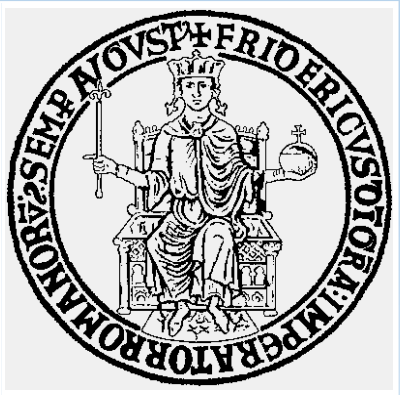
GeoVirginia 2018
Lessons Learned in Geotechnical Engineering
Williamsburg VA
April 9th - 11th

Lessons learned from the stabilization of the Leaning Tower of Pisa



Carlo Viggiani
University of Napoli Federico II, Italy

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.

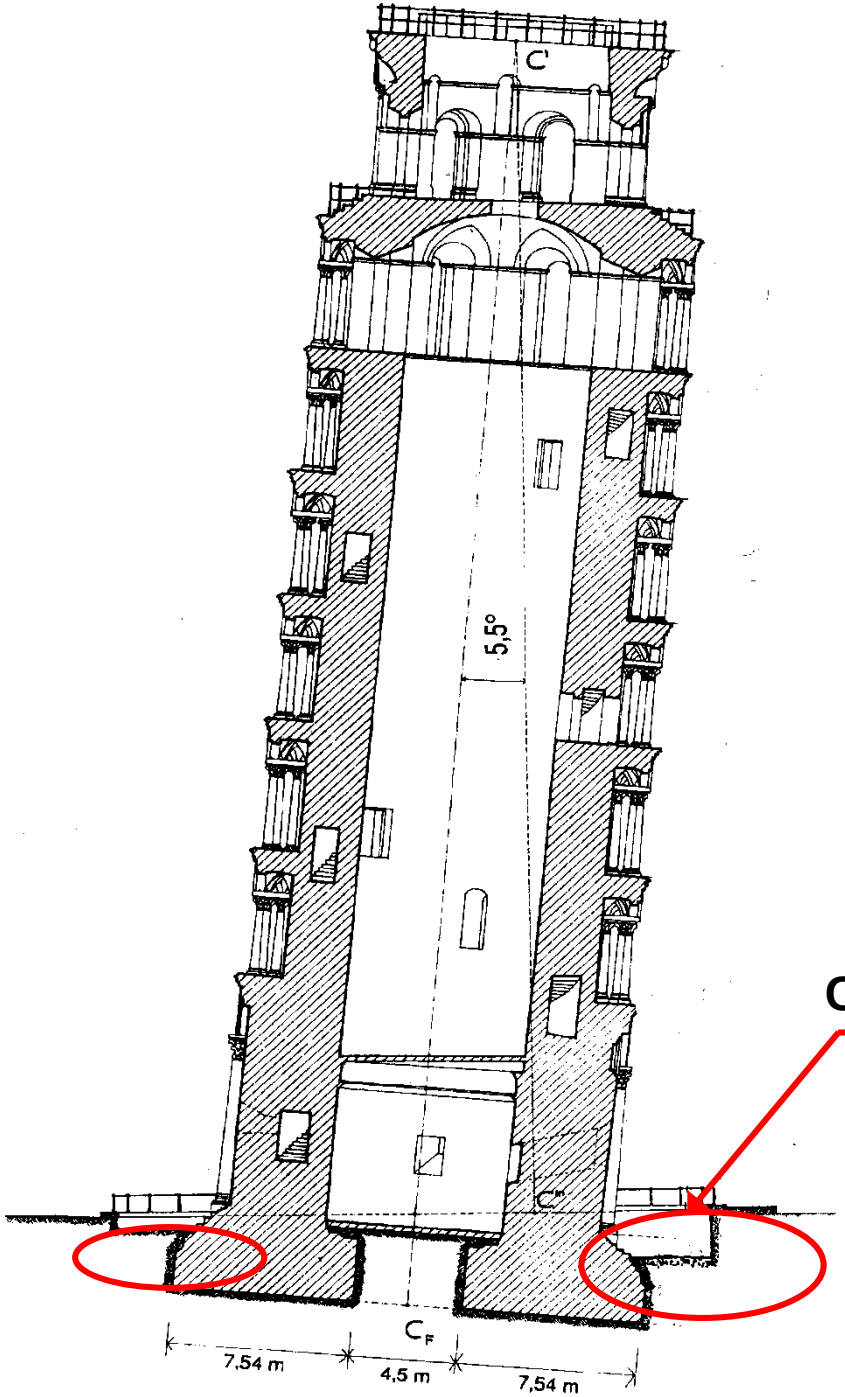
Piazza dei Miracoli: stupendous manifestation
of the **ideal unity** at the time
among religious, spiritual, and political powers.

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



South

Height (C_F – C') = 58.4 m

Weight = 142 MN (~14.500 t)

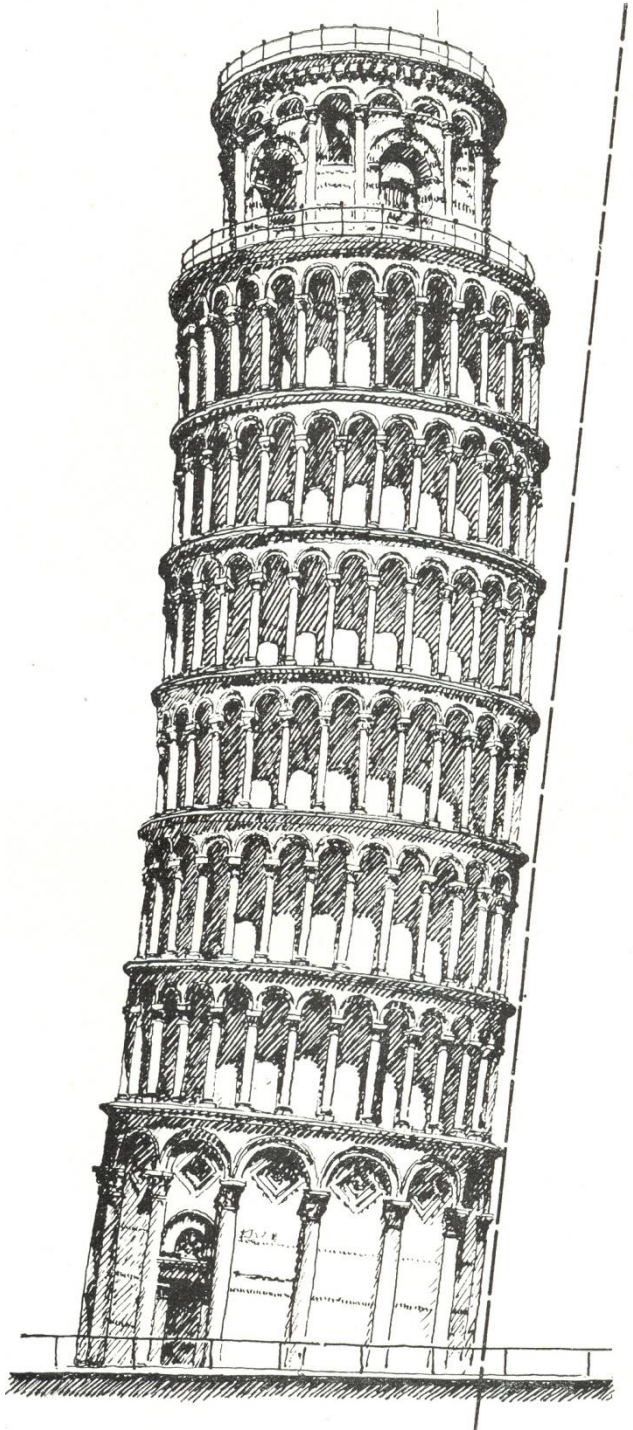
Diameter of the foundation = 19.6 m

Height of the centre of gravity = 22.6 m

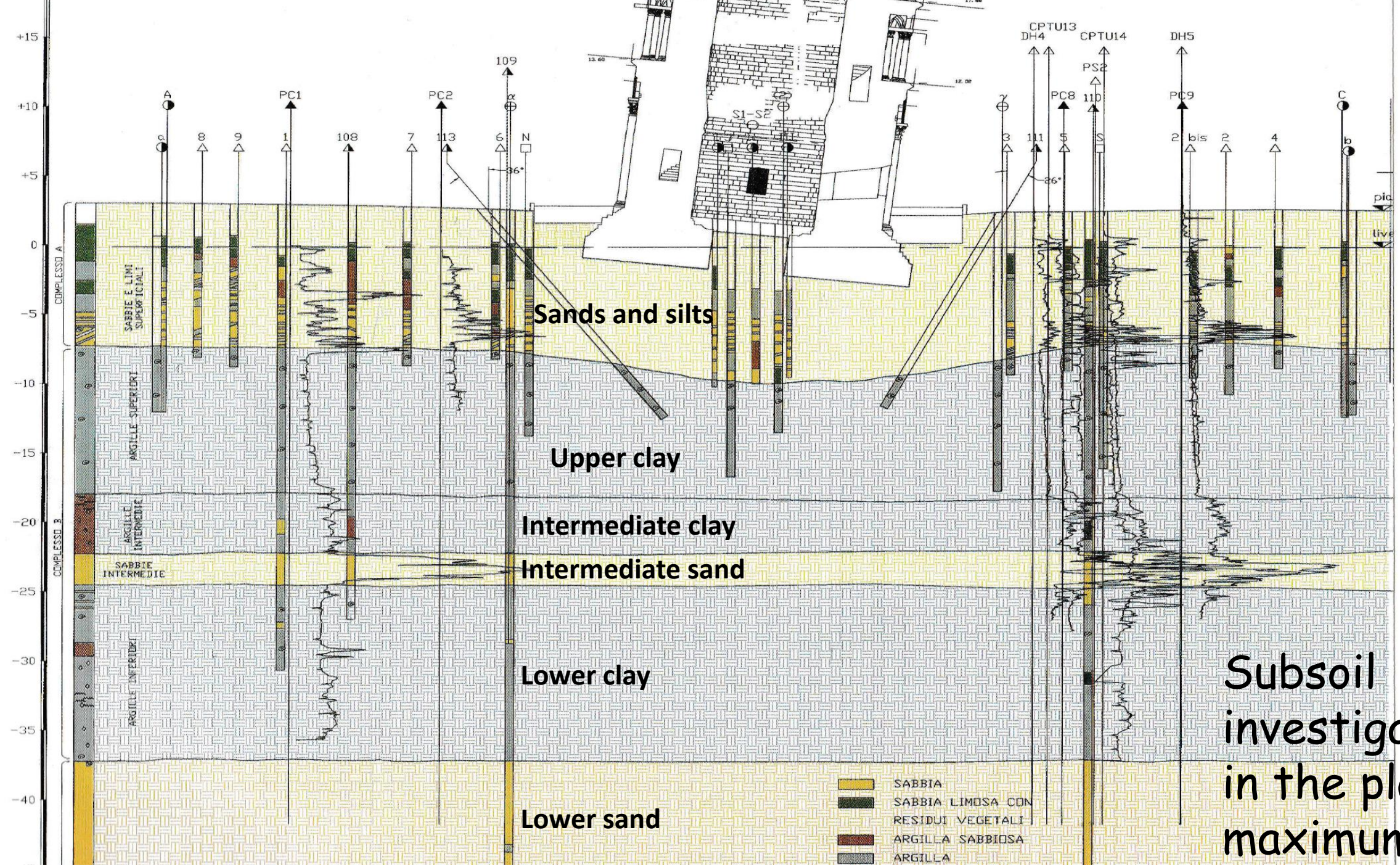
Average foundation pressure = 497 kPa (~50 t/m²)

Catino (1838)

Cross section in the plane of maximum inclination

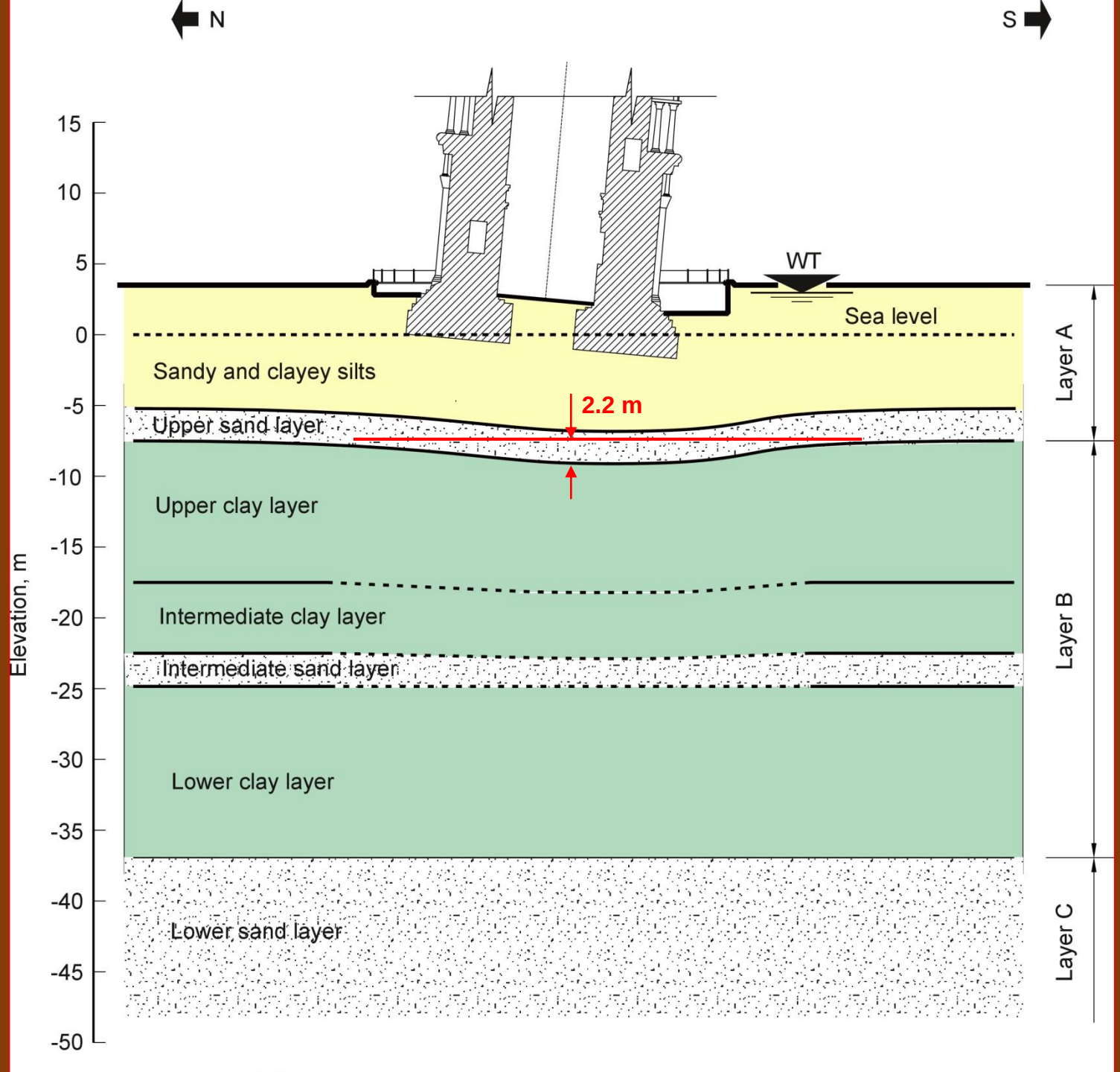


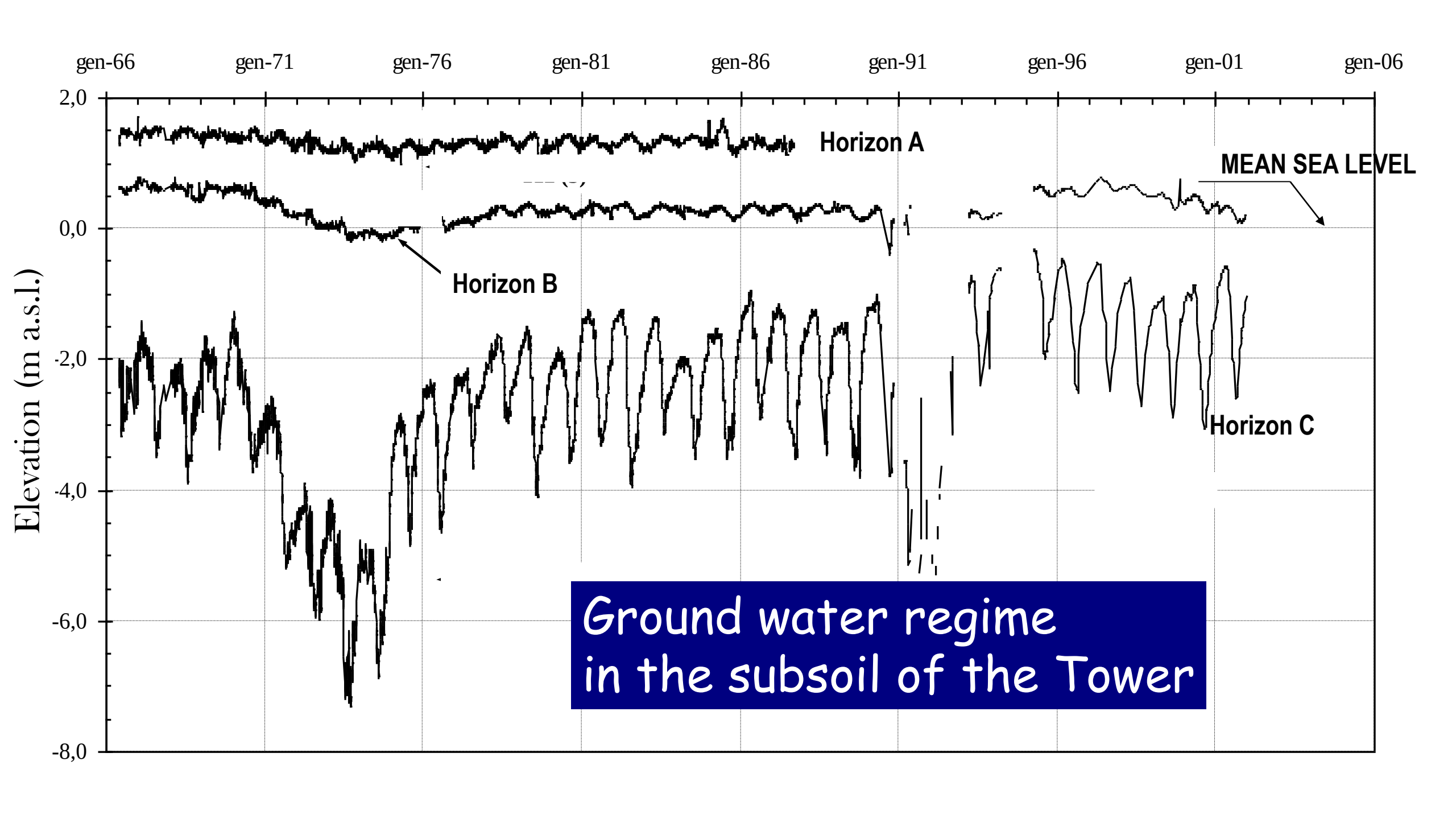
The "banana shape" of the Tower



Subsoil investigations in the plane of maximum tilt

The subsoil of the Tower




gen-66
gen-71
gen-76
gen-81
gen-86
gen-91
gen-96
gen-01
gen-06
2,0
0,0
-2,0
-4,0
-6,0
-8,0
Elevation (m a.s.l.)
Horizon A
MEAN SEA LEVEL
Horizon B
Horizon C
Ground water regime
in the subsoil of the Tower

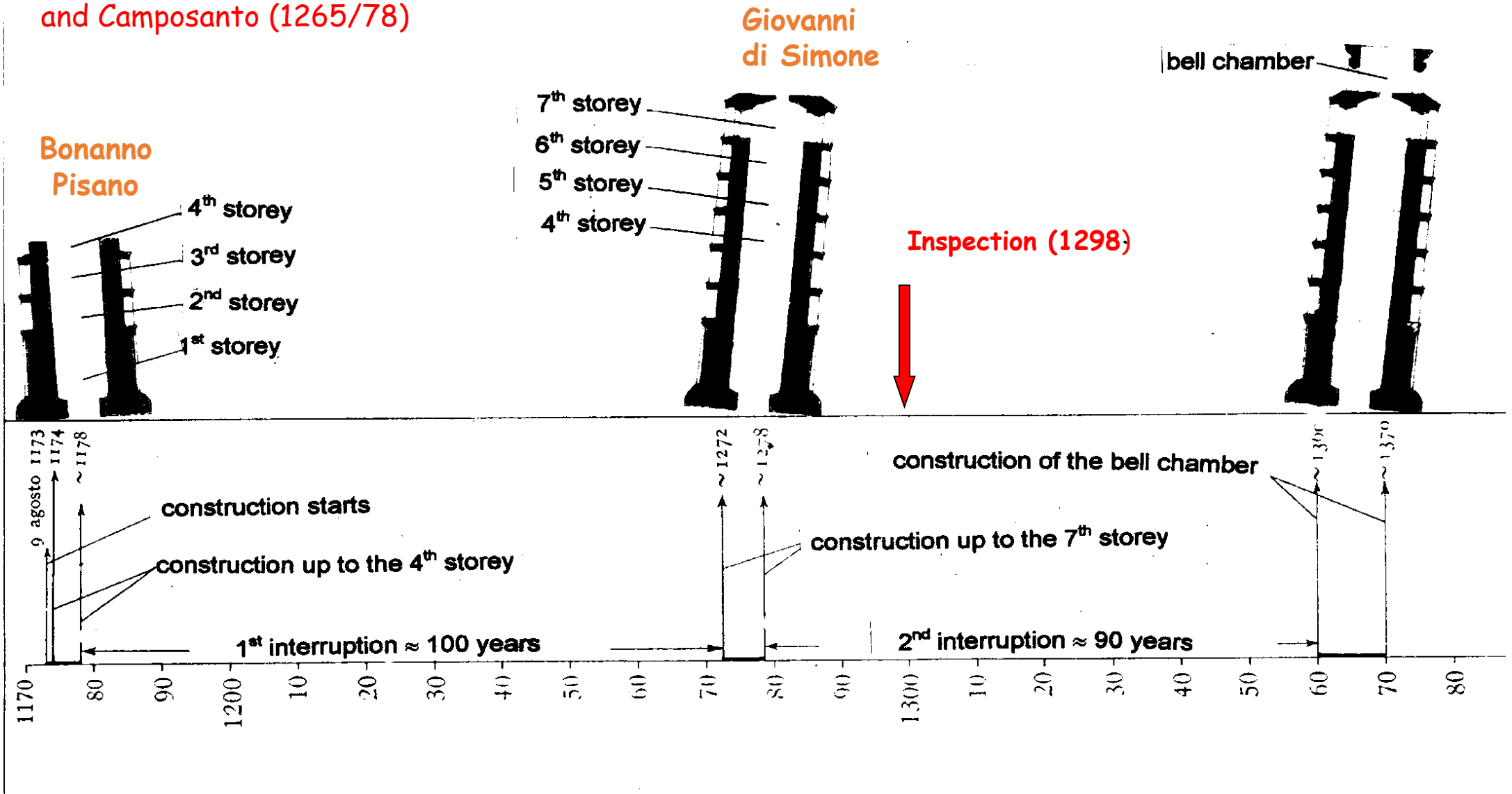
Is the inclination of the Tower intentional?

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)



Die Merchurii, XV Marcii, sapientes viri magister Johannes quondam Magistri Nicoli Magister lapidum, Magister Guido quondam Magistri Johannis Magister lapidum et Magister Ursellus Magister lignaminis, omnes simul unanimiter et concorditer scandiglantes campanile pisane ecclesie maioris cum corda et plumbo a summo usque deorsum concordaverunt simul coram me notario quod plumbum, quod erat appensum et ligatum ad cordam predictam veniebat recto tramite super punctam clavi exterioris positi in ligno posito in dicto loco ubi dictum plumbum cadebat in terram, et ibi recte fecerunt signum de comuni concordia

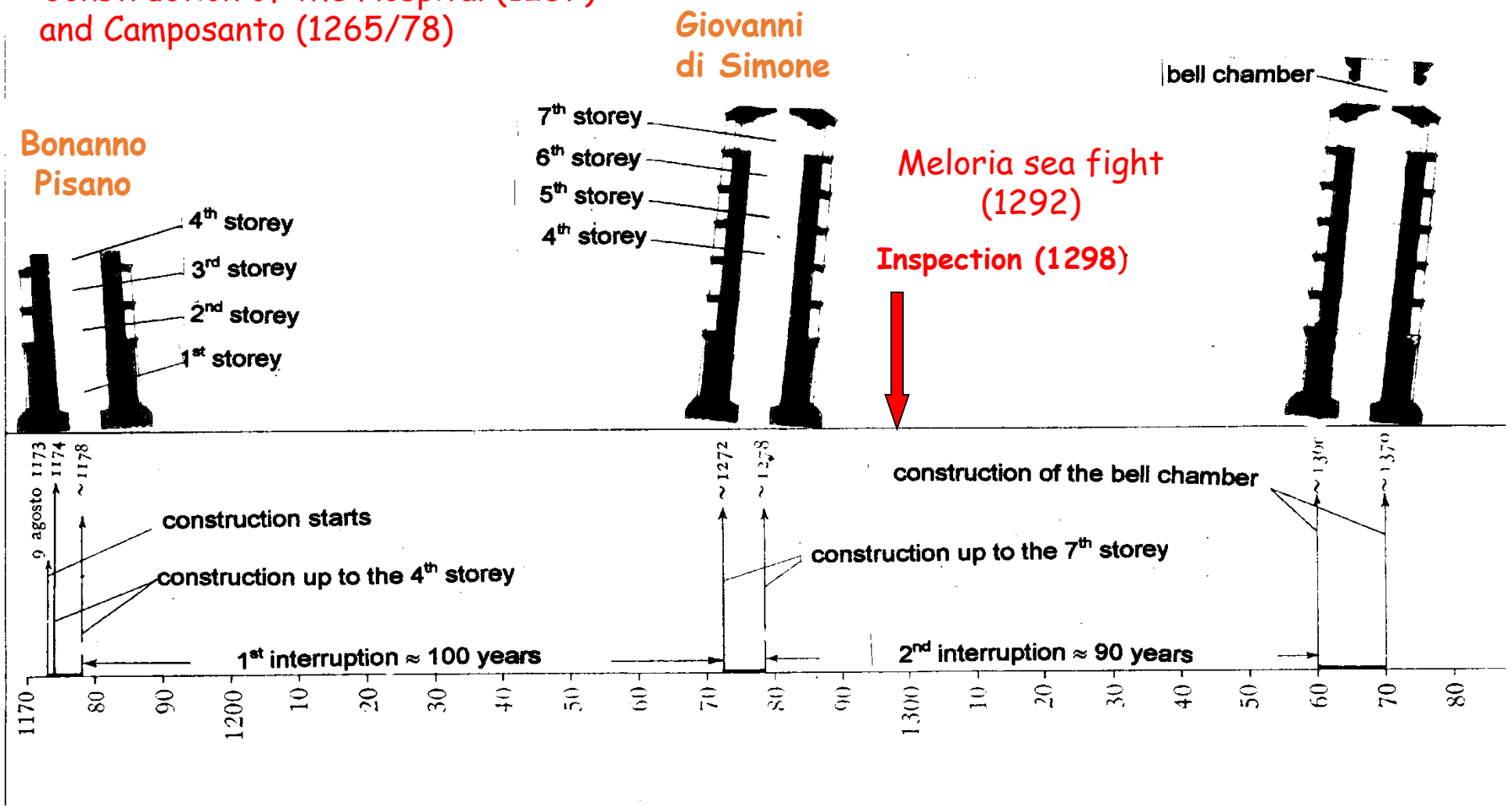
On Wednesday March 15 the wise men Master John, son of Nicholas, Mason, Master Guy, son of John, Mason and Master Ursellus, Woodworker, together plumbing by common consent the bell tower of the pisan cathedral by means of a plumb line, from the top to the bottom, agreed in the presence of me notary that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

Actum Pisis in dicto loco presentibus domino Guelfo pisano canonico, Nerio clerico filio Guidonis et Ceccho clerico pisani capituli et aliis pluribus testibus ad hec MCCXCVIII Indictione XII^{a}.

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 …..

Archives of the Chapter of Pisa, Atti, 1298 - 1306

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



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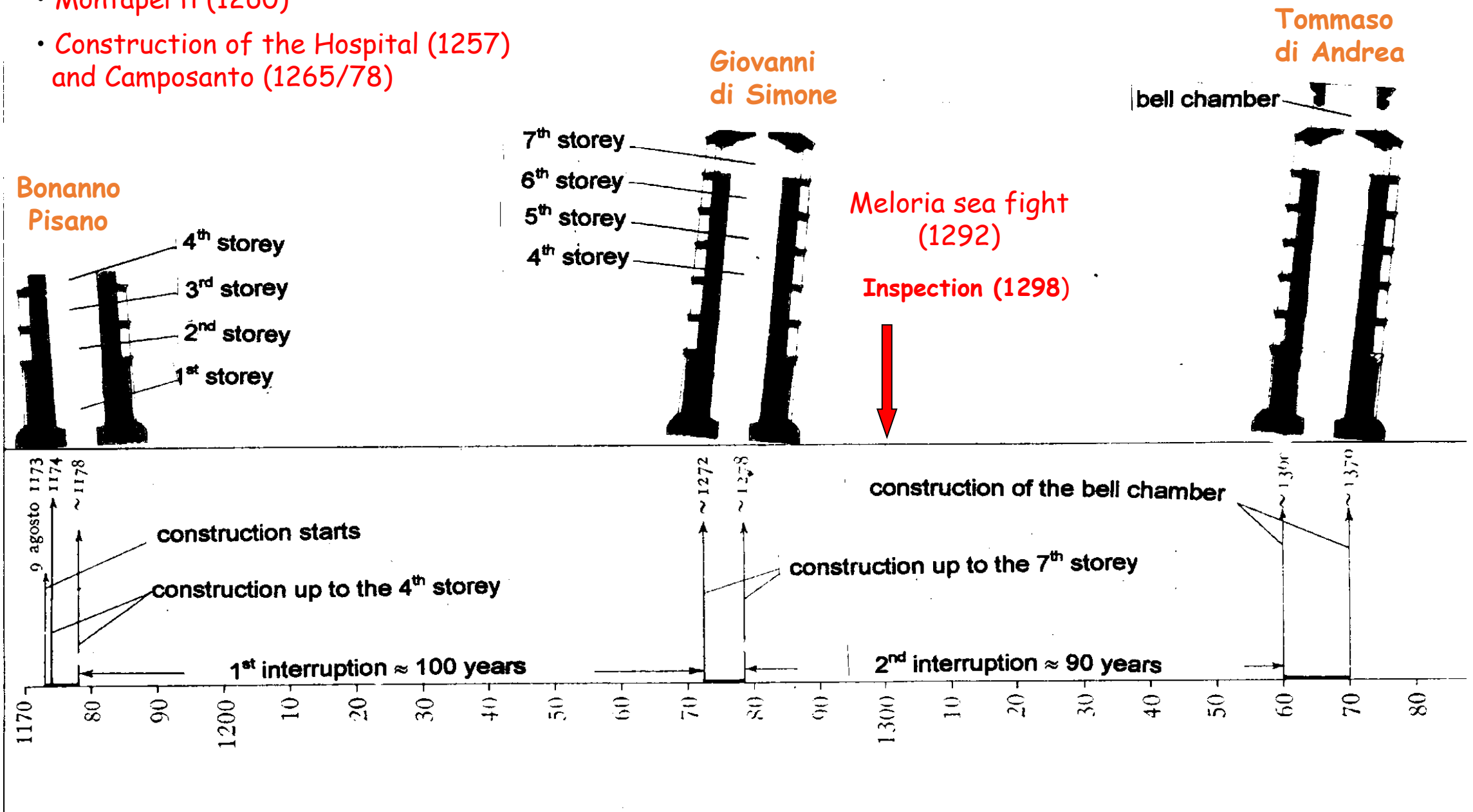
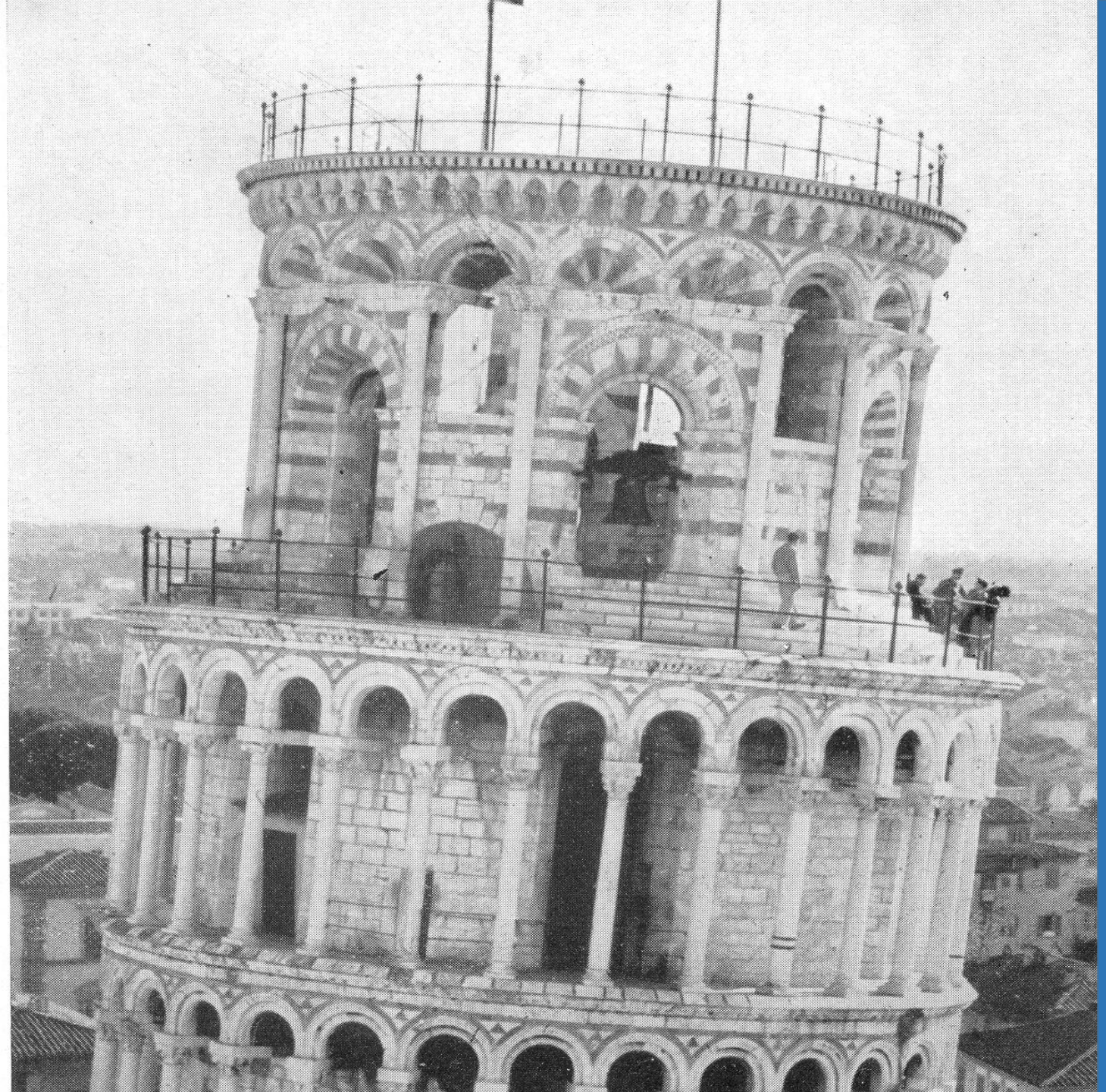
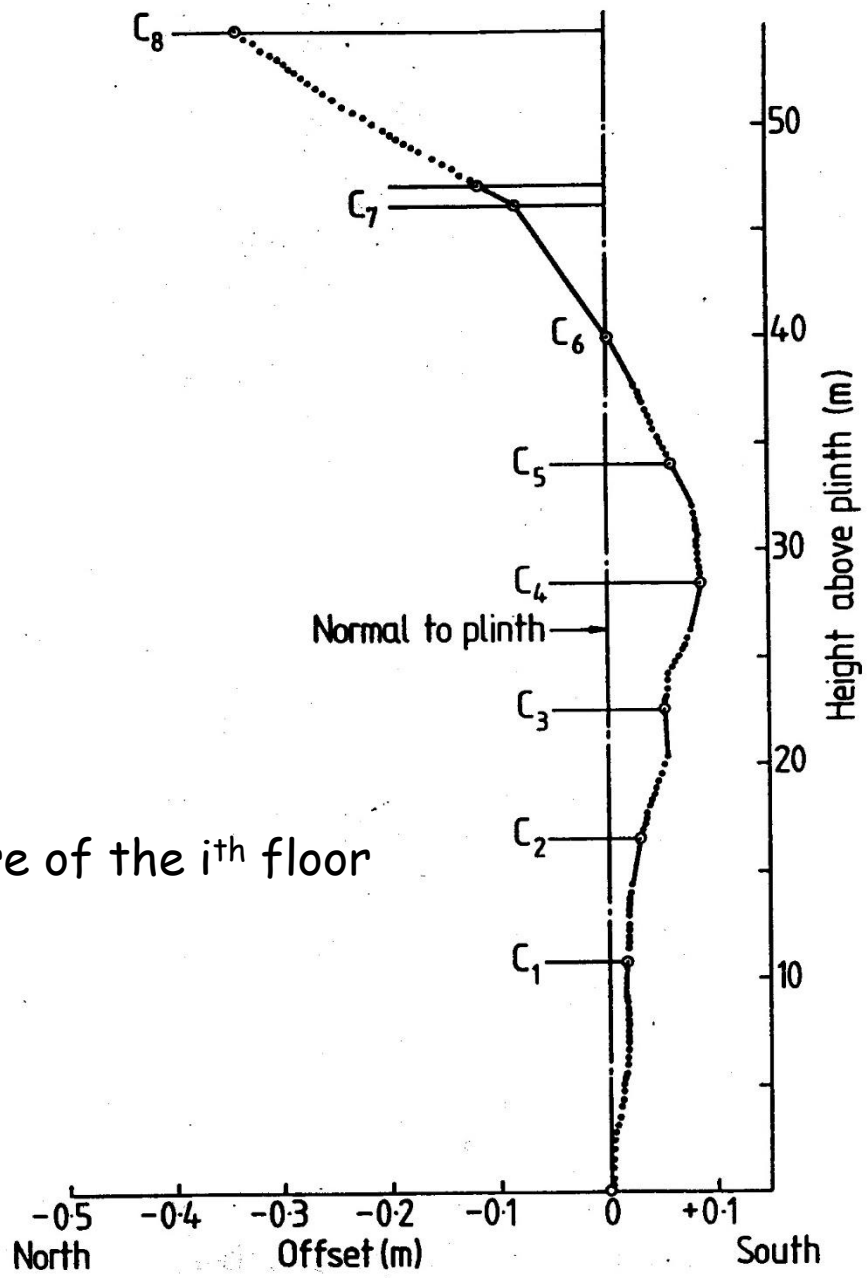




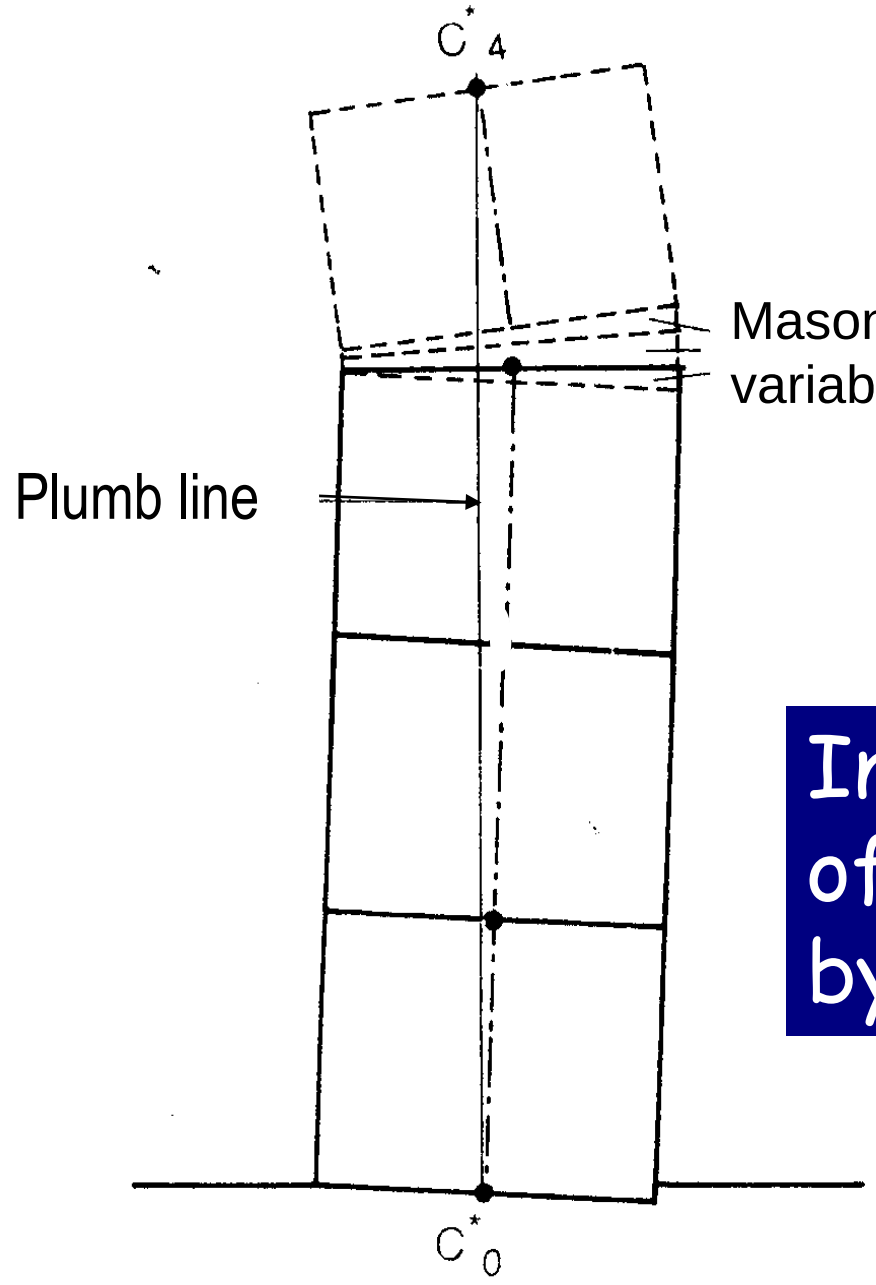
4 steps north,
6 steps south

Shape of the axis of the Tower

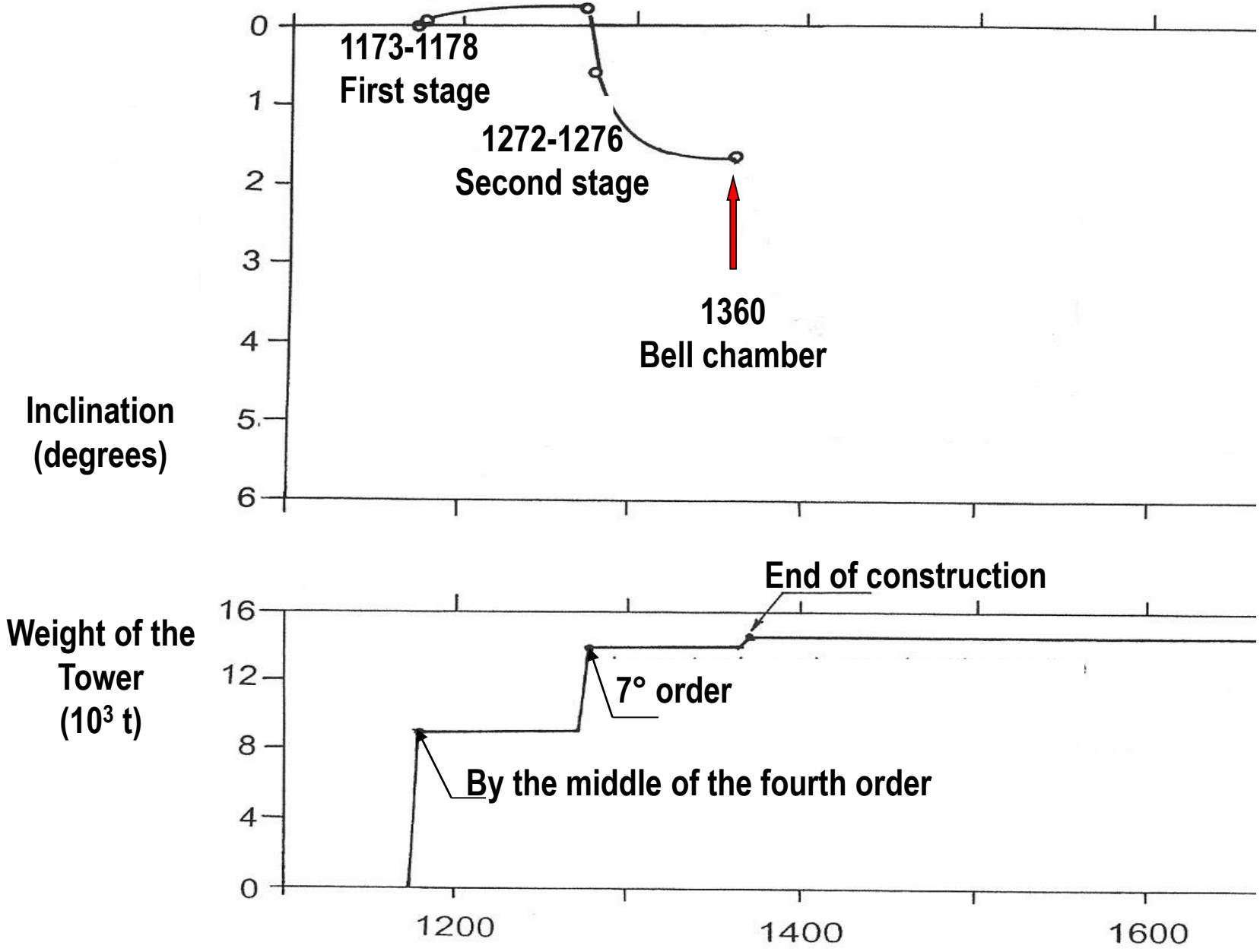


C_i = centre of the i^{th} floor

Question mark shape?



Interpretation of the corrections by the ancient masons


Inclination
(degrees)
0
1
2
3
4
5
6
1173-1178
First stage
1272-1276
Second stage
1360
Bell chamber
Weight of the
Tower
(10³ t)
16
12
8
4
0
End of construction
7° order
By the middle of the fourth order
1200
1400
1600

Antonio Veneziano
(~ 1385)

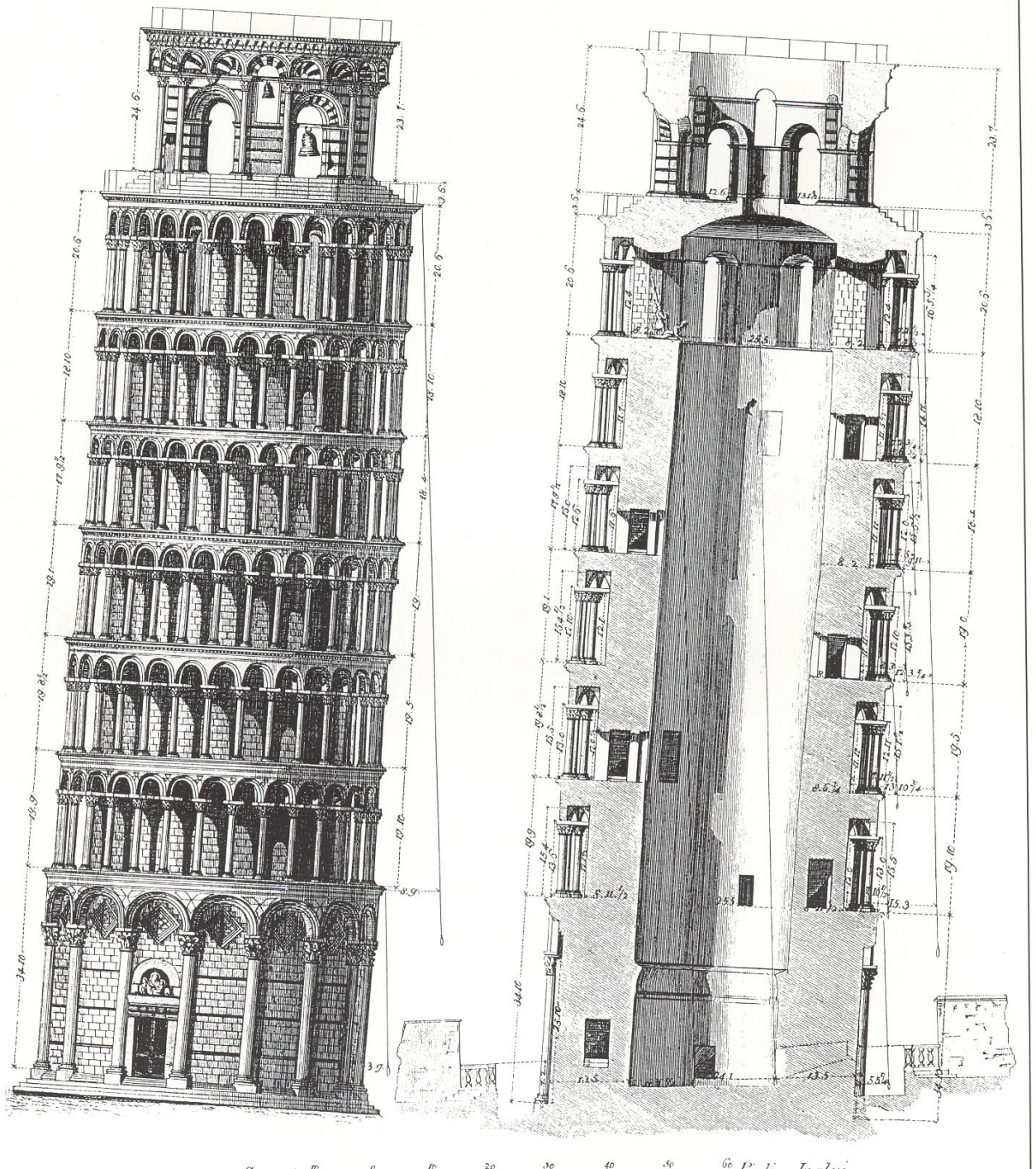
The body of
St. Ranieri
brought back in Pisa
(particular)

Fresco in the Camposanto

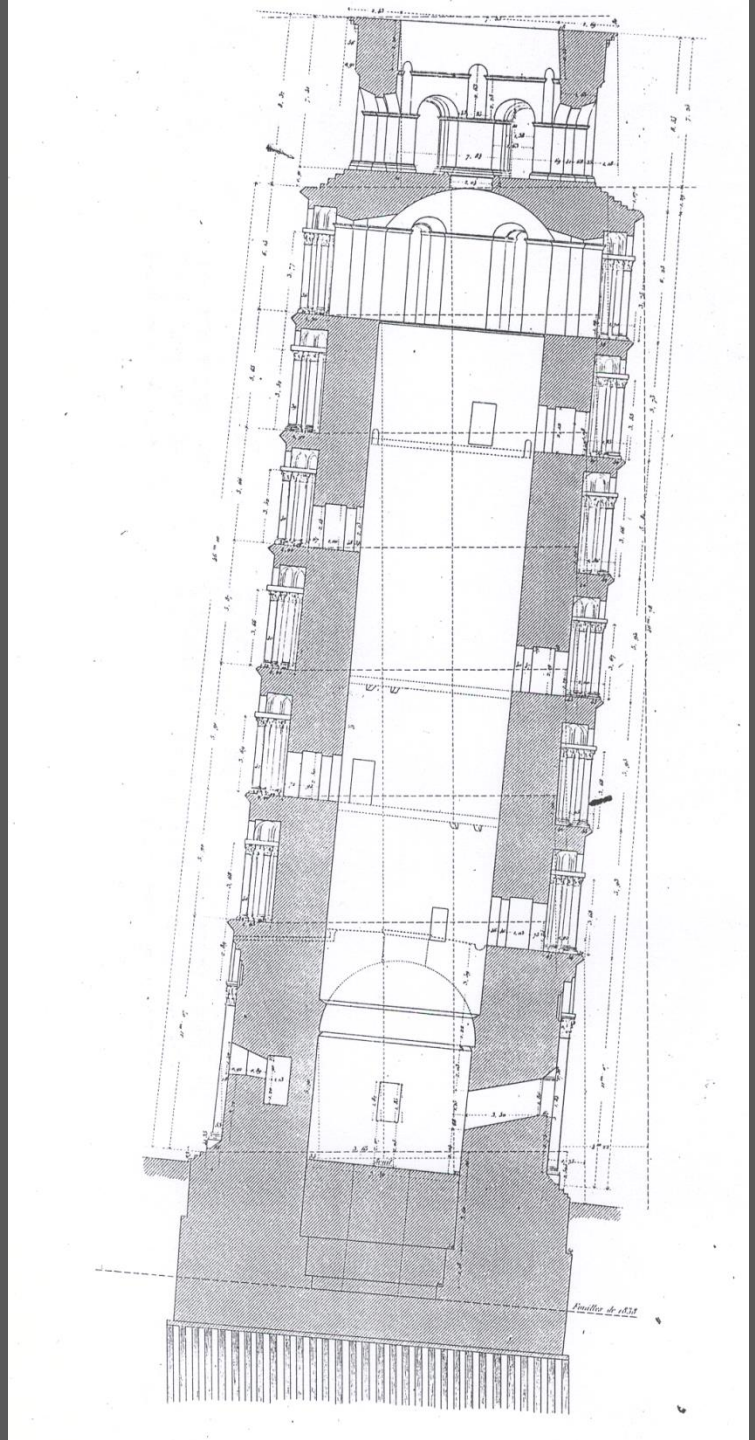
Questo Guglielmo secondo che si dice, l'anno 1174 insieme con Bonanno scultore fondò in Pisa il Campanile del Duomo.... Ma non avendo questi due architetti molta pratica di fondare in Pisa, e perciò non palificando la platea come dovevano, prima che fossero al mezzo di quella fabbrica essa inclinò da 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.

G, Vasari, *The life of Arnolfo di Lapo.*
1566
Life of the illustrious men, 1, 274

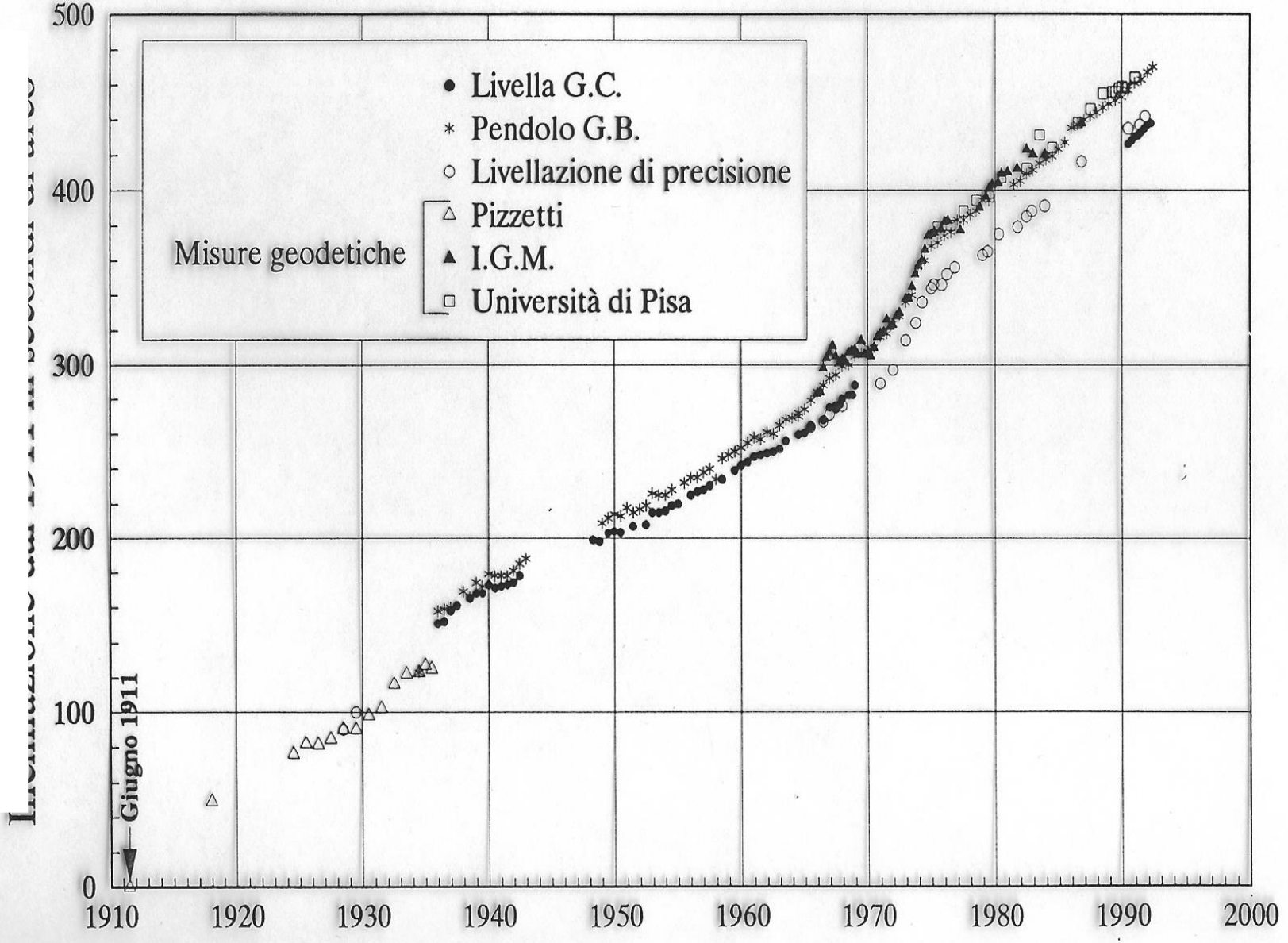


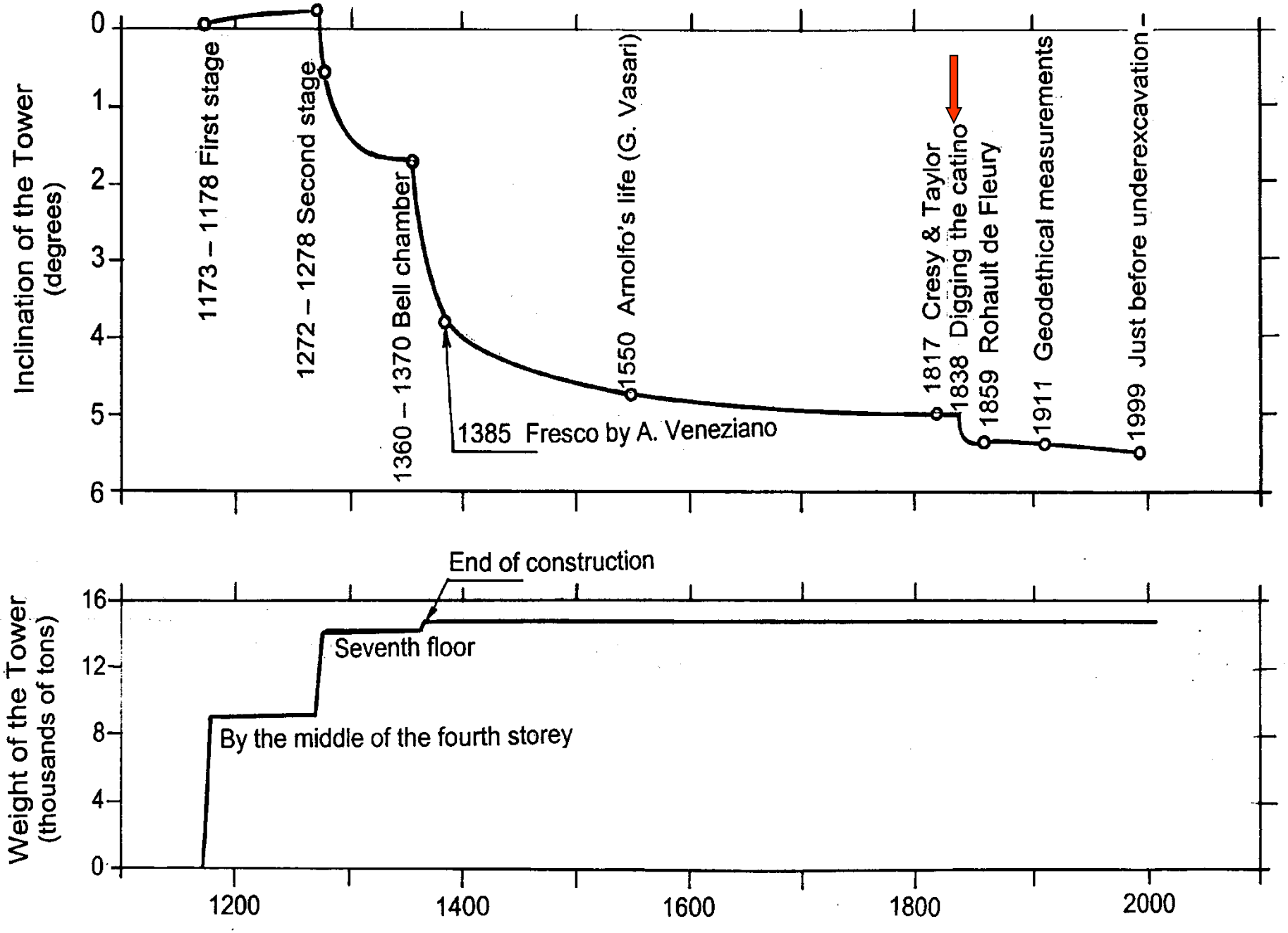
The survey by Cresy & Taylor (1817)

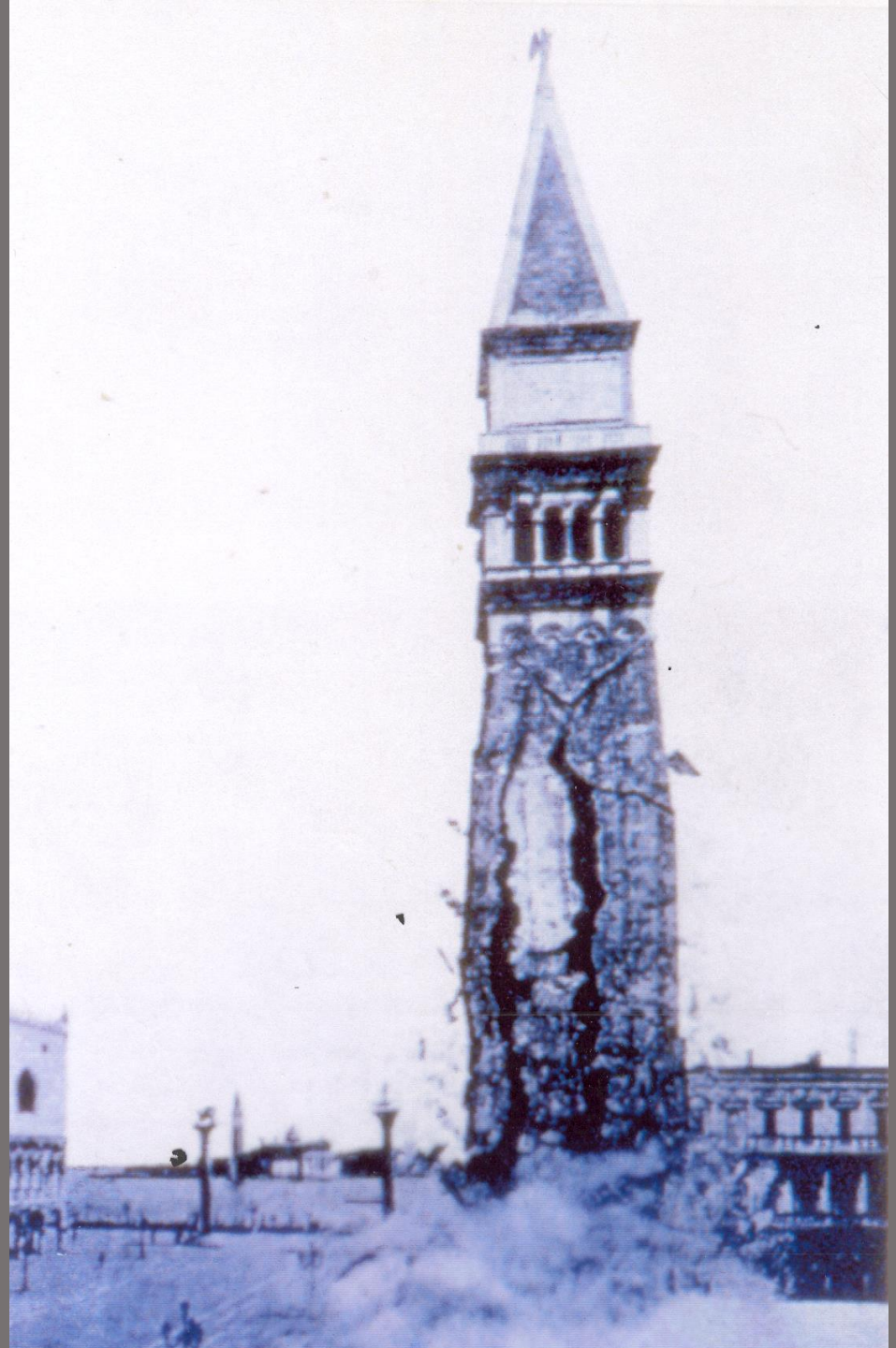


The survey by Rohault de Fleury (1859)

Modern measurements of the tilt




Inclination of the Tower (degrees)
0
1
2
3
4
5
6
1173 – 1178 First stage
1272 – 1278 Second stage
1360 – 1370 Bell chamber
1385 Fresco by A. Veneziano
1550 Arnolfo's life (G. Vasari)
1817 Cresy & Taylor
1838 Digging the catino
1859 Rohault de Fleury
1911 Geodethical measurements
1999 Just before underexcavation
Weight of the Tower (thousands of tons)
16
12
8
4
0
End of construction
Seventh floor
By the middle of the fourth storey
1200
1400
1600
1800
2000



July 14, 1902 Collapse of the S. Marco bell Tower in Venice

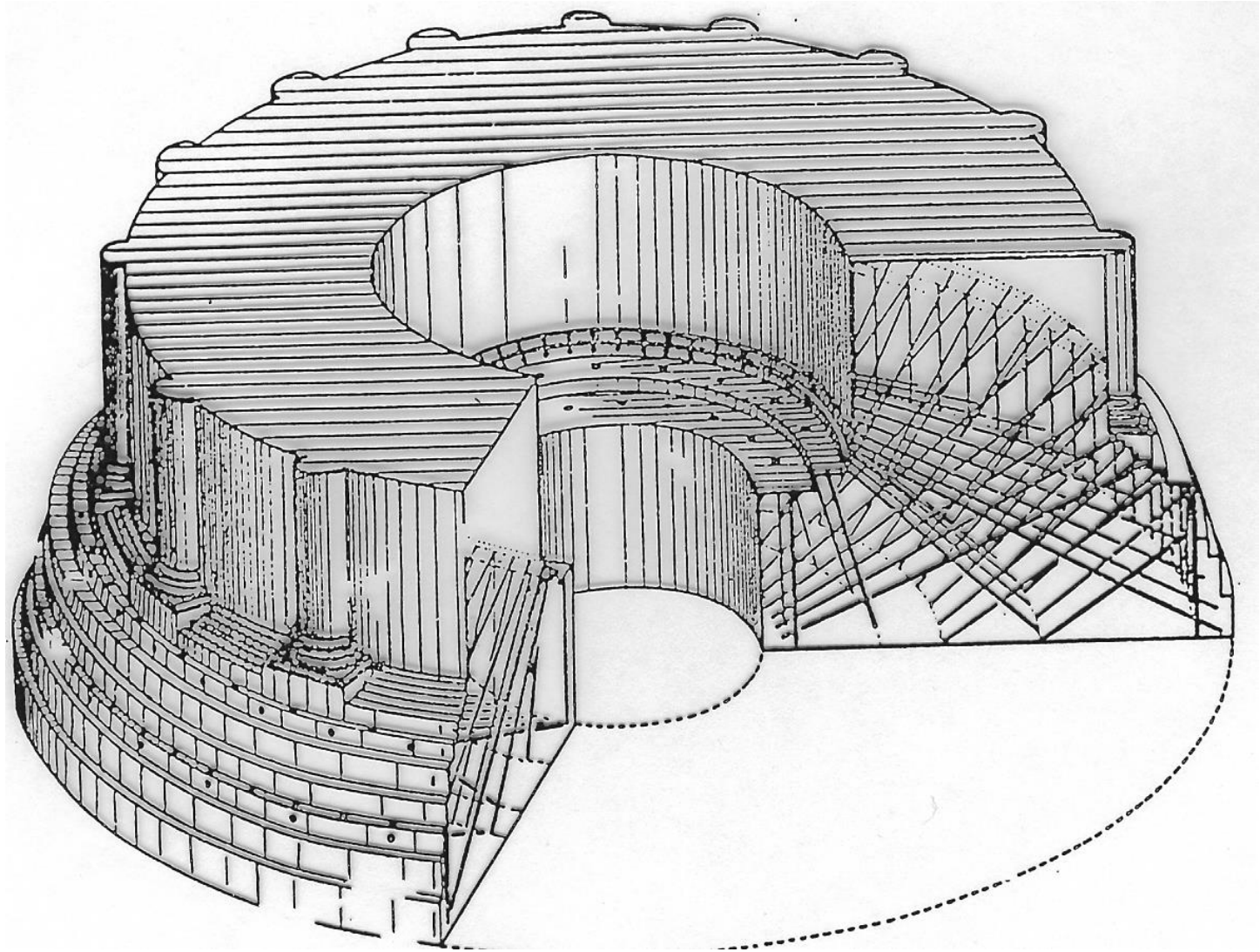
Between 1908 and 1935 a number of Commissions follow one another

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 watertighting the foundation of the Tower and the soil surrounding the catino

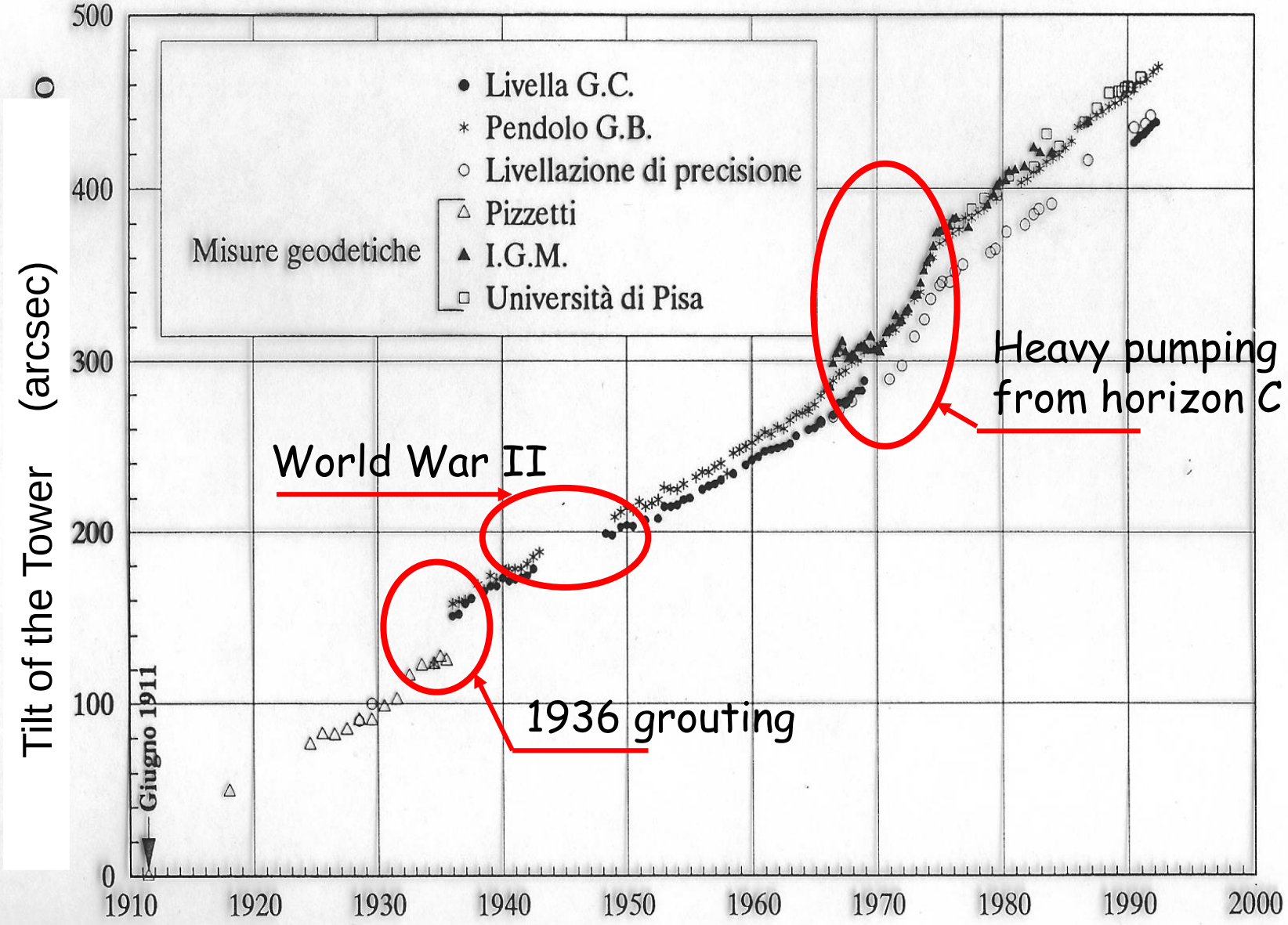


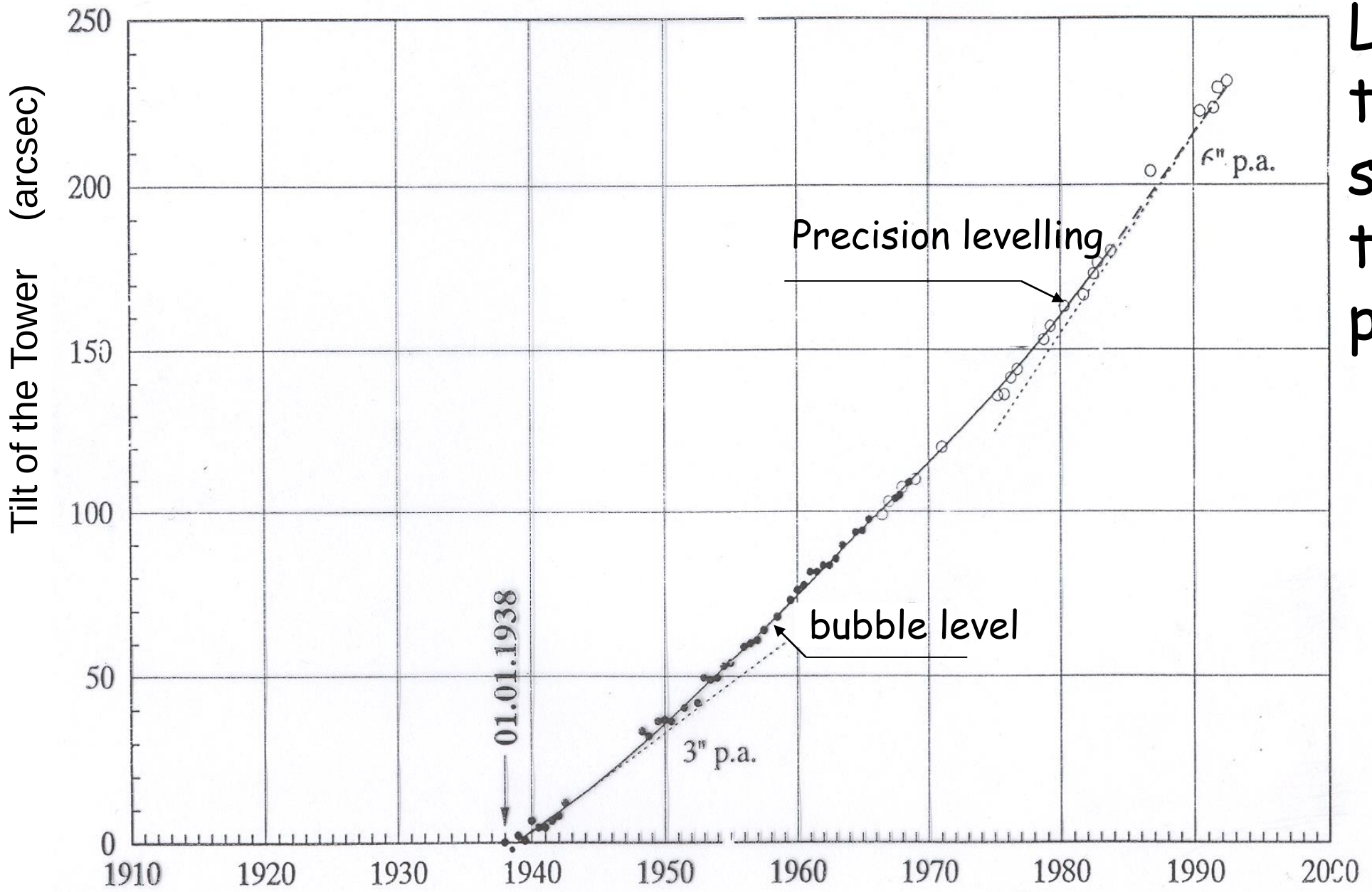
Holes for cement grouting in 1936

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


Misure geodetiche
Livella G.C.
Pendolo G.B.
Livellazione di precisione
Pizzetti
I.G.M.
Università di Pisa
Tilt of the Tower (arcsec)
Giugno 1911
World War II
1936 grouting
Heavy pumping
from horizon C
0
100
200
300
400
500
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000



Long term trend subtracting the perturbations

Italian Government

appoints a Commission

(the Polvani Commission)

with the task of preparing an international tender

for designing and implementing

the necessary stabilization works

From left to right: C. Viggiani, C. Cestelli Guidi, E. Schultze, A. Croce, A.W. Skempton, G. Calabresi.

Geotechnical Group of the Polvani Commission Rome, 1965

Exhaustive investigations on the Tower and the subsoil

27 groups of contractors, consultants and designers participate to the competition

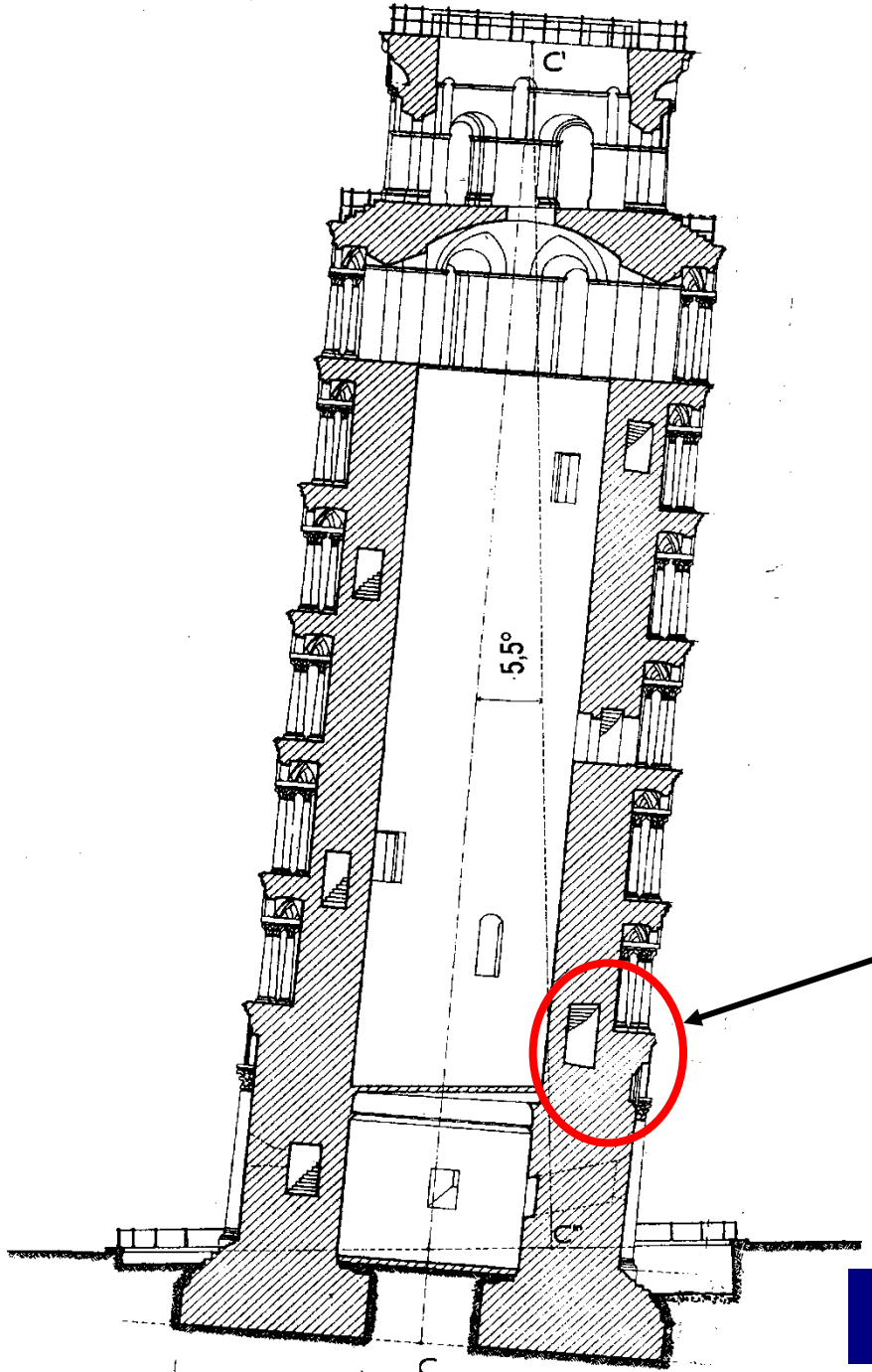
11 are admitted

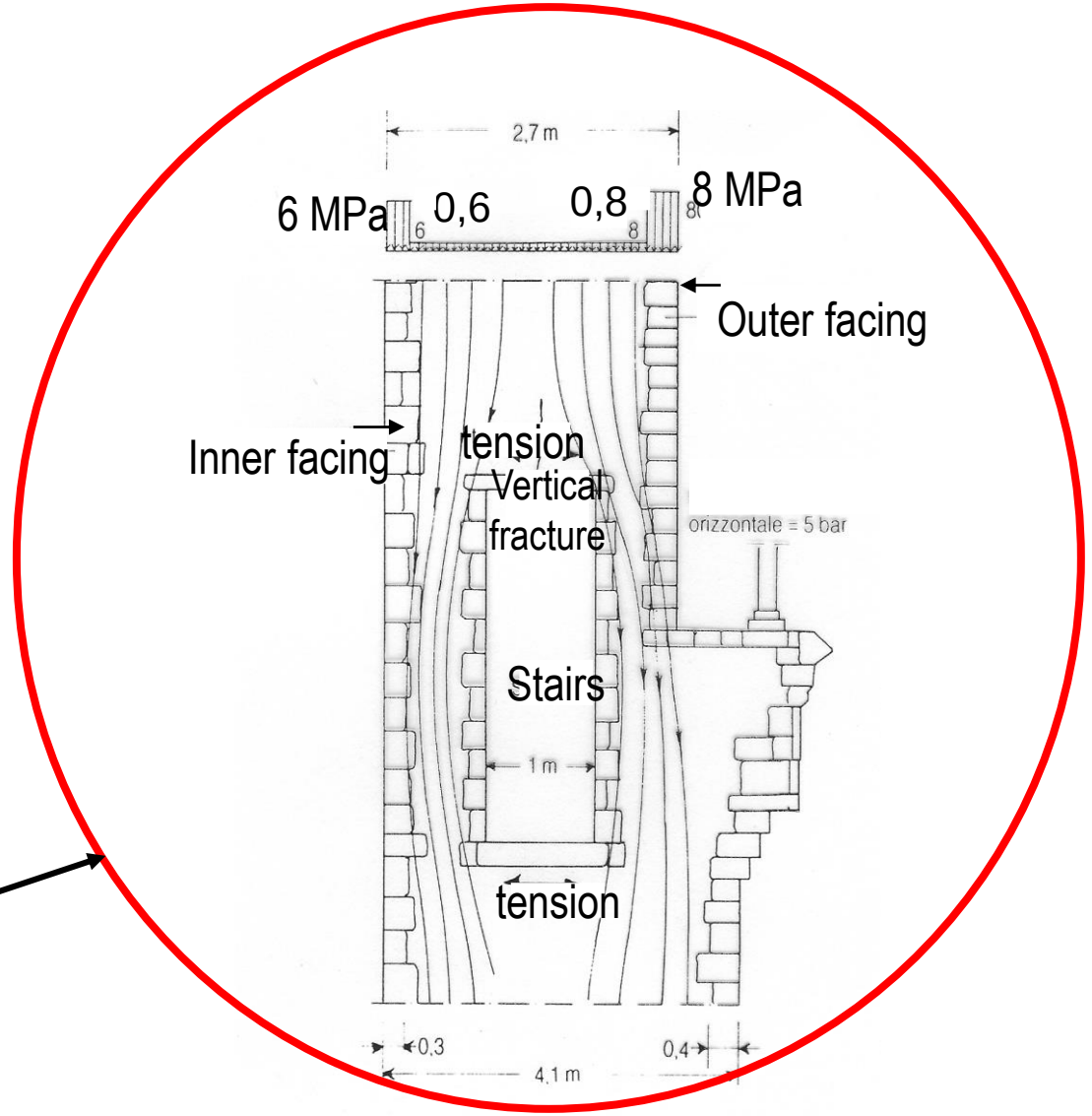
5 projects are pointed out as worthy of consideration

But eventually the contract is not awarded

The civic tower of Pavia, 1988

The collapse of the civic tower of Pavia, 1989





Risk of sudden brittle failure

For safety, the Tower is closed to visitors in December, 1989

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

1965

The International Committee, 2001

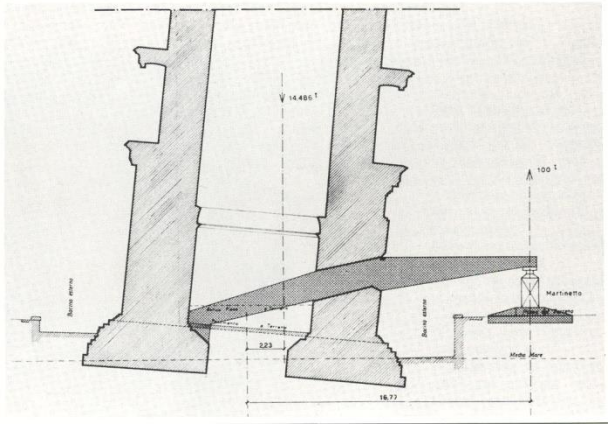
The old boys!

A number of solutions to stabilize the Tower had been proposed in 20° Century

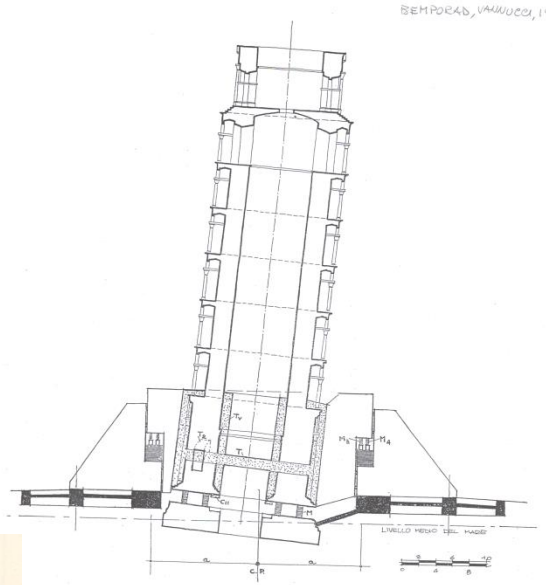
They have to be considered

among the most serious risks threatening the monument

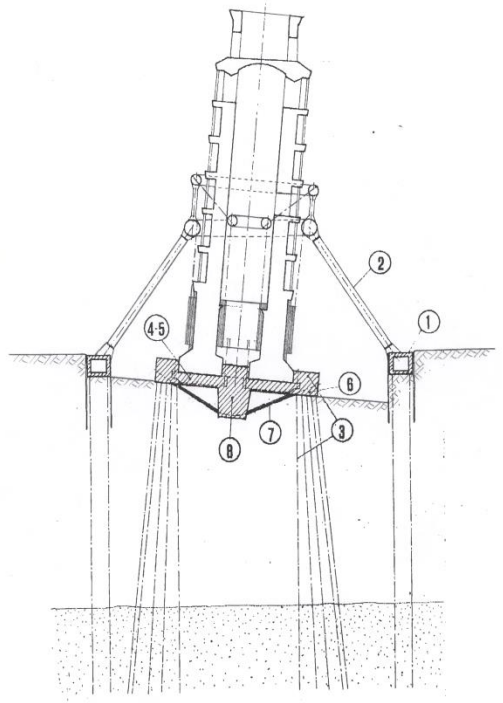
Colonnetti, 1963

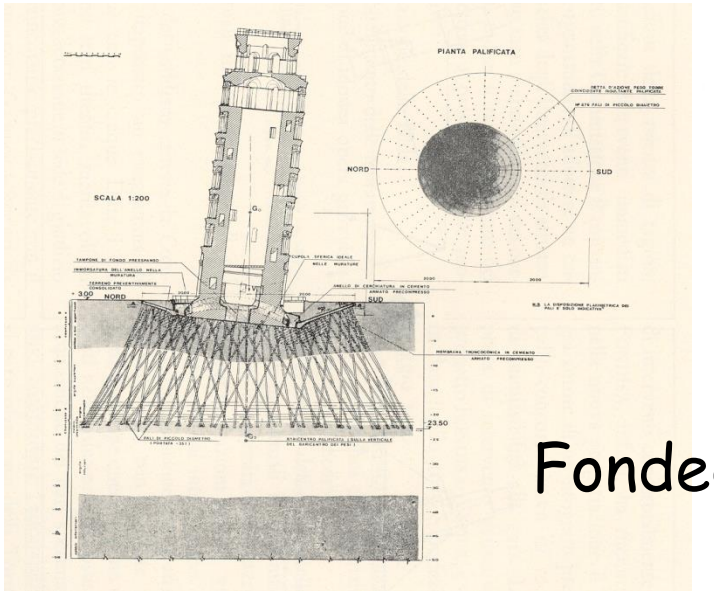


Benporad, Vannucci, 1963



Design group, 1987





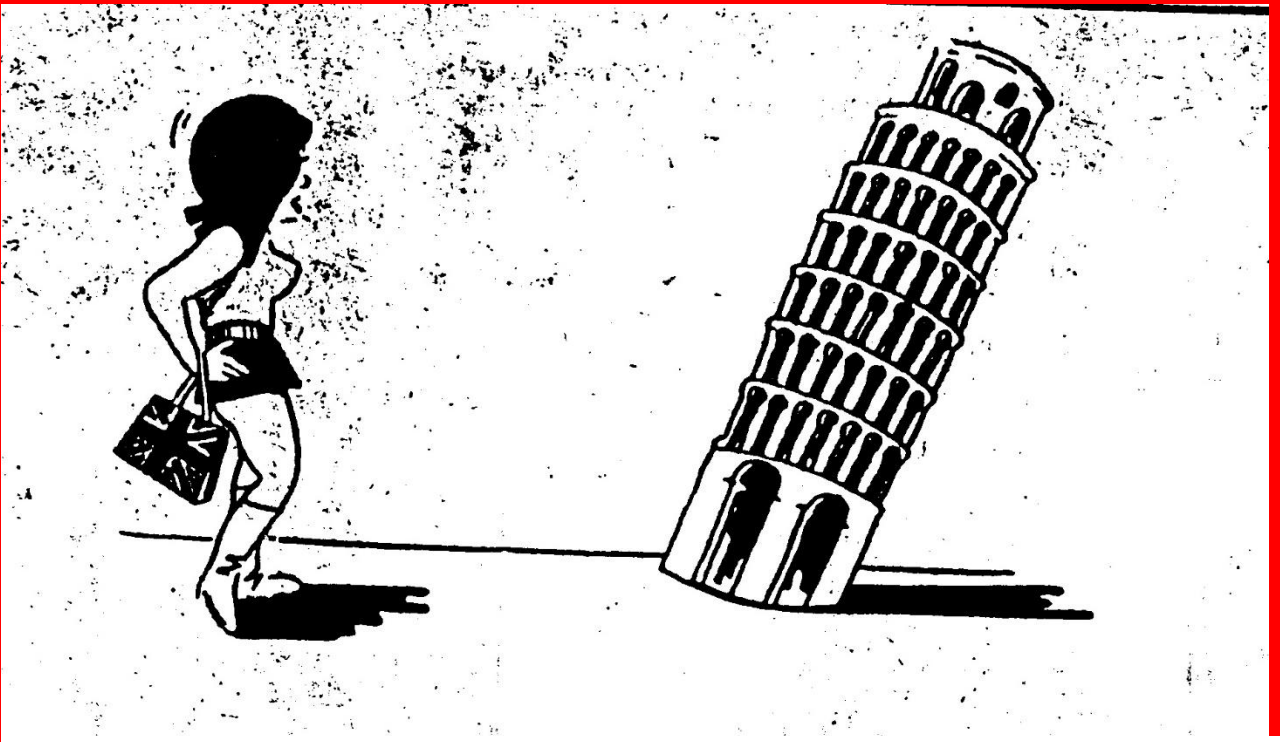
Fondedile, 1973

Some of the solutions proposed for the stabilisation of the Leaning Tower of Pisa

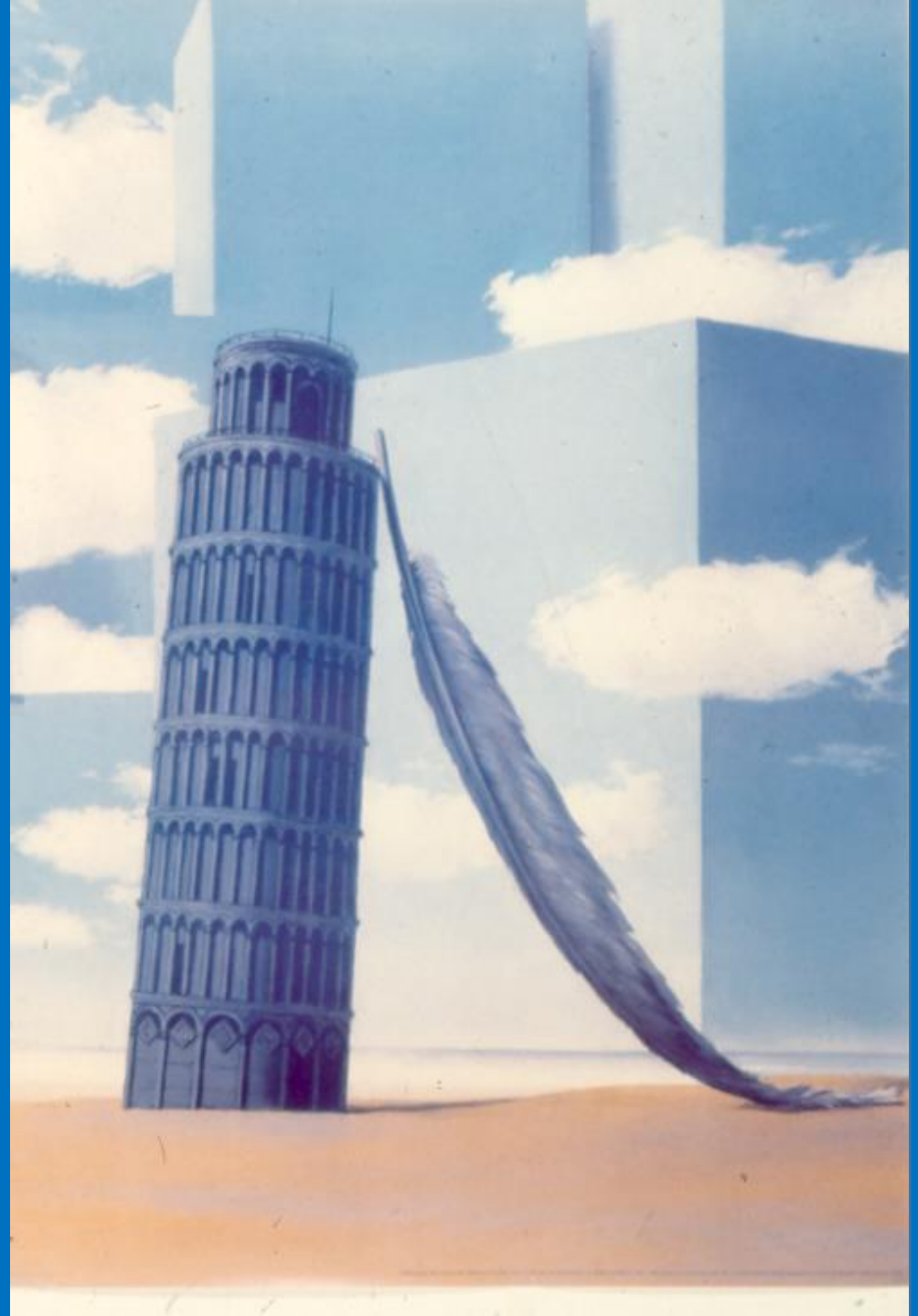
The challenge of the
International Committee
established in 1990:
a completely different
kind of solution

Respectful of the iconic, historical
and material integrity

There were
some examples

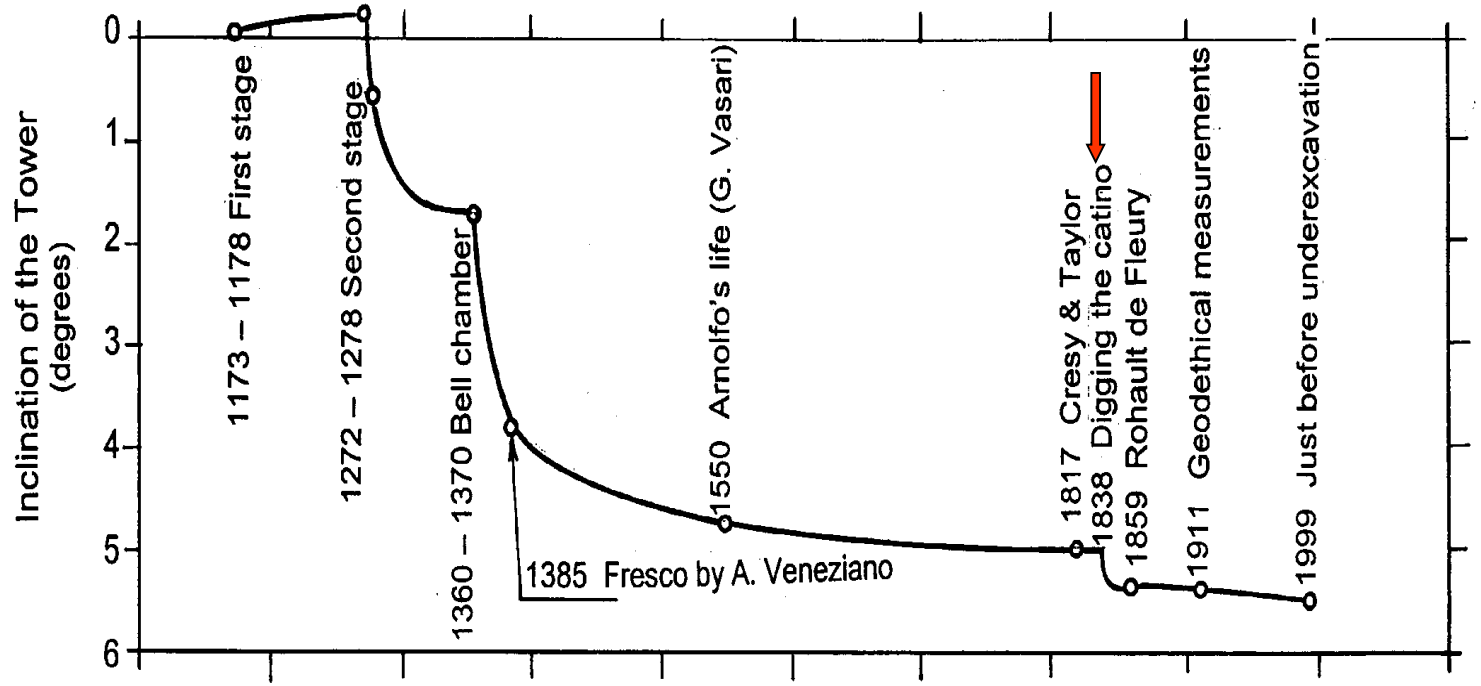


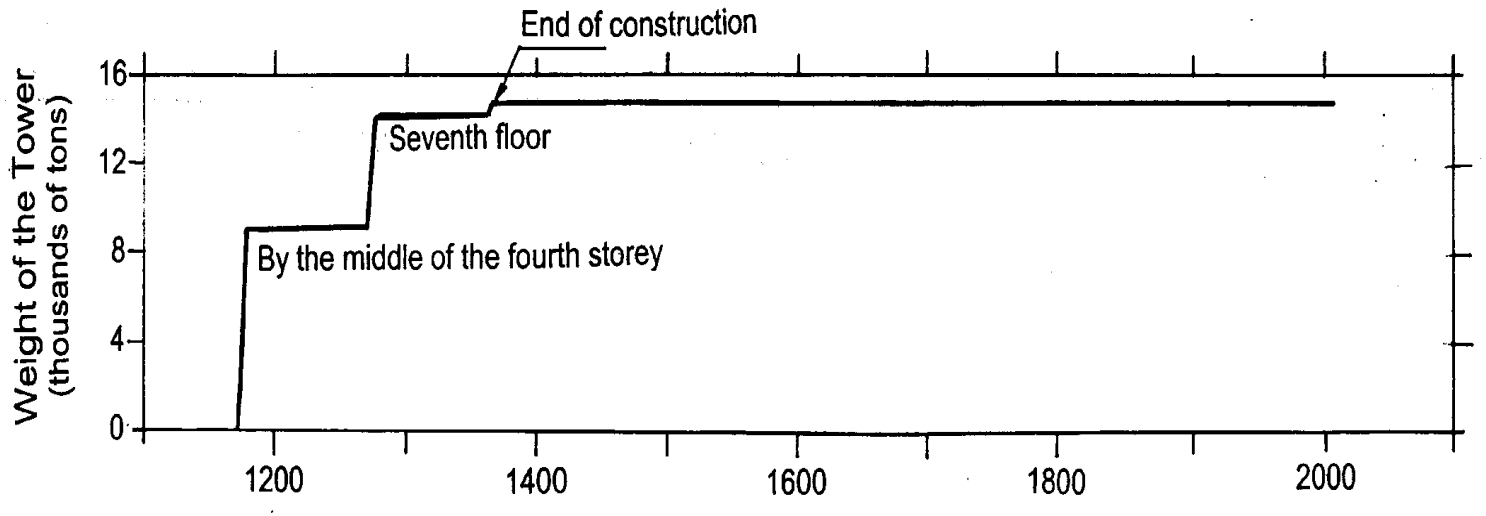
The solution
of the
students
of the
University
of Pisa

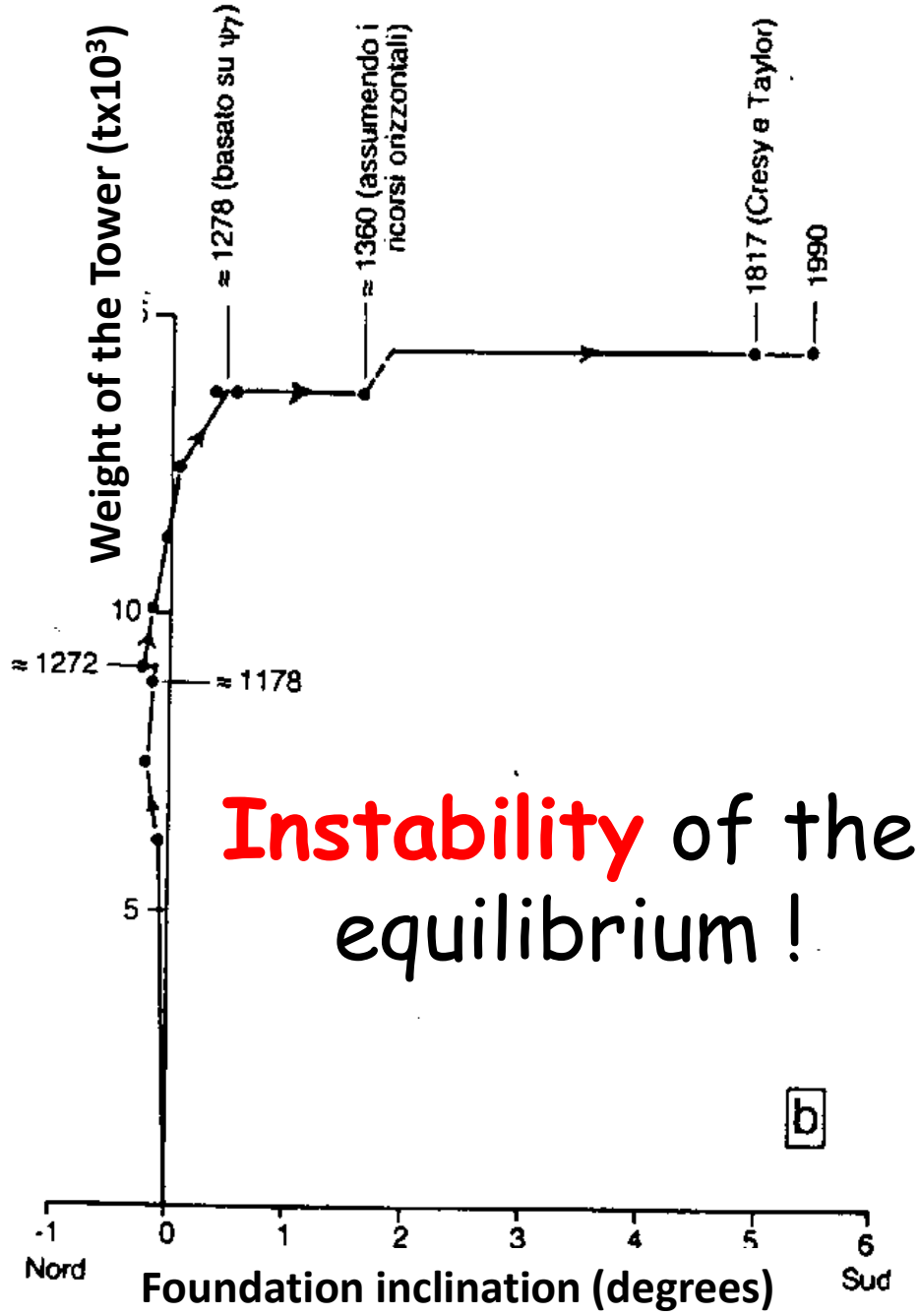


René Magritte
Le domaine enchanté

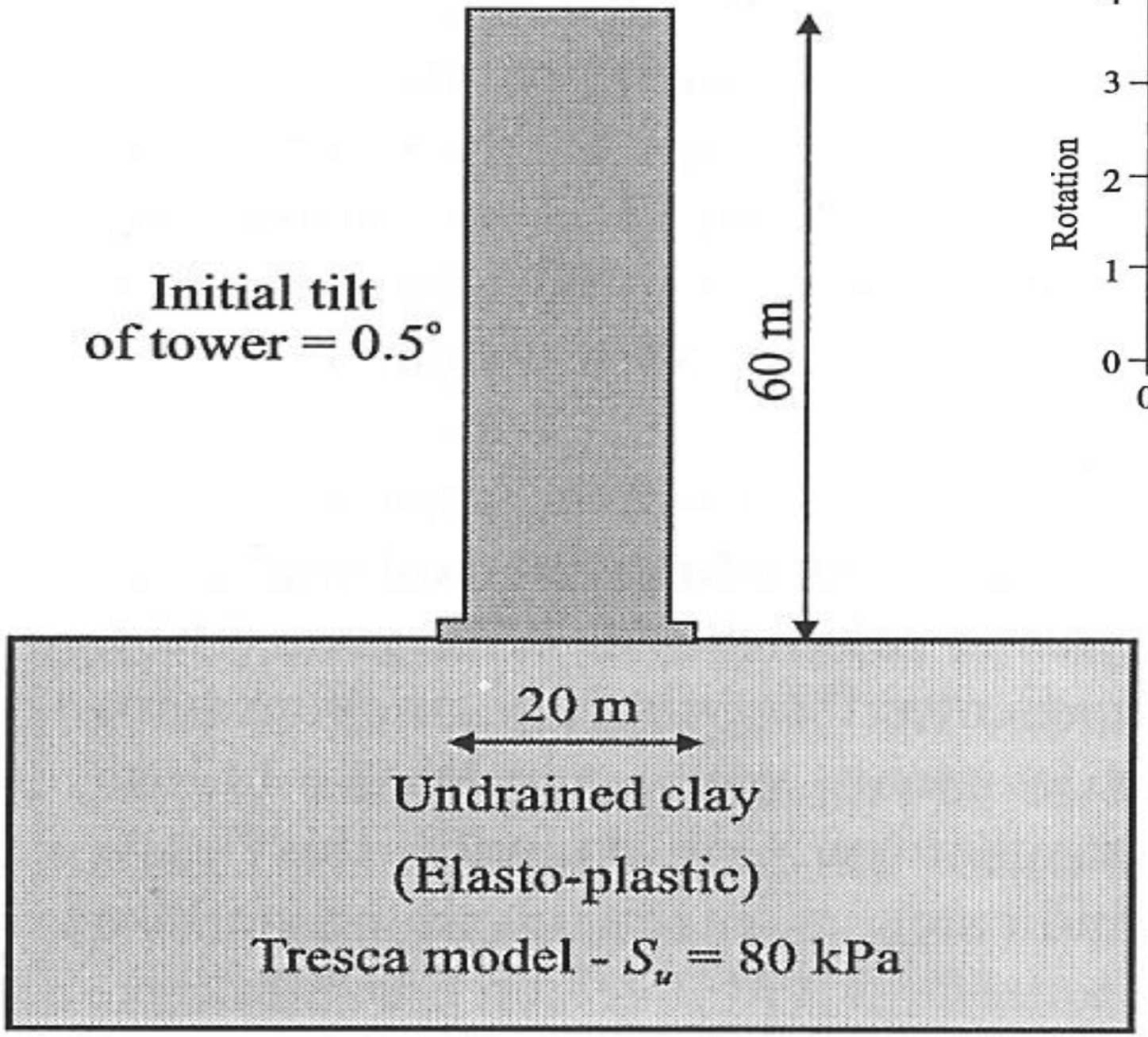
Geotechnical modelling and analysis of the behaviour of the Tower

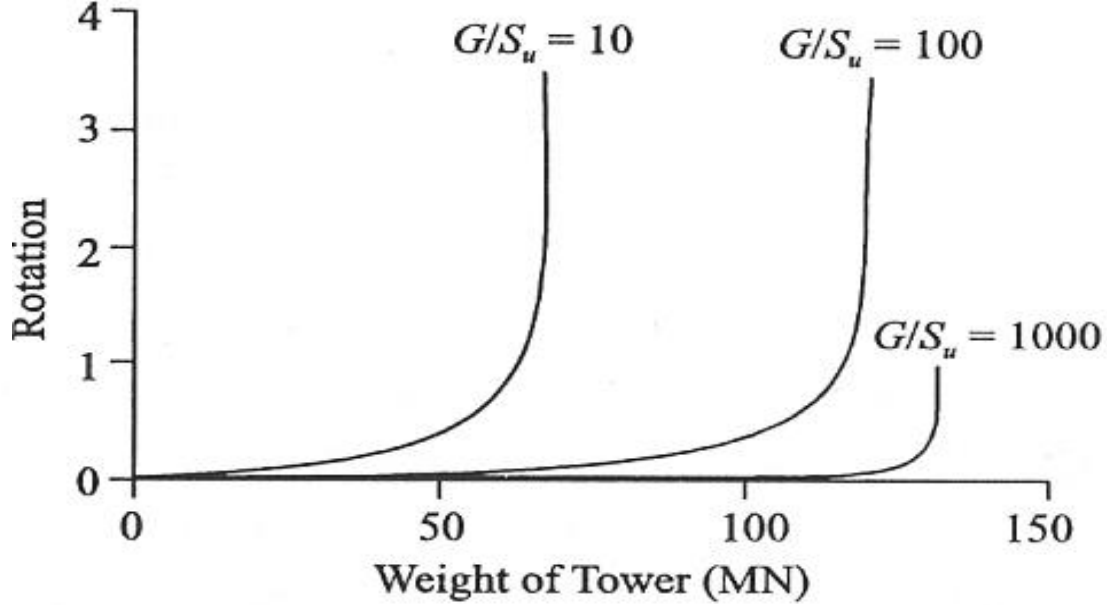


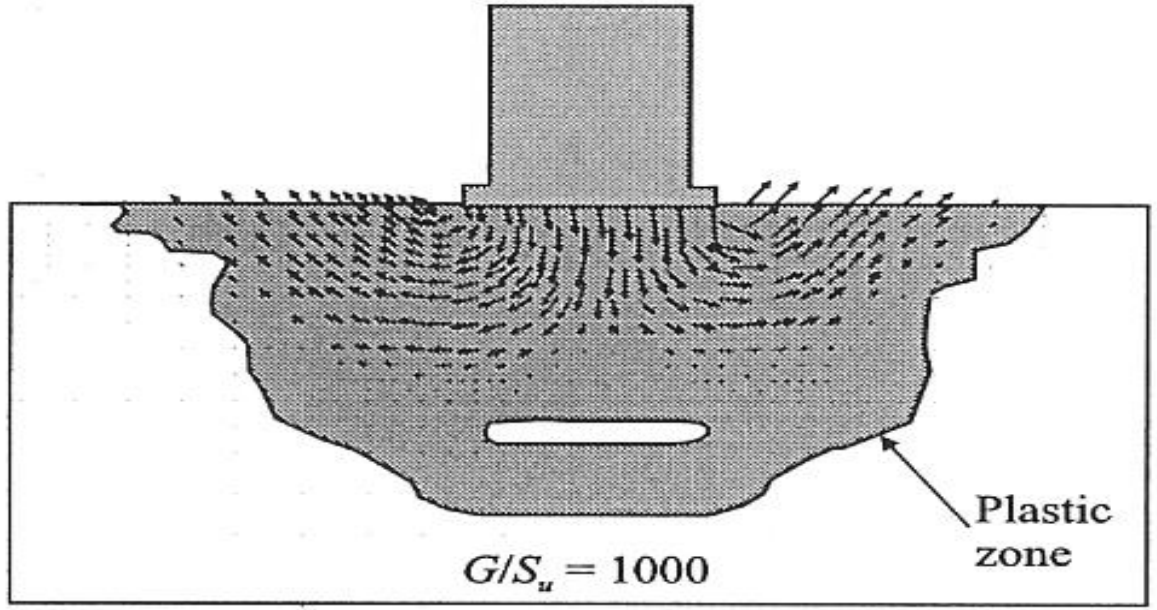


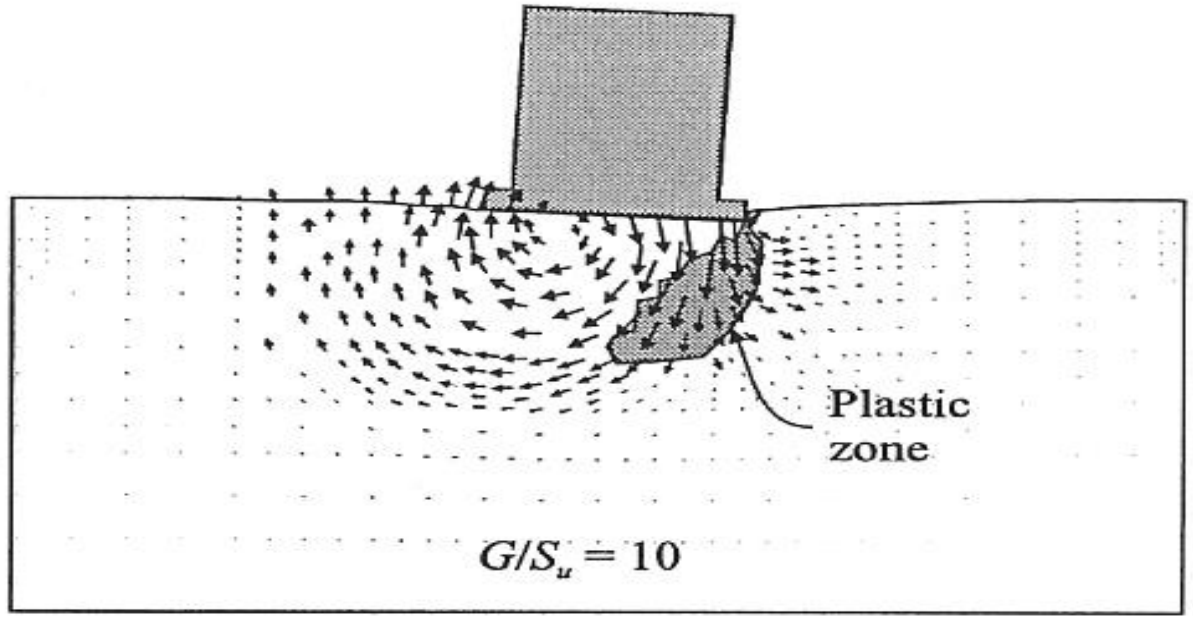


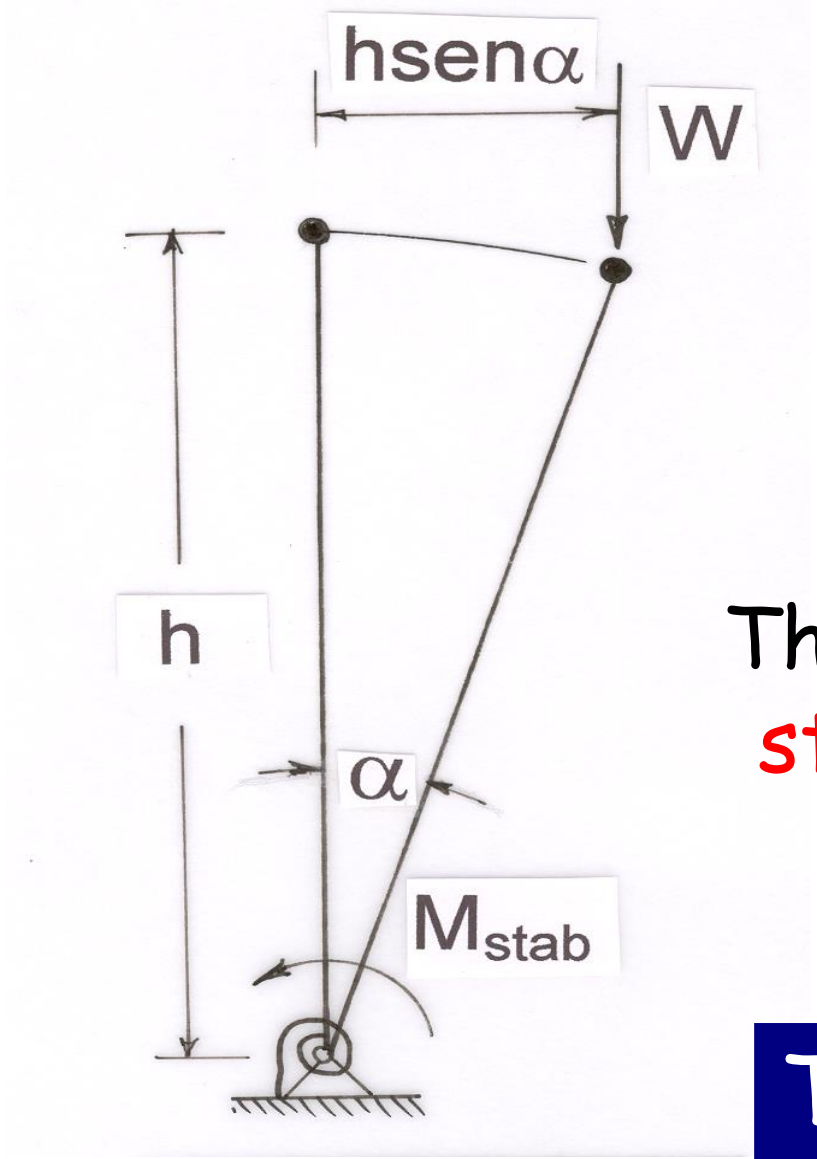
Instability of the equilibrium !


Initial tilt
of tower = 0.5°
60 m
20 m
Undrained clay
(Elasto-plastic)
Tresca model - S_u = 80 kPa


G/S_u = 10
G/S_u = 100
G/S_u = 1000
Rotation
0
1
2
3
4
0
50
100
150
Weight of Tower (MN)


Plastic
zone
$G/S_u = 1000$


Plastic
zone
$G/S_u = 10$



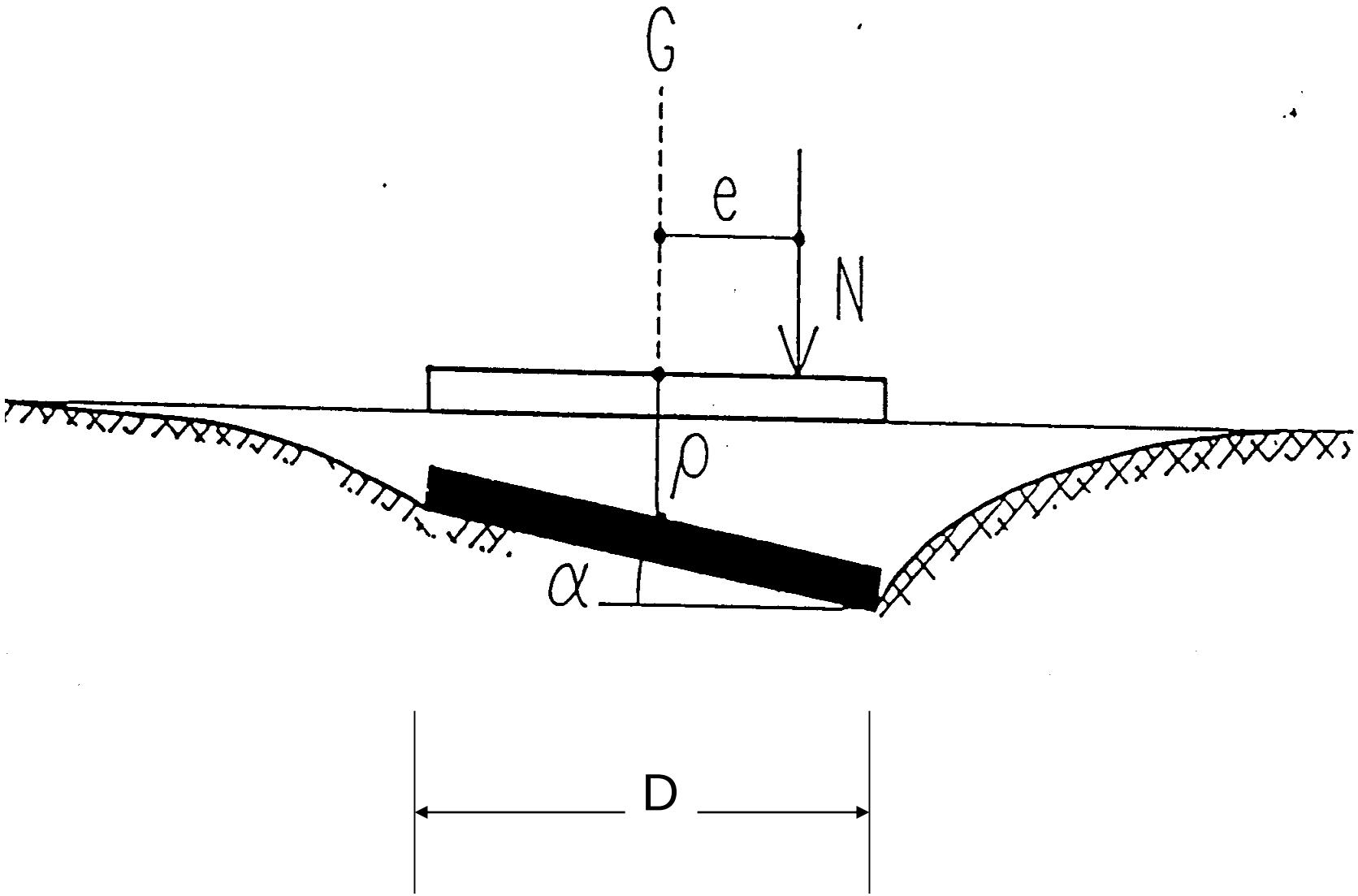
$$M_{rib} = W \cdot h \cdot sin\alpha$$

$$M_{stab} = k_{\alpha} \cdot \alpha$$

$$FS = \frac{M_{stab}}{M_{rib}} = \frac{k_{\alpha}}{W \cdot h}$$

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: ρ, α

Linearly elastic model

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

k_ρ, k_α = constant for a given foundation – subsoil system

Settlement and rotation uncoupled

Linearly elastic model

Winkler's independent springs, coefficient of subgrade reaction k

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

Elastic half space, Young modulus E, Poisson ratio ν

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

k_ρ , k_α = constant for a given foundation - subsoil system, depending on the soil properties (k, or E, ν) and on foundation characteristics (D)

Linearly elastic model

In the case of the Tower:

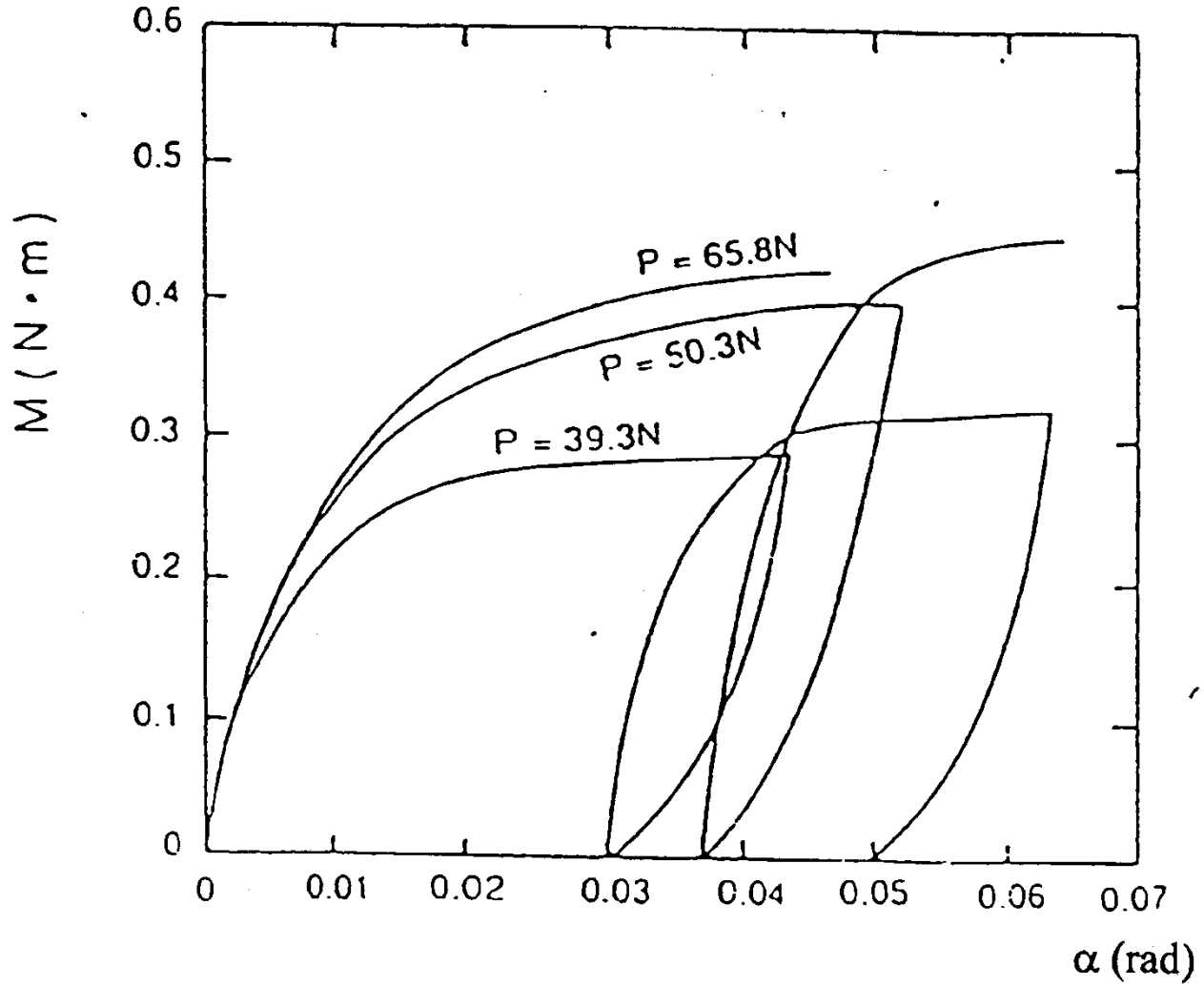
$$k_\rho = \frac{N}{\rho} = \frac{14.500\,t}{3\,m} = 4.850\,t/m$$

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

$$FS = \frac{k_\alpha}{Wh_G} = \frac{307.400}{14.500 \times 22{,}6} = 0{,}95 \approx 1$$

In a linearly elastic model, the tower is very nearly in neutral equilibrium

Centrifuge model tests



Elasto plastic strain hardening

Cheney *et al.* (1991)

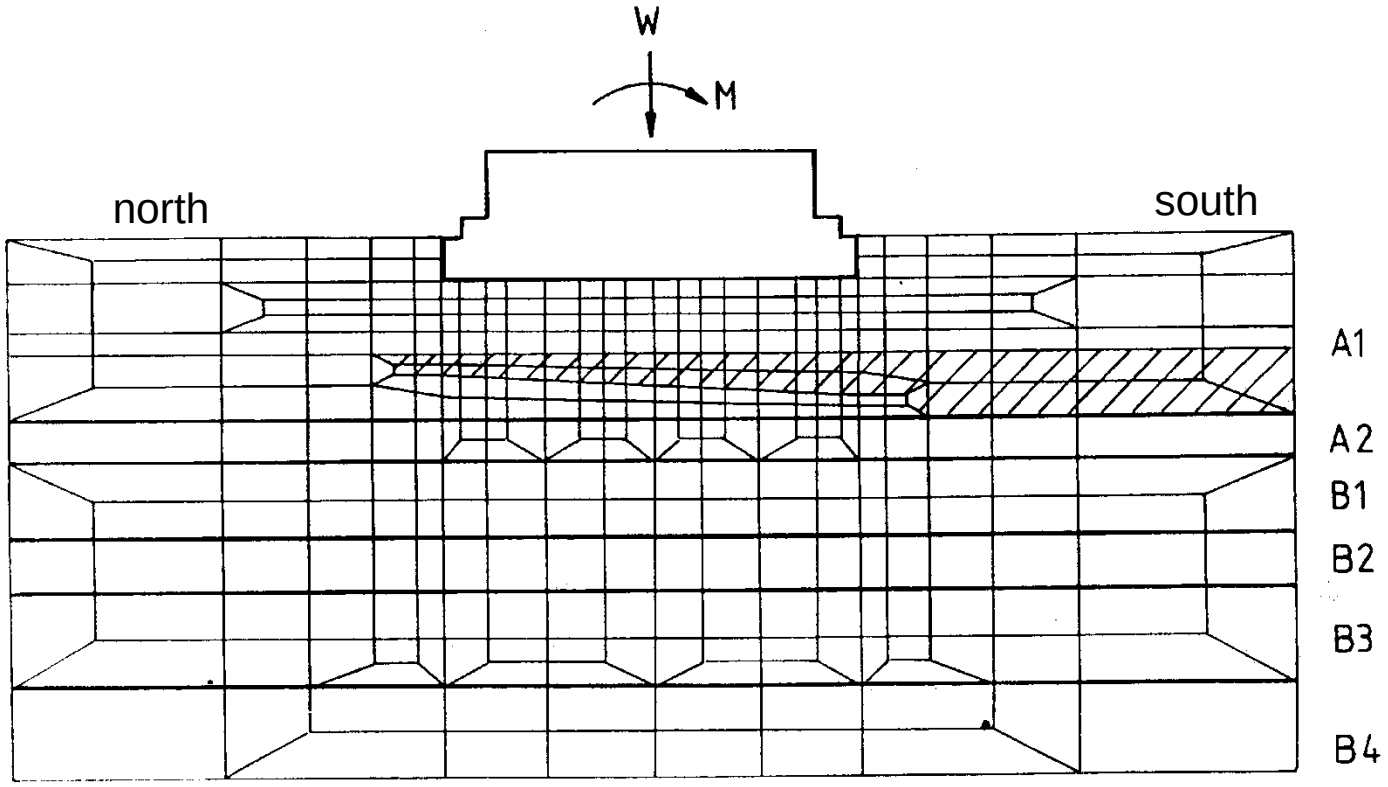
Elasto-plastic strain hardening model

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

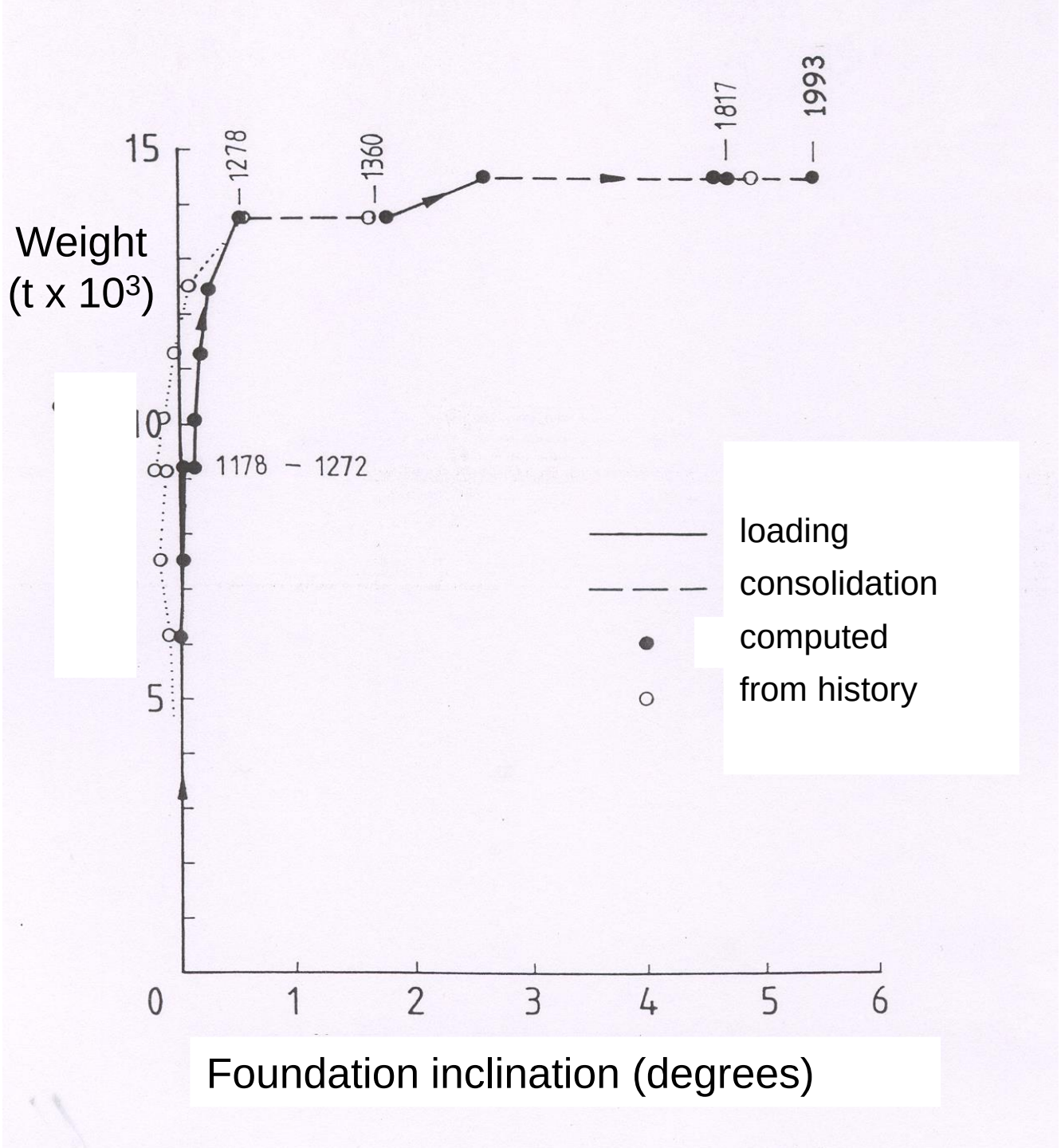
- non linearity $\Rightarrow$ relations in incremental form
- coupling between settlement and rotation
- k_{ij} depending on current stress state and on stress history

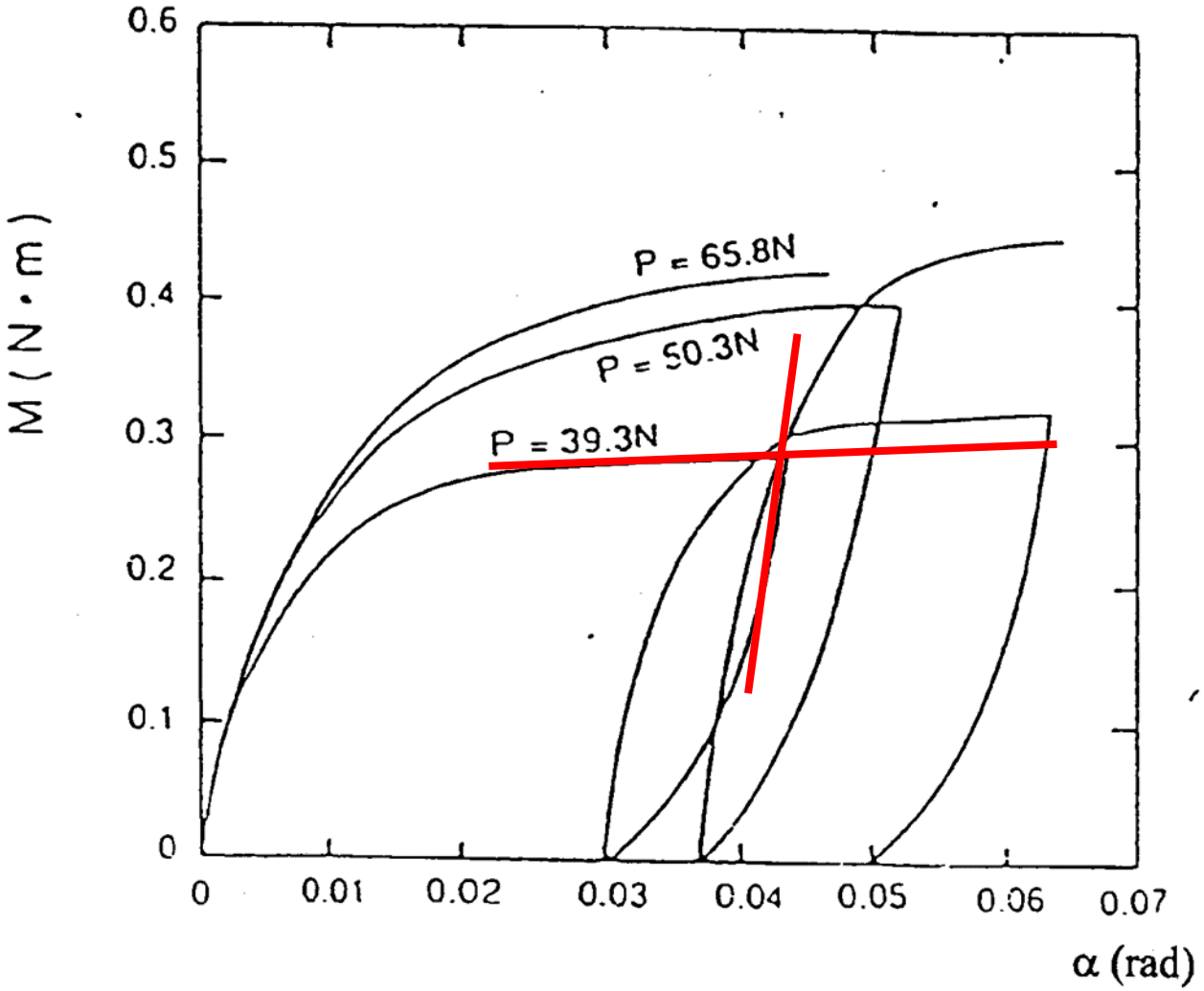
hence

- 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 10³)
15
10
5
0
1
2
3
4
5
6
1178 – 1272
1278
1360
1817
1993
loading
consolidation
computed
from history
Foundation inclination (degrees)



Cheney *et al.* (1991)

$$\frac{k_\alpha}{Wh} = F_s$$

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**

Strategy of the Committee

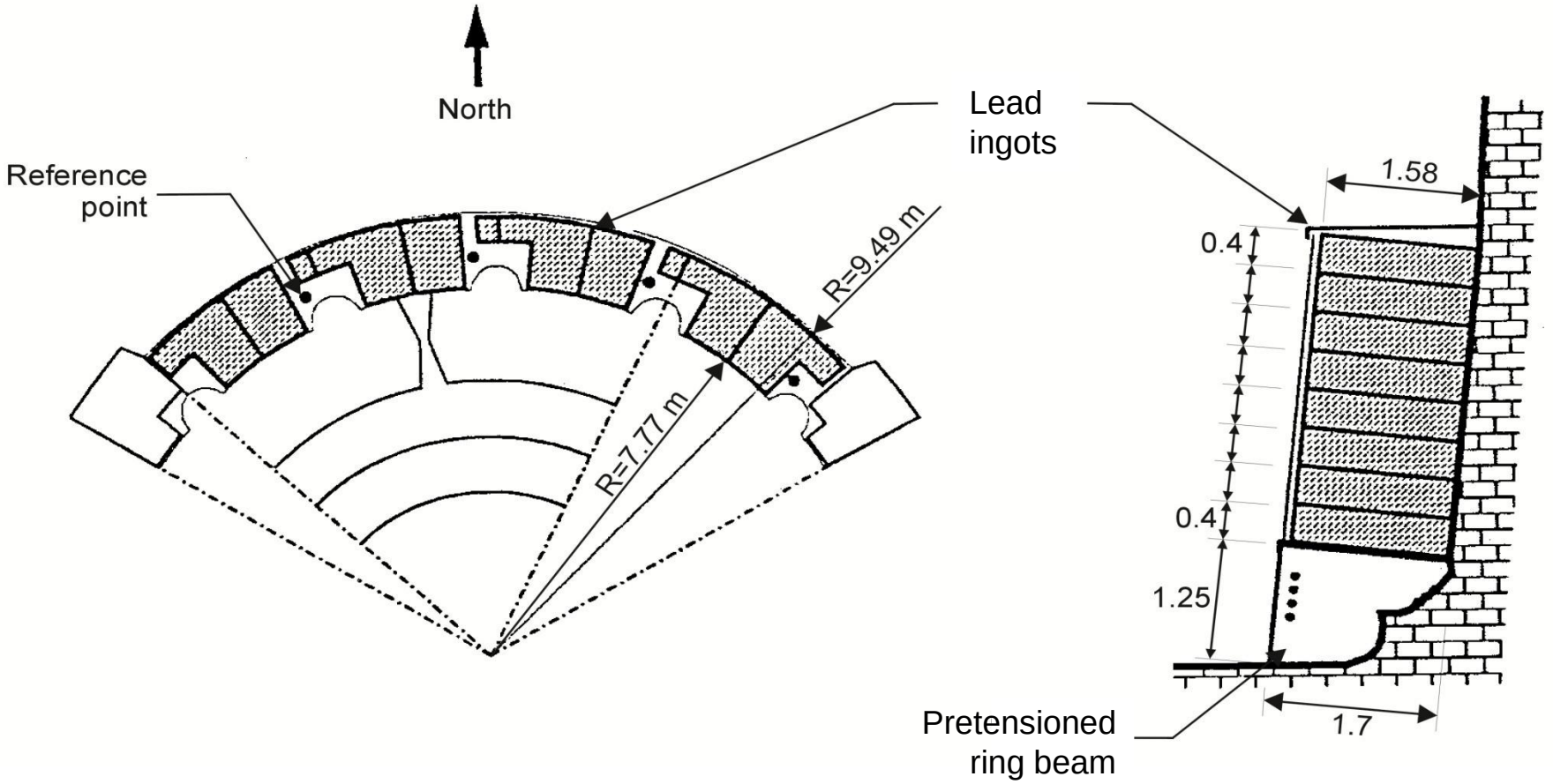
Two stages:

1. Temporary

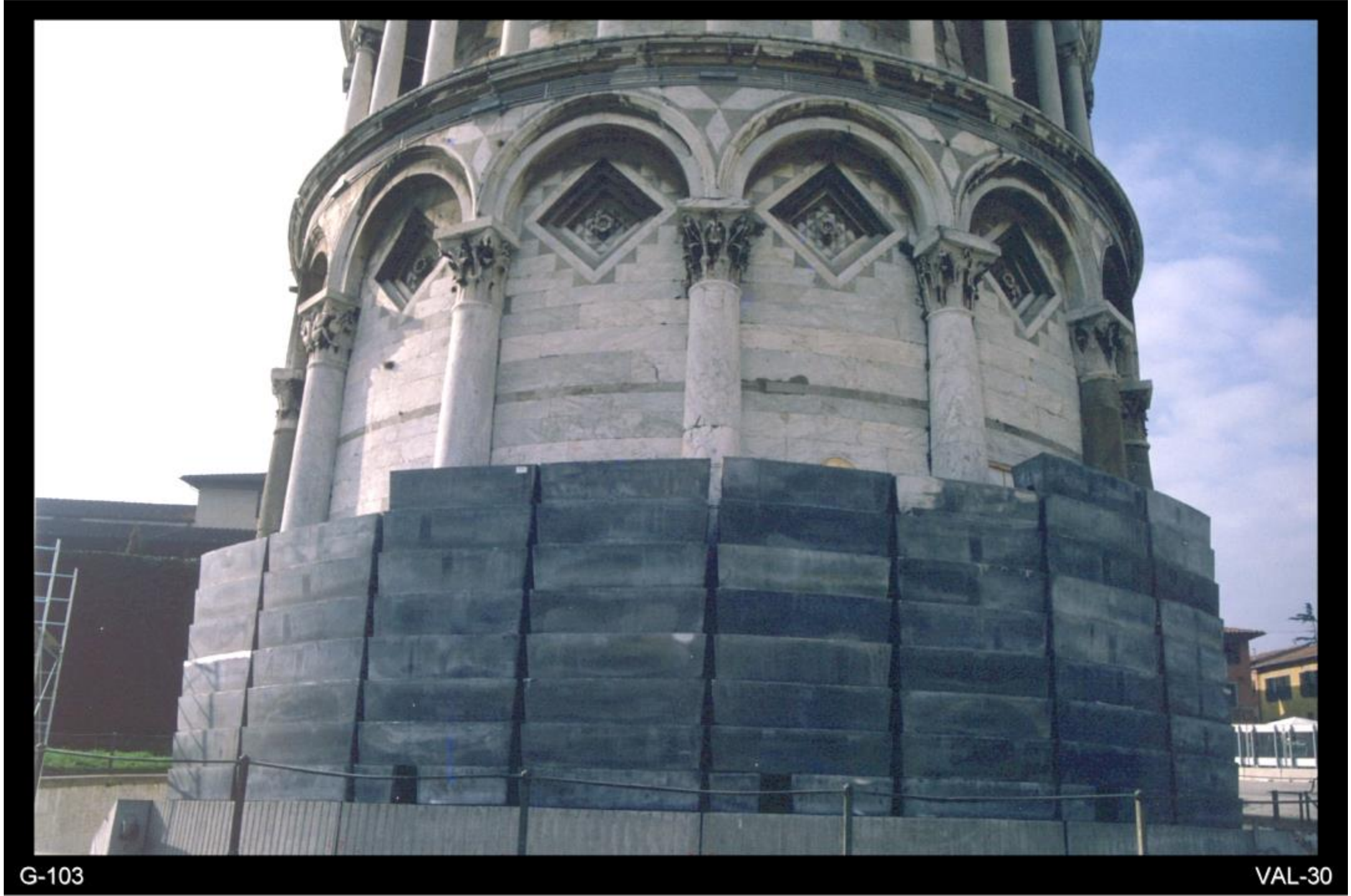
- To improve the stability and gain time to properly devise, design and implement the permanent solution
- Fully reversible

2. Permanent

- to permanently (?) stabilise the Tower

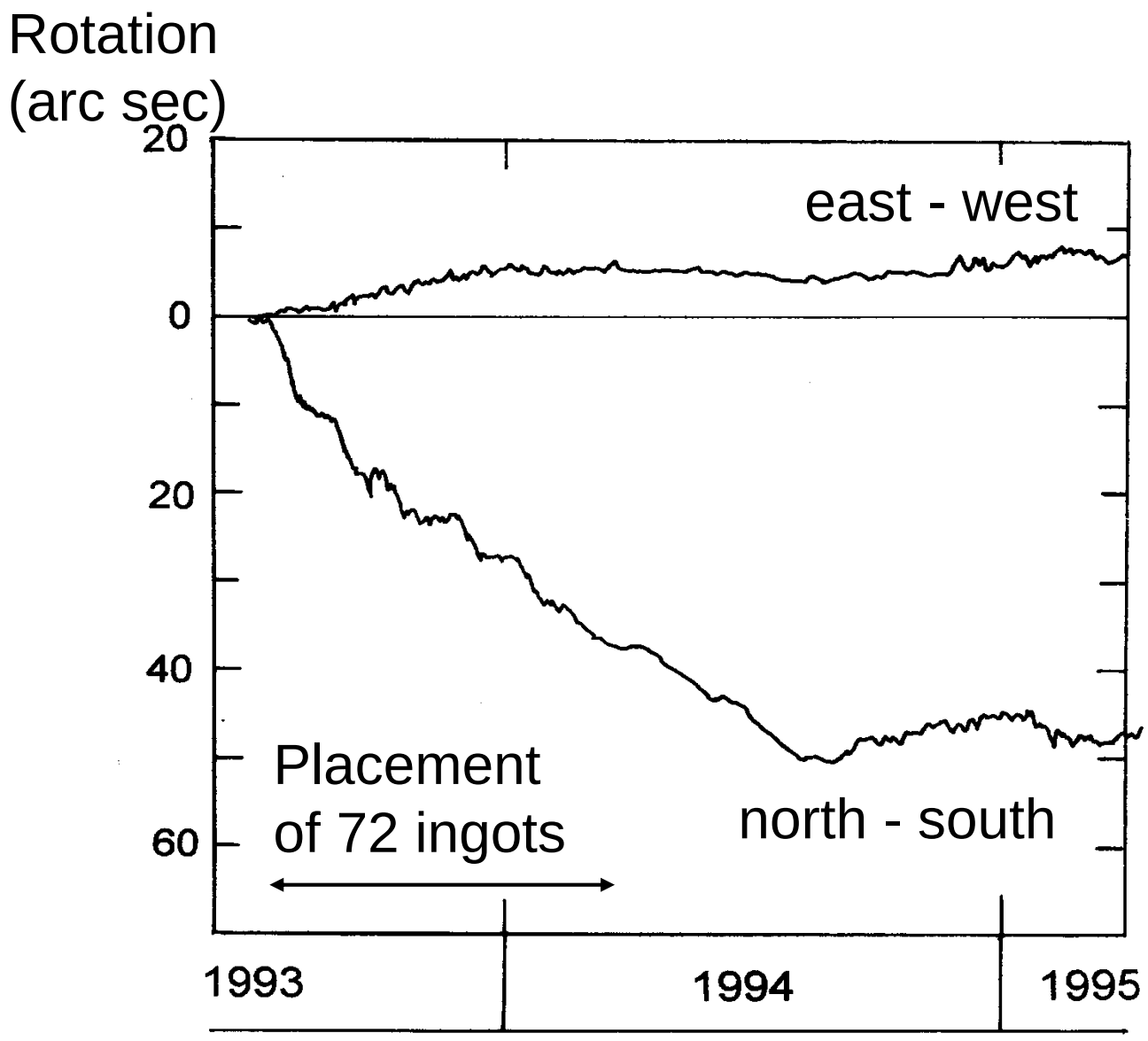


Temporary geotechnical stabilisation



G-103

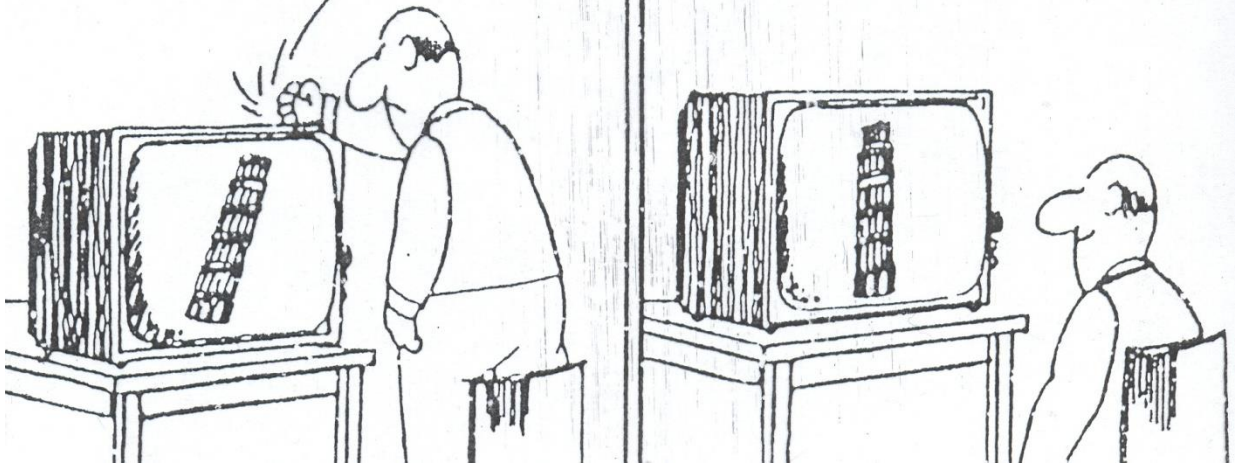
VAL-30



Decrease of inclination by placement of lead counterweight

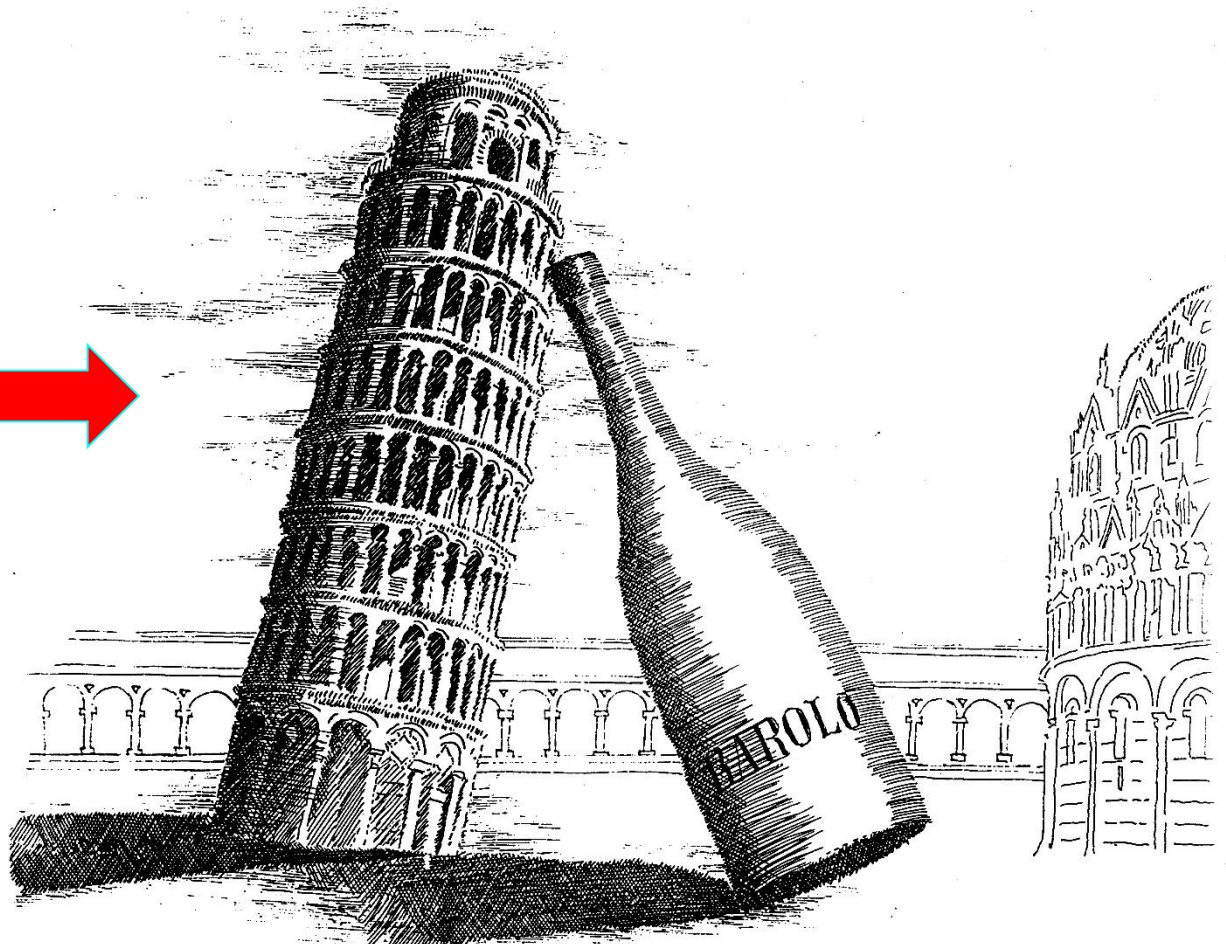
Permanent Geotechnical Solution

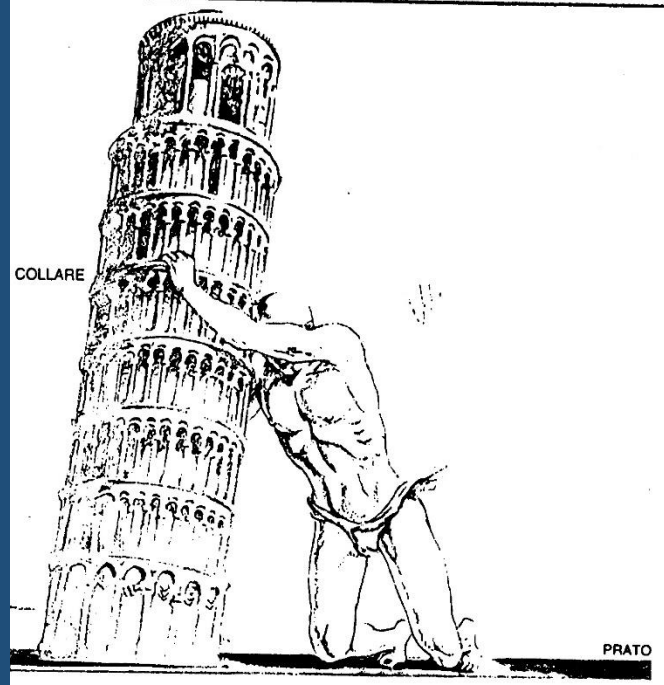
- many possibilities
- many ideas

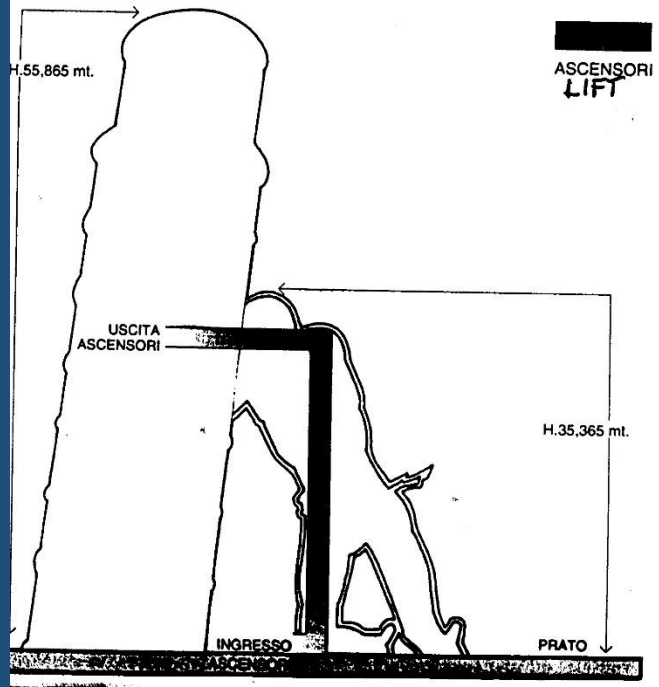


The dynamic impulse solution

My favorite solution







Spett. COMUNE DI PISA
epc Sovrintendenza BENI CULTURALI DI PISA
epc MINISTERO DELLA CULTURA
epc ASS. COMMERCIANTI E TURISMO PISA
epc REGIONE TOSCANA
epc MINISTERO LAVORI PUBBLICI
epc APT PISA
epc STAMPA

IPOTESI DI SISTEMAZIONE E PERCORRIBILITÀ TURISTICA DELLA **TORRE DI PISA**

Del Cav. Uff.
RODOLFO GENTILI

Sono appassionato delle opere d'Arte ed in particolare della Torre di Pisa. Propongo una soluzione attuabile per fermare l'inclinazione e rendere agibile il monumento. Si tratterebbe di realizzare una gigantesca statua di sostegno, con struttura in acciaio (tipo torre Eiffel) e calcestruzzo 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 ammortizzerà in breve e lascierà 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 prefabbricato componibile in calcestruzzo leggero.

Cav. Uff. RODOLFO GENTILI
Macerata - P.zza N. Sauro, 69
Tel. (0733) 238619
1993

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

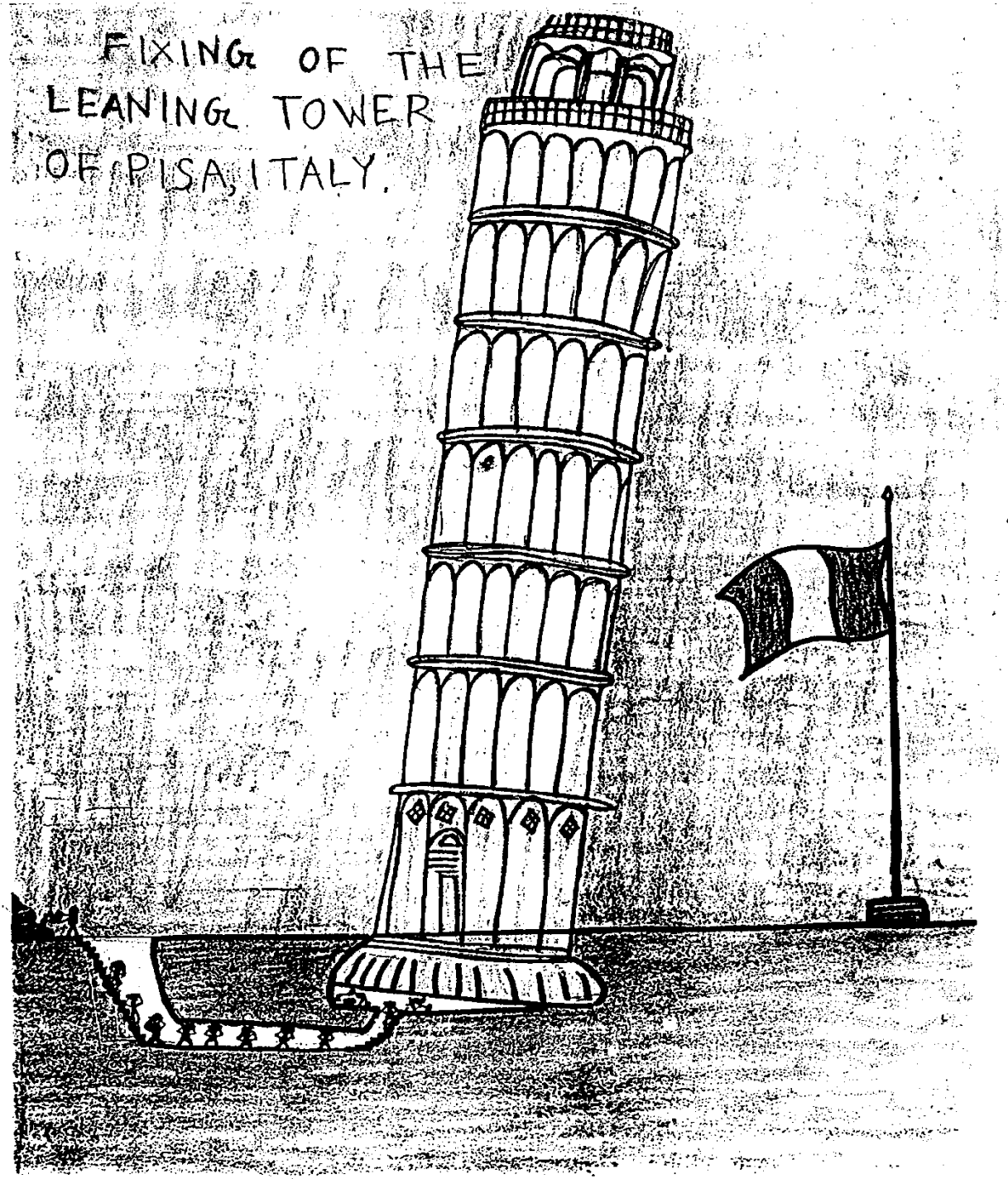
The solution devised by the Committee

The following mechanisms have been considered:

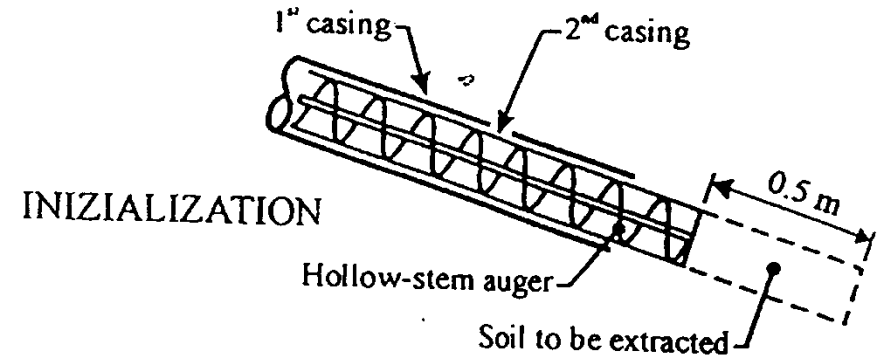
- surface loading north of the Tower, by means of a pressing slab and pretensioned ground anchors;
- inducing a shrinkage of the pancone clay below the north edge of the foundation either by electroosmosis or by vacuum pumping;
- controlled removal of small volumes of soil below the north edge of the 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

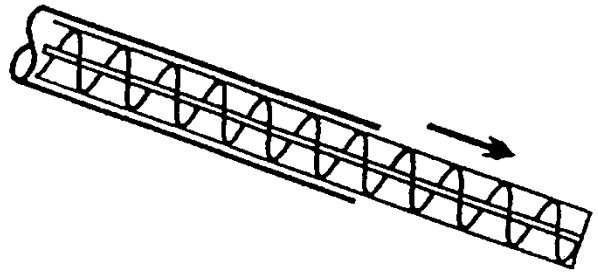
The solution devised by the Committee



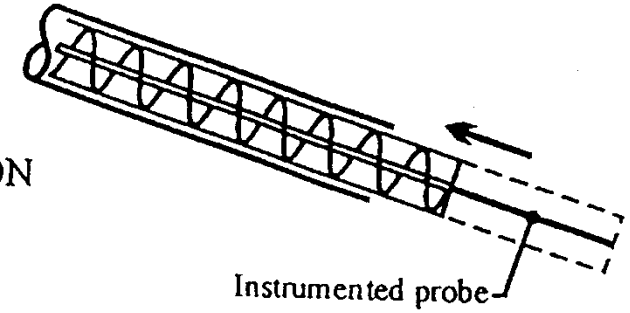
Chumki Bhaban, Bangla Desh
9 years old in 1992
To the Committee via
UNESCO, Paris



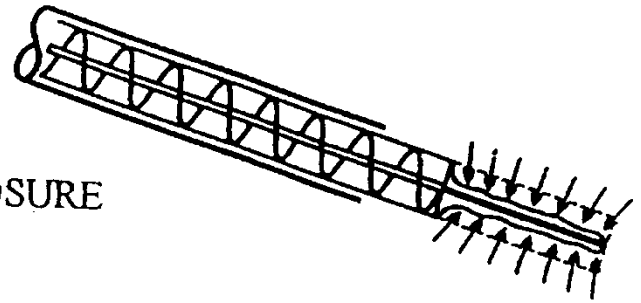
INIZIALIZATION



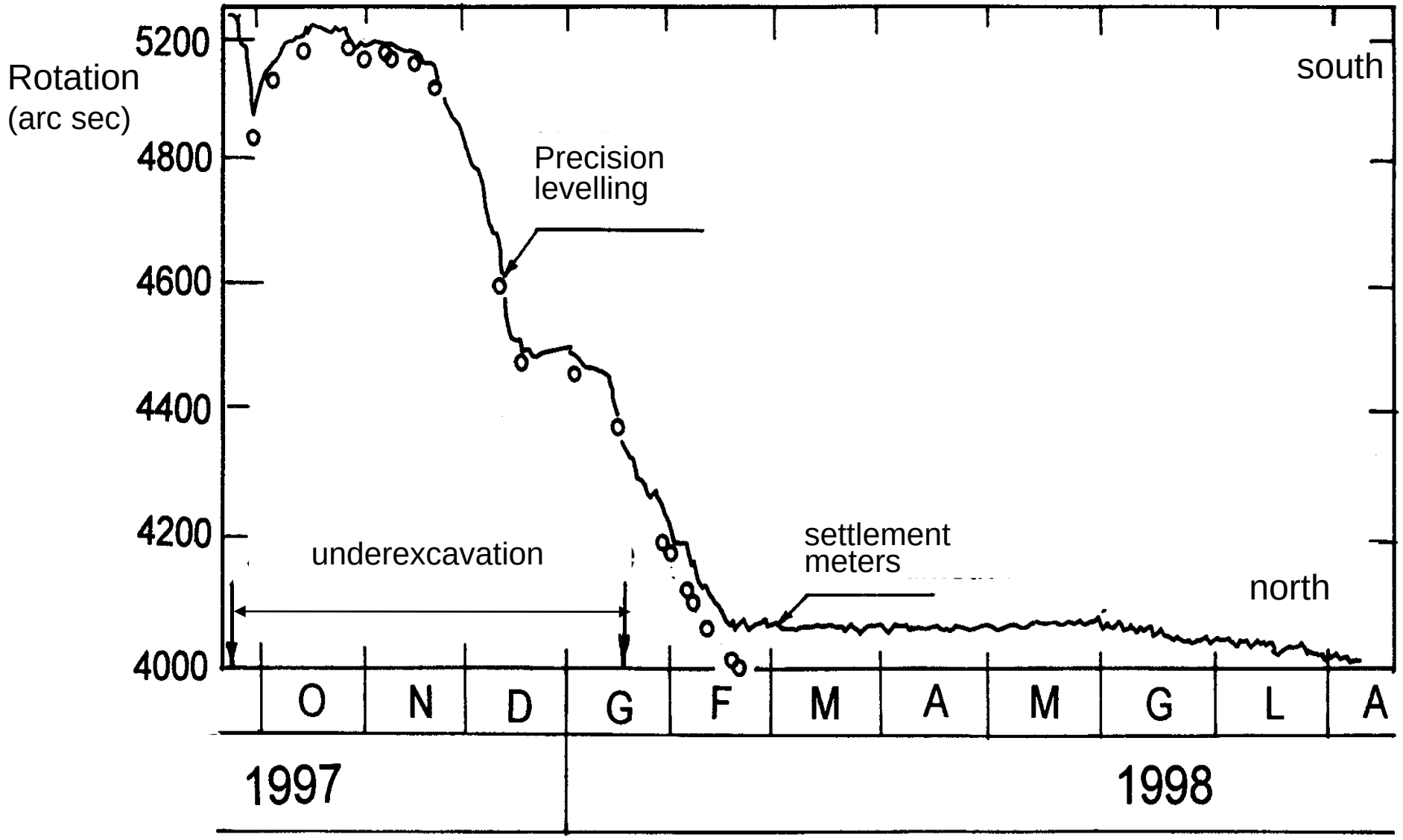
INSERTION



EXTRACTION

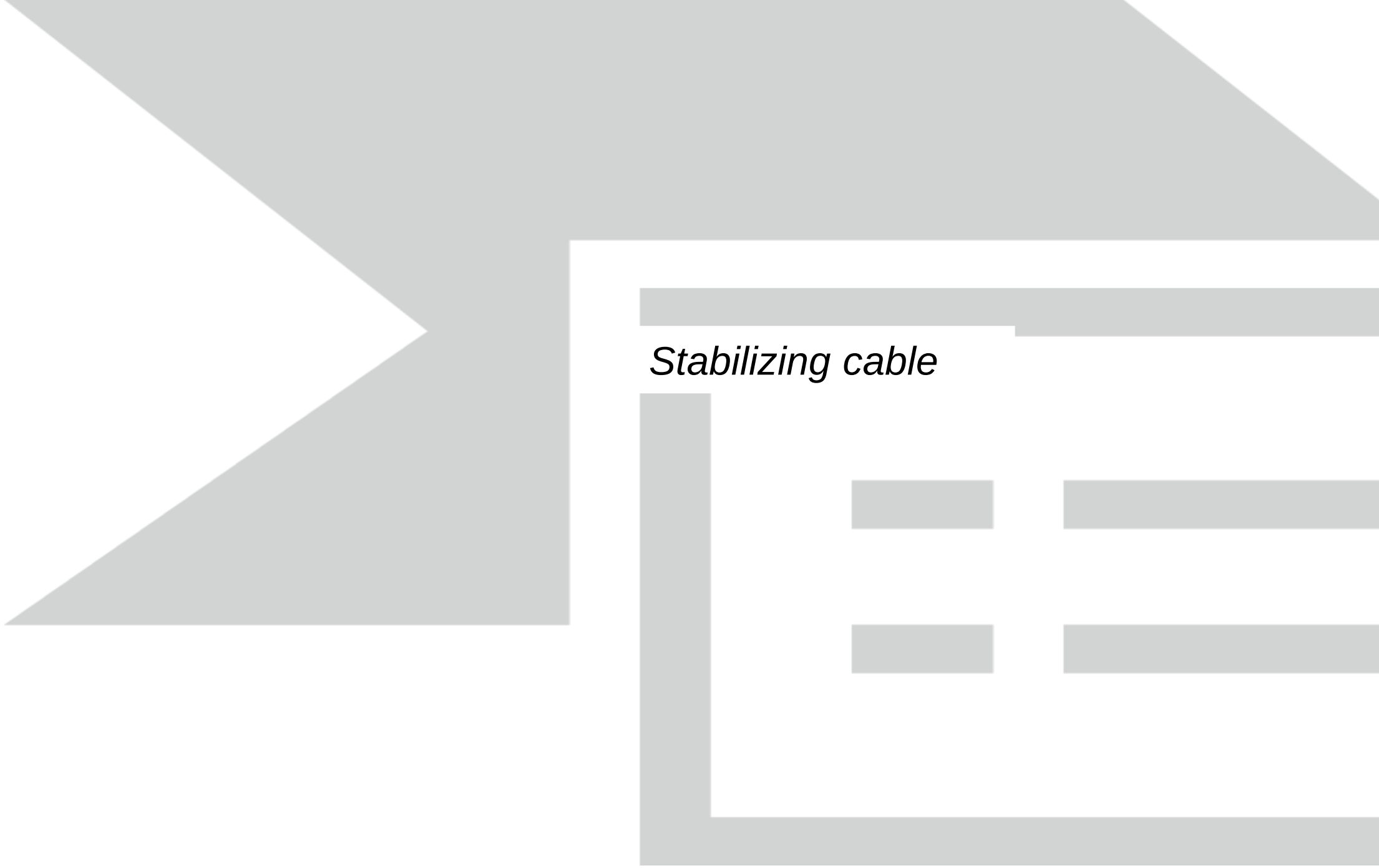


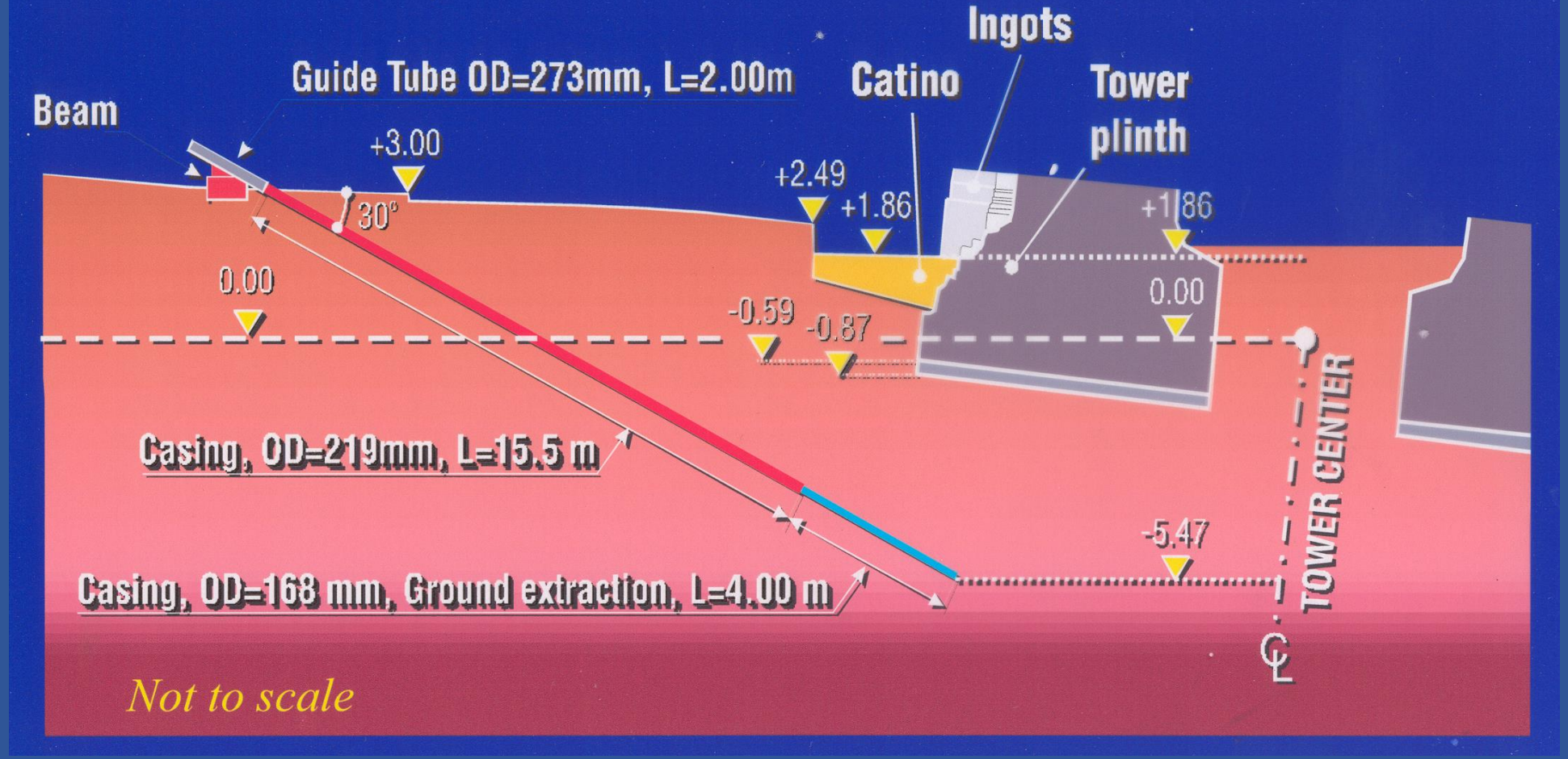
CAVITY CLOSURE



Field experiment of underexcavation: rotation of the plinth

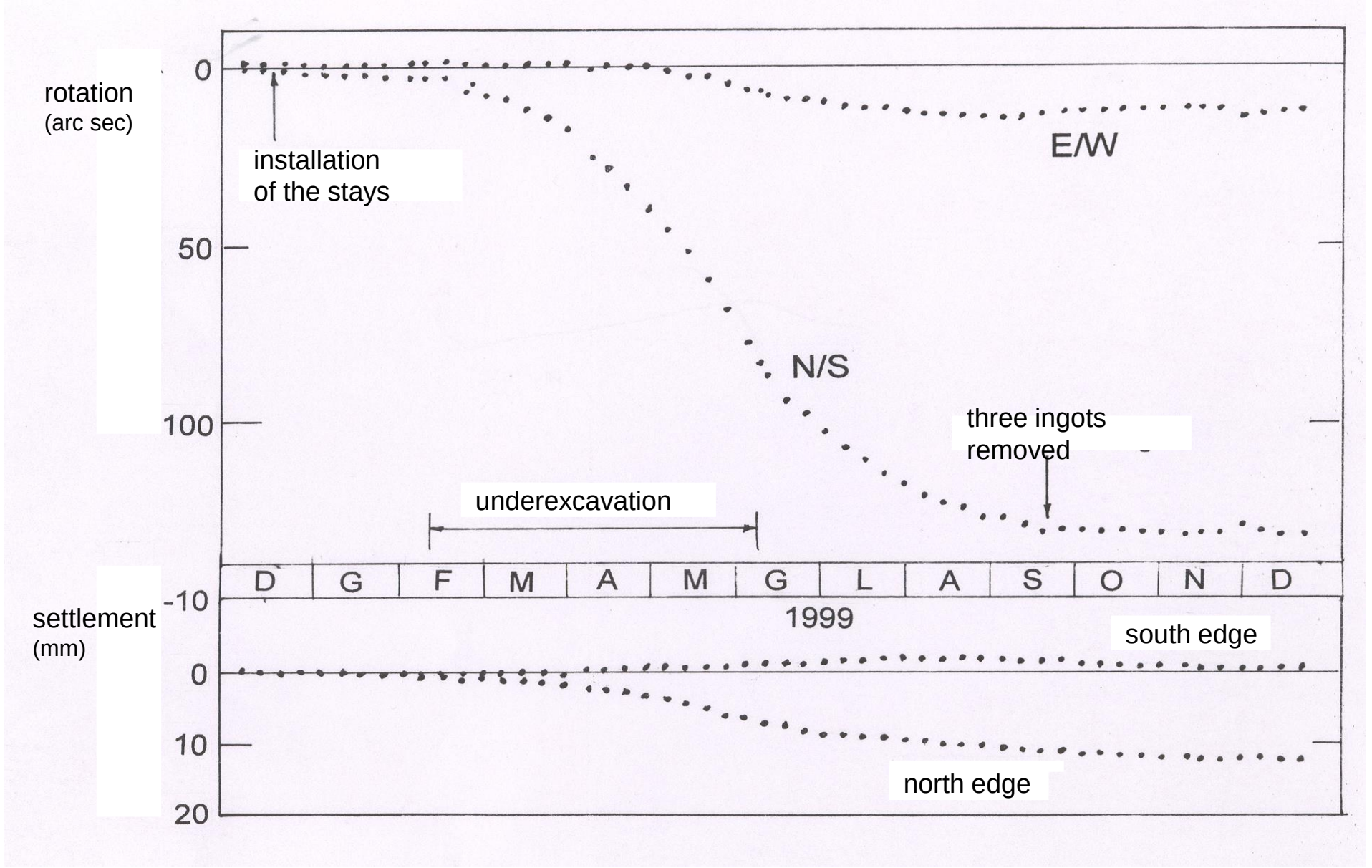

7ª Cornice
3ª Cornice
2ª Cornice

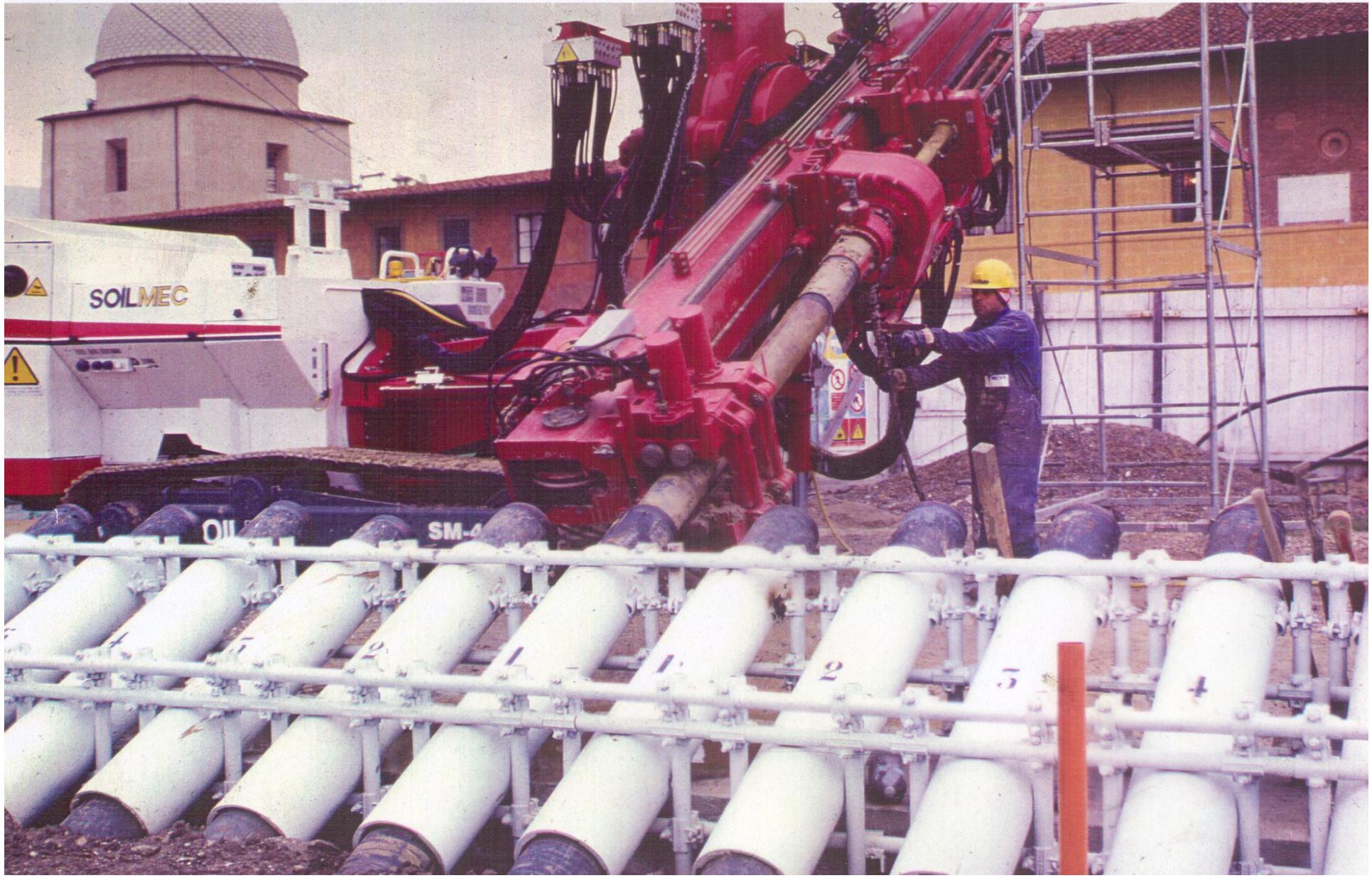

Stabilizing cable

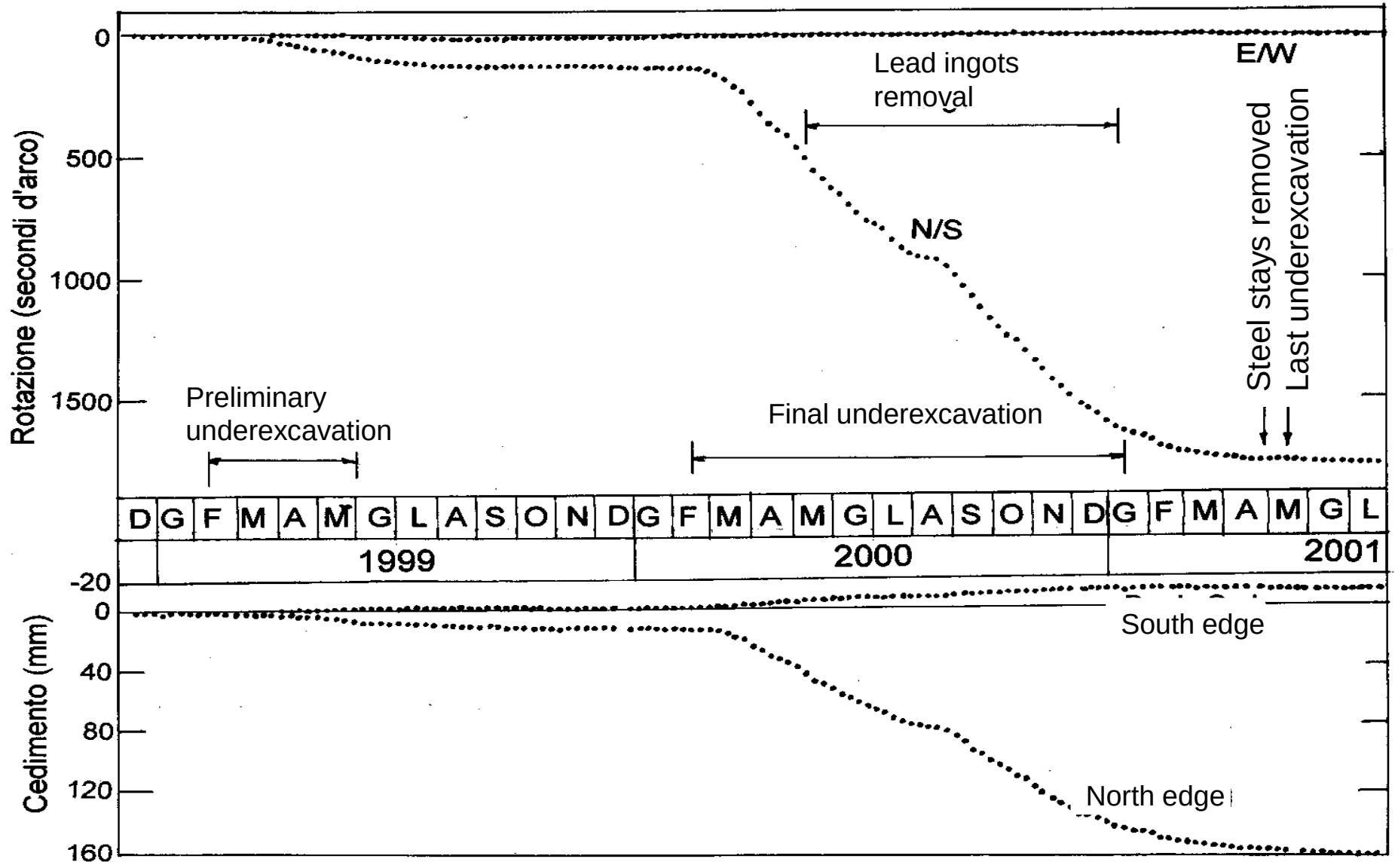


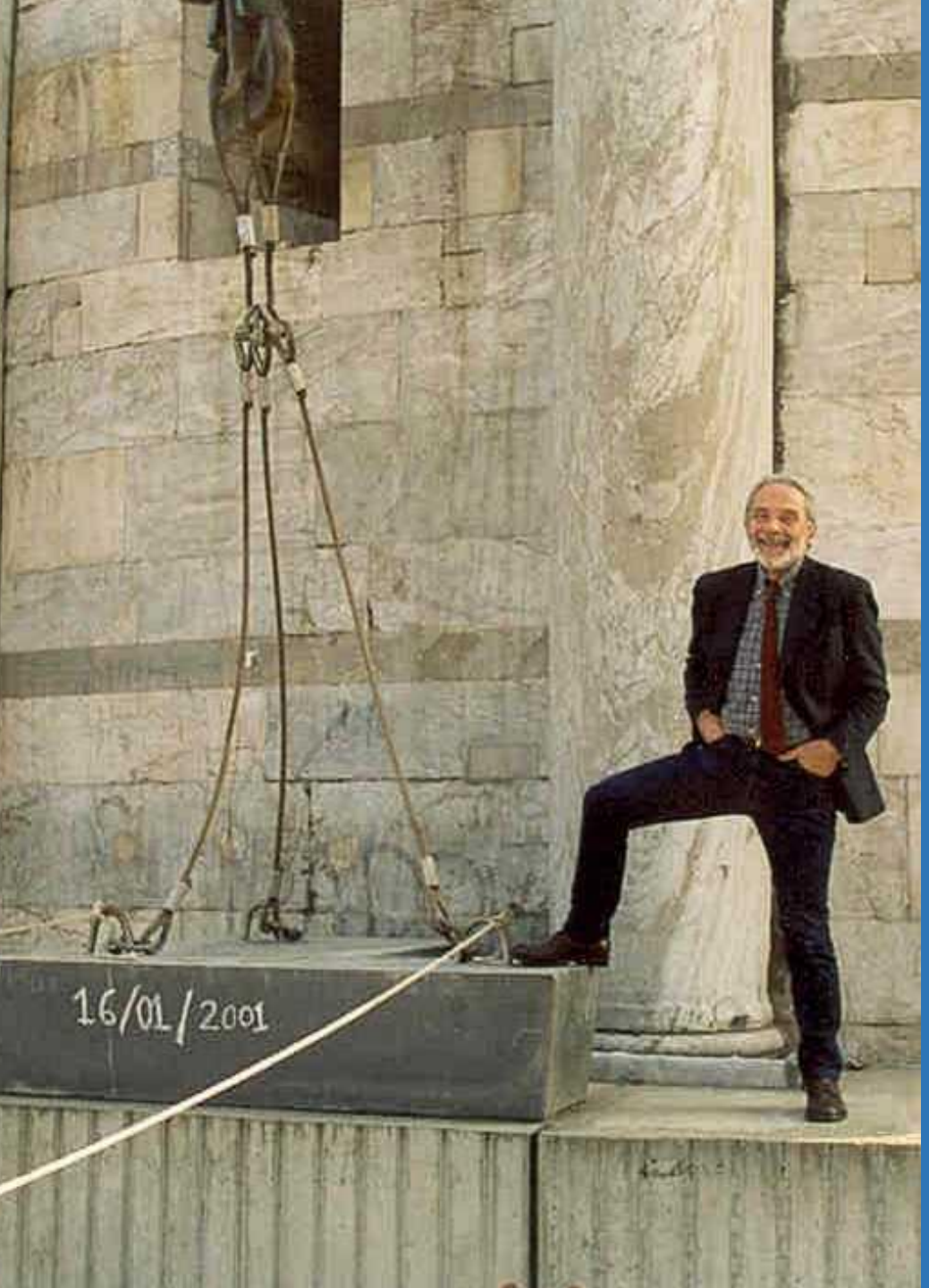
Preliminary underexcavation: cross section


SOILMEC
SOILMEC

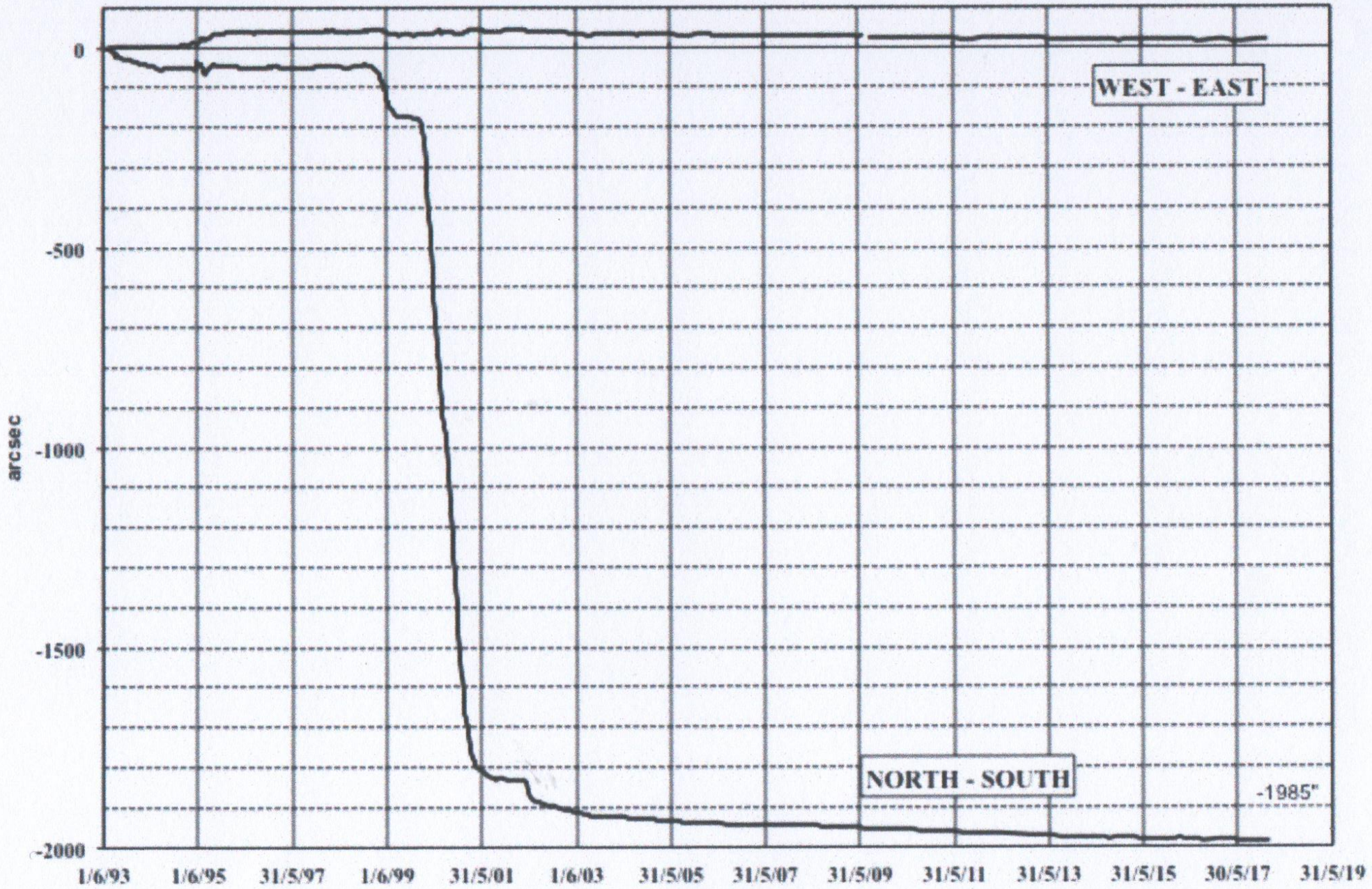

rotation
(arc sec)
0
50
100
installation
of the stays
E/W
N/S
three ingots
removed
underexcavation
D
G
F
M
A
M
G
L
A
S
O
N
D
1999
settlement
(mm)
-10
0
10
20
south edge
north edge

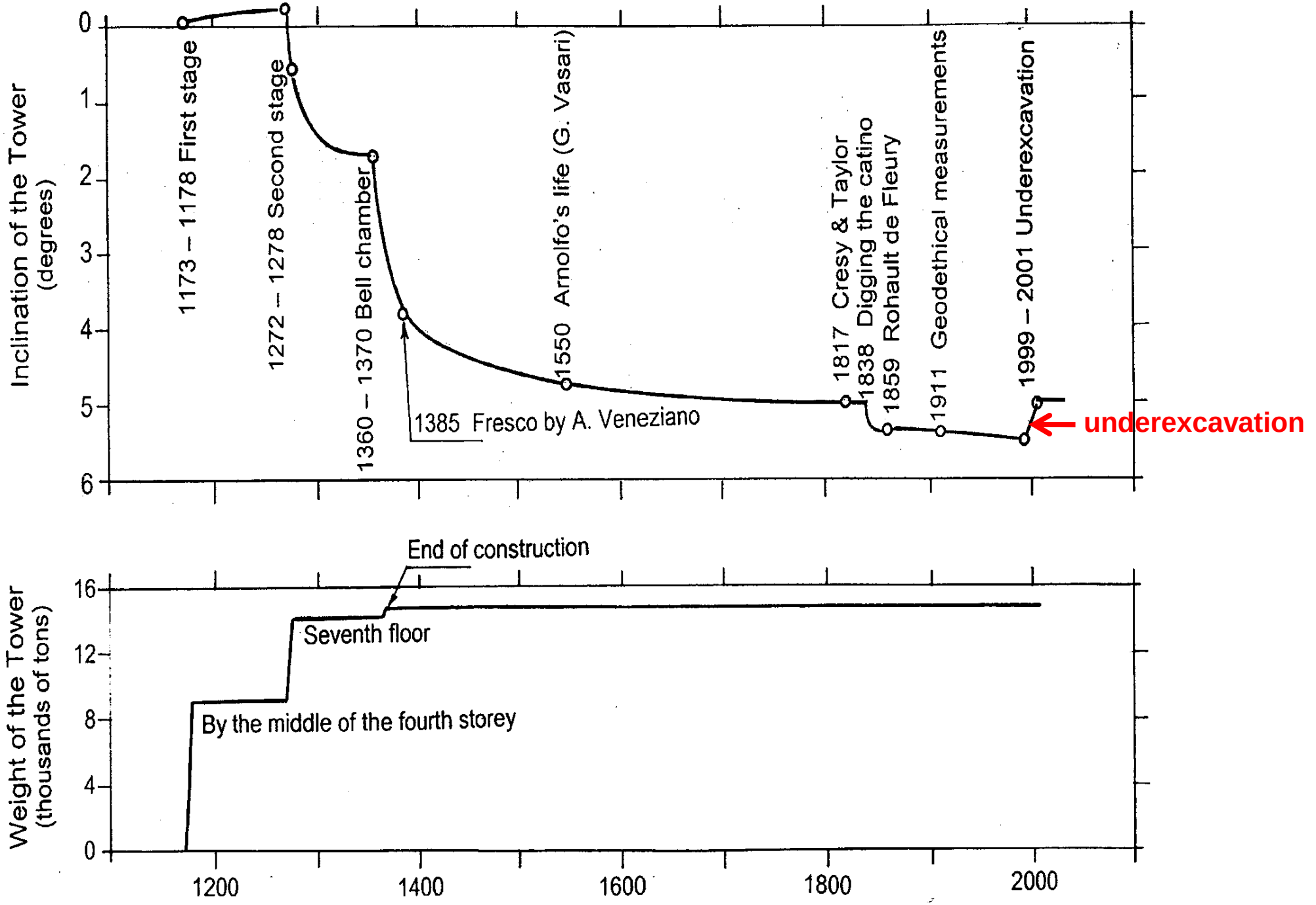

SOILMEC

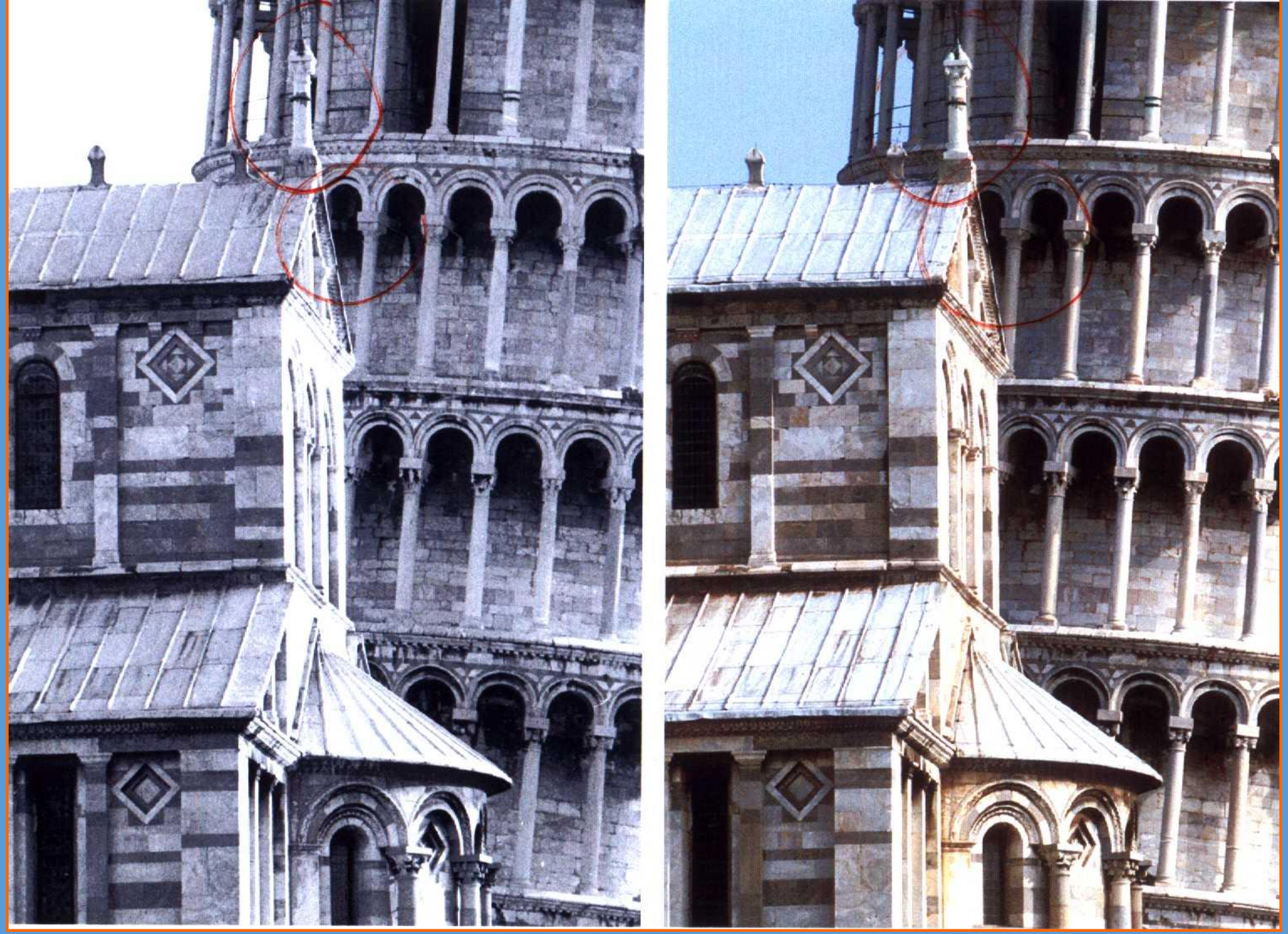

Rotazione (secondi d'arco)
0
500
1000
1500
E/W
N/S
Lead ingots
removal
Steel stays removed
Last underexcavation
Preliminary
underexcavation
Final underexcavation
D G F M A M G L A S O N D G F M A M G L A S O N D G F M A M G L
1999
2000
2001
-20
Cedimento (mm)
0
40
80
120
160
South edge
North edge



Removal of the last ingot January 2001


0
-500
-1000
-1500
-2000
arcsec
WEST - EAST
NORTH - SOUTH
-1985"
1/6/93
1/6/95
31/5/97
1/6/99
31/5/01
1/6/03
31/5/05
31/5/07
31/5/09
31/5/11
31/5/13
31/5/15
30/5/17
31/5/19


Inclination of the Tower
(degrees)
0
1
2
3
4
5
6
1173 – 1178 First stage
1272 – 1278 Second stage
1360 – 1370 Bell chamber
1385 Fresco by A. Veneziano
1550 Arnolfo's life (G. Vasari)
1817 Cresy & Taylor
1838 Digging the catino
1859 Rohault de Fleury
1911 Geodethical measurements
1999 – 2001 Underexcavation
underexcavation
Weight of the Tower
(thousands of tons)
16
12
8
4
0
End of construction
Seventh floor
By the middle of the fourth storey
1200
1400
1600
1800
2000



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.

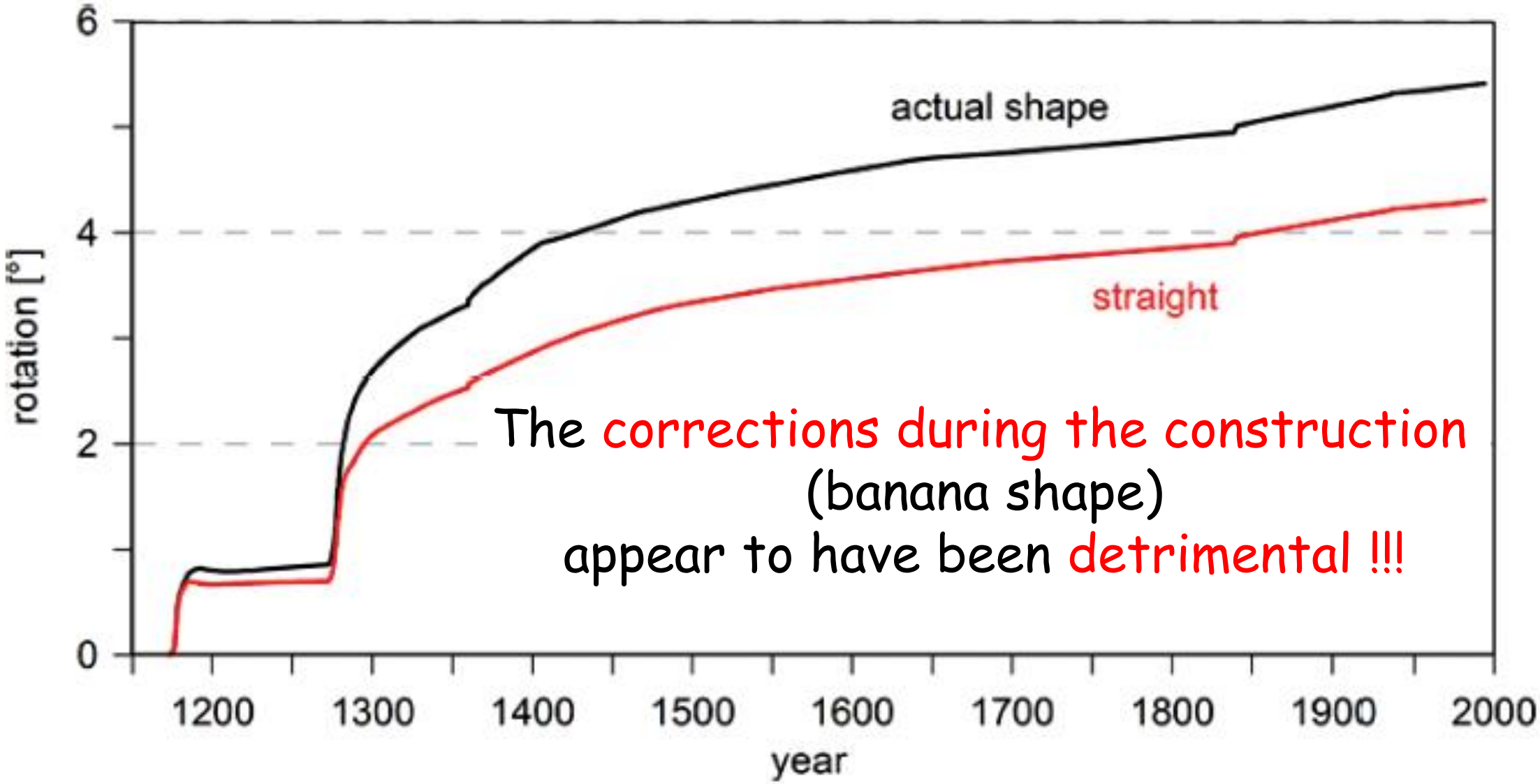
Lessons learned

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

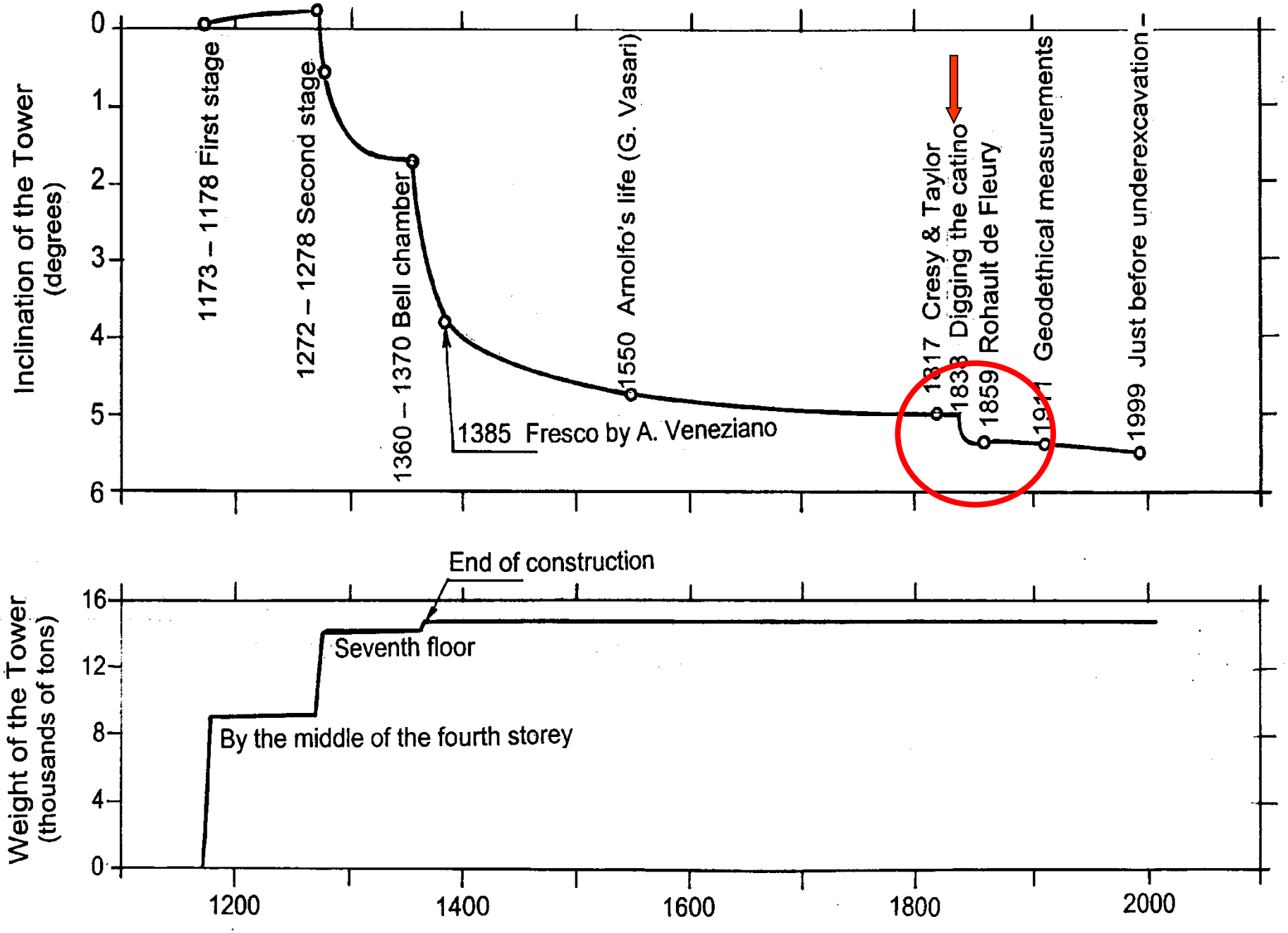
Obstinacy of modern engineers
succeeding in saving the Tower
through over a century of attempts
and in spite of many difficulties and some errors

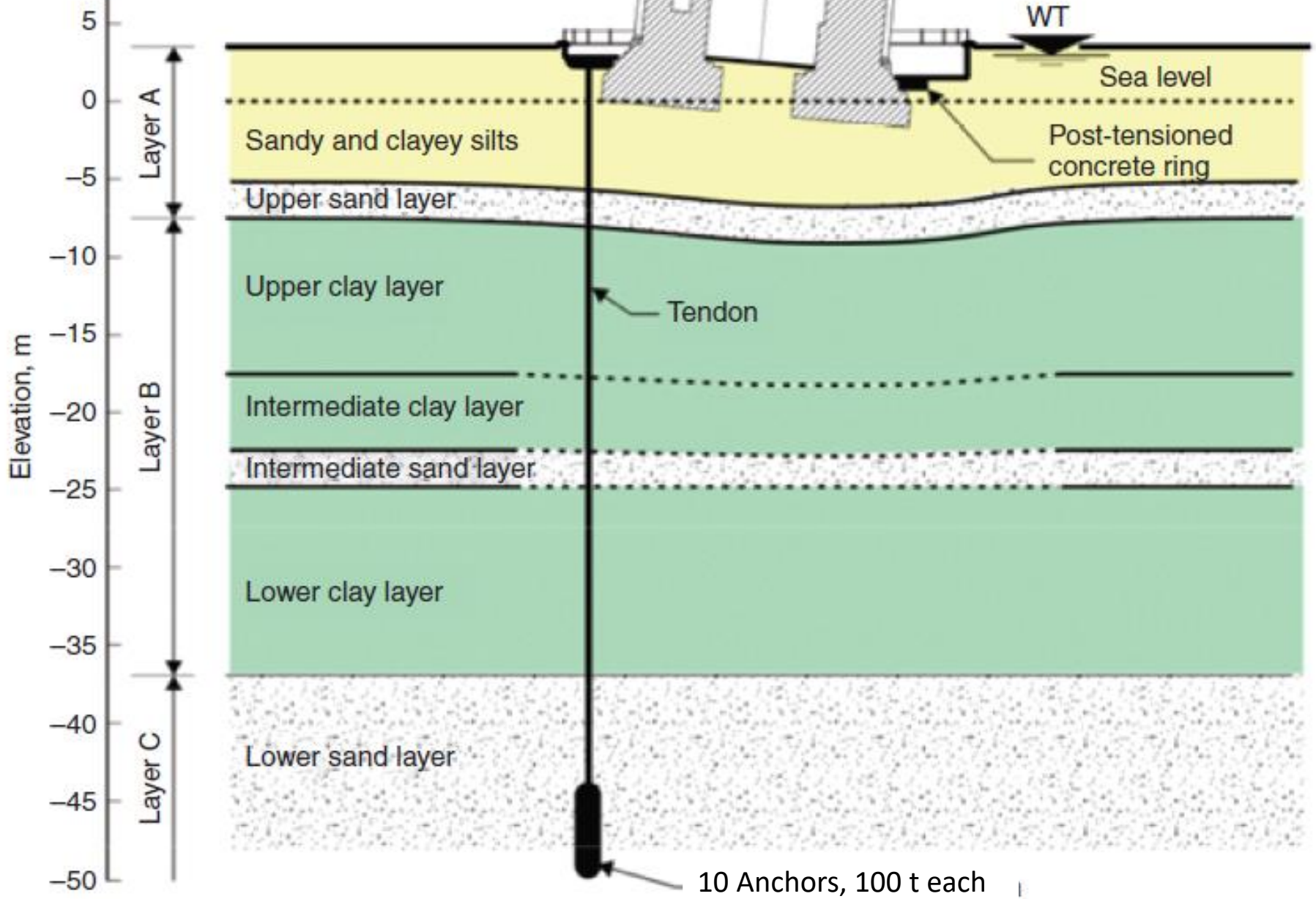
First lesson

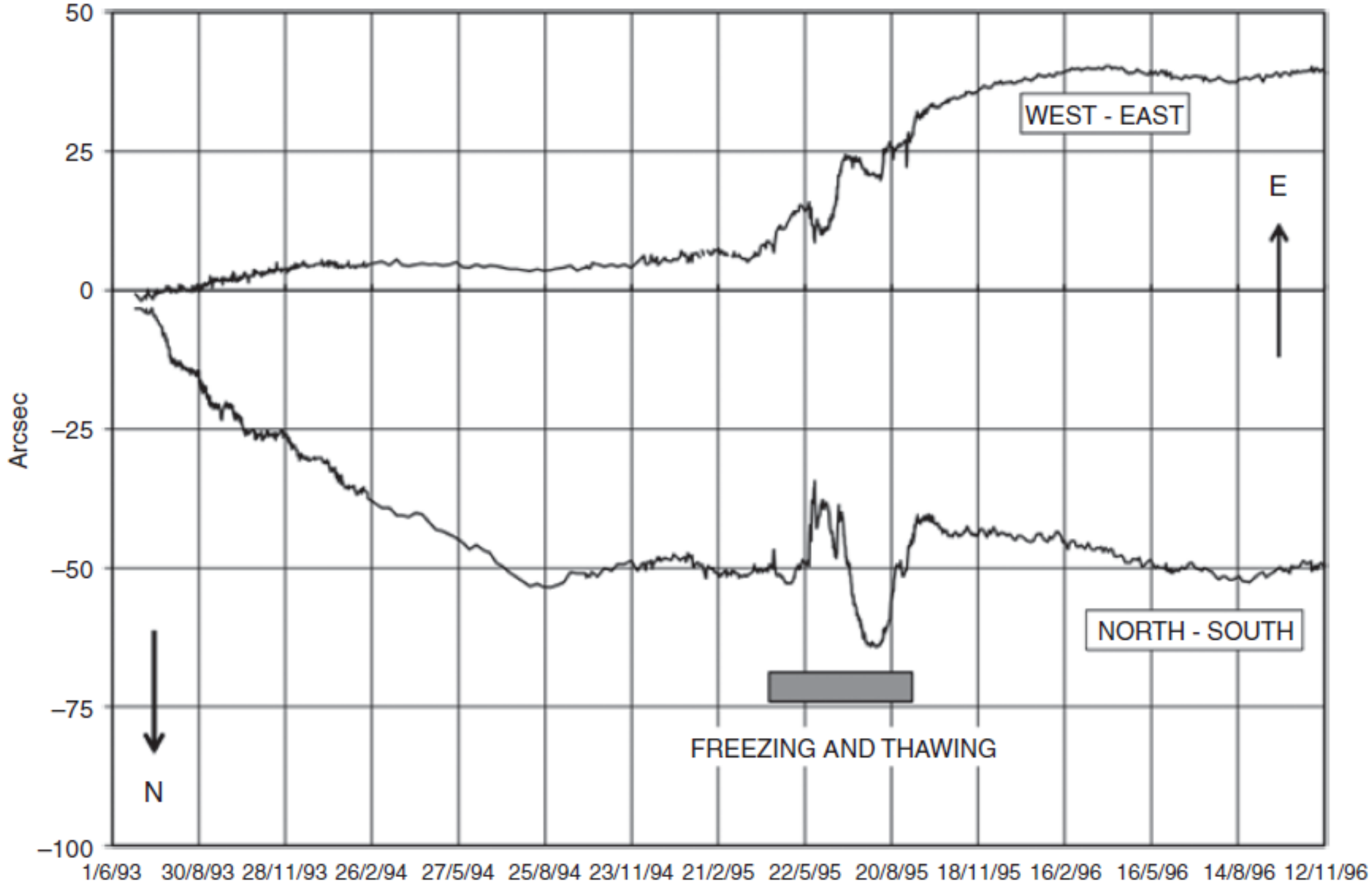
Perseverate!

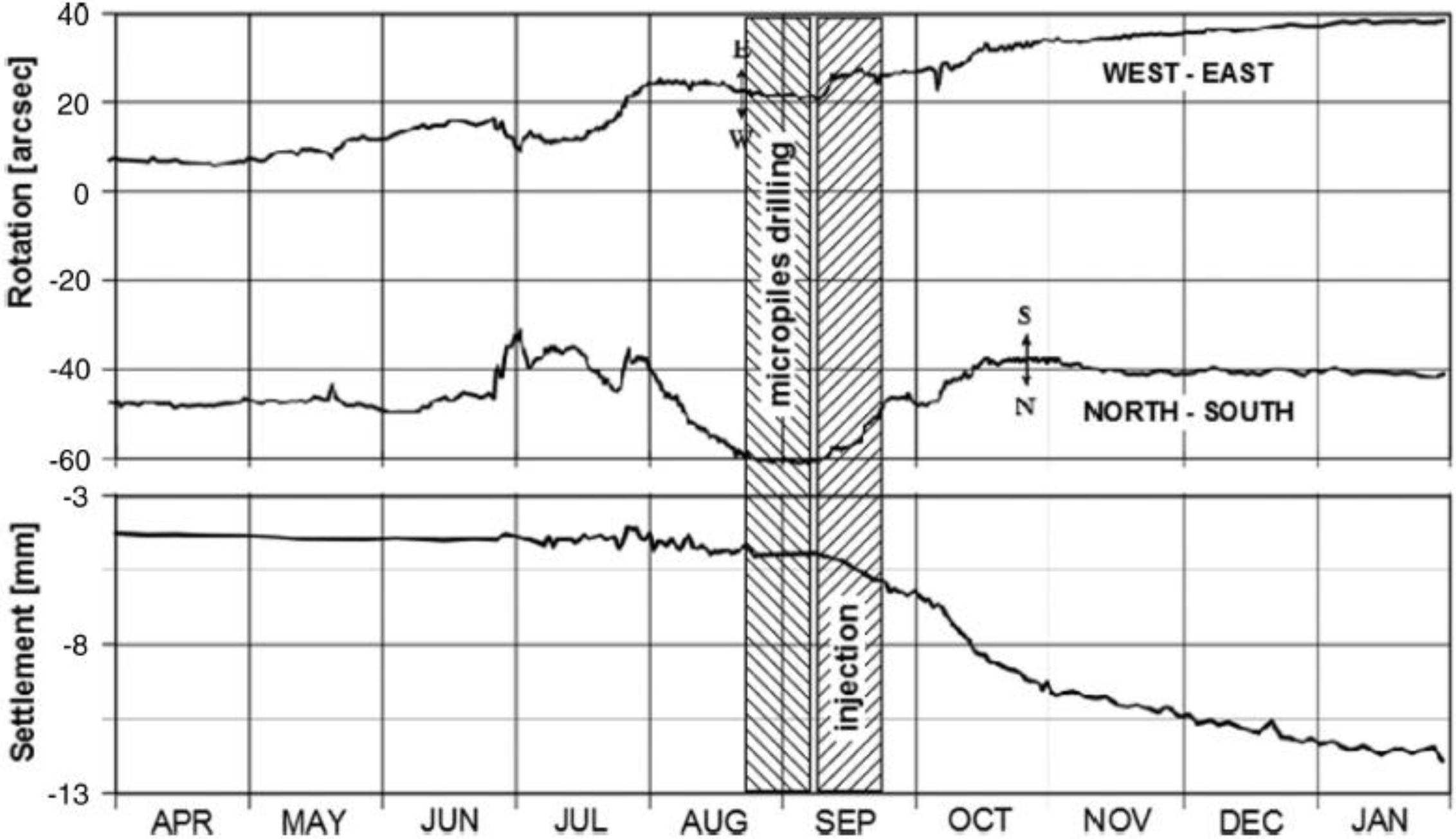


The corrections during the construction
(banana shape)
appear to have been detrimental !!!


Inclination of the Tower (degrees)
0
1
2
3
4
5
6
1173 – 1178 First stage
1272 – 1278 Second stage
1360 – 1370 Bell chamber
1385 Fresco by A. Veneziano
1550 Arnolfo's life (G. Vasari)
1817 Cresy & Taylor
1838 Digging the catino
1859 Rohault de Fleury
1911 Geodethical measurements
1999 Just before underexcavation
Weight of the Tower (thousands of tons)
16
12
8
4
0
End of construction
Seventh floor
By the middle of the fourth storey
1200
1400
1600
1800
2000

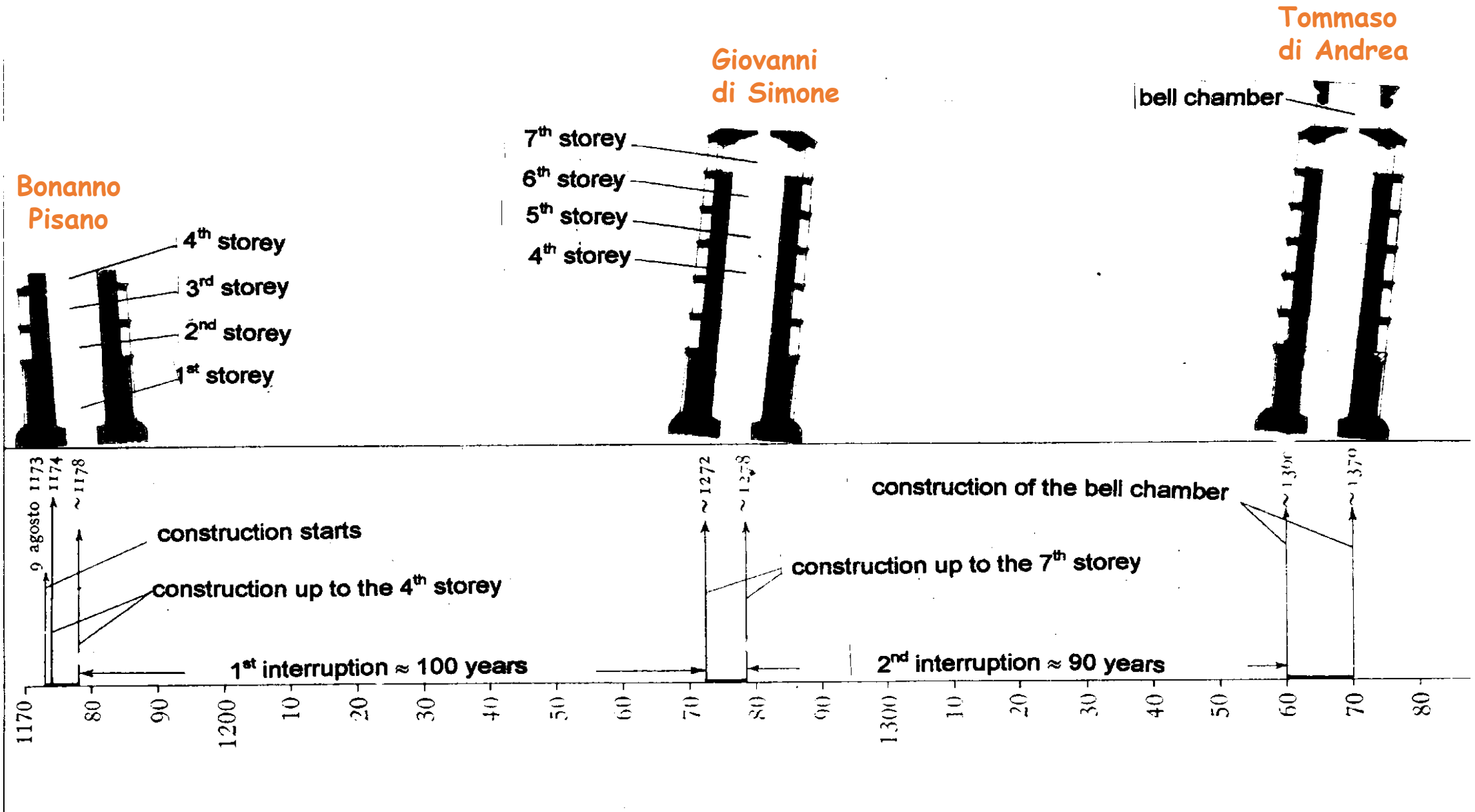

WT
Sea level
Post-tensioned
concrete ring
Sandy and clayey silts
Upper sand layer
Upper clay layer
Tendon
Intermediate clay layer
Intermediate sand layer
Lower clay layer
Lower sand layer
10 Anchors, 100 t each
Elevation, m
5
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
−50
Layer A
Layer B
Layer C

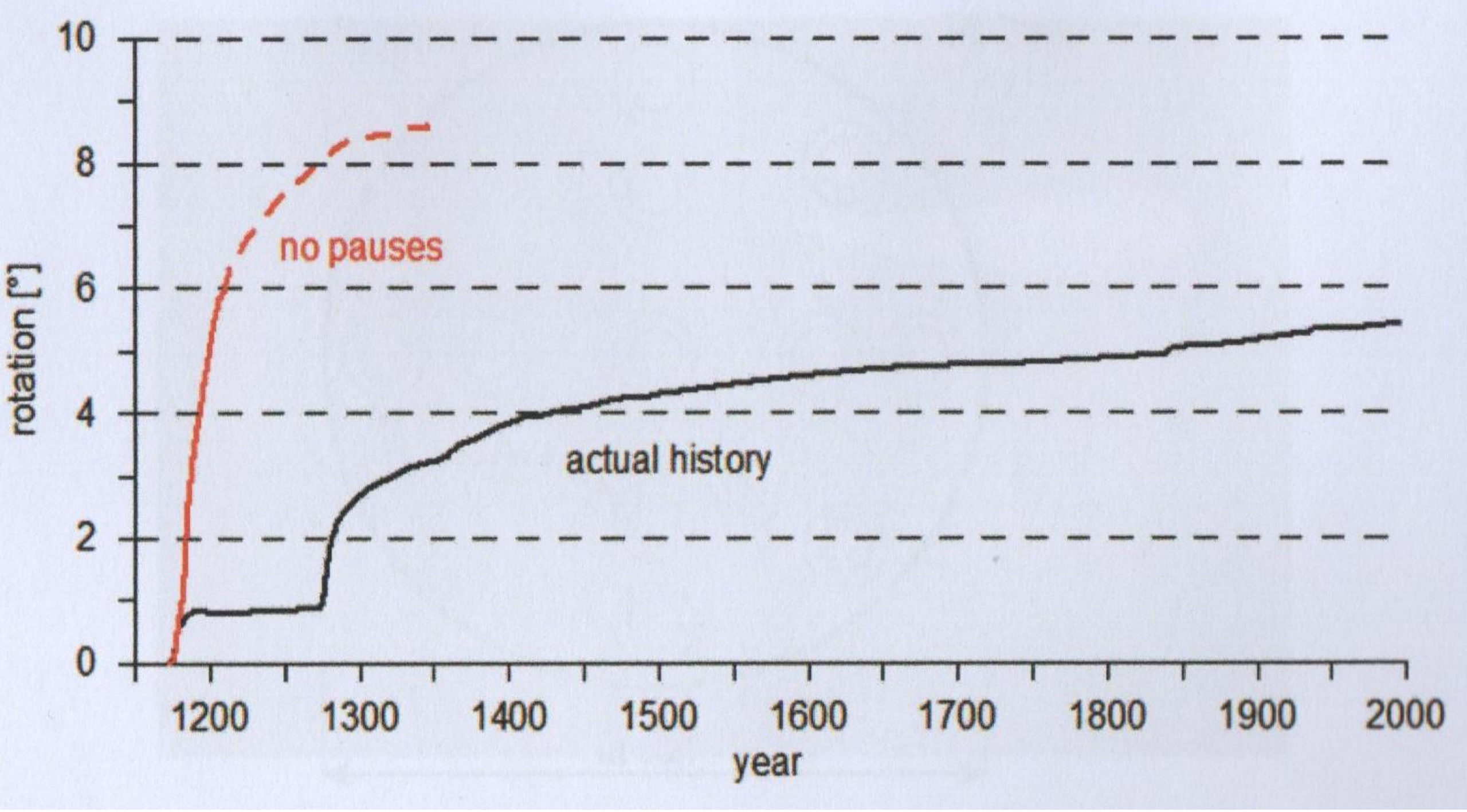

50
25
0
−25
−50
−75
−100
Arcsec
WEST - EAST
E
NORTH - SOUTH
N
FREEZING AND THAWING
1/6/93
30/8/93
28/11/93
26/2/94
27/5/94
25/8/94
23/11/94
21/2/95
22/5/95
20/8/95
18/11/95
16/2/96
16/5/96
14/8/96
12/11/96


Rotation [arcsec]
40
20
0
-20
-40
-60
E
W
micropiles drilling
WEST - EAST
S
N
NORTH - SOUTH
Settlement [mm]
-3
-8
-13
injection
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN

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
Tommaso di Andrea
bell chamber
9 agosto 1173
1174
~ 1178
construction starts
construction up to the 4th storey
1st interruption ≈ 100 years
~ 1272
~ 1278
construction up to the 7th storey
2nd interruption ≈ 90 years
construction of the bell chamber
~ 1370
1170
80
90
1200
10
20
30
40
50
60
70
80
1300
10
20
30
40
50
60
70
80

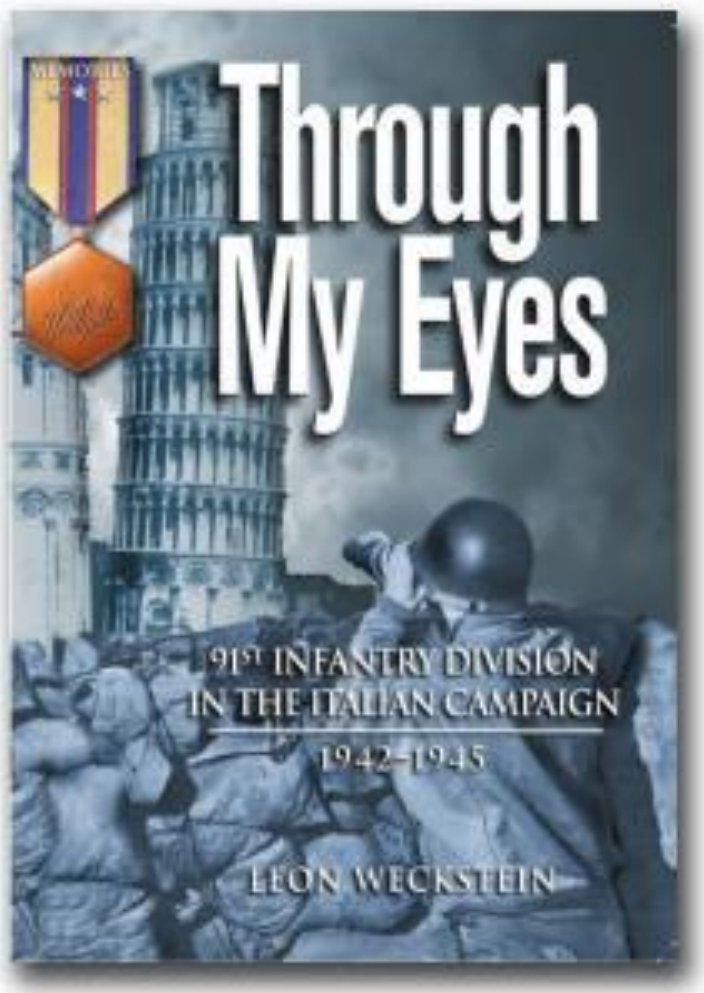

10
8
6
4
2
0
rotation [°]
no pauses
actual history
1200
1300
1400
1500
1600
1700
1800
1900
2000
year

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 short-sighted.

"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!