Lessons learned from the stabilization of the Leaning Tower of Pisa

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Pisa,
Piazza dei Miracoli
Leaning Tower, Cathedral, Baptistry, Cemetery built in the Middle Ages period of maximum splendor and power of the Republic of Pisa.

Piazza dei Miracoli: stupendous manifestation of the ideal unity at the time among religious, spiritual, and political powers.

From the very beginning history of art and civil history intertwine, giving those monuments an outstanding character of sign and symbol of the city.
Challenge for modern engineering

Stabilize the Tower respecting its integrity
The Tower by night
Height ($C_F - C'$) = 58.4 m
Weight = 142 MN (~14,500 t)
Diameter of the foundation = 19.6 m
Height of the centre of gravity = 22.6 m
Average foundation pressure = 497 kPa (~50 t/m$^2$)

Cross section in the plane of maximum inclination
The “banana shape” of the Tower
Subsoil investigations in the plane of maximum tilt
The subsoil of the Tower
Ground water regime in the subsoil of the Tower
Is the inclination of the Tower intentional?

In the XIX Century, heated debate in Pisa and elsewhere. The majority of people inclined to believe in a virtuosity of the unknown ancient architect.

Another school of thought: a foundation accident.

The answer to the ancient question is written in the Tower itself. To discover it, let’s follow the history of the monument.
• Frederic II vs. Pope
• War against Genua, Lucca and Florence
• Construction of the Hospital (1257) and Camposanto (1265/78)

Bonanno Pisano

Giovanni di Simone

7th storey
6th storey
5th storey
4th storey

Inspection (1298)

construction starts
construction up to the 4th storey

construction of the bell chamber
construction up to the 7th storey

1st interruption ≈ 100 years
2nd interruption ≈ 90 years

bell chamber
On Wednesday March 15 the wise men Master John, son of Nicholas, Mason, Master Guy, son of John, Mason and Master Ursellus, Woodworker, together plumbing by common consent the bell tower of the pisan cathedral by means of a plumb line, from the top to the bottom, agreed in the presence of me notary that plumb, hanging from the wire, touched the ground in a place that they marked unanimously......

Recorded in Pisa in that place, in the presence of sir Guelfo, canon of Pisa, of Nerio cleric son of Guy, and Ceccho clergyman of Pisan chapter and many other witnesses .....
- Frederic II vs. Pope
- War against Genua, Lucca and Florence
- Montaperti (1260)
- Construction of the Hospital (1257) and Camposanto (1265/78)

Giovanni di Simone

Bonanno Pisano

Meloria sea fight (1292)

Inspection (1298)
• Frederic II vs. Pope
• War against Genua, Lucca and Florence
• Montaperti (1260)
• Construction of the Hospital (1257) and Camposanto (1265/78)

- Construction starts
- Construction up to the 4th storey
- First interruption ≈ 100 years

- Construction up to the 7th storey
- Second interruption ≈ 90 years

- Construction of the bell chamber
- Meloria sea fight (1292)
- Inspection (1298)
4 steps north, 6 steps south
Shape of the axis of the Tower

Question mark shape?

$C_i = \text{centre of the } i^{th} \text{ floor}$
Masonry layers with variable thickness

Plumb line

Masonry layers with variable thickness

Interpretation of the corrections by the ancient masons
Inclination (degrees)

Weight of the Tower ($10^3$ t)

1173-1178
First stage

1272-1276
Second stage

1360
Bell chamber

1173-1178
First stage

1272-1276
Second stage

1360
Bell chamber

By the middle of the fourth order

End of construction

By the middle of the fourth order
Antonio Veneziano
(~ 1385)

The body of St. Ranieri brought back in Pisa
(particular)
Fresco in the Camposanto
Questo Guglielmo secondo che si dice,
l’anno 1174 insieme con Bonanno
scultore fondò in Pisa il Campanile del
Duomo.... Ma non avendo questi due
architetti molta pratica di fondare
in Pisa, e perciò non palificando la
platea come dovevano, prima che
fossero al mezzo di quella fabbrica
essa inclinò da un lato et piegò in sul
più debole di maniera che il detto
campanile pende sei braccia e mezzo
fuor dal dritto suo secondo che da
quella banda calò il fondamento.
Et se bene ciò nel disotto è poco,
all’altezza si dimostra assai con fare
stare altrui meravigliato come possa
essere come non sia rovinato o non
abbia gettato peli..

They say that this Wilhelm, together
with Bonanno sculptor, in the year 1174
founded in Pisa the bell tower of the
Cathedral... But since those two
architects were not used to the practice
of founding in Pisa, and therefore they
did not use piles as they should, before
reaching half the height of the tower
it inclined toward the weaker side thus
it leans six and half braccia out of the
vertical, on the side where the
foundation settled.
At the base it does not appear too much,
but at the top it is so much that no one
can believe it is still standing without
collapsing or fissuring.

1566
Life of the illustrious men, 1, 274
The survey by Cresy & Taylor (1817)
The survey by Rohault de Fleury (1859)
Modern measurements of the tilt
July 14, 1902
Collapse of the
S. Marco bell
Tower in Venice
Between 1908 and 1935 a number of Commissions follow one another.

A Commission designated by the Ministry want to fill the catino with concrete.

This solution is rejected in Pisa. A Pisan Countercommission is formed by the Major and the Bishop.

In 1927 things are smoothed out and a new Commission is set by the Ministry, including Pisan members.

The new Commission postpones any stabilising action after watertightening the foundation of the Tower and the soil surrounding the catino.
Holes for cement grouting in 1936
World War 2 stops all activities

But it does not stop the movement of the Tower

After the war, it is evident that the injections of 1936 have actually stopped the inflow of water into the catino but they have not stabilised the Tower
Tilt of the Tower (arcsec)

- Livella G.C.
- Pendolo G.B.
- Livellazione di precisione
- Pizzetti
- I.G.M.
- Università di Pisa

Heavy pumping from horizon C

World War II

1936 grouting
Long term trend subtracting the perturbations

Tilt of the Tower (arcsec)

Precision levelling

bubble level

01.01.1938

3° p.a.
Italian Government appoints a Commission (the Polvani Commission) with the task of preparing an international tender for designing and implementing the necessary stabilization works.
Exhaustive investigations on the Tower and the subsoil.
27 groups of contractors, consultants and designers participate to the competition.

11 are admitted.

5 projects are pointed out as worthy of consideration.

But eventually the contract is **not** awarded.
The civic tower of Pavia, 1988
The collapse of the civic tower of Pavia, 1989
For safety, the Tower is closed to visitors in December, 1989.

Risk of sudden brittle failure

Stress concentration in the masonry
International Committee for the Safeguard and Restoration of the Leaning Tower of Pisa

• Appointed by the Italian prime Minister in May, 1990, with the task of conceiving, designing and implementing the necessary stabilisation works
• a 15 members multidisciplinary body, including experts of:
  • Restoration
  • History of Art
  • Archaeology
  • Petrography and construction stones
  • Structural Engineering
  • Geotechnical Engineering
The International Committee, 2001

The old boys!
A number of solutions to stabilize the Tower had been proposed in 20° Century

They have to be considered among the most serious risks threatening the monument
Some of the solutions proposed for the stabilisation of the Leaning Tower of Pisa.
The challenge of the International Committee established in 1990: a completely different kind of solution.

Respectful of the iconic, historical and material integrity.

There were some examples.
The solution of the students of the University of Pisa
René Magritte
Le domaine enchanté
Geotechnical modelling and analysis of the behaviour of the Tower
Instability of the equilibrium!

Foundation inclination (degrees)

Weight of the Tower (tx10^9)

Inclination of the Tower (degrees)

1173 – 1178 First stage
1272 – 1278 Second stage
1360 – 1370 Bell chamber
1385 Fresco by A. Veneziano
1540 Amalfo’s life (G. Vasari)
1838 Digging the cellaro
1899 Roncalli Measurments
1911 Just before underexavation
1817 (Cresy e Taylor)

Weight of the Tower (thousands of tons)

End of construction

Seventh floor

By the middle of the fourth storey

1800

1400

1600

2000
Initial tilt of tower = 0.5°

Undrained clay (Elasto-plastic)
Tresca model - $S_u = 80$ kPa
The factor of safety depends on the stiffness, and not on the strength!

The inverted pendulum: a simple model of leaning instability
Generalised stress variables: $N, M = Ne$

Generalised displacement variables: $\rho, \alpha$
**Linearly elastic model**

\[
\begin{bmatrix}
\rho \\
\alpha
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{k_{\rho}} & 0 \\
0 & \frac{1}{k_{\alpha}}
\end{bmatrix}
\begin{bmatrix}
N \\
M
\end{bmatrix}
\]

\(k_{\rho}, k_{\alpha} = \text{constant for a given foundation - subsoil system}\)

Settlement and rotation \textit{uncoupled}
Winkler’s independent springs, coefficient of subgrade reaction $k$

$$k_\rho = k \frac{\pi D^2}{4} \quad k_\alpha = k \frac{\pi D^4}{64}$$

Elastic half space, Young modulus $E$, Poisson ratio $\nu$

$$k_\rho = \frac{ED}{1-\nu^2} \quad k_\alpha = \frac{ED^3}{6(1-\nu^2)}$$

$k_\rho$, $k_\alpha$ = constant for a given foundation - subsoil system, depending on the soil properties ($k$, or $E$, $\nu$) and on foundation characteristics ($D$).
In a linearly elastic model, the tower is very nearly in neutral equilibrium.

In the case of the Tower:

$$k_\rho = \frac{N}{\rho} = \frac{14.500}{3} = 4.850 \text{ t/m}$$

$$k_\alpha = \frac{D^2}{6} k_\rho = \frac{19,5^2}{6} = 4.850 = 307.400 \text{ tm}$$

$$FS = \frac{k_\alpha}{Wh_G} = \frac{307.400}{14.500 \times 22.6} = 0.95 \approx 1$$
Centrifugae model tests

Elasto-plastic strain hardening

Cheney et al. (1991)
Elasto-plastic strain hardening model

\[
\begin{bmatrix}
\frac{\partial \rho}{\partial \alpha} \\
\frac{\partial N}{\partial M}
\end{bmatrix} =
\begin{vmatrix}
1 & 1 \\
\frac{1}{k_{\rho \rho}} & \frac{1}{k_{\rho \alpha}} \\
\frac{1}{k_{\alpha \rho}} & \frac{1}{k_{\alpha \alpha}}
\end{vmatrix}
\begin{bmatrix}
\frac{\partial \rho}{\partial \alpha} \\
\frac{\partial \alpha}{\partial \alpha}
\end{bmatrix}
\]

- non linearity \( \Rightarrow \) relations in incremental form
- coupling between settlement and rotation
- \( k_{ij} \) depending on current stress state and on stress history

\[
\text{hence}
\]

- safety factor depending on current stress state and on stress history
No closed form analytical solution
FEM analyses
Different approaches; results shown obtained by ICFEP
Weight (t x 10^3)

Foundation inclination (degrees)

loading
consolidation
computed from history

Taratura del modello ad elementi finiti contro la storia della Torre
A decrease of the inclination (even a small one) produces a substantial stiffening of the foundation-subsoil rotational response, and hence a substantial increase of the safety factor

\[ \frac{k\alpha}{W h} = F_s \]

Cheney et al. (1991)
Strategy of the Committee

Two stages:

1. Temporary
   • To improve the stability and gain time to properly devise, design and implement the permanent solution
   • Fully reversible

2. Permanent
   • to permanently (?) stabilise the Tower
Temporary geotechnical stabilisation

Reference point

Lead ingots

Pretensioned ring beam

North

R=7.71 m

R=0.49 m

1.25

0.4

0.4

1.58

1.7
Construction of the ring beam to stack on the leading ingots.
Decrease of inclination by placement of lead counterweight.
Permanent Geotechnical Solution

- many possibilities
- many ideas
My favorite solution

The dynamic impulse solution
Sono appassionato delle opere d'Arte ed in particolare della Torre di Pisa. Propongo una soluzione attuabile per fermare l'inevitabile e rendere agibile il monumento. Si tratterebbe di realizzare una gigantesca statua di sostegno, con struttura in acciaio (tipo torre Eiffel) e calostruzo leggero, rivestita di marmo bianco, sistemando al centro due ascensori, il tutto agganciato alla torre stessa con un collare e appoggiato su una enorme piattaforma. Il costo, potendo contare sul rilevante flusso turistico, si amortizzerà in breve e lasciando un segno di funzionalità presente. Il passato ha lasciato il segno del bello.

A titolo informativo negli anni '60 ho costruito e brevettato il primo pre-fabbricato componibile in calostruzo leggero.
It was decided to decrease the inclination by half a degree (1800 seconds of arc), by inducing a differential settlement of the Tower opposite to the existing one.

The differential settlement is obtained by acting on the soil and not on the Tower; the solution is perfectly respectful of the formal, historic and material integrity of the Tower.
The following mechanisms have been considered:

- **surface loading** north of the Tower, by means of a pressing slab and pretensioned ground anchors;

- inducing a **shrinkage of the pancone clay** below the north edge of the foundation either by electroosmosis or by vacuum pumping;

- controlled **removal of small volumes of soil** below the north edge of the foundation (**underexcavation**)

All these techniques have been explored by small scale physical models at natural gravity and in centrifuge, by numerical modelling, by large scale field experiments

The solution devised by the Committee
Chumki Bhaban, Bangla Desh
9 years old in 1992
To the Committee via
UNESCO, Paris
The large scale field experiment of underexcavation
Pressure cells in the base of the plinth for the large scale field experiment of underexcavation.
Technology developed for the underexcavation process.
Field experiment of underexcavation: rotation of the plinth.
The safety provision with steel stays (never operated!)
Stabilizing cable
Installing the steel cables
Preliminary underexcavation: cross section
installation of the stays

underexcavation

three ingots removed

rotation (arc sec)

settlement (mm)

Decrease of the inclination of the Tower due to the preliminary underexcavation

south edge

north edge
The 41 holes for the final underexcavation seen from the Tower
The drilling machine performing the underexcavation
Underexcavation: the material extracted
Preliminary underexcavation

Lead ingots removal

Decrease of the inclination of the Tower due to the final underexcavation

Steel stays removed

Last underexcavation

North edge

South edge
Removal of the last ingot
January 2001
16 June 2001
St. Ranieri’s day
After a century of attempts
the stabilised Tower is given
back to the people
As all well-mannered monuments, the Tower intertwines again with the civil history and the life of the City
Equilibrium between the conflicting requirements of safety and conservation found at a satisfactory level.

Achievement of the Committee to be seen as the final stage of an effort carried out for over a century including a number of trials and errors.
Lessons learned
Perseverance of the ancient Pisans in completing the construction over a time span of two centuries in spite of evident inclination, political and economic difficulties.

Obstinacy of modern engineers succeeding in saving the Tower through over a century of attempts and in spite of many difficulties and some errors.

First lesson Perseverate!
The corrections during the construction (banana shape) appear to have been detrimental!!!
10 Anchors, 100 t each
Second lesson

The way to hell is paved by good intentions !!!
Bonanno Pisano

4th storey
3rd storey
2nd storey
1st storey

Giovanni di Simone

7th storey
6th storey
5th storey
4th storey

construction starts
construction up to the 4th storey

1st interruption ≈ 100 years

construction of the bell chamber
construction up to the 7th storey

2nd interruption ≈ 90 years

Tommaso di Andrea

bell chamber
1944, July the 22nd. Pisa was divided: Germans located at North; Americans at South. Every bend of road, every farmhouse and every escarpment seemed to be occupied by groups of obstinate German defenders.

As the number of American dead and wounded mounted, the advance was in danger of stalling. How the Germans could be so accurate in such flat, coastal terrain? They had to have a vantage point; may be the leaning Tower?

Sergeant Leon Weckstein was delivered to the most dangerous mission of his war: to get close to the tower to find out if the Germans were inside. If enemy activity was detected, Americans were not going to sacrifice men for a chunk of masonry, no matter how old.

I took my time - Weckstein says - training the binocular slowly up and down, attempting to discern anything that might be hidden within those recesses and arches. But after a whole day of observation he did not call down fire. Waiting for the signal were inland gun batteries and a destroyer offshore.
What the 91st Infantry Division did not know was that they were entrusting one of the war's most fateful missions to a man rejected by the navy for being shortsighted.

"In 1942 the navy had told me to go away and eat carrots for six months," says Weckstein. "Then the infantry took me - but they take anyone."
Most major undertakings rest, at least partially, on the effect of casual favourable circumstances.

Third lesson

A modicum of good luck won’t do any harm!