alpha + 11'25"$

(*) Year 1993: θ = 20089", α = 19362"

Fig. 12 - Inclination of Pisa Tower: Terms of Reference.



M → MODEL OF SOIL RESTRAINT:

- LINEAR OR NON-LINEAR ELASTIC
  Hambly (1985), Abghari (1987), Cheney et al (1991)
- NON-LINEAR ELASTO-PLASTIC
  Lancellotta (1993), Desideri and Viggiani (1994), Nova and Montrasio (1995), Desideri et al (1997), Lancellotta and Pepe (1997)
- VISCO-PLASTIC MAXWELL SOLID
  unlimited creep under M_e=cost.
  Como (1965), Veneziano et al (1995)
- VISCO-PLASTIC STANDARD SOLID
  limited creep under M_e=cost., Veneziano et al (1995)

Fig. 13 - Leaning Instability: Soil-structure Interaction Idealization.

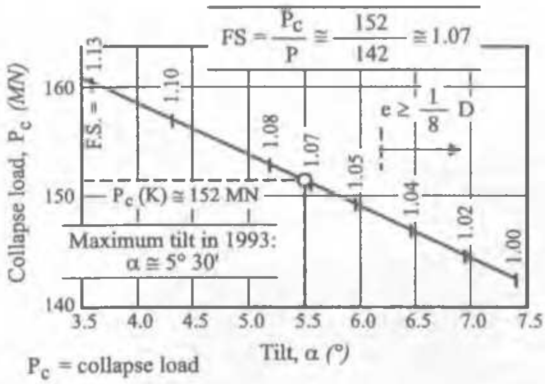


Fig. 14 - Leaning Instability of Pisa Tower: Evolution of safety margin with tilt, Pepe (1995).

6 THE COMMITTEE

In the previous section of this paper it has been pointed out that the phenomenon of the leaning instability, responsible for the continuous increase of inclination was jeopardising the Tower and if not stopped the consequences would be catastrophic leading in a few decades to its toppling.

Moreover, in 1989 the Governmental Committee declared the scarce safety margin of the Monument with respect to a possible masonry collapse of the most severely stressed South section of the tower between the 1st and 2nd cornice. In this section of the masonry very high compressive stresses exist in the external (>8 MPa) and internal facings (>6 MPa) (Fig. 15). In addition:

- in correspondence of the first cornice, the heavy stressed external facing is laying directly on the infill masonry (Fig.15);
- there is an obvious weakening of the tower shaft due to the opening of the stair case;
- voids and cracks in the infill masonry as well as lack of the bond strength between it and facing (Fig. 16);
- severe stress concentrations in the bedding joints of the marble stones of the facings (Fig. 16).

The situation of the masonry as above depicted, together with the unexpected, catastrophic collapse of the XIII century Civic Tower of Pavia in 1989 [Macchi (1993)], whose masonry was very similar to the Pisa Tower, rose great concern about the structural safety of the monument.

Consequently, in 1990 the Ministry of Public Works decided its closure to the visitors, generating large echo in the public opinion worldwide, and leading to the appointment of an International Committee for the Safeguard and Stabilisation of the Leaning Tower of Pisa by the Italian Prime Minister.

The Committee, the seventeenth in the long history of the monument [Luchesi (1995)] was entrusted to stabilise the foundation, strengthen the masonry and plan the architectural restoration.

The Committee, conceived as an independent authority responding in a straight line to the Prime Minister Office was charged to study the problem, to develop a reliable monitoring system, to conceive, design and implement the interventions on the Tower, and also to express an opinion on the possible future use of the Monument.

Because of the great artistic and historical value of the Tower of Pisa, the Committee was established as a highly multidisciplinary body including a broad spectrum of experts on: history of the mediaeval arts, archaeology, construction stones, architecture, structural engineering and geotechnical engineering.

Information about the present composition of the Committee and about its past members can be found in Appendix A.

The activities of the Committee can be grouped as follows:

- Various experimental investigations aimed at a comprehensive knowledge of all the relevant features of the monument and its environment. These investigations and studies covered the areas of: archaeology, history of construction, strength of materials, numerical and physical modelling of structure and foundation soils, in situ and laboratory geotechnical tests, possible approaches for remedial works, as architectural restoration, etc.
- The design and implementation of the modern and redundant monitoring system, an essential condition to implement in security any remedial action. The system consisted in:
  - Eight internal benchmarks, 101 through 109, see Fig.17 installed at the ground floor level at the Tower entrance.
  - These survey points are linked to the previously mentioned fifteen external benchmarks, 901 through 915 in Fig.17, located externally on the Tower plinth.
  - Twenty-four benchmarks, 1 through 24, see Fig.17, used to monitor the movements of Piazza dei Miracoli by means of precision levelling.
  - Deep datum point, DD1 in Fig.17, the most important point of reference for all levelling, reveals the absolute movements of the tower and the ground surrounding it.
  - Biaxial electrolytic inclinometers, IBIA in Fig.18, are located on the ground floor at the Tower entrance. The inclinometers and

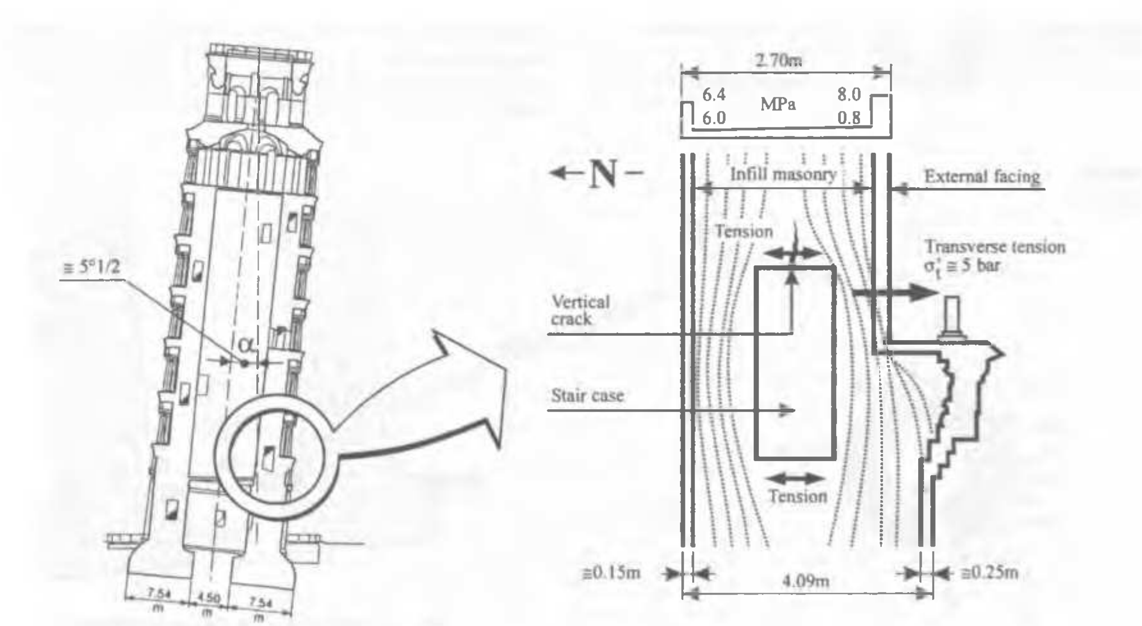
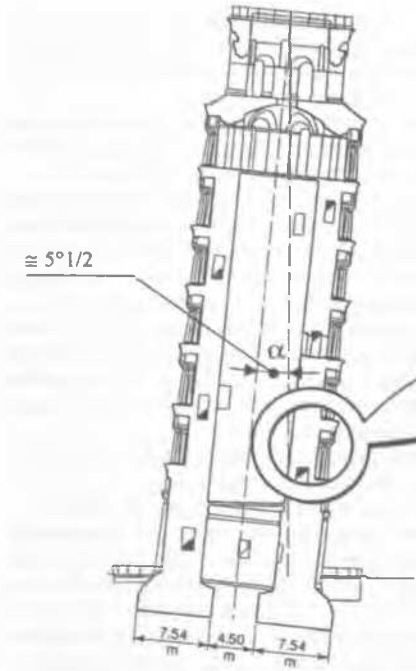


Fig. 15 - Leaning Tower of Pisa - Critical section of the masonry.



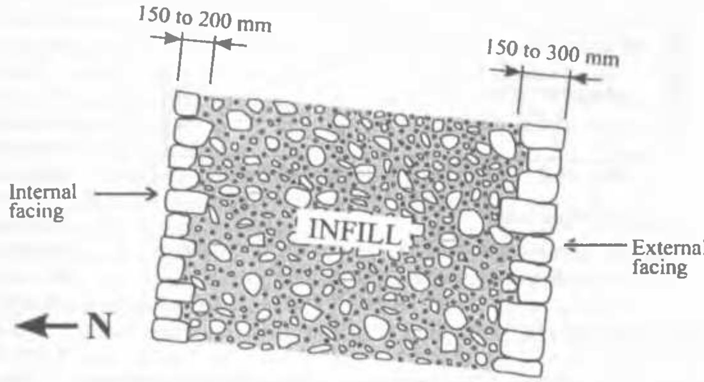


Fig. 16 - Leaning Tower of Pisa - Masonry features.

the automatic hydraulic livellometers, shown in the same figure, allow for the continuous measurement, in real time, of any change in the Tower tilting .

The description of additional instrumentation, also installed to monitor the movements of the Tower above the plinth and its masonry is beyond the scope of this paper.

Fig.12 shows the relationships between the inclination of the monuments (α) and its overhanging (h) as well as that between the plinth tilt (θ) and the relative settlement of its South edge (δ).

More details about the monitoring system can be found in the works by Burland and Viggiani (1994) and Burland (1995).

- The design and implementation of remedial works regarding the stabilisation of the foundation, the strengthening of the masonry and the architectural restoration.

The Committee, aware that the selection of the design and the implementation of the final interventions would require a long time and considering the reduced safety margin of the Tower resolved to carry out in a short time some temporary and fully reversible works aimed at reducing the risks to lose the monument [see Jamiolkowski (1999)].

In the following part of the paper the Committee's activities aimed at the foundation stabilisation are summarised. Information concerning the masonry strengthening and the architectural restoration can be found in the works by Macchi (1997, 2000) and Capponi and Vedovello (2001).

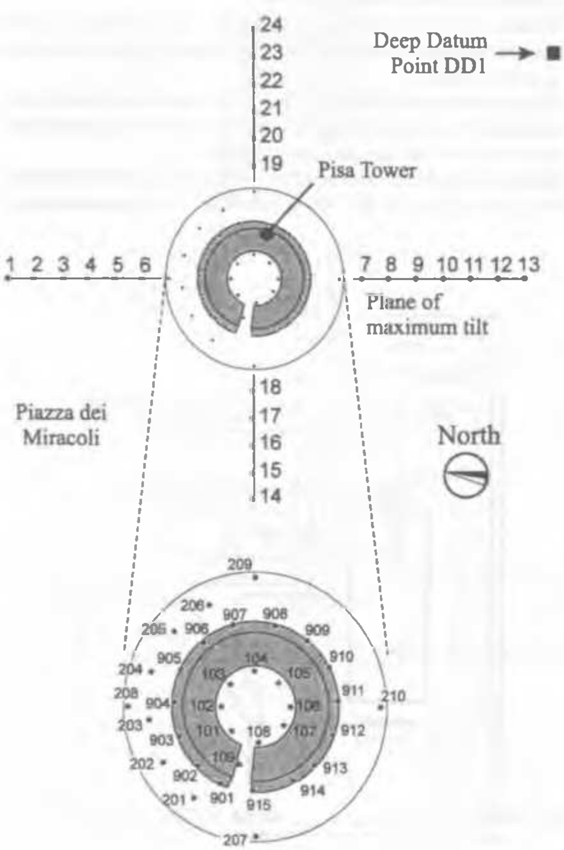


Fig. 17 - Benchmarks for high precision levelling.

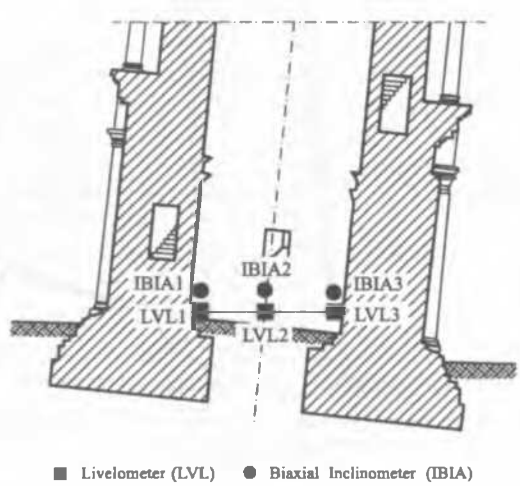


Fig 18 - Measurements of inclination at Tower base.

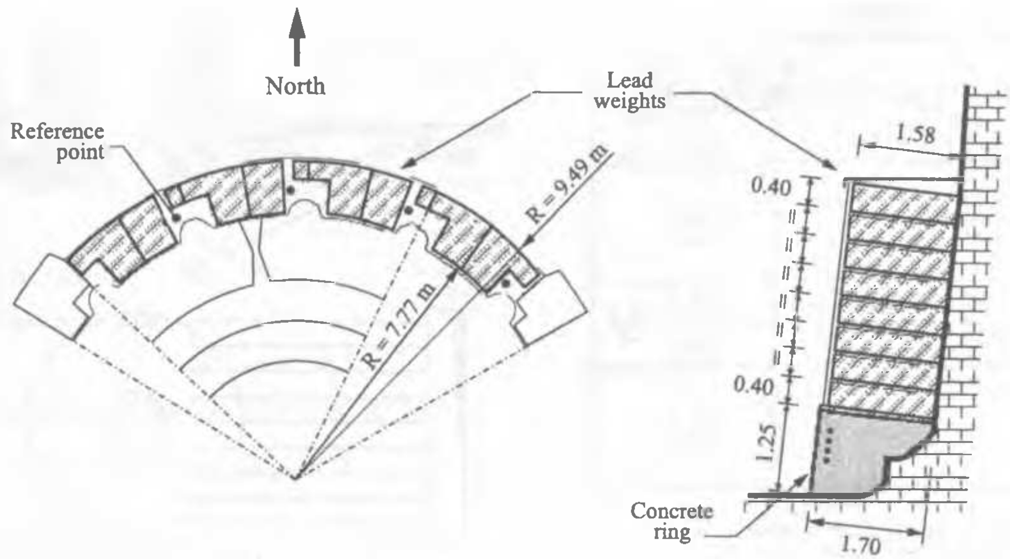


Fig. 19 - Counterweight on North edge of Tower plinth.

7 TEMPORARY STABILIZATION

The reduced safety margin with respect to toppling and the steady motion of the Tower increasing its inclination by 5' to 6" per annum, led to the decision to implement a temporary and fully reversible intervention aimed at reducing its inclination or even stopping it for a limited period of time.

The intervention consisted in placing 6 MNm of lead ingots on the North edge of the plinth (Fig.19). The lead ingots were gradually placed on the prestressed concrete ring, generating a stabilising moment of 45 MNm (included the small stabilising moment ≅1.5 MNm generated by prestressed concrete ring). The counterweight placed in the period between May 1993 and January 1994, produced a very positive response of the monument, which, for the first time in its history, inverted the direction of the movement (Fig. 20).

As a result during the loading stage the monument reduced its inclination by 34" with a further increase to 54" in the next six months.

In view of the positive response of the Tower to the counterweight, and to overcome its visual impact, it was decided to replace the lead ingots by ten deep anchors having each a working load of 1000 kN (Fig.21). This intervention was conceived as an intermediate measure between the temporary and the final one.

The implementation of this solution required the construction of a second prestressed concrete ring below that supporting the lead ingots, hidden beneath the catino. This required an excavation ranging from 0.3 m below the perched G.W.L. at the North of the catino, to 2.0 m at South.

The design of the ten anchors solution was developed based on the information gathered by the previous Commissions, considering the catino statically independent from the Tower plinth.

The only known connection was the waterproofing joint located in proximity of the foundation perimeter.

During the implementation of this solution it was discovered that in the past there had been two attempts to enlarge the Tower foundation:

- The first, probably due to Della Gherardesca, who during the construction of the catino, placed around the Tower plinth a 0.7 to 0.8 m thick layer of conglomerate having the same width of the catino.
- The second was implemented by the local authority for public works that in mid thirties had redone the catino. During this intervention, involving the cement grouting of the Tower plinth, the under-catino conglomerate was connected to the foundation by means of steel tubes 70-mm in diameter and approximately 700 to 800 mm long. Information about this work was never reported in the official documents and was unknown to the professionals dealing with the Tower until the summer of 1995.

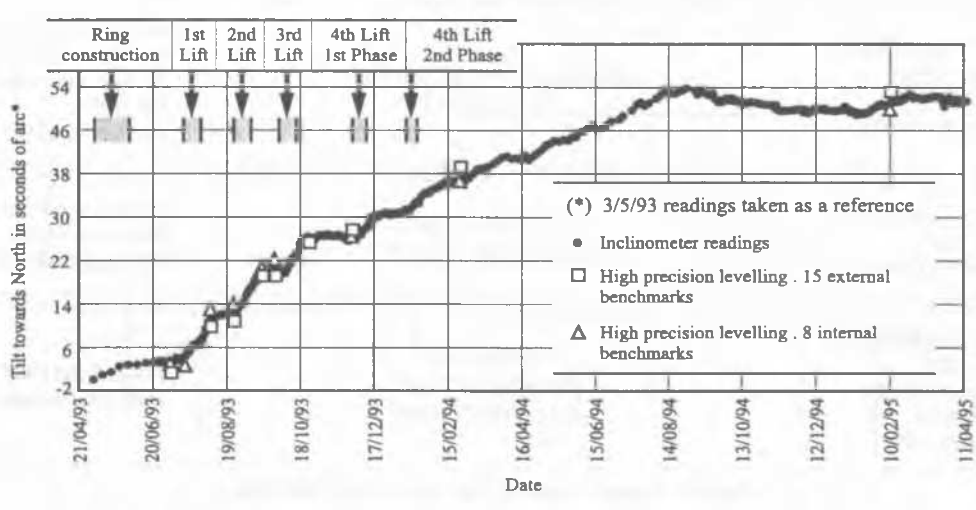


Fig. 20 - Tilt towards North as result of counterweight application.

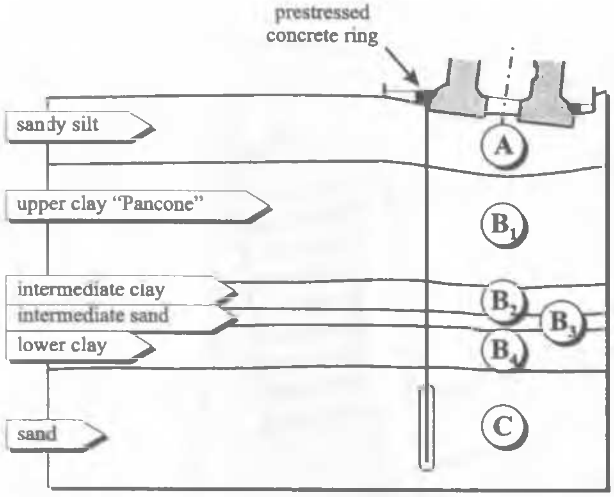


Fig. 21 - Ten Anchors solution.

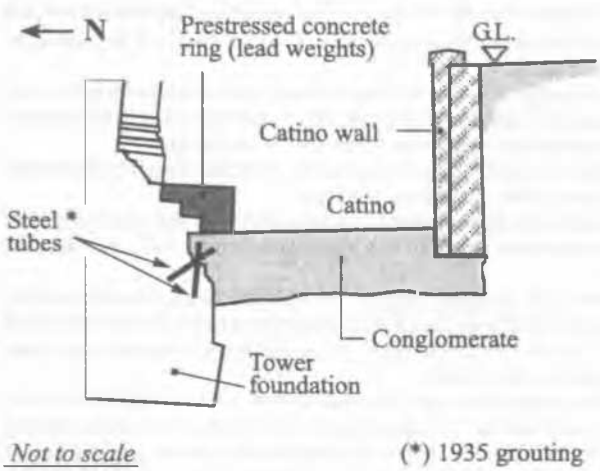
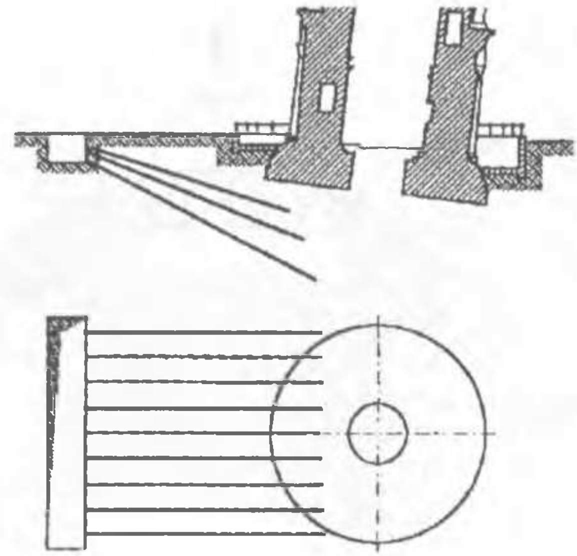


Fig. 22 - South section of Catino - Configuration in year 1993.



- Reduction of contact pressure on South side
- Reduction of present (~ 10%) inclination by 1% would suffice.
- Simplest manner, removal of soil under North side by series of borings.
- Regulating number position and diameter of borings, desired reduction of tower inclination can be achieved

Fig. 23 - Underexcavation for correcting inclination of Pisa Tower (Terracina 1962).

Considering the above, the hypothesis that the catino is statically independent from the Tower is no more correct (Fig.22). Moreover, considering that since mid thirties, the South edge of the Tower plinth has settled 20 to 25 mm more than the North one, it is likely that some load has been transferred from the Monument to the South part of the catino.

During the first attempt to remove in small segments the South part of the catino to build the prestressed concrete ring for the ten anchors, the Tower started to tilt towards South at a rate of 3" to 4" per day with serious concern for its stability. Such phenomenon was counteracted successfully by applying additional 3700 kN of lead ingots on the North edge of the plinth. The Committee decided then to discard the ten-anchor solution and to focus all the efforts on the development of the final stabilisation intervention with led ingots on the tower.

PHYSICAL	*AIMED AT:*	NUMERICAL, F.S.A.
MULTI - g MODEL: Phillips (1992) Pepe (1995) Fioravante (1998)	SIMULATING HISTORY OF TILTING	Borja et al (1994, 1995) Mitchell and Soga (1995) Burland and Potts (1994) Bai (1998) Potts and Burland (2000)
MULTI - g MODEL: Pepe (1995) Fioravante (1998)	INVESTIGATING LEANING INSTABILITY	Burland and Potts (1994) Borja et al (1994) Potts and Burland (2000)
MULTI - g MODEL : Pepe (1995) Fioravante (2000) 1-g MODEL: Edmunds (1993)	VALIDATING STABILIZATION INTERVENTIONS	Burland and Potts (1994) Potts and Burland (2000)

Fig. 24 - Leaning Tower of Pisa - Modelling Behaviour.

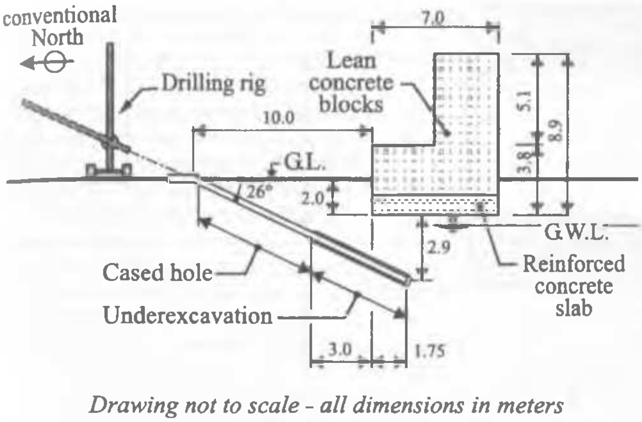


Fig. 25 - Underexcavation field trial.

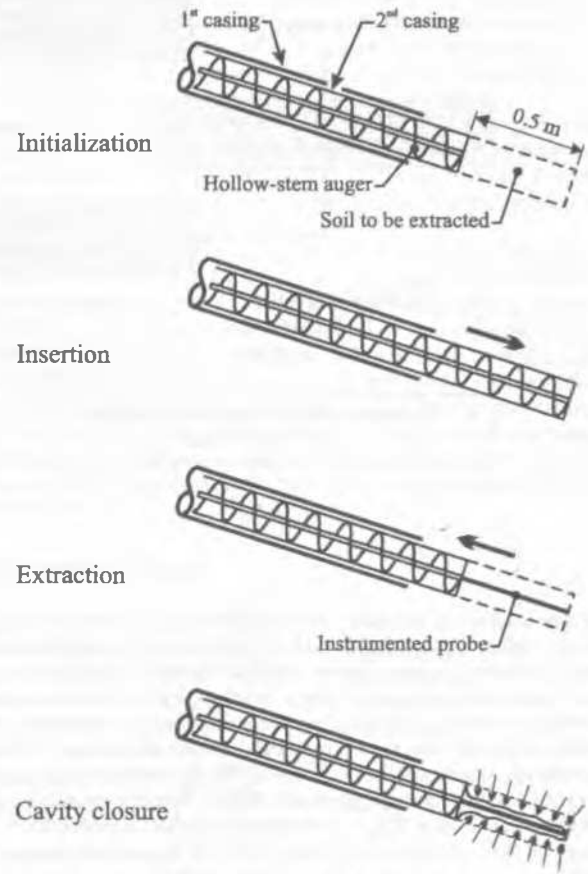


Fig. 26 - Soil extraction process.

8 FINAL STABILIZATION

Since 1993, the Committee has undertaken studies aimed at finding a solution to reduce significantly the inclination acting only on the foundation soils without affecting the structure of the Tower.

Three possible interventions, able to induce differential settlement of the North edge of the plinth with respect to the South one, have been taken into consideration:

- Groundwater lowering in the intermediate sand layer B-3.
- Electro-osmosis aimed at reducing the water content hence inducing a volume change in the upper part of Pancone clay.
- Gradual extraction of the soil from the lower part of Horizon A, as previously postulated by the Italian civil engineer Terracina (1962), (Fig.23). The same method has recently been applied successfully to mitigate the impact of very large differential settlements suffered by the Metropolitan Cathedral of Mexico City [Tamez et al. (1992), Ovando et al. (1996), Tamez (1997)].

The first solution was disregarded after the preliminary studies because of the many uncertainties involved to implement it and first of all, because of the difficulties in predicting the effectiveness and the ability to steer the tower during long term localised pumping.

As to the electro-osmosis method, the large-scale field trial test performed on the Piazza dei Miracoli pointed out the feasibility of such intervention in the upper Pisa clay layer B-1.

Accordingly, the Committee focused on investigating the possibility to apply the ground extraction technique under the North part of the Tower. This intervention is thereafter named underexcavation. To determine its feasibility, numerical analyses, physical modelling both in terrestrial gravity field and in centrifuge, as well as large scale trial field were performed, see Figs.24 and 25. The large-scale trial field was very useful to prove the feasibility of the underexcavation and allowed testing and finalising the technological aspects of the intervention.

To perform the trial field, a 7 m in diameter circular reinforced concrete footing was built on the Piazza, far from the Tower, see Fig.25,

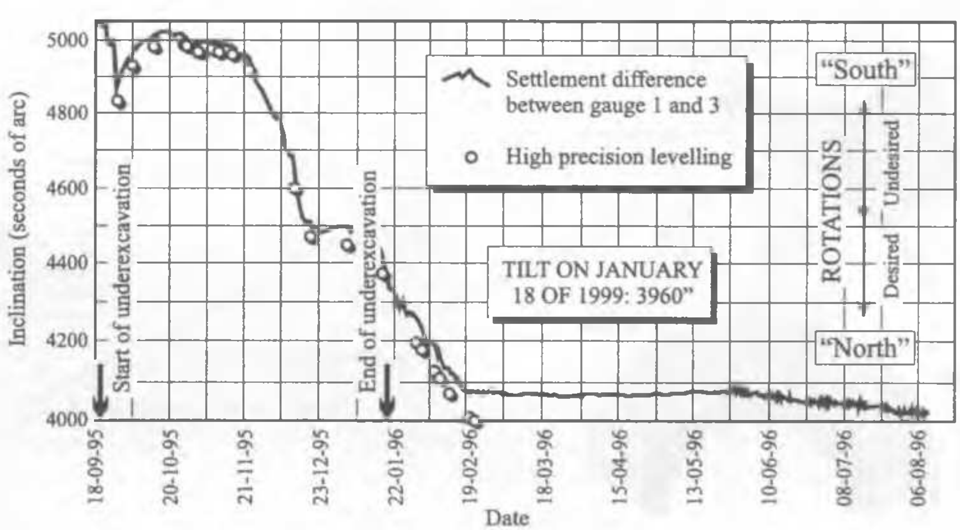


Fig. 27 - Underexcavation Field Trial - Inclination of Plinth in Plane of Maximum Tilt.

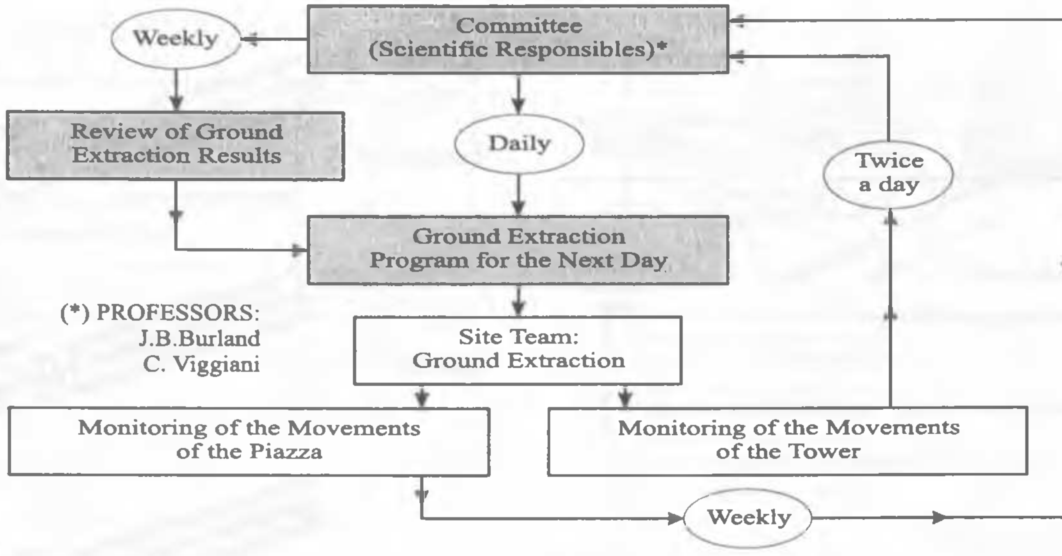


Fig. 28 - Underexcavation: Observational Approach.

and was loaded eccentrically with concrete blocks. Both the footing and the underlying soil were heavily instrumented to monitor settlements, rotations, contact pressure and the induced excess pore pressure during the experiment. After a waiting-period of a few months allowing to develop the major part of consolidation settlements, the ground extraction was started by means of inclined borings 168 mm in diameter, as schematically shown in Fig.26. The underexcavation was performed by removing gradually the soil from Horizon A through a procedure, shown in Fig.26, that made it possible to reduce the inclination of the trial plinth by almost 1000" of arc, as documented in Fig.27.

During this experiment, the following important lessons were learned:

- A critical penetration exists under the plinth and if the extraction hole exceeds it a rotation of the foundation in the undesired opposite direction is experienced, occurrence that happened in September 1995 as can be detected from Fig.27.
- By means of an appropriate sequence of ground extraction operations it was possible to steer the plinth movements both in N-S and W-E plan as required.
- On February 1996, soon after the completion of the underexcavation, the trial plinth came to rest and up to January 1999 exhibited only negligible movements.

In addition, the trial field operations led to the definition of a robust and reliable scheme of communications between the Committee and the Contractor, as schematically shown in Fig.28. The way to proceed, shown in this figure, in combination with a reliable, redundant and in real time monitoring, allowed, subsequently to perform safely the underexcavation interventions under the Tower, which was agreed on and decided considering the successful validation of the underexcavation by trial field.

A preliminary ground extraction under the monument was planned, well aware that, by no means, the trial plinth was to consider as a model reflecting completely a possible response of a Tower suffering from the leaning instability. This preliminary intervention consisted in twelve holes, see Fig.29, whose penetration under the North rim of the Tower plinth was planned not to exceed 2.5 m referring to the scheme shown in Fig.30.

However, before starting the final stabilisation works under the Tower, to prevent any unexpected adverse movement during this intervention, a safeguard structure was implemented consisting in a cable stay, as shown in Fig.31. Each cable being able to apply pure horizontal force of 2 MN to the Tower at the height of ≅22 m above its base. Moreover, due to the divergence of two cables, the cable stay was also giving some capacity of steering the Monument in case of undesirable movements in East-West plane, perpendicular to that of maximum tilt.

Providentially, the underexcavation interventions did not require the use of the safeguard structure so that the cable stay was never put into operation.

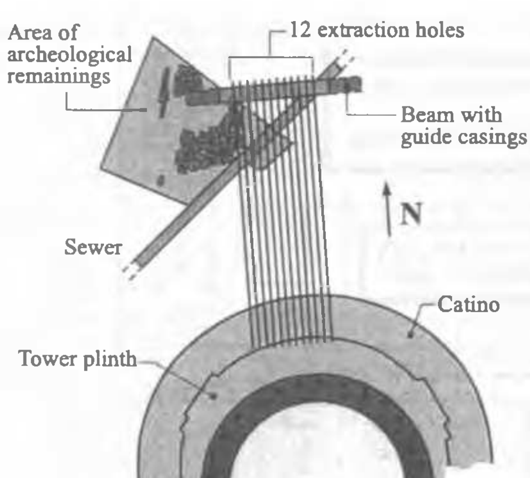


Fig. 29 - Preliminary underexcavation scheme.

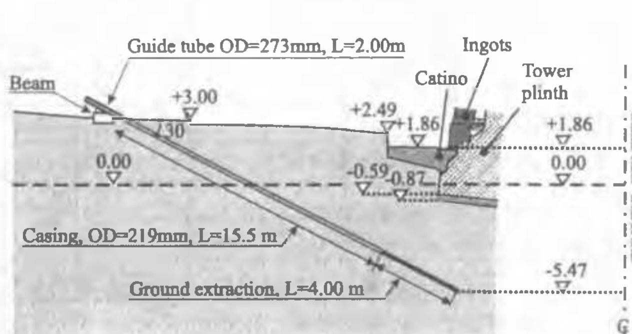


Fig. 30 - Hole for preliminary soil extraction.

At the beginning of 1999, with the safeguard structure set to be employed, the Committee was ready to attempt the underexcavation.

The preliminary intervention started on February 9th, 1999. It was completed on June 6th, 1999. All together 7 m^3 were extracted from the twelve holes shown in Fig.29. Out of this value only $\cong$1.2 m^3 were dug out under the plinth and the remaining volume under the catino. The maximum penetration of the central extraction holes (Fig.29) under the North edge of the foundation was limited to 1.5 m.

The Tower responded satisfactorily in terms of observed rotations and settlements to the preliminary underexcavation, see Figs.32 and 33, from which one can infer the following:

- At the end of the preliminary underexcavation the Tower rotated Northward by 90 seconds.
- Thereafter, it continued its rotation Northward at a reduced rate until mid September 1999, achieving a reduction of inclination of 132 seconds. Ever since and until the end of January 2000, the Tower has been motionless as far as the inclination is concerned, see Fig.32.
- As result of the preliminary underexcavation, the Southern edge of the plinth has risen by 1.5 mm while the Northern edge has settled at 12 mm, see Fig.33. The observed behaviour evidentiated two positive phenomena: *a)* the point of instantaneous rotation is located within the imprint of the plinth; *b)* as a consequence, a small reduction of contact stresses under the highly stressed Southern edge of the foundation occurs.

In view of the encouraging response of the Tower to the preliminary intervention, the Committee carried out the full underexcavation aimed at reducing the Tower's inclination by 1800 seconds of arc. The intervention was started on February 21st, 2000 and was performed using 41 extraction holes, as shown in Fig.34.

A maximum penetration of the central extraction holes beneath the plinth of 3.5 m was planned, see Fig.35. On January 19th 2001 when the massive ground extraction was stopped the total extracted volume of soils was $\cong$37 m^3. Out of this value, $\cong$14.5 m^3 was extracted from the stretches located directly beneath the Tower, and the remaining under the catino. The maximum penetration of the central holes beneath the plinth was limited to 2.5 m as shown in Fig.36 that reports the massive ground extraction plan as implemented during the final intervention. Each square cell, shown in this figure, corresponds to 500-mm long stretch of the extraction hole, while the numerals indicate the total

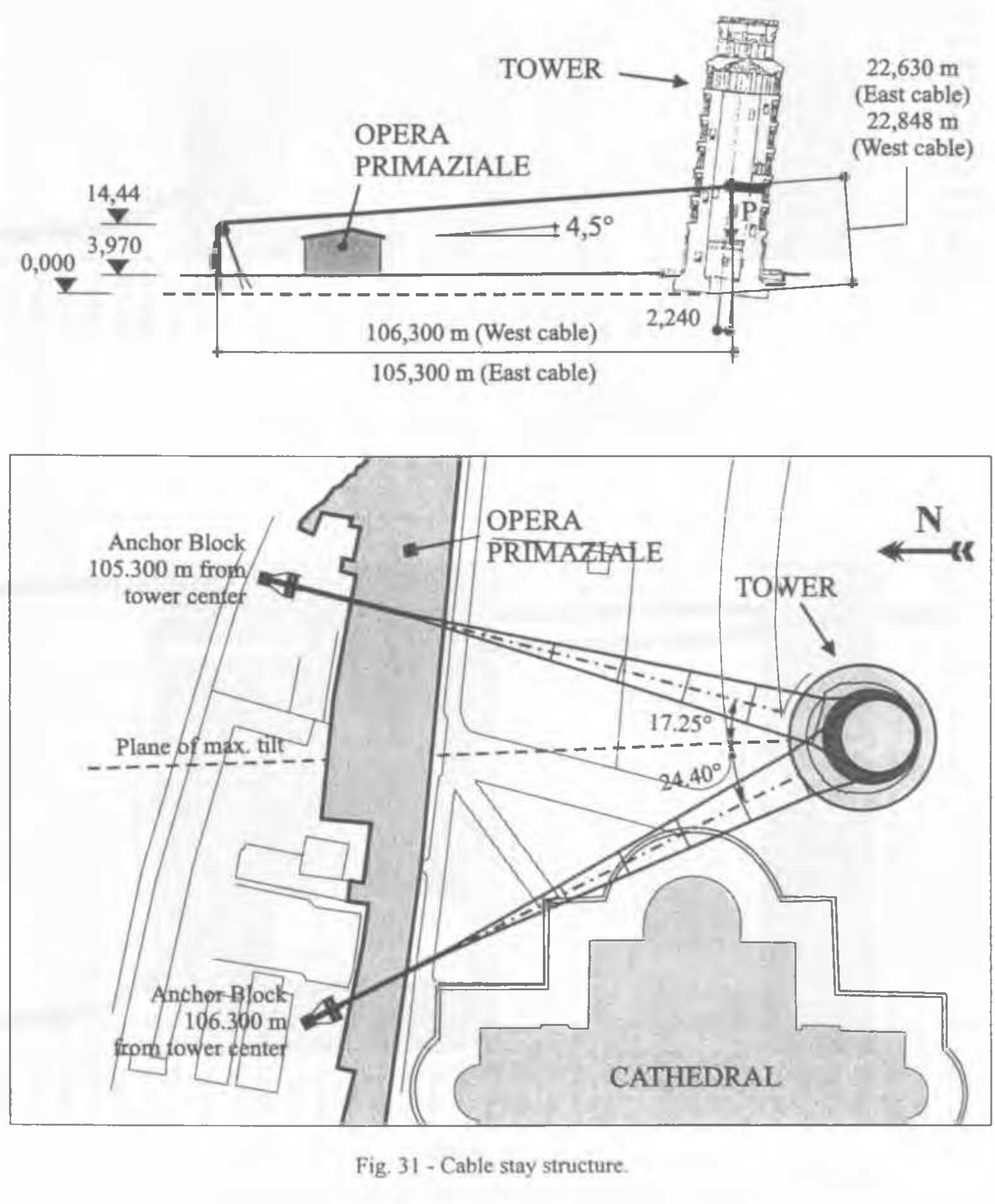


Fig. 31 - Cable stay structure.

volume of the extracted soil at each stretch in dm^3.

The response of the Tower to the final ground extraction is summarised in Figs. 32 and 33. At the end of this intervention the inclination of the Tower was further reduced to 1621 seconds of arc. Ever since in absence of ground extraction the Tower continued its rotation Northward approaching in July 2001 the value 1788 seconds. If we add the 54 seconds resulted from the lead counterweight, the total reduction of the inclination reached 1842 seconds, which corresponds to a reduction of 446 mm of the overhang, one tenth of the value recorded in 1993. During the preliminary and particularly during the massive underexcavation the Tower resulted, for all practical purposes, motionless in the East-West plane. During the massive ground extraction, see Fig.33 the South edge of the plinth further rose and reached the value of $\cong$12 mm confirming the extremely positive response of the Tower to the adopted stabilisation measure.

During the final underexcavation, the Tower was cleared from the lead ingots and all the other temporary interventions. Fig.37 summarises the overall reduction of the Tower inclination as result of all the intervention implemented by the Committee since 1993.

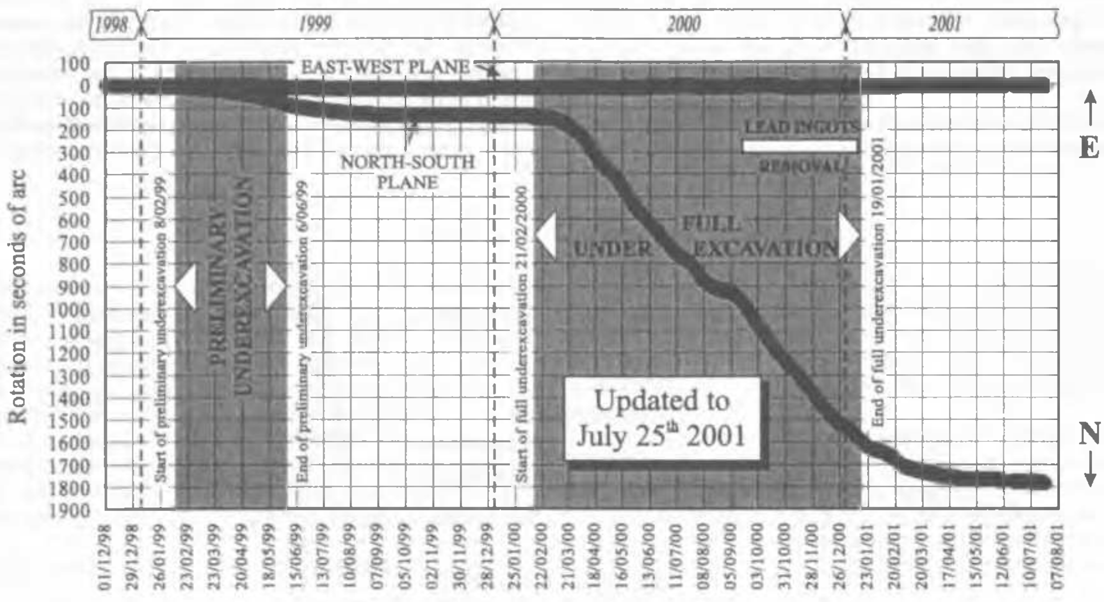


Fig. 32 - Tower, rotation during underexcavation.

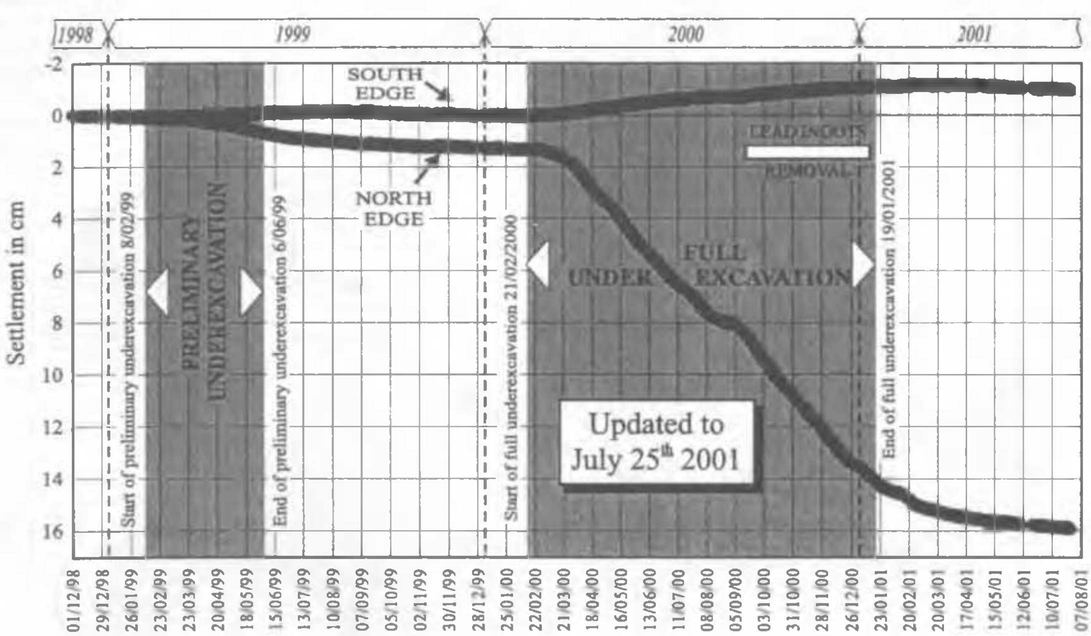


Fig. 33 - Settlement of Tower plinth during underexcavation.

9 FINAL REMARKS

The underexcavation intervention as summarised in Chapter 8 was successful and the inclination of the Tower was reduced significantly bringing it to the same geometrical configuration that the Monument had at the beginning of XIX Century, see Fig.11.

In addition to this significant achievement, the stability of the Tower was further improved creating a structural connection between the catino slab and the Tower plinth. This measure, increasing the virtual radius of foundation, is beneficial to the Tower suffering from the leaning instability enhancing twice the rotation stiffness of the plinth.

As to the future behaviour of the Tower, the answer is far from being simple also due to a complete lack of former experience in the use of ground extraction with tall heavy structures suffering from the leaning instability such as the Tower of Pisa.

After extensive debate within the Committee the following two scenarios were envisaged by the geotechnical team, pictured in Fig.38:

- Pessimistic scenario
  The Tower will remain stable for a period of time, followed by a rotation resumption at a much reduced rate. This scenario qualitatively linked to elementary creep theories for soil, grants a long period of time, measurable in hundreds years before approaching the rate of rotation the Tower had experienced before the Committee's interventions.
- Optimistic scenario
  As a result of the inclination reduction, the stress unloading at the South plinth edge and the enhancement of the foundation's rotational stiffness, the leaning instability phenomenon was stopped, the rotation will cease [except very small largely reversible rotations due to ratcheting caused by seasonal ground water and temperature fluctuations].

The Committee returns the Tower to the Italian Government in a largely improved safety conditions, once its task ends, at December 2001. The Committee has requested a careful monitoring to be carried out for at least the next ten years. It will be achieved using the surveillance system arranged by the Committee and that will hopefully be able in 3 to 5 years to clarify to scientific community if the mentioned scenarios are realistic and, in the end, which of the two will prevail.

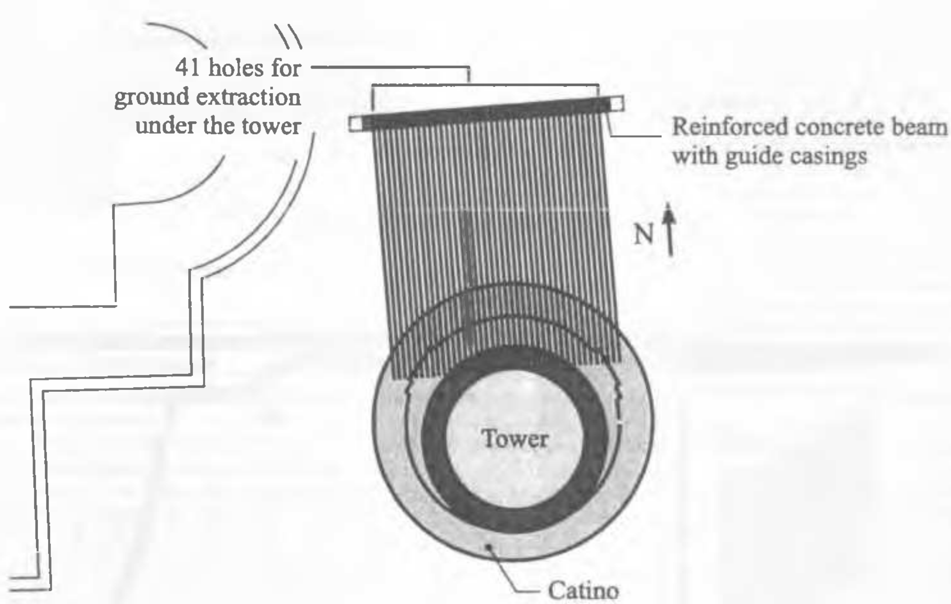


Fig. 34 - Final underexcavation scheme.

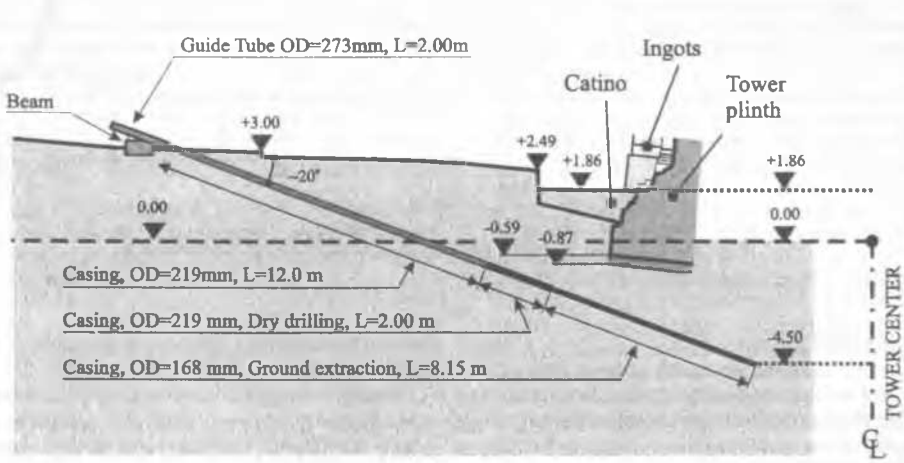


Fig. 35 - Hole for soil extraction - Full underexcavation.

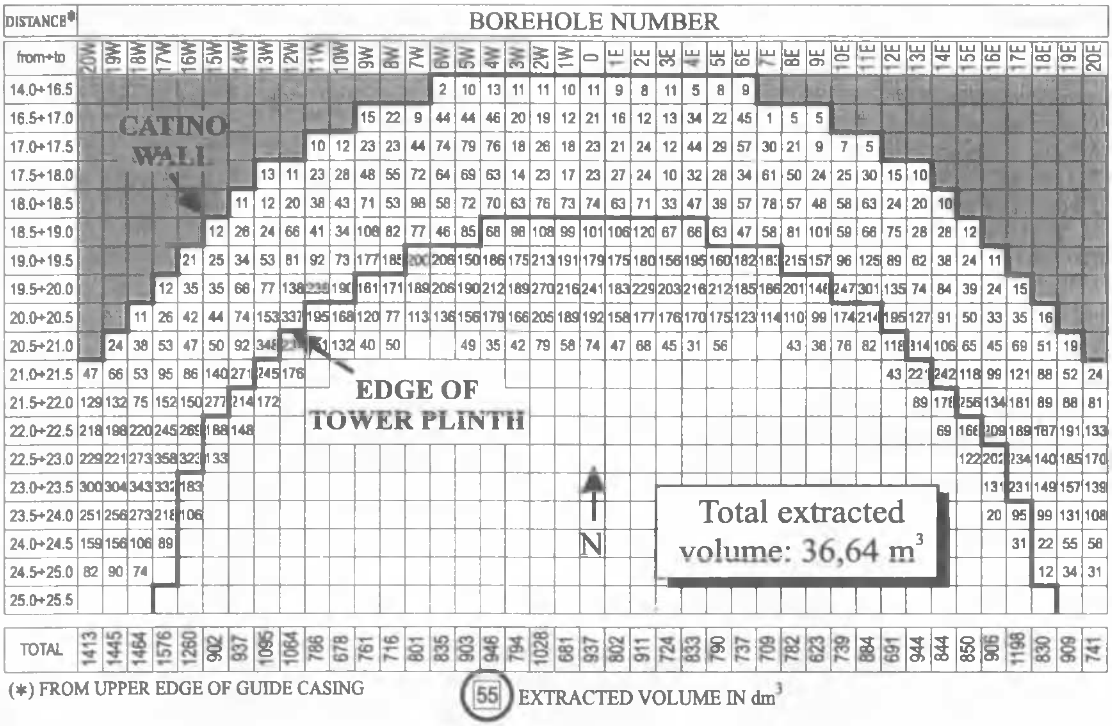


Fig. 36 - Plan of massive ground extraction.

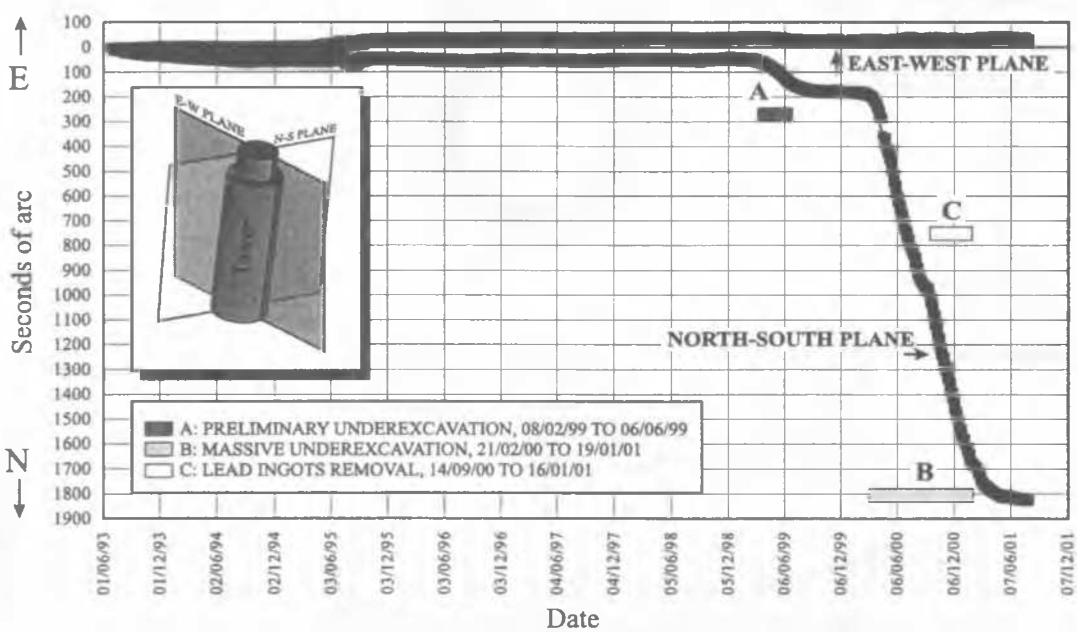


Fig. 37 - Rotation of Tower plinth during stabilization interventions.

10 ACKNOWLEDGEMENTS

I owe a special thank you and my appreciation to all the Committee's Colleagues, whose high scientific knowledge and expertise have made possible the achievement of our multidisciplinary tasks, in full respect of the artistic and historical value of this very special Monument.

A special acknowledgement and heartfelt thanks to the friends and Colleagues, Profs. John B. Burland and Carlo Viggiani. In their chore of scientific responsible they have presided over the underexcavation intervention setting a memorable example of observational method application.

Finally, I strongly wish to recall, with sincere emotion, a celebrated scientist and good friend, Prof. G.A. Leonards, passed away in 1997, whose contribution has been valuable to the studies and the definition of the Committee's strategy.

Fig. 38 - The Geotechnical Team.

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12 ADDENDUM : THE COMMITTEE

Sixteen government commissions have studied, measured and worried for years, over this Italian symbol. The present International Committee for the Safeguard and Architectural Restoration of the Leaning Tower of Pisa was appointed by the Italian Prime Minister on May 1990, based on a Law voted by the Parliament. The Committee was given the role of a special autonomous Authority for the Tower of Pisa with the task of studying, designing and implementing all the appropriate measures aimed at the geotechnical stabilisation, the structural strengthening and the architectural restoration of the Tower of Pisa. The multidisciplinary Committee is composed of the following thirteen Scientists:

J. Barthelemy	(Belgium)	Architect, Expert on Preservation and Restoration of Monuments
J.B. Burland	(UK)	Geotechnical Engineering
M. D'Elia	(Italy)	Expert in Preservation and Restoration of Monuments
R. Di Stefano	(Italy)	Expert in Preservation and Restoration of Monuments
R. Calzona	(Italy)	Structural Engineer
A.M. Mignosi	(Italy)	Expert in Preservation and Restoration of Monuments
G. Creazza	(Italy)	Structural Engineer
G. Croci	(Italy)	Structural Engineer
M. Jamiolkowski	(Italy)	Geotechnical Engineer (Chairman)
G. Macchi	(Italy)	Structural Engineer
L. Sanpaolesi	(Italy)	Structural Engineer
S. Settis	(Italy)	Expert in Medieval Art and Archaeology
F.Veniale	(Italy)	Mineralogist, Expert in Construction Stones
C.Viggiani	(Italy)	Geotechnical Engineer

Other distinguished Experts have served the Committee in the past:

M. Cordaro	(Italy)	Expert in Preservation and Restoration (passed away)
M. Desideri	(Italy)	Structural Engineer (until 1995)
F. Gurrieri	(Italy)	Architect (until 1992)
R. Lancellotta	(Italy)	Geotechnical Engineer (until 1996)
G.A. Leonards	(USA)	Geotechnical Engineer (passed away)
R. Lemaire	(Belgium)	Expert in Preservation and Restoration of Monuments (passed away)
F. Leonhardt	(Germany)	Structural Engineer (passed away)
A.M. Romanini	(Italy)	Expert of Medieval Art (until 1996)

Moreover, among the many the following eminent scientists and engineers have, over the years, contributed to the studies carried out by the Committee:

R. Bartelletti	(Italy)	Technical Advisor to the Site Engineer
G. Calabresi	(Italy)	Geotechnical Engineer
E. Faccioli	(Italy)	Earthquake Engineer
G. Grandori	(Italy)	Earthquake Engineer
J.K. Mitchell	(USA)	Geotechnical Engineer
D. Potts	(U.K.)	Geotechnical Engineer
G. Solari	(Italy)	Expert in Wind Engineering

Overall, the Committee has been meeting every six weeks to take decisions as far as the execution of studies, the approval of design documents and the implementation of works are concerned. Reunions of a limited number of experts are held at regular intervals aimed at developing and preparing the documents to be approved during the plenary meetings.

For each important activity one or two members are appointed as scientific responsible. Moreover, Prof. R. Di Stefano acts as Chief Site, responsible for contractual obligation with respect to contractors operating on site and the writer chairs the Committee.