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TREVI

TECHNICAL REFERENCE

The restoration of the leaning Tower of Pisa

Pisa, Italy

Under-excavation

Reinforcement

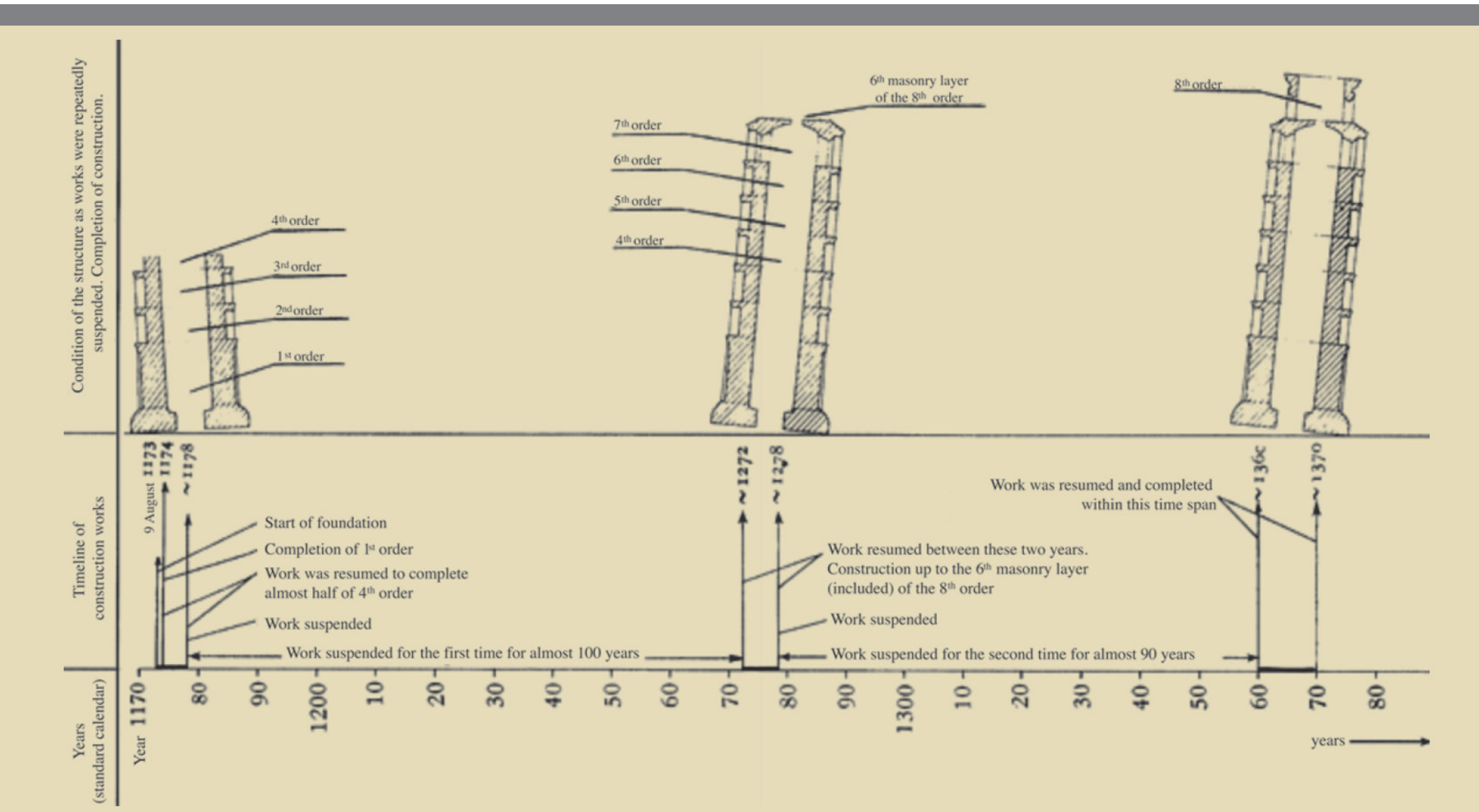
Owner:	OPERA PRIMAZIALE - PISA
Main Contractor:	**Consorzio Progetto Torre di Pisa**
Duration of works:	**1990 - 2001**

Introduction

The stabilisation of the Leaning Tower of Pisa was completed a long time ago. On June 16, 2001, the day of Saint Rainier (Pisa's Patron Saint), the citizens of Pisa were returned their monument. On December 31 of the same year the International Committee that had been established more than 10 years before with the task of studying and implementing measures to restore the tower to health, was disbanded.

The Committee studies, the gradual and painstaking research and understanding of the tower's problems, the devising and definition of temporary and permanent stabilisation works and lastly their implementation have repeatedly been mentioned and dealt with in several scientific articles published in specialised journals. The executive planning and actual implementation of the works devised and planned by the Committee, thoughless known, but equally rich and interesting was carried out with passion, commitment and great skill by the Consorzio Progetto Torre di Pisa *(Tower of Pisa Project Consortium)* composed of the companies Trevi, Rodio, Italsonda, Ismes and Bonifica.

This chapter wants to provide readers, mainly by the means of images, with an overview of the works carried out in the Campo dei Miracoli from 1990 to 2001.



The structure of the Tower

The building of the Tower by architect and sculptor Bonanno Pisano began in August 1173. When the building works were temporarily interrupted in 1178, about one quarter of the fourth order had been built; works were resumed in 1272 by Giovanni di Simone. In 1278 works were stopped again after the seventh and last order had been built.

Works were resumed only in 1360, when Tommaso di Andrea Pisano started to complete the bell chamber which was finished in 1370 when the bells were mounted.

The tower has a cylindrical body surrounded by open galleries with arches and columns. The tower's structure is divided in eight segments, called "orders". The monument is 58.4 m tall from the foundation level and 55 m tall from ground level. The main corpus of the building is a hollow cylinder with two walls, the inner and the outer wall.

The annular cavity between the walls is filled with the technique of rubble masonry: blocks of bricks and irregular shaped stones, held together with lime. The outer surface is faced with San Giuliano marble; the inner one is faced with the same marble up to the third level, and lighter limestone for the upper levels. The tower diameter is 15.54 metres. The annular foundation has an outer diameter of 19.6 metres and the central hole diameter is 4.5 metres. The overall weight of the monument is 142 MN *(14,500 tons).*

In 1993 the tower's inclination was 5.5°; the corresponding eccentricity on the foundation floor was 2.3 metres

Geology

The subsoil in Piazza dei Miracoli features a geologically young lagoon deposit. The soil's stratigraphy is as follows:

- **layer A**, about 10 m thick, is composed of alternating sands, clays and silts; an intermediate level of medium-fine sands, about 2 m thick, in contact with the clays of the level below;

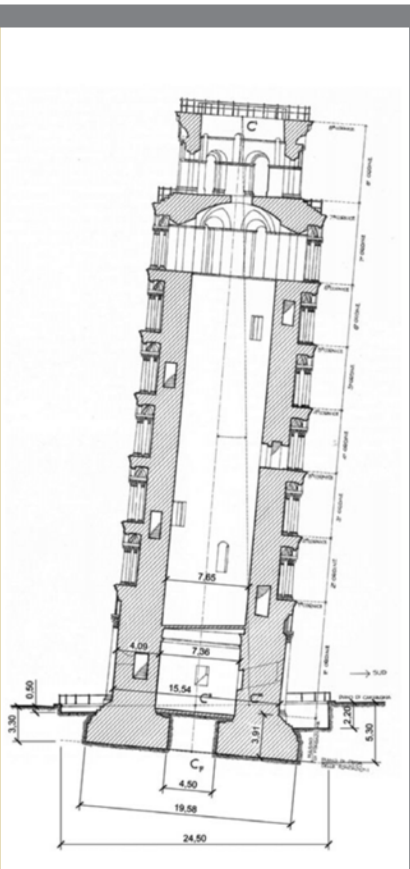
- **layer B** goes down as far as 40 metres from the surface and is called "Pancone", it consists of medium and soft clays (with various consolidation levels, from overconsolidated to normally consolidated), hard clays (intermediate clays) and lastly sands, hard clays (lower clays) normally consolidated;
- **layer C**, going down to at least 70 metres, consists of sands.

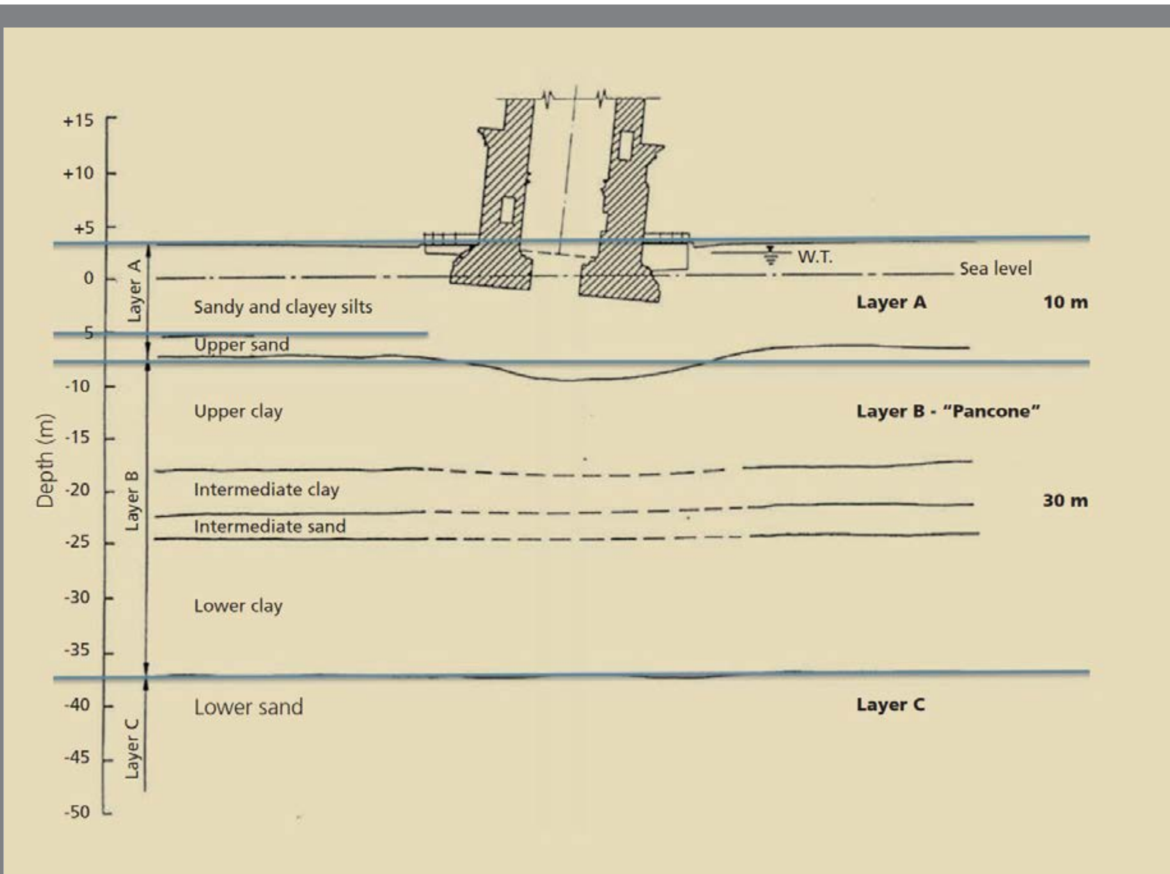
The surface separating the upper sands from the "Pancone" rests on a horizontal plane with a thickness difference of a few centimetres, except for the depression just below the Tower, which features a difference of about 2.2 metres. This deformation is caused by the weight of the Tower.

architects, Cressy and Taylor: at that time inclination had reached 5°. The post-1817 inclination increase was mainly due to the excavation of the Catino in 1838.

Beginning in 1911 the inclination of the tower was regularly monitored and recorded by means of topographic surveys, installing levelling points, a pendulum inclinometer and a spirit level. These measurements showed that the gradual increase of the inclination along the North-South axis was accompanied by a series of small, low width cyclical movements: daily deformations caused by changes of the solar irradiation of the building, seasonal cyclical variations caused by the changing of the height of the water table, etc.

From 1911 onwards inclination grew significantly and constantly with two abrupt major accelerations: in 1935,





Change of the Tower's inclination over time

The tower axis' bend on the plane of maximum inclination was fairly evident. This bend was created by the masons of the tower that introduced it by moving the centre of the upper ashlars towards the centre of the foundation during the tower's building.

At the beginning of its building the tower leaned towards North and reached a **maximum inclination of about 0.2° in 1272 when the building was resumed after the first long stop. In 1278, when the seventh cornice was built, inclination was about 0.6° South.**

During the ninety-year stop inclination increased and by the time the bell-chamber was built it had reached 1.6°.

The 1817 inclination was measured by two British

as a result of a campaign of injections into the foundation aimed at stopping water from infiltrating the Catino, and later on in the mid-60s, because of an intensification in the pumping of water from the lower underground sands because of particularly dry, low rain seasons.

Monitoring also highlighted the Tower's tendency to rotate, caused by the deformation of the masonry works due to the increase in eccentric vertical load resulting from the increase in inclination.

Studies and conclusions of the International Committee

The situation continued to deteriorate until, **in 1990, just after Piazza dei Miracoli had been inscribed on Unesco's World Heritage list**, the International Committee for the

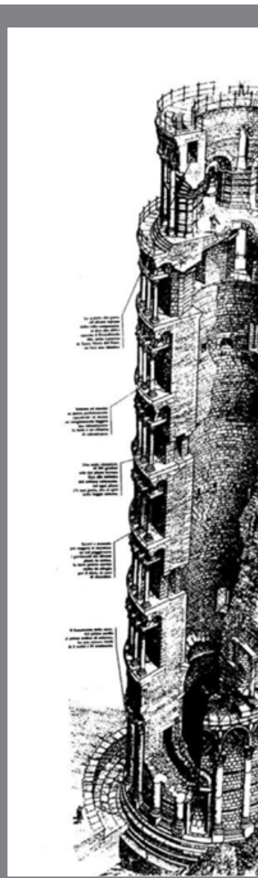
Safeguard of the Leaning Tower of Pisa, chaired by the geotechnical engineer Michele Jamiolkowski, professor at the Turin Politecnico university was established.

The Committee, composed of geotechnical and structural engineers, stone craft specialists, conservation specialists and historians, concluded that:

1) the physical and mechanical features of the Tower and its underground were known in detail;

2) analysis of the Tower movements, resulting from monitoring with instruments, carried out from the early 20th century onwards, resulted in an in-depth understanding of its behaviour;

3) the tower suffered from a problem of balance leaning instability, strictly connected with the insufficient stiffness *(and not to the insufficient resistance)* of the foundation soils; this conclusion was justified both by the interpretation of the movements of the Tower and from the results of theoretical and experimental analyses;



4) it was quite difficult to quantify the margin of safety for a collapse of the Tower in the early ‘90s, but all data from analyses pointed out that it was quite limited; in other words, the risk of overturning was very high;

5) the elevated structure was subject, in some points, to a high tensile stress; this entailed the risk of a localised brittle fracture - taking into account also the decay of the masonry works - that may have caused the Tower to collapse without any warning sign;

6) the time available for any works was quite limited; furthermore, the gradual worsening of the situation made taking any measure increasingly harder as time went by.

In other words the risk was basically two-fold. The first type of risk was caused by the tensile stress in some areas of the wall, which may have caused sudden breaking of the masonry works and subsequent collapse. The second type was caused by the risk of overturning of the whole monument due to the yielding of the ground under the foundation.

Action strategies

Because of this two-fold risk *(geotechnical risk of overturning and structural risk of failure due to brittle fracture)* and also because of the worsening situation, the Committee adopted a two-stage strategy: immediately carrying out temporary stabilisation works, making sure these works were reversible, so as to buy some time and then carefully study, experiment and implement the final stabilisation works.

As with regards to the structural risk, temporary works consisted of circling some parts of the Tower with slightly pre-tensioned strands. Final, permanent works consisted of inserting stainless steel bars to connect the inner and outer surfaces, performing injections in the masonry works and wrapping the top of the first order and the bottom of the second order with harmonic stainless steel wires; these works affected very small areas of the Tower.

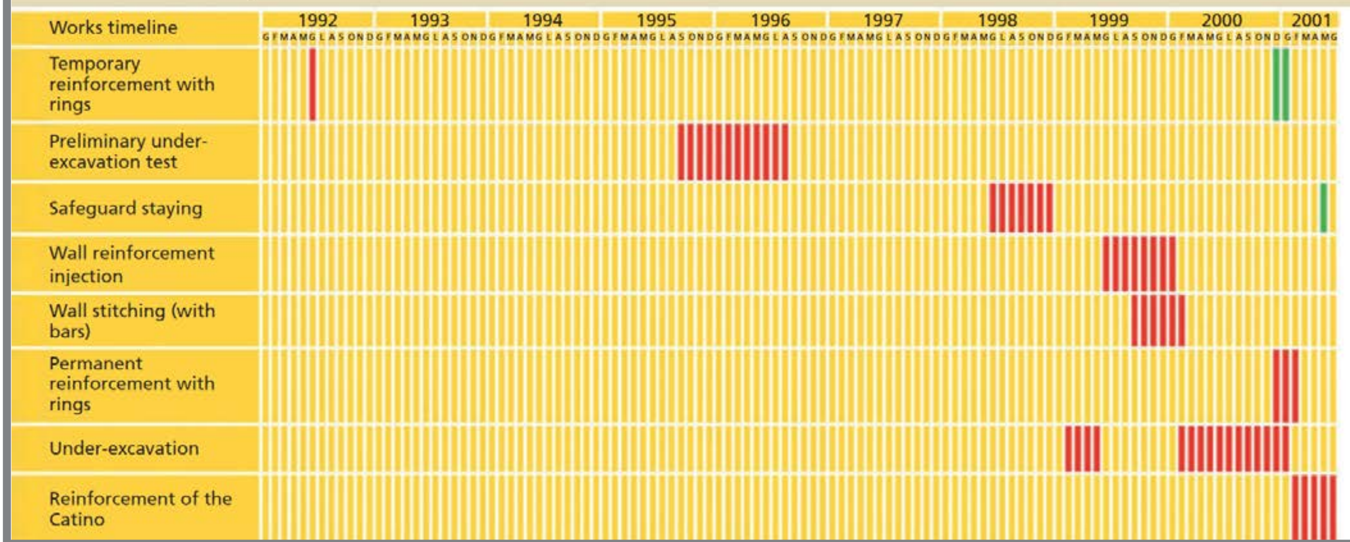
As with regards to the geotechnical risk, the temporary works consisted of applying a counterweight to the Tower, on the Northern side; the counterweight was made of a pile of lead ingots weighing about 1,000 tons.

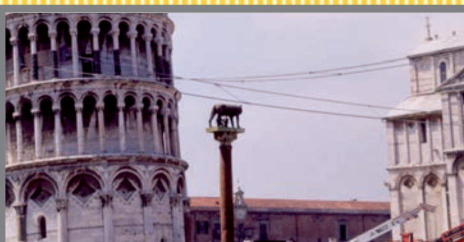
Devising and planning the final, permanent geotechnical stabilisation works required the Committee to carry out an in-depth analysis of the balance stability problem: considering the non-linear, inelastic nature of the restraint applied by the foundation soil, the researchers concluded that reducing the inclination by a smaller amount would have been enough to stop the inclination from increasing and substantially improve stability.

After a long and heartfelt debate the Committee decided to reduce the Tower inclination by about one half degree, that is about 10% of the current value, inducing controlled subsidence beneath the Northern edge of the foundation. In addition to substantially improve the stability conditions of the foundation, these works should also be able to reduce the tensile stress in the Tower, thus reducing the necessary structural reinforcement; moreover, this work would also fully respect not just the formal integrity of the monument but also its material and historical integrity.

Operations timeline

The works were completed in June 2001 with the reinforcement of the Catino





Possible solutions identified

The Committee reviewed several possible means to reach the desired result; examples included a reinforced concrete slab installed on the surface of the soil on the Northern side so as to apply a load on the soil by means of pre-tensioned steel wires anchored to the lower sand layers, or compressing the upper clay layers, *(North of the Tower)* by electro-osmosis or vacuum pumping.

These solutions were studied by employing various types of numerical analyses, with small- scale models in natural gravity conditions and in centrifuge and also by means of large-scale in-situ surveys.

Following this series of complex studies and research, the final decision was to carry out a small intervention that caused settlement of the Northern side of the Tower by means of the controlled extraction of small amounts of soil on the North side, below the foundation level *(so called under- excavation)*. Before working on the Tower it was decided to carry out an in-situ large-scale test.

Although the results of all analyses carried out had been, so far, positive, the Committee could not be certain that these results were actually representative of the behaviour of a tower which was at the verge of instability. For this reason it was decided to start working on the Tower with a limited preliminary under-excavation stage to be started only after having installed a safeguard structure that could effectively cope with unforeseen events.

The safeguard structure consisted of two quasi-horizontal stays connected to the Tower *(at the height of the 3rd order)* and in turn fastened to two anchoring structures located North to the Tower, on the rear of the Opera Primaziale building.

After that the actual Tower under-excavation works started, in turn divided in a preliminary stage and a final stage. Once all the temporary structures were removed, the Catino had to be restored and reinforced, a series of works with a highly structural nature. These works, amongst other things, also had the side effect of increasing the geotechnical safety level as an effective and valid connection was made between the Catino and the Tower foundations.

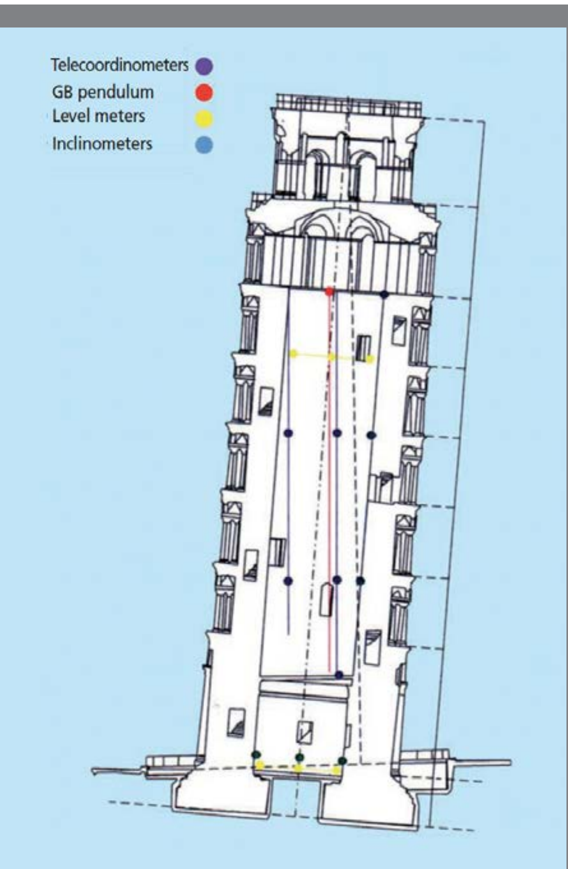
The monitoring system

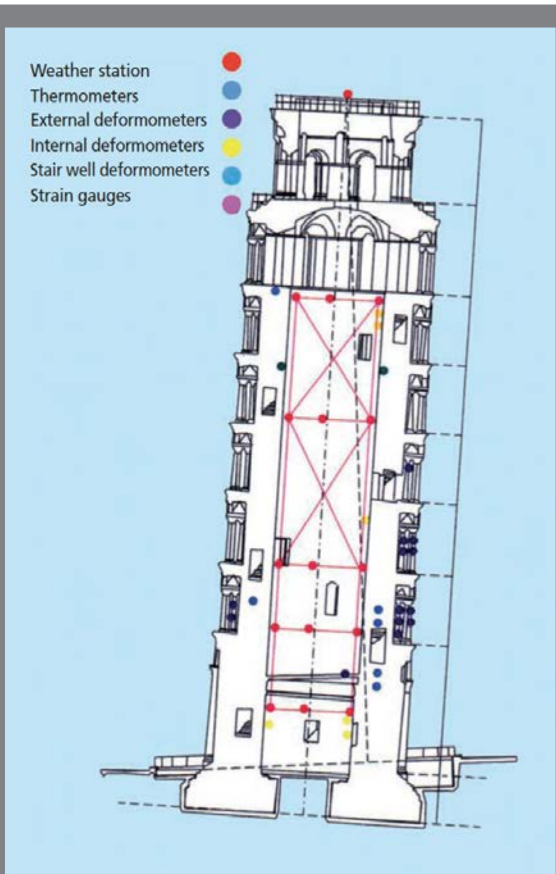
During the works a complex monitoring system had been installed to continuously monitor several parameters, relevant to Monument control. After the works had been completed, the monitoring system was modified as needed, indeed it was also simplified, to adapt it to the different needs of control of the Tower's behaviour over time.

The most important geometrical parameter measured was, of course, inclination which was continuously monitored by three pendulums, one of which was an inverted pendulum, i.e. the pendulum's wire was locked to the tower's base and the ball was connected to a float. Unlike traditional pendulums, which are basically plumb wires, the inverted pendulum does not suffer from the deformations of the elevated structure and it is therefore the most suitable tool to measure the foundation movements. The pendulum swings were detected by laser telecoordinometers that conveyed the movement data, via the pipes that ran through the Tower wall on the North side, under the Catino and then underground until they reached the data retrieval room in the Opera Primaziale building.

As works progressed, the foundation movements were also controlled via a levelling system consisting of a hydraulic circuit covering the area of the Tower's ground floor.

There were also some deformometers that monitored the changes in width of all damages and cracks being monitored; wire strain gauges to measure changes in the Tower's dimensions; accelerometers to monitor all dynamic events *(i.e. movements, in particular seismic phenomena, that may involve the monument)*.





In many cases installation of instruments on the Tower walls, inside the cavity that is the Tower's body required the help of rock climbers specialised in working at height.

Temporary works with lead counterweights

The main problem was applying on the Northern side of the Tower a vertical strength of some hundreds of tons, and this problem was solved by building around the base of the monument an annular beam of prestressed reinforced concrete on which lead ingots were to be loaded; the beam in turn would transfer the weight to the Tower itself.

The annular lead-bearing beam was built from May to June 1993.

The beam was made of blocks separated by couplings, so that it could be dismantled easily.

The placing of the lead ingots began in July 1993 and continued, gradually, until January 1994 for a total weight of about 700 tons, including the beam weight.
This additional load caused the Tower's inclination to decrease by about 50 arc seconds, corresponding to an overhang decrease of about 12 mm.

More important than that the application of the counterweight caused the Tower to gradually move southwards, with a movement speed that previously was about 1 mm per year.

Later on, the counterweight of lead ingots was increased up to 1,000 tons.

Structural reinforcement works

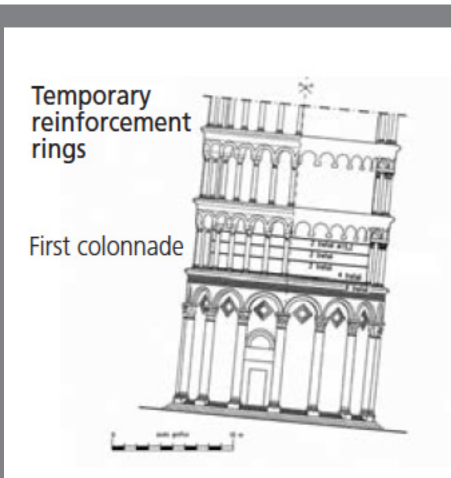
Ever since the early stages of the Committee works it had been fairly evident that some areas of the tower's aboveground structure were subject to very intense stress and there was the risk of the stones breaking.

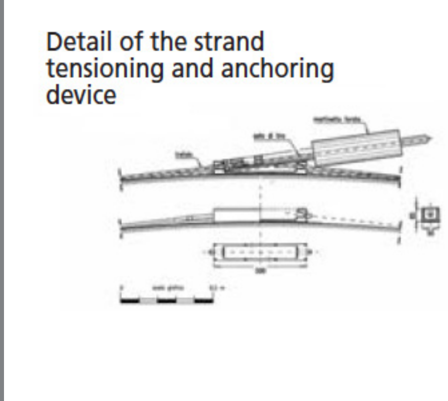
This risk was particularly serious in the second order area, SW side; in this area there was, in fact, a sharp narrowing of the wall section compared to the first order, and in addition to that the structure had been weakened by the openings of the spiral staircase and of the door that leads to the loggia out of the first cornice.

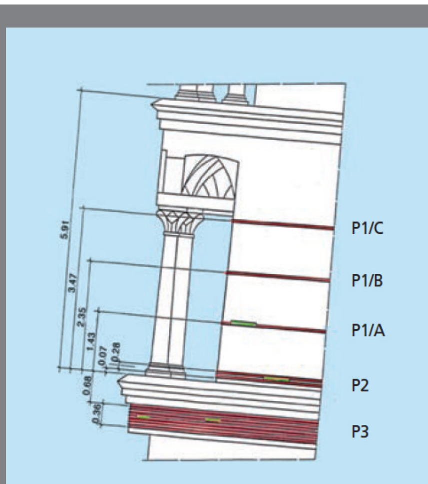
The danger of a breakage of the masonry lays in the fact that it can occur suddenly, without any warning sign.

At the same time the preservation status of the masonry structure was thoroughly researched by means of drilling, tests on samples, down-hole video inspections, various types of endoscopies and tomographies. By overlapping the stress status map to the map of the tower masonry decay it was understood that only a limited area of the Tower was under an actual state of danger.

Therefore, the permanent reinforcement was applied only in this part, trying to achieve the best compromise between safety requirements and preservation of the monument's integrity. The operation consisted of injecting cement mortar, inserting bars that radially connected the internal and external walls of the Tower and applying a ring reinforcement to the first cornice and to the foot of the second order.







Temporary reinforcement rings

Because of these risks it was necessary to carry out temporary reinforcement works that consisted in circling the most critical spots with slightly pre-tensioned steel strands coated with a Teflon sheath. These works were carried out in June 1992. The reinforcements were designed to be fully reversible, and therefore all of them were removed from November 2000 to January 2001, shortly before installing the final reinforcement rings.

Reinforcing the masonry structure

Meanwhile, the masonry structure's tensile stress status had been comprehensively studied by means of an extremely detailed finite elements model. Seismic actions and the effects of winds were taken into account, and in-depth research was made on both these phenomena.

The injections were carried out in the time ranging from June 1999 to January 2000.

The mortar, which was especially designed for this work, had the following composition:

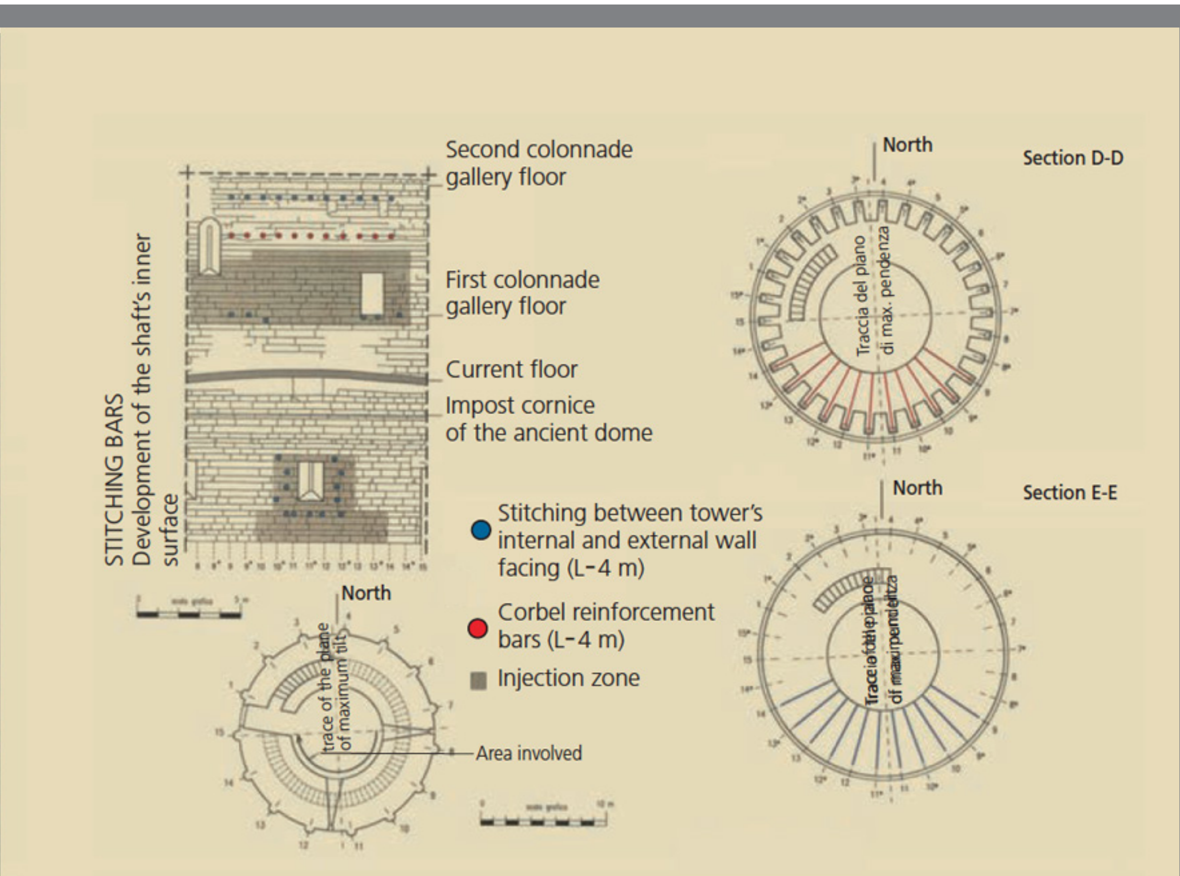
- 75 kg of Microlite FSTP *(ultra-fine iron cement with silica fume)*
- 75 litres water;
- 2.25 litres of Rheobuild additive;
- weight per volume of the mixture 1.6 t/m^3;
- maximum injection pressure 0.4 atm.

The areas involved in the treatment were the Southern area of the 1st order masonry works over the plane of maximum inclination and the masonry works of the 2nd order in the area weakened by the stair opening and by the door that accesses the opening of the 1st loggia.

The pictures provided contain all the positions of the primary and secondary holes required by the project; during works execution stage new holes were added to improve absorption of the masonry.

The total amount of injected mixture was about 18 m^3. The bars radially connecting inner and outer were in AISI 410 stainless steel and threaded. These bars were installed by drilling the wall from the inside and then anchored, after tensioning, to a specific niche on the inner wall using a nut and washer. All the bars stopped at a distance of 10 to 20 cm from the external Tower wall.

The internal anchoring was made either with cement injection or vials of resin depending on a case by case basis.
All the aforesaid operations were carried out from September 1999 to January 2000.



New reinforcement rings

In order to integrate the containment effect provided by the radial stitching of the masonry in the most critical area *(which corresponded to the areas of abrupt narrowing of the walls in the point of transition between the first and the second order)* the Committee decided that after removing the temporary rings these rings should be at least partly replaced by other rings with aesthetic and functional features that made them suitable for permanent use.

The new reinforcement rings replaced the temporary ones *(8-strand for those below the 1st order cornice and 4-strand for those at the base of the 1st loggia; while no reinforcement ring was required to replace the 6 upper strands).*

The final and permanent rings were made with 4mm diameter stainless cold-drawn steel wire; cold-drawn wire was chosen as it further increased the wire's mechanical features bringing them to values closer, yet a little lower, than those of harmonic steel. The features of the rings were also chosen with the aim of significantly reducing their encumbrance.
A special device, similar to the one used to prestress cylindrical concrete silos was used to install and tension these reinforcement rings.

The ring under the 1^{st} order cornice consisted of 116 coils on 4 layers (35+31+27+23); every layer contained only one wire, anchored with clamps at its ends.
The overall tensile stress on the wires was about 9 tons. Installation of this reinforcement ring started in December 2000 and finished in January 2001.

The ring under the 1^{st} loggia cornice consisted of 60 coils on 3 layers (24+20+16); the overall tensile stress on the wires was about 4.6 tons. Installation was carried out in January and February of 2001.

Under-excavation works experimental model

Today, after the under-excavation has been successfully completed, this work may seem even trivial, but the truth is that choosing it was, at that time, a troublesome choice. After an extended calculation and small-scale testing stage it was decided to try a large-scale test in Piazza dei Miracoli in order to demonstrate the efficiency of the method and fine-tune the technological details.

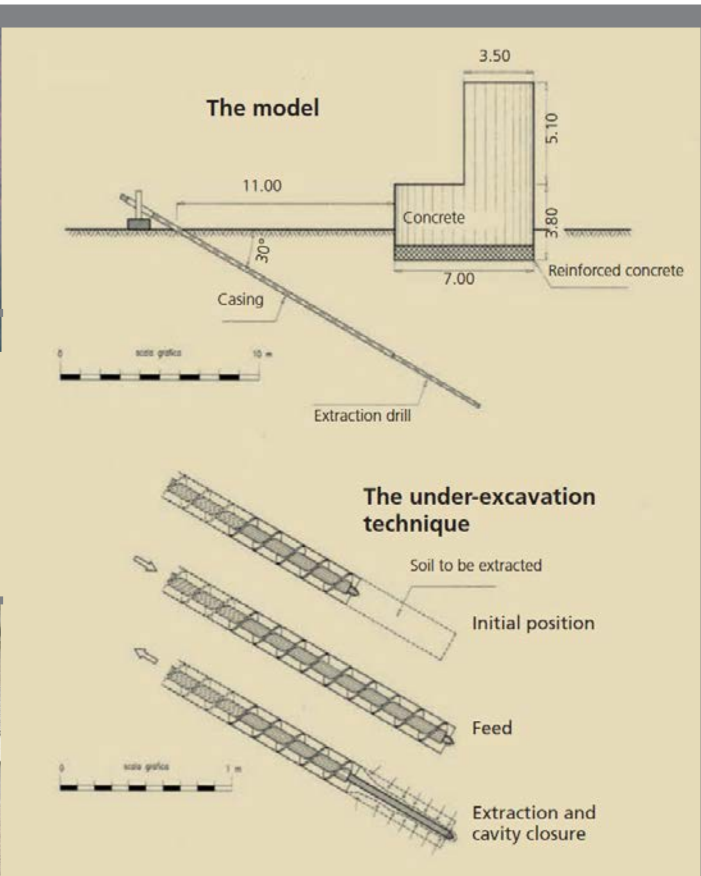
A circular reinforced concrete slab, 7 m diameter, was built in the Piazza dei Miracoli corner between Porta del Leone and the Camposanto *(cemetery)*, after fitting the contact surface between the ground and the slab, as well as the underground, with all the relevant instruments.

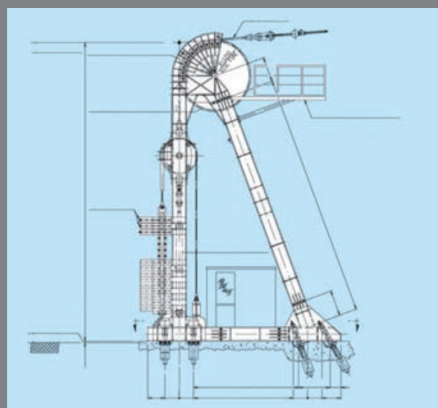
The slab was then loaded with a concrete weight, thus applying an eccentric load on the slab and causing a rotation movement towards South. This rotation was then partially corrected experimenting the under-excavation technique. The large-scale under-excavation test, that took place from September 1995 to August 1996, was successful and was the final step needed to convince the sceptics about using this technique on the Tower.

was then checked with load tests.

The metal frame of the elevated structure was directly bound to the piles, which were connected together by a reinforced concrete platform.

Please note that staying was not designed as a means to restrain the Tower but rather to apply a stabilising force to it if needed; therefore each stay, in addition to the pulley that returned it to the vertical position, was fastened and controlled by a mechanism that tensioned the stay both with leadweights and with jacks controlled by a hydraulic control unit. Each of the two pulling and tensioning systems was able to apply to each stay a maximum load of 150 tons; it bears mentioning that even if both weights and hydraulic jacks were used, the overall load could not exceed 200 t per cable stay.





Protective staying of the Tower

When the actual works on the Tower started, it was considered necessary to employ a safeguard structure to be used should any unforeseen circumstance arise and threaten the monument's integrity.

The safeguard structure chosen consisted of a series of quasi- horizontal steel cable stays made of two 50 mm diameter steel ropes, circling the Tower at the height of the 3rd order and fastened to two metal stands anchored to the ground and located to the back of the Opera Primaziale building bordering Piazza dei Miracoli on the North side.

The two anchoring stands conveyed to their foundation all stresses, including tensile and shear stresses, and it was therefore necessary to equip them with a foundation of small diameter bored piles, about 33 m long. The piles' load capacity

The stabilisation works on the Tower by means of under-excavation were completed without any further unforeseen ccident and therefore the safeguard structure was never actually used, except for the application of the minimum load (about 12 t for the Western stay and 7 t for the Eastern stay) needed to set up the stays in the desired geometric configuration.

The works needed to set up the protective staying started in June 1998 with the drilling of the foundation piles and ended in December 1998 when the stays were tensioned.

Tower stabilisation by means of under-excavation

The under-excavation as a means of permanent stabilisation of the Tower has several positive features, including total

respect for the formal, historical and material integrity of the Monument.
Another major advantage of this technique is that it does not require any major structure or engineering work; because of the "discreet" nature of this work there is no spectacular feature of it that can be portrayed in pictures.

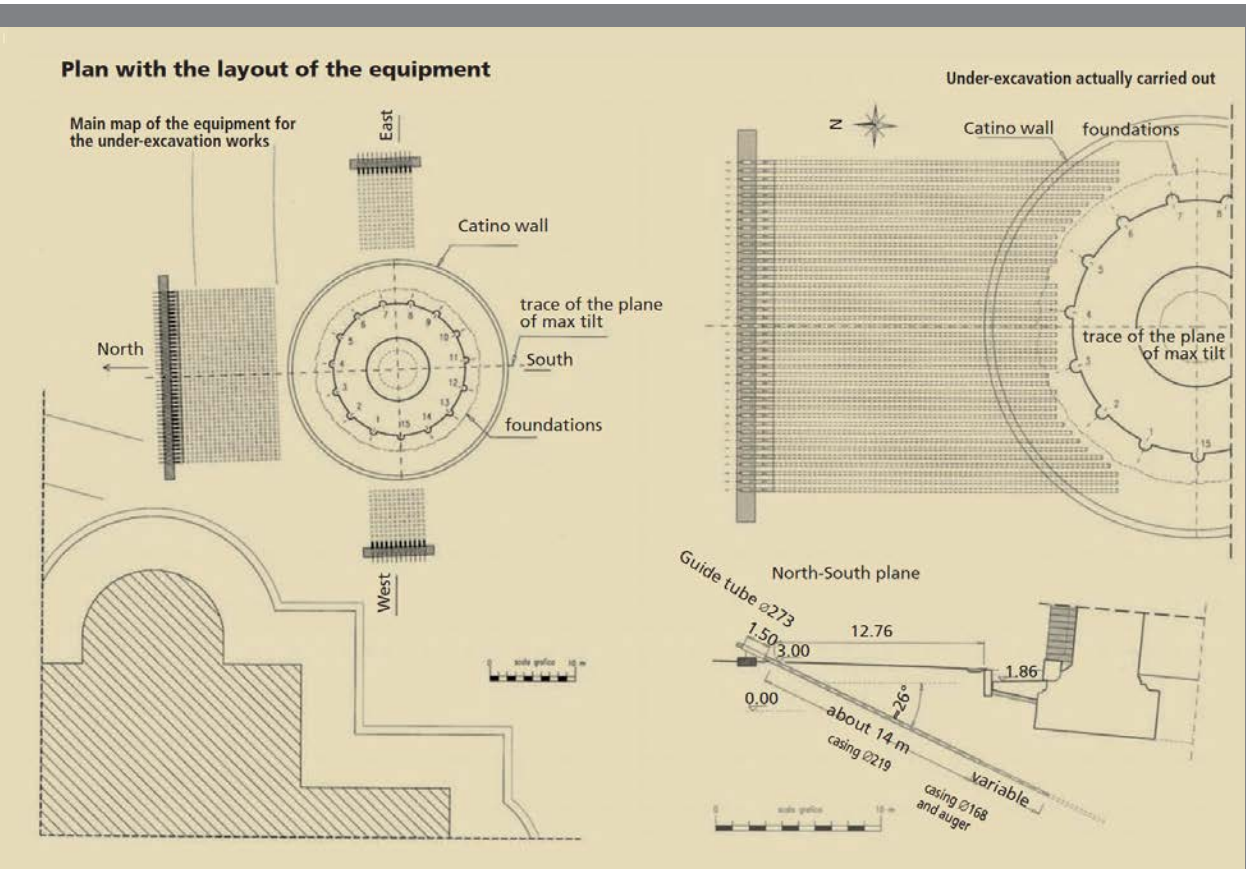
In the diagram for the preparation of the equipment required for the works it is possible to see, on the North, the main rig to be used for tower under-excavation and on the West and East the two secondary rigs on the East and West to be used for the removal of the earth from under the Catino so as to facilitate *(if need be)* the Catino's movement which is integral with the Tower.
However, since the Catino, with the proper reinforcements,

Operating procedure

A machine was especially designed to be able to rotate, counter-rotate, drive and withdraw the casing and the auger at the same time, as well as to run an instrument-fitted drill bit coaxially with the auger.

Under-excavation was carried out by having the casing, the auger and the bit advance simultaneously; in a subsequent stage the casing and auger were retracted simultaneously while pulling out the drill bit so that it basically remained in the cylinder-shaped cavity created in the soil by the auger and casing withdrawal.

The drill bit, thanks to its sensors, was then able to signal the partial or total filling of the borehole.



did not show any peculiar problem during under-excavation, the secondary rigs were not used. The plan details, for each of the 41 pipes used for drilling and soil extraction, the maximum length the casings reached, and it may be useful and interesting to relate this data with the foundation's borders *(represented as a dotted line)*; the cross- section shows the side elevation view of the casings, which features the following elements:

- guide pipes positioned on the reinforced concrete beam;

- outer casing pipes, which were inserted in the guide pipes and pushed down to the foundation distance (about 2.6 m) which is the distance at which soil removal was required to have its effect;

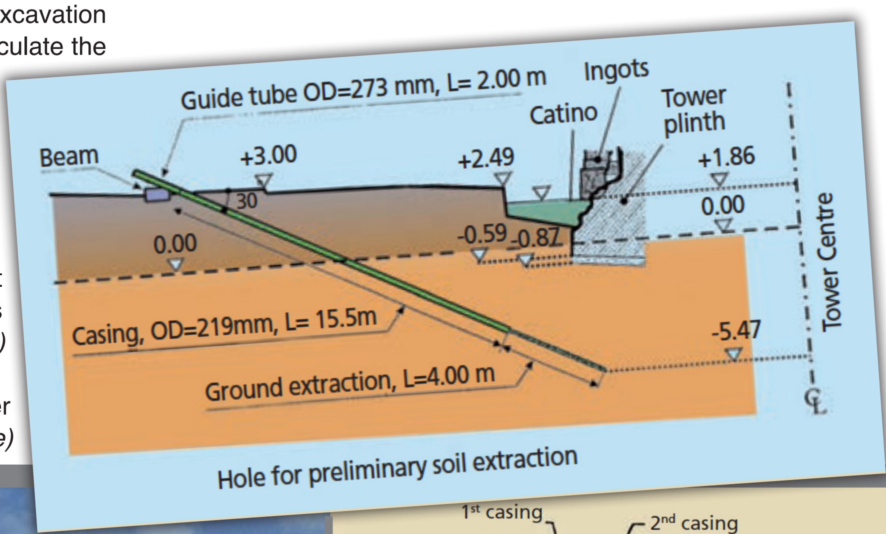
- inner casing pipes, inside the abovementioned ones which rotated and moved forward and had an auger inside that rotated in the opposite direction.

Extraction was made in 50 cm steps; the maximum volume that could be extracted during the first operation was about 17 litres.

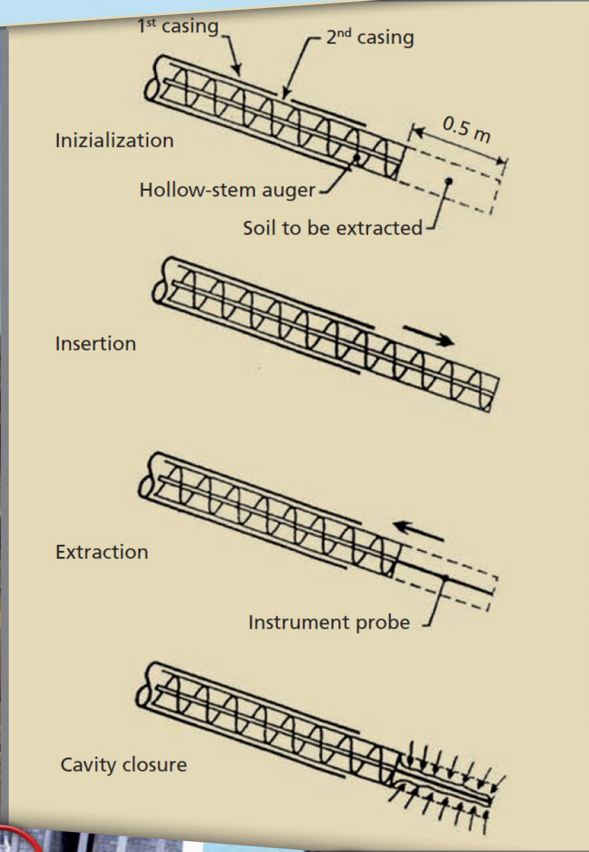
When the casing and the auger inside where etracted the hole closed almost completely; the amount of filling of the hole could be detected with the bit but also by monitoring the amount of soil removed in any subsequent operation, a fact that was easily measurable considering the equivalent water volume that flew out of the casing surface. Repeating the same operation in later moments on the same site made it possible to remove the desired amount of soil from each spot. When the casing was completely filled with soil, the auger was extracted and cleaned. **The overall volume of extracted soil was about 38 cubic metres.**

The extraction map, complete with a colour scale and drawn basing on daily operation reports made it possible to evaluate the distribution of the intensity of the under-excavation operations in the various spots on the map and calculate the extracted volume in litres per square metres.

From the map it is easy to understand how soil extraction took place mostly outside the Tower foundation, penetrating no more than 2 m under the foundations, with a slight asymmetry compared to the plane of maximum inclination. Basically, under-excavation was a bit more marked on the West side for the purpose of compensating the Tower's tendency to rotate also *(albeit significantly less)* towards the East.
At the end of the under-excavation works the tower had rotated about 1,800 arc seconds *(half a degree)*

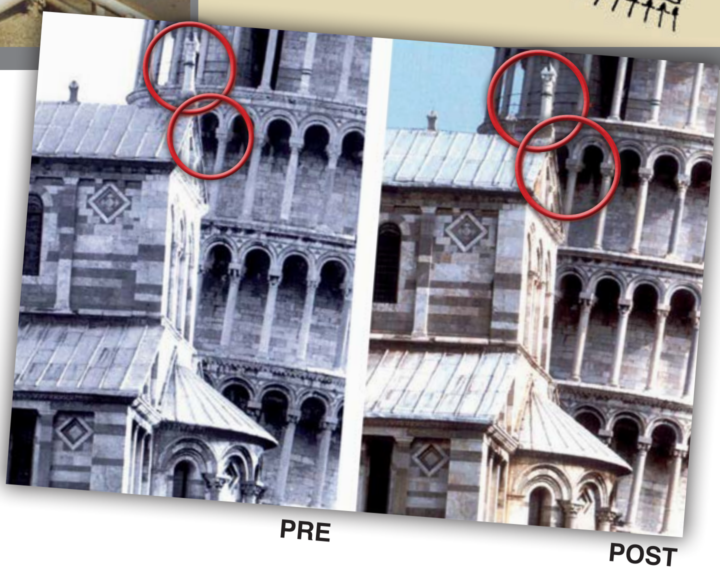


Hole for preliminary soil extraction



towards North, and because of this the 7th cornice moved towards North by about 43 cm and **the Northernmost point of the Catino was lowered by about 17 cm.**
The "straightening" works, in addition to returning the Tower to the inclination it had about 200 years ago, reduced the pressure on the soil to the South to such an extent that itincreased significantly the safety level of the Monument which, as far as instability is concerned, had almost reached the critical limit before works began.

After a smaller scale preliminary under-excavation carried out in February-May 1999 the actual under-excavation works began in 2000 and were basically completed in January 2001, though other, smaller works were made up to June 6, 2001, when the rigs were completely removed.



After 11 years of research, experiments, projects and works, on ***June 16, 2001****, what was considered an impossible miracle for centuries finally takes place; the Tower of Pisa straightened by 44 centimeters and with a* ***guarantee of safety for at least 300 years*** *was returned to its citizens and the whole world*

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