UNIVERSITY OF PATRAS
ERASMUS+
29 February 2016

BEHAVIOUR OF THE TOWER DURING AND AFTER STABILIZATION WORKS

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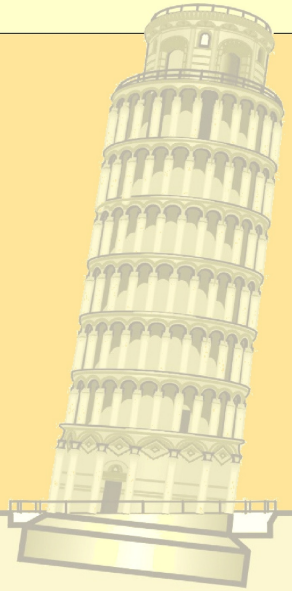


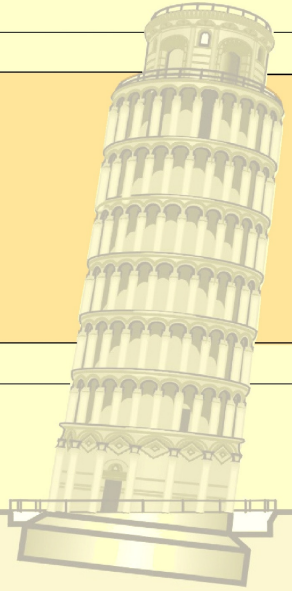
LECTURE OUTLINE

- Historical background
- Subsoil conditions
- Restoration works
- Closing remarks

G-183 OCT-11

G-131 FIR-20

Pisa,
Piazza dei Miracoli



HISTORICAL BACKGROUND

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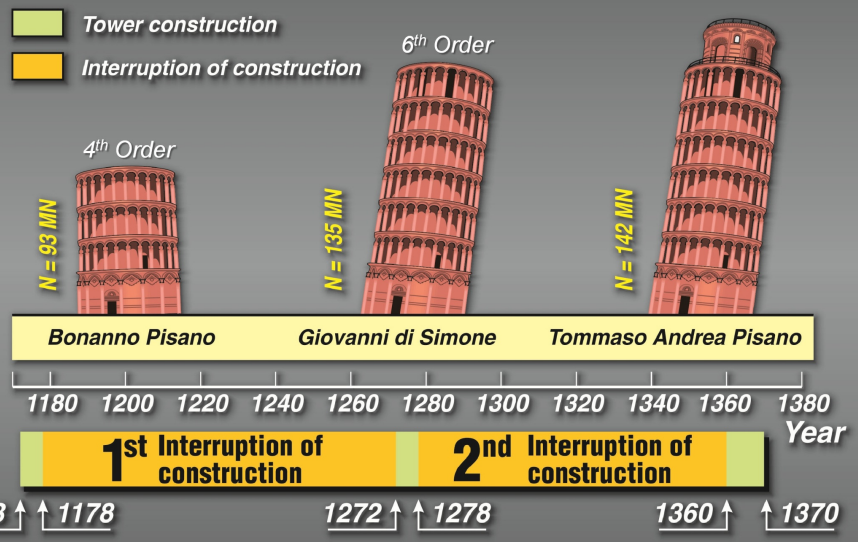
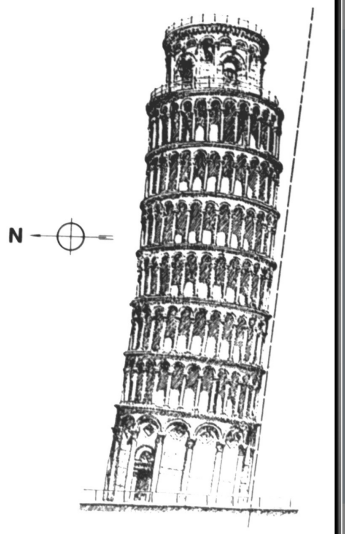
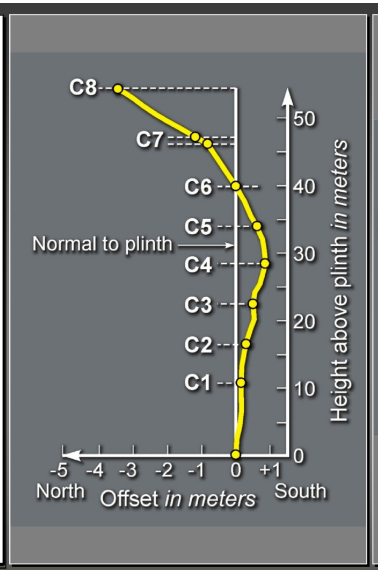
CONSTRUCTION HISTORY



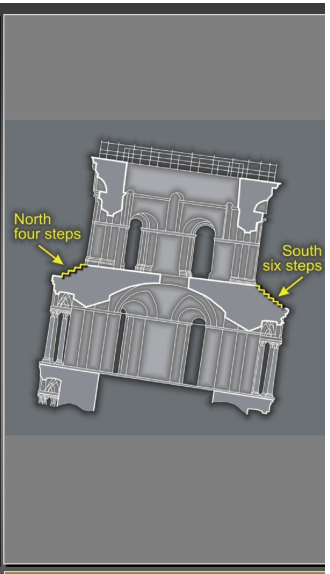
G-262 PISA-04



Shape of the Tower

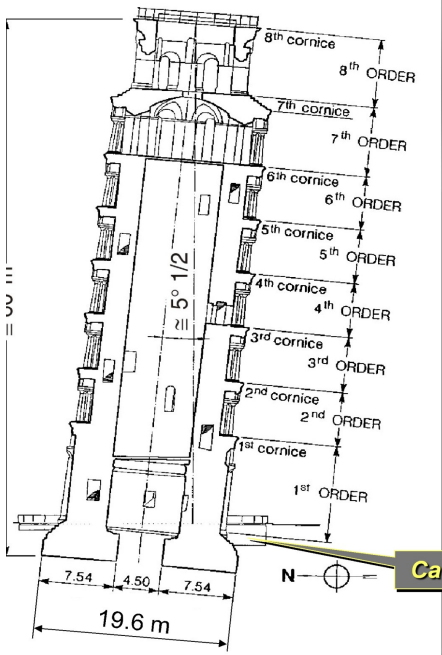


Shape of the Tower Axis



Bell chamber

G-160 ATL-11



Catino (1838)

Cross section in the plane of maximum Inclination*

Weight	142 MN
Height of the centre of gravity	22.6 m
Overturning moment	327MNm
Foundation pressure: Average	≈500 kPa
Maximum	≈980 kPa
Minimum	≈ 60 kPa

(*) Situation in year 1993

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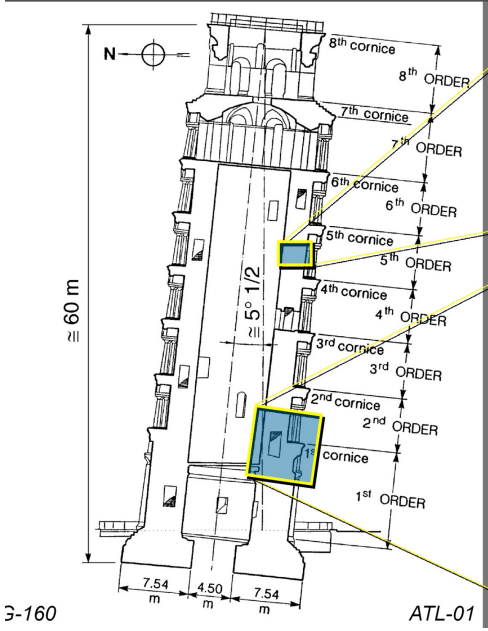
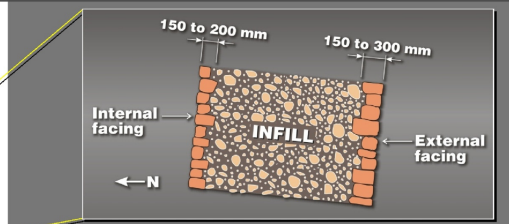
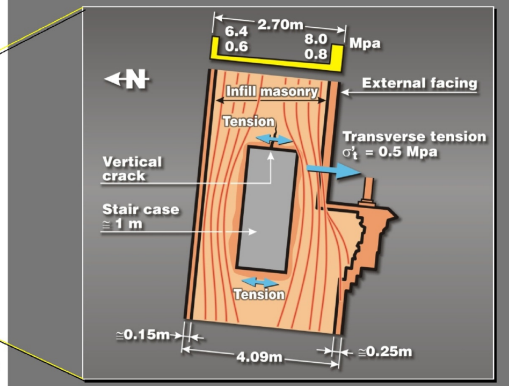
LEANING TOWER OF PISA – STRUCTURAL FEATURES

V ≅ 142 MN; M ≅ 327 MNm; e = 2.3 m





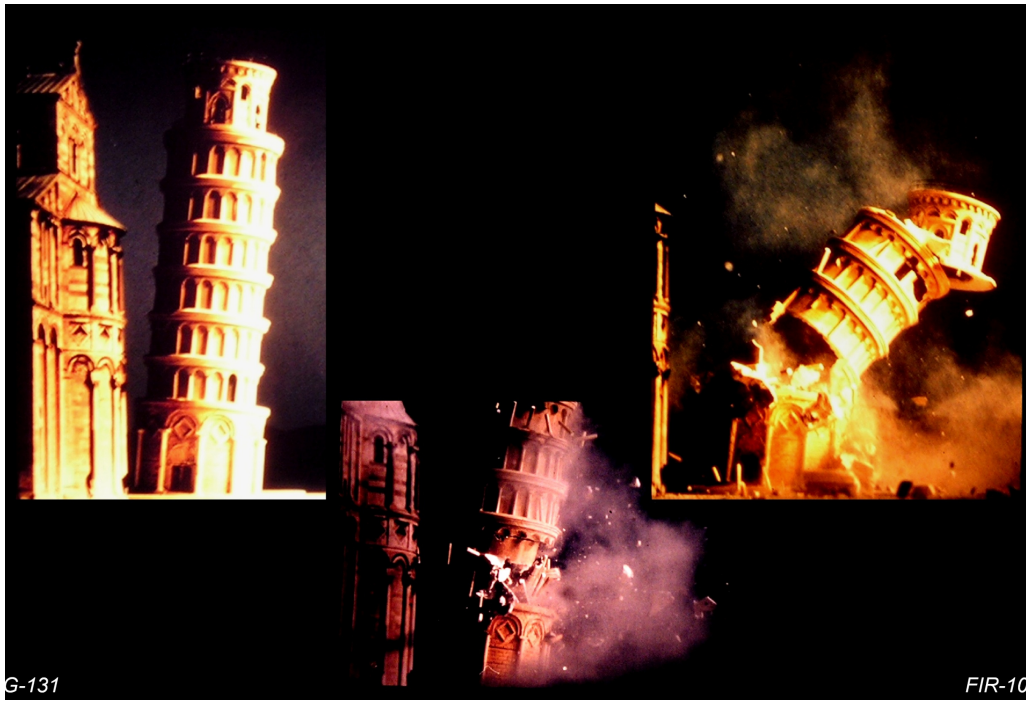


G-160 ATL-01

WHY CONCERN ABOUT STRUCTURAL SAFETY?

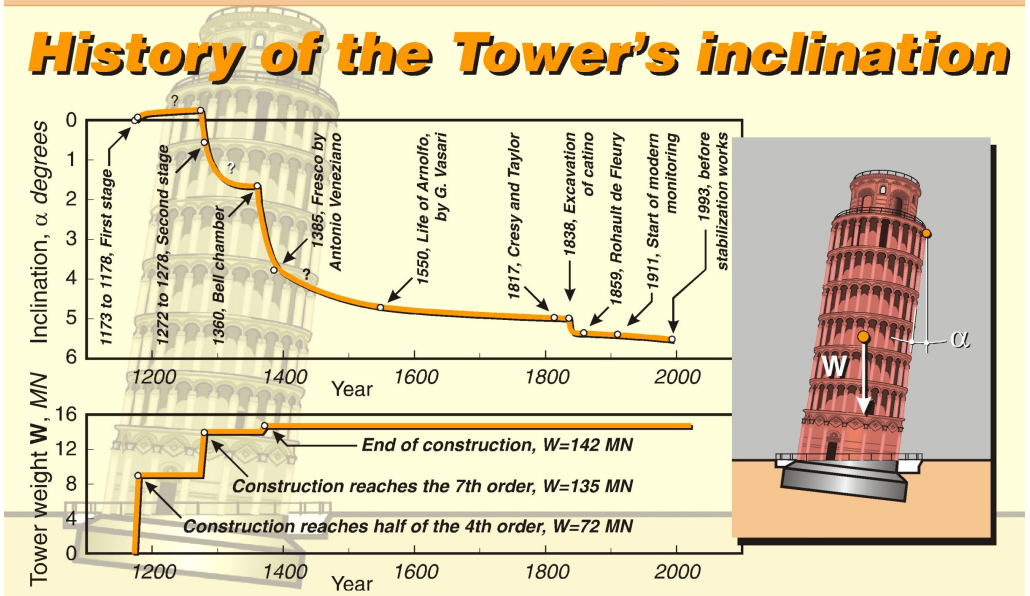
- High compressive stresses on external facing*
- External facing laying directly on infill masonry*
- Infill rubble; voids, cracks, inhomogeneities
- Almost no bond strength between infill and facing
- Stress concentration in bed joints of facing
- Weakening of tower shaft due to presence of stair case*

(*) Especially dangerous at level of first cornice



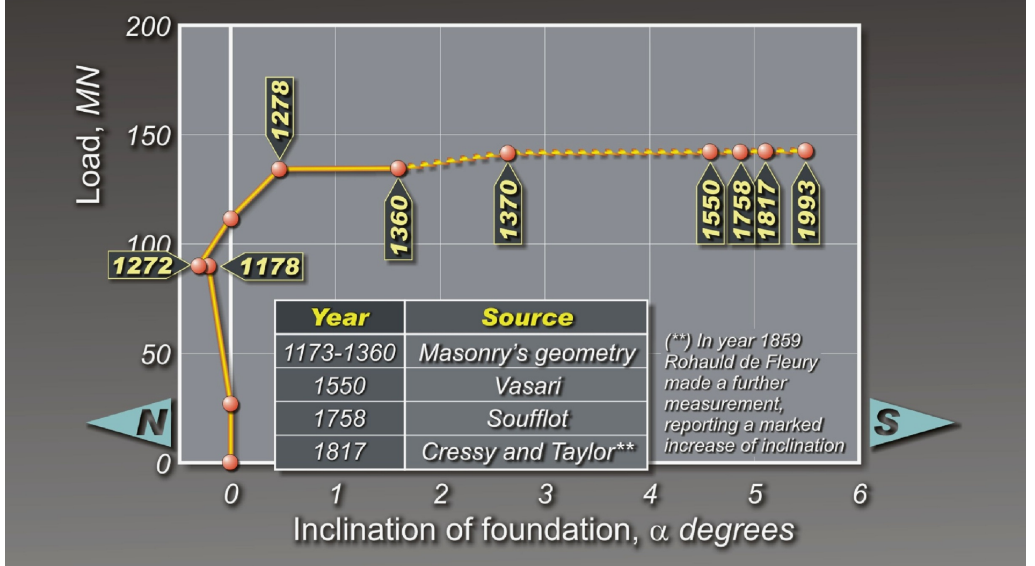
Leaning Tower of Pisa

History of the Tower's inclination



LEANING TOWER OF PISA

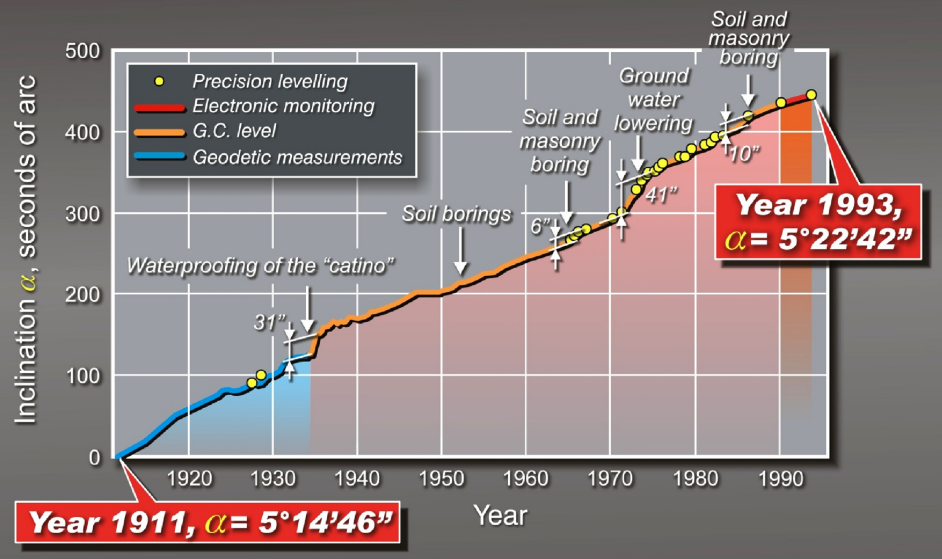
DEDUCED HISTORY OF INCLINATION



Year	Source
1173-1360	Masonry's geometry
1550	Vasari
1758	Soufflot
1817	Cressy and Taylor**

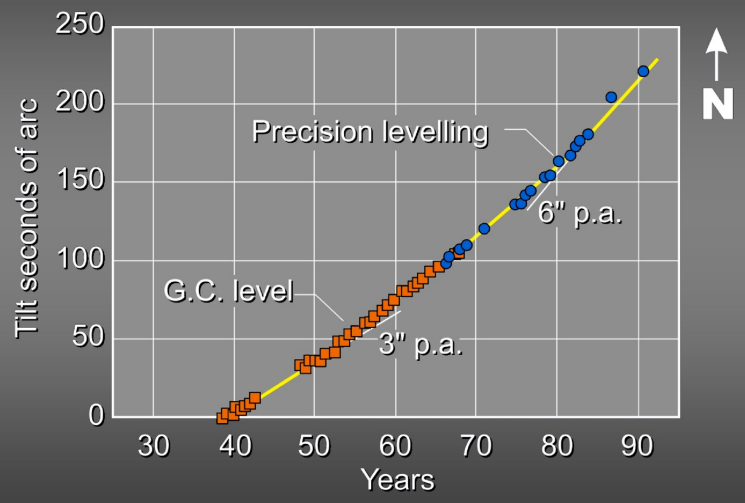
(**) In year 1859 Rohauld de Fleury made a further measurement, reporting a marked increase of inclination

TILT OF PISA TOWER SINCE 1911



NET TILT OF TOWER FOUNDATION

(1938 through 1991)

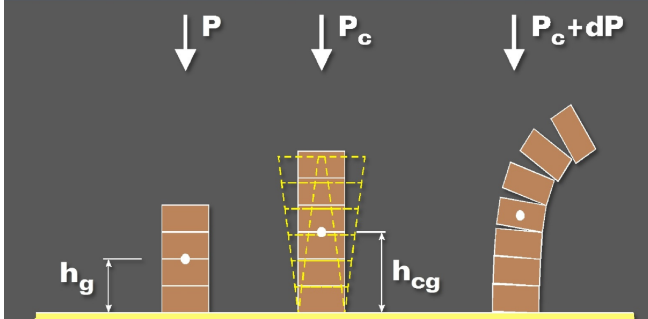


PHENOMENON OF LEANING INSTABILITY

- Relevant for tall, heavy top, structures seated on compressible ground
- Soil structure interaction problem controlled by ground stiffness
- Evolving in self-driving process
- Column of wooden bricks built on a springy foam stratum [Hambly (1985)]

LEANING INSTABILITY PHENOMENON

Hambly (1985)

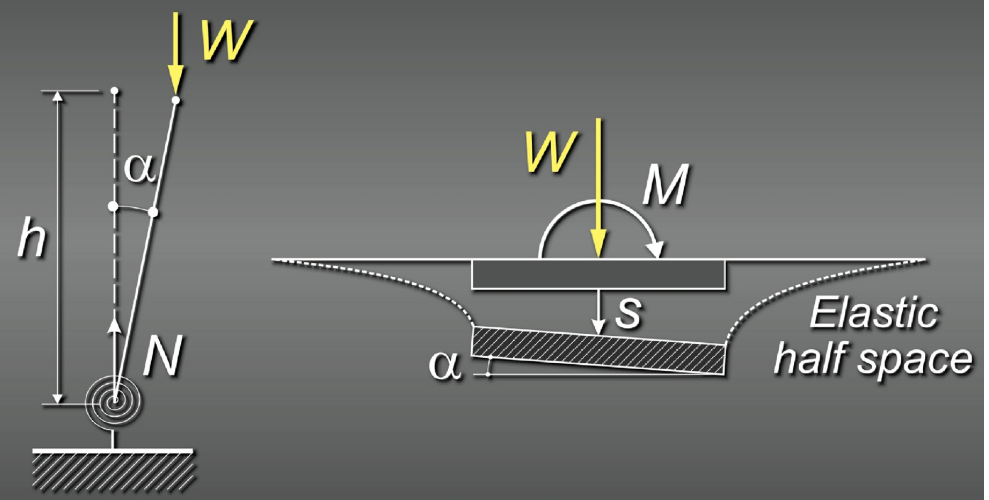


e.g.:
COLUMN OF BRICKS BUILT ON SPRINGY FOAM

- TALL AND HEAVY TOP STRUCTURES SEATED ON COMPRESSIBLE SOIL
- SOIL-STRUCTURE INTERACTION PROBLEM
- ANALOGY WITH BUCKLING OF INELASTIC COLUMN

INVERTED PENDULUM: A SIMPLE MODEL OF LEANING INSTABILITY

Humbly (1985), Lancellotta (1993), Desideri & Viggiani (1994), Burland et al.(2013)



INVERTED PENDULUM: A SIMPLE MODEL OF LEANING INSTABILITY

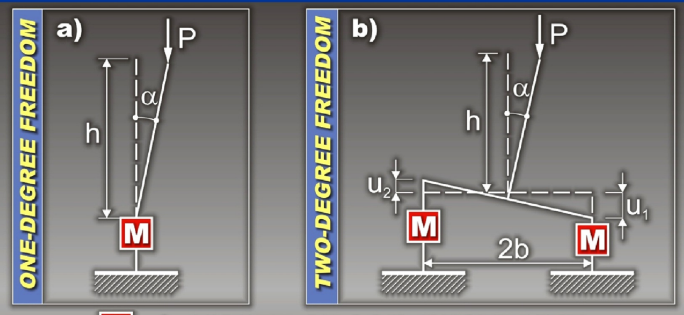
Humbly (1985), Lancellotta (1993), Desideri & Viggiani (1994), Burland et al.(2013)

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

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

- **Circular plate on elastic half-space**
- **Vertical Load (W) and Overturning Moment (M_o)**
- **Settlement (s) and Rotation (α)**
- **Resisting Moment (M_R)**
- **Safety Factor ($FS=M_R / M_o$)**

LEANING INSTABILITY: SOIL STRUCTURE INTERACTION IDEALIZATION

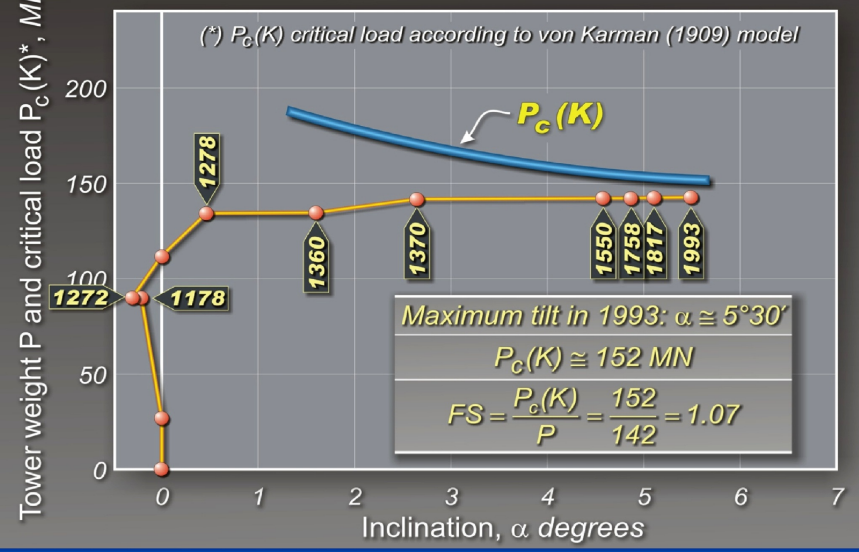


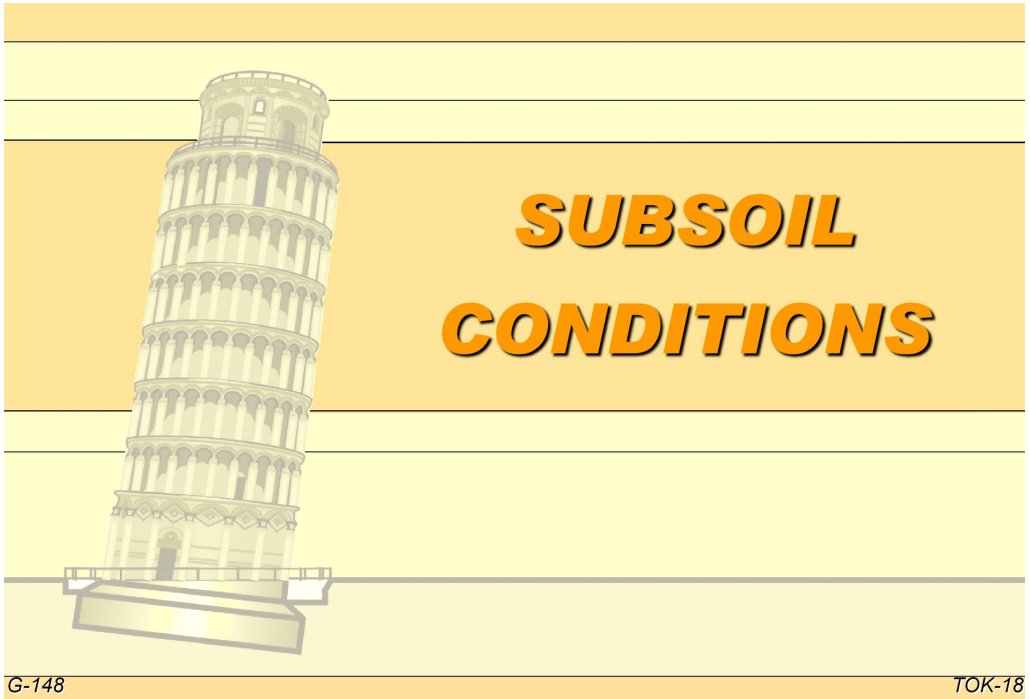
M → MODEL OF SOIL RESTRAINT:

a	Linear or non linear elastic spring
b	Linear or non linear elasto-plastic spring
c	Viscoplastic Maxwell model unlimited creep under
d	Viscoplastic standard solid limited creep

LEANING TOWER OF PISA STABILITY OF EQUILIBRIUM

Pepe (1995)
Lancellotta and Pepe (1998)

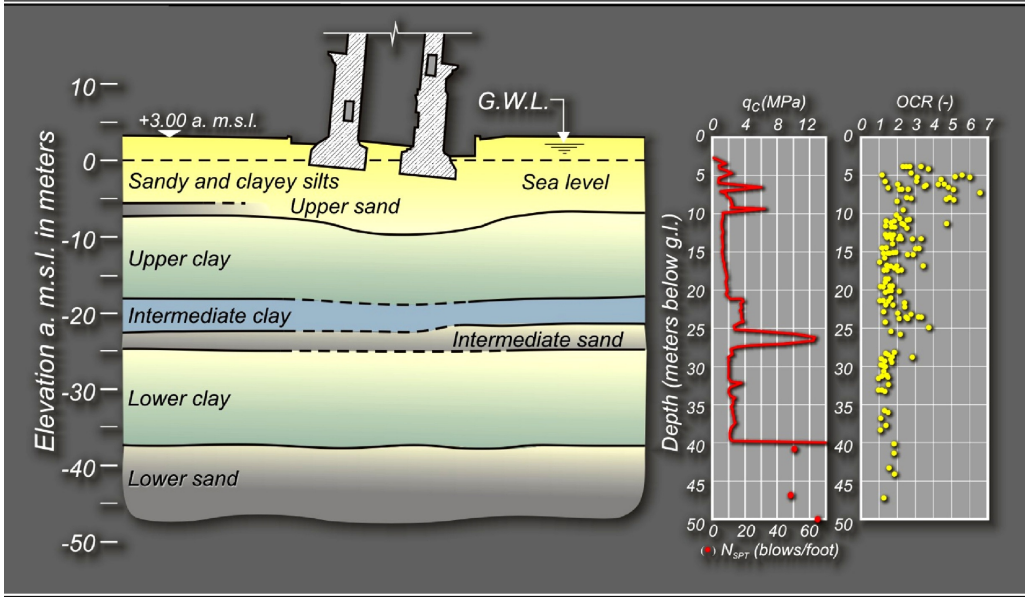




SUBSOIL CONDITIONS

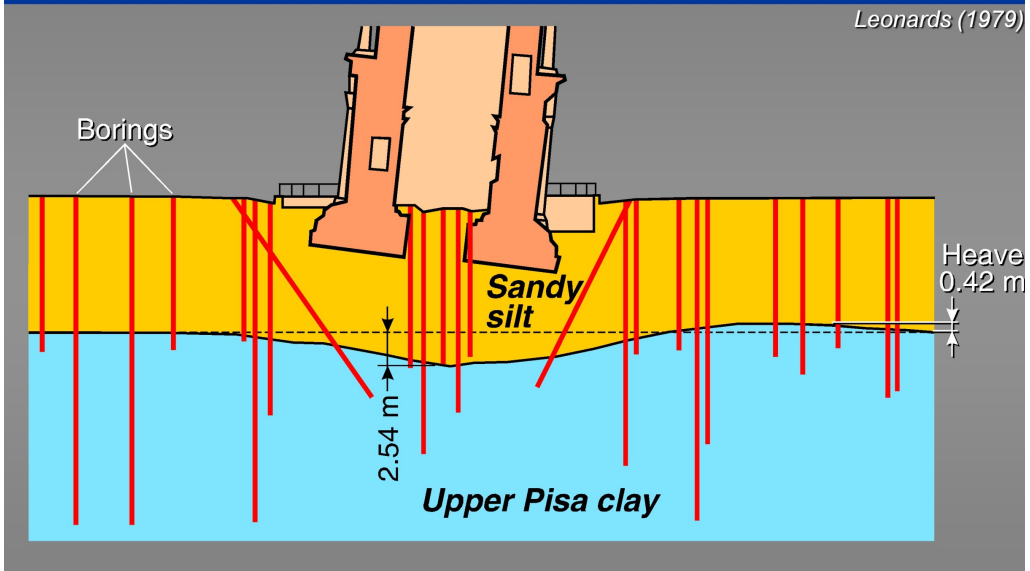
G-148 TOK-18

SUBSOIL PROFILE AND SOIL PROPERTIES



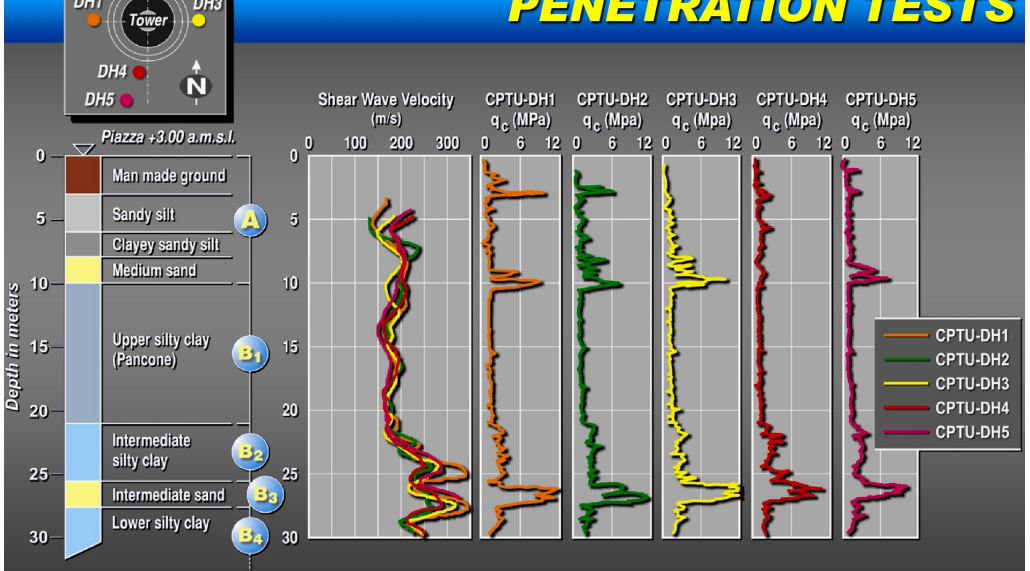
G-204 DUB-03

SETTLEMENT AND HEAVE OF SURFACE OF UPPER PISA CLAY



A-112 MAD-7

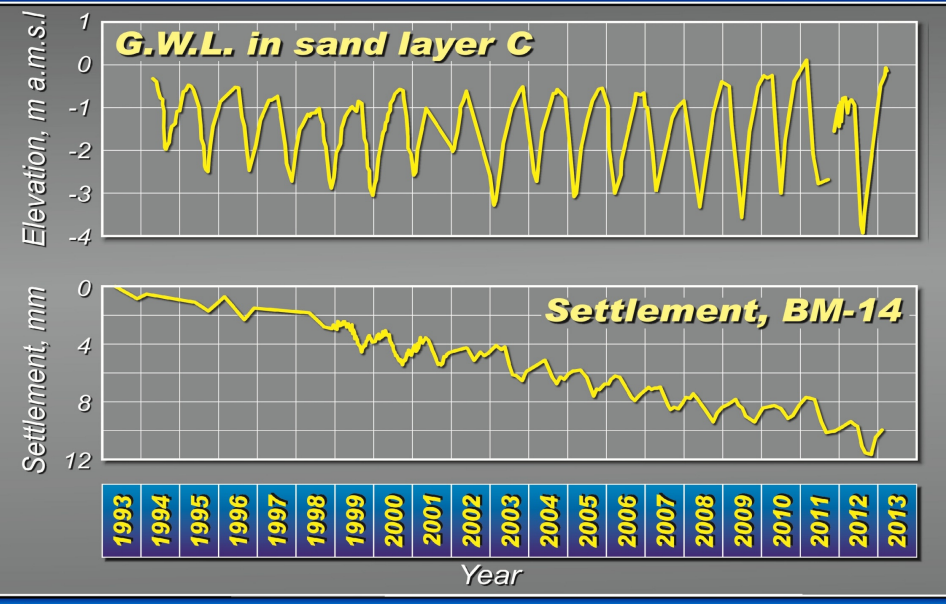
RESULTS OF SEISMIC CONE PENETRATION TESTS



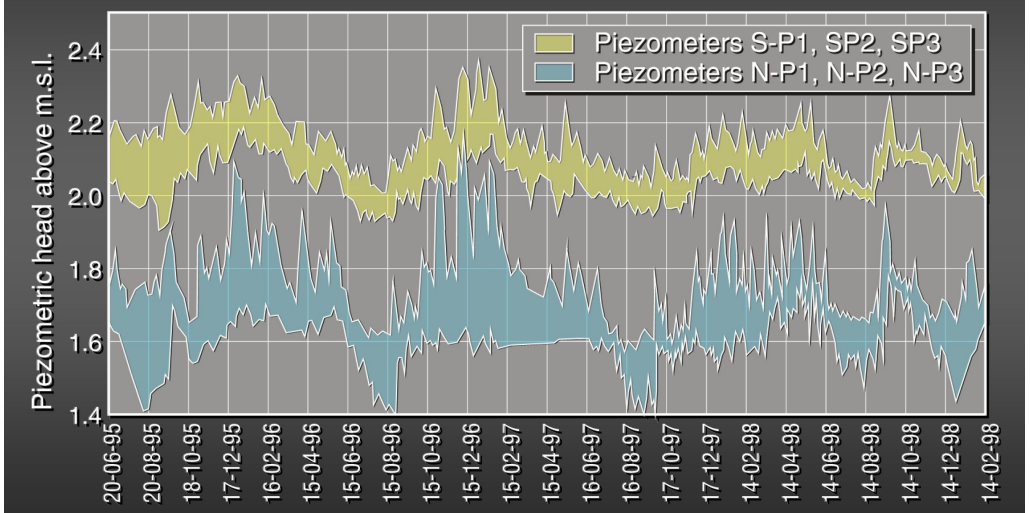
G-148 TOK-02

GROUND WATER BENEATH PIAZZA DEI MIRACOLI

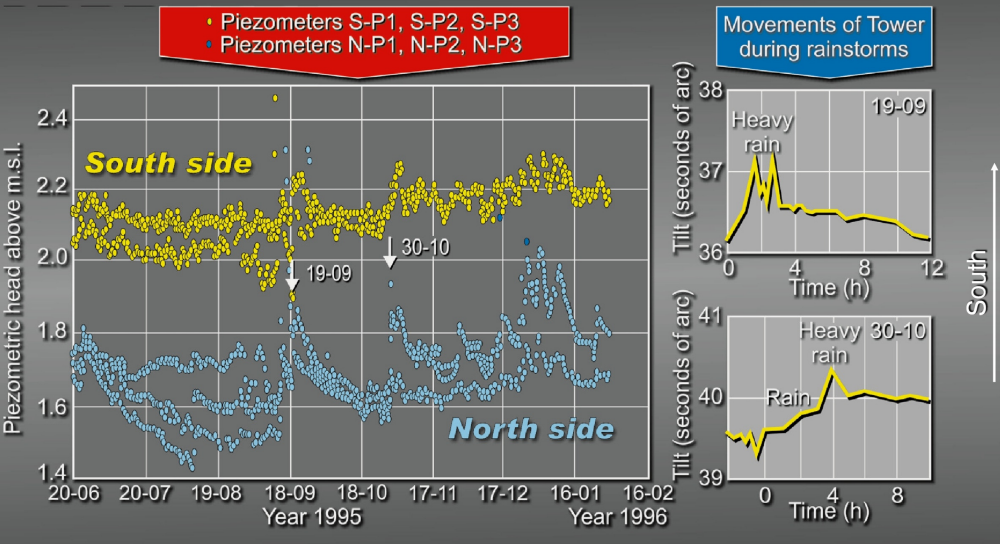
PIAZZA DEI MIRACOLI - ELEVATION +3.5 m m.s.l

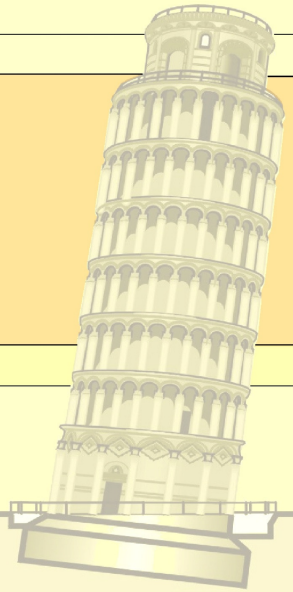


PERCHED GROUND WATER TABLE IN HORIZON "A" IN PROXIMITY OF PISA TOWER



EFFECT OF GWL OSCILLATIONS WITHIN HORIZON A ON THE TOWER MOVEMENTS





RESTORATION WORKS

(1990 to 2001)

THREATS TO THE TOWER INTEGRITY

- Progressive growth of rotation at increasing rate, risk of falling over
- Risk of sudden masonry failure on the South side, between 1st and 2nd cornice

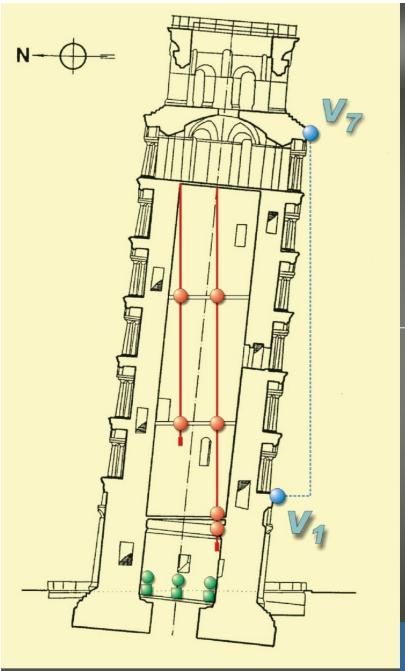
INTERNATIONAL COMMITTEE FOR THE SAFEGUARD AND RESTORATION OF THE LEANING TOWER OF PISA

- Appointed by Italian Prime Minister in May 1990
- A fourteen-member multidisciplinary body including experts of:
  - Restoration
  - History of Arts
  - Archeology
  - Petrography and construction stones
  - Structural Engineering
  - Geotechnical Engineering

TOWER SAFETY

COMMITTEE'S LONG-STRUGGLED PRONOUNCEMENTS

- Tower affected by instability of the equilibrium (leaning instability)
  [Hambly (1985), Lancellotta (1993), Desideri and Viggiani (1994)]
- Simple rheological models suggested that Tower was in state of neutral equilibrium
  [Shanley (1946,1947)]
- According to physical and numerical modeling a further increase in inclination would have put the Tower at risk of collapse
  [Edmunds (1993), Pepe (1995), Viggiani (2002), Potts and Burland (2000)]
- In the event of leaning instability, even a minor reduction in inclination should lead to a significant safety upgrade against collapse.



GEOTECHNICAL MONITORING DURING STABILIZATION WORKS

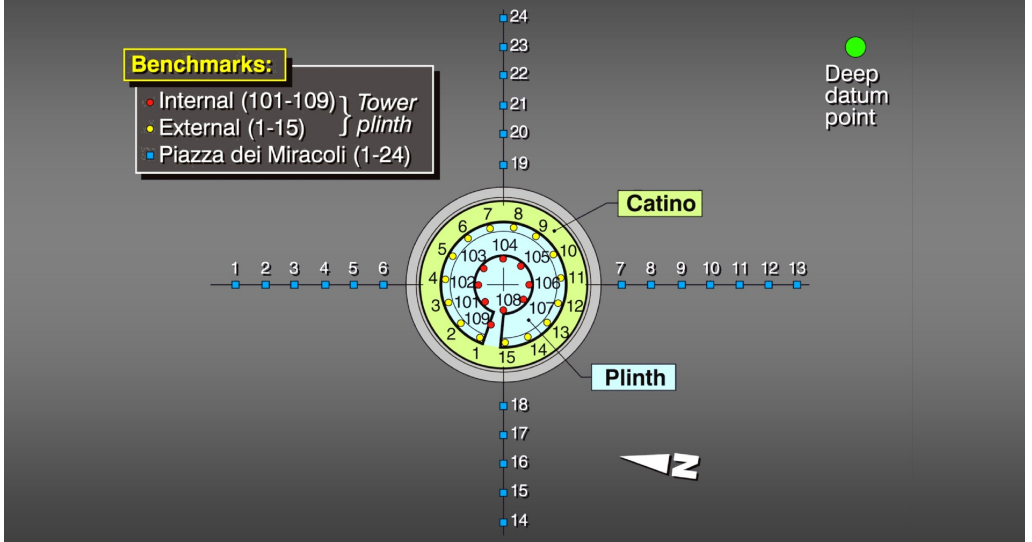
- **AUTOMATIC, CONTINUOUS, REAL-TIME**
  - 8 Livellometers
  - 7 Biaxial inclinometers
  - 4 Monoaxial inclinometers
  - 6 Telecoordinometers
  - 23 Piezometers
  - 9 Seismometers
- **TOPOGRAPHICAL SURVEYING, DISCONTINUOUS**
  - High precision levelling of 23 points near the Tower base*
  - Geodetic measurements, horizontal movements of points V_1 and V_7
  - High precision levelling of 24 points on Piazza*

(*) All referred to the Deep Datum Point on the Piazza

HIGHLY REDUNDANT, SHORT AND LONG TERM ORIENTED

G-160 ATL-10

BENCHMARKS FOR HIGH PRECISION LEVELLING OF TOWER AND OF PIAZZA DEI MIRACOLI



G-142 PAR-03

GEOTECHNICAL STABILIZATION (1)

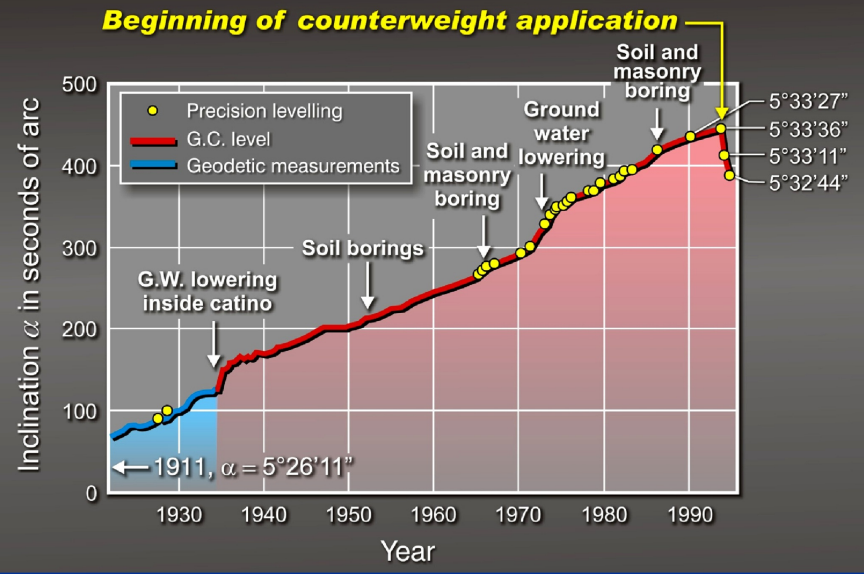
- **Temporary, fully reversible (1993)**
  - 600(2) kN Counterweight on North edge of plinth, safeguard against overturning
- **Final interventions aimed at long term stabilization (1998-2001)**
  - Controlled ground extraction(3) on North side
  - Structural connection of the Tower plinth to catino slab
  - Control of ground water table within Horizon A

(1) Simultaneously, temporary and final masonry strengthening have been carried out
(2) In 1995 increased to 980 kN
(3) Called hereinafter Underexcavation

G-204 DUB-02

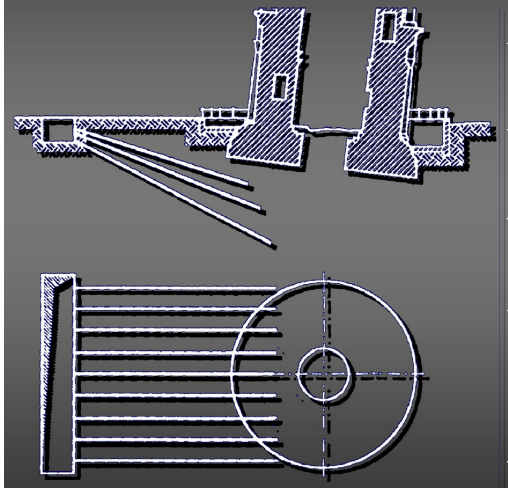
G-103 VAL-30

TILT OF PISA TOWER SINCE 1911



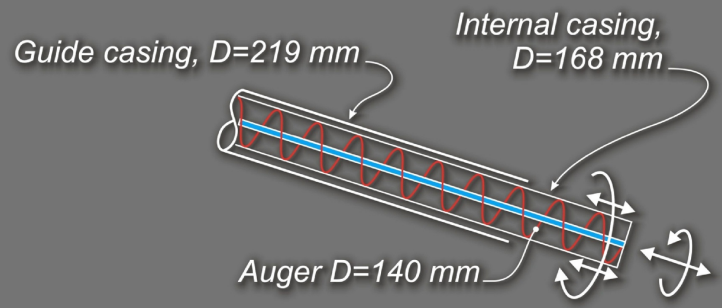
UNDEREXCAVATION TO CORRECT PISA TOWER INCLINATION

Terracina (1962)



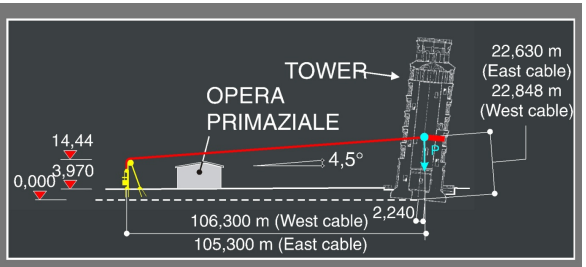
- *Reduction of contact pressure on South side*
- *The reduction of present inclination by max. 1° should be enough*
- *Simplest tool: removal of soil under North side by series of borings*
- *Desired reduction of Tower inclination can be achieved by regulating number, position and diameter of borings*

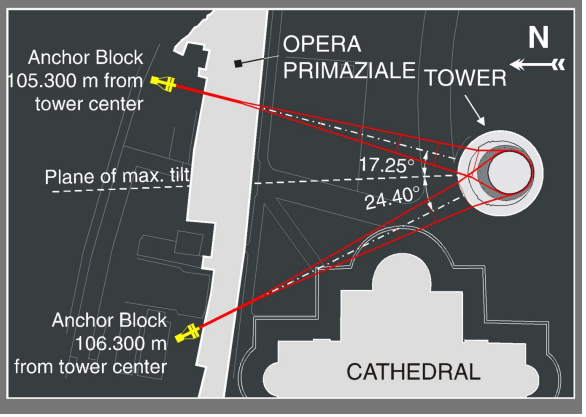
TOOL FOR GROUND EXTRACTION



- ***Internal casing rotating clockwise***
- ***Auger rotating counter-clockwise***

CABLE STAY STRUCTURE

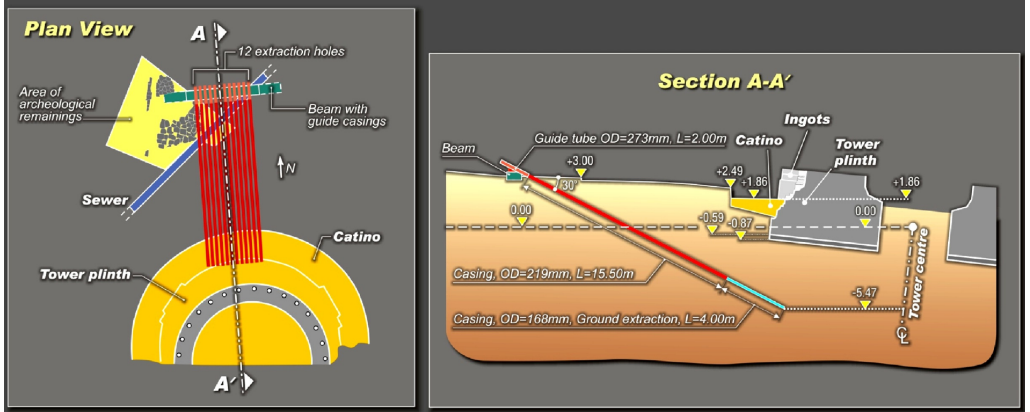




G-103 VAL-42

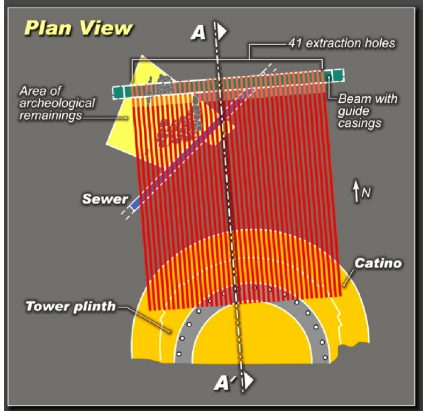
G-131 FIR-07

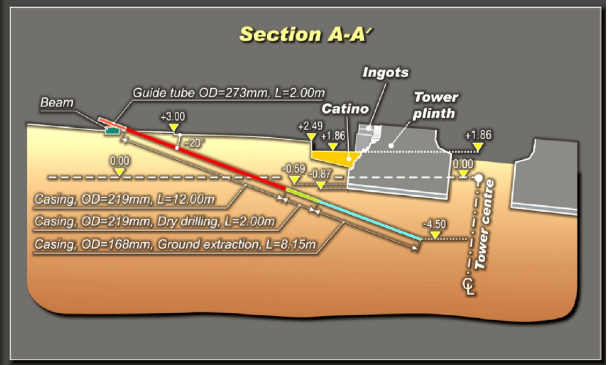
HOLES FOR GROUND EXTRACTION PRELIMINARY UNDEREXCAVATION



G-204 DUB-04

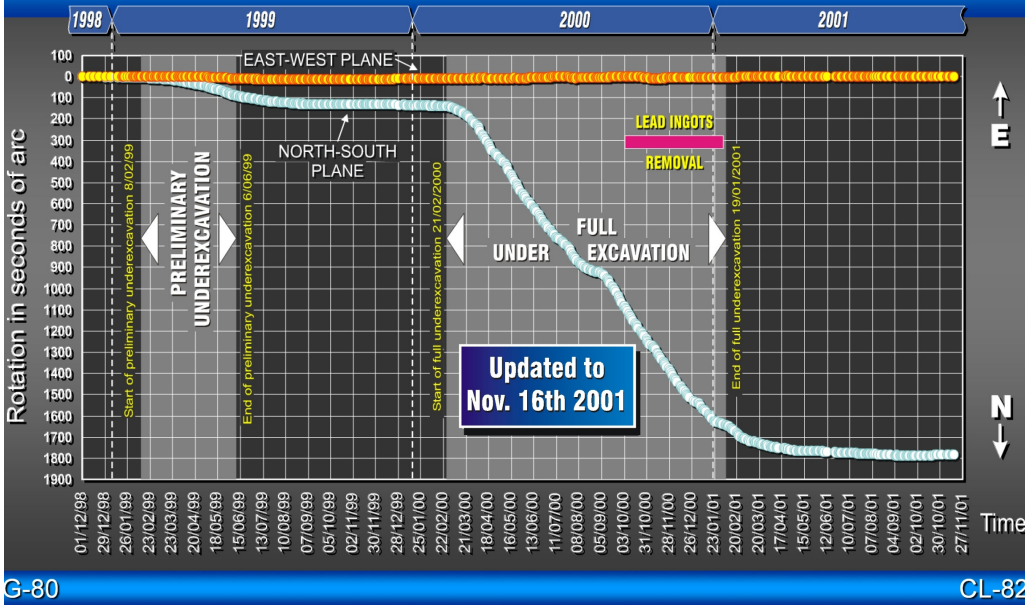
HOLES FOR GROUND EXTRACTION
FINAL UNDEREXCAVATION





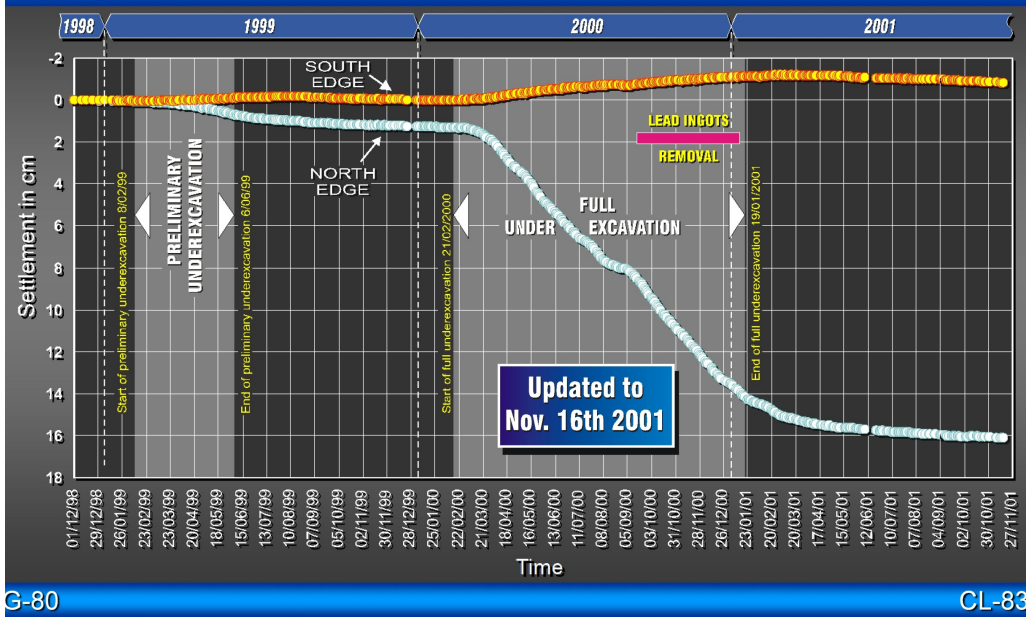
G-204 DUB-05

ROTATION OF TOWER PLINTH DURING UNDEREXCAVATION



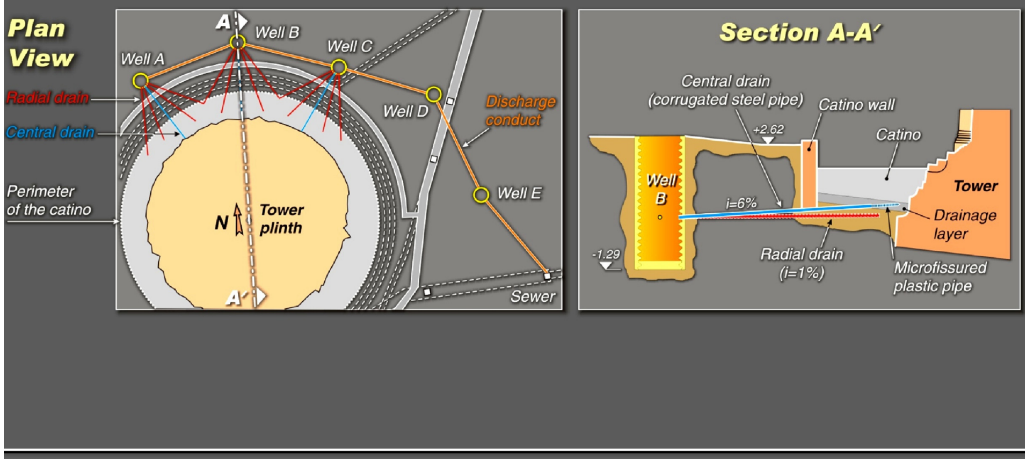
G-80 CL-82

SETTLEMENT OF TOWER PLINTH DURING UNDEREXCAVATION

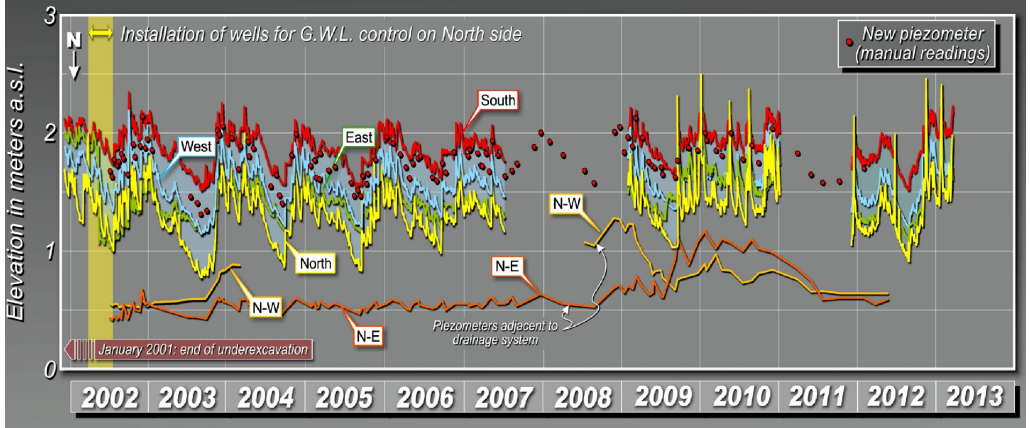


G-80 CL-83

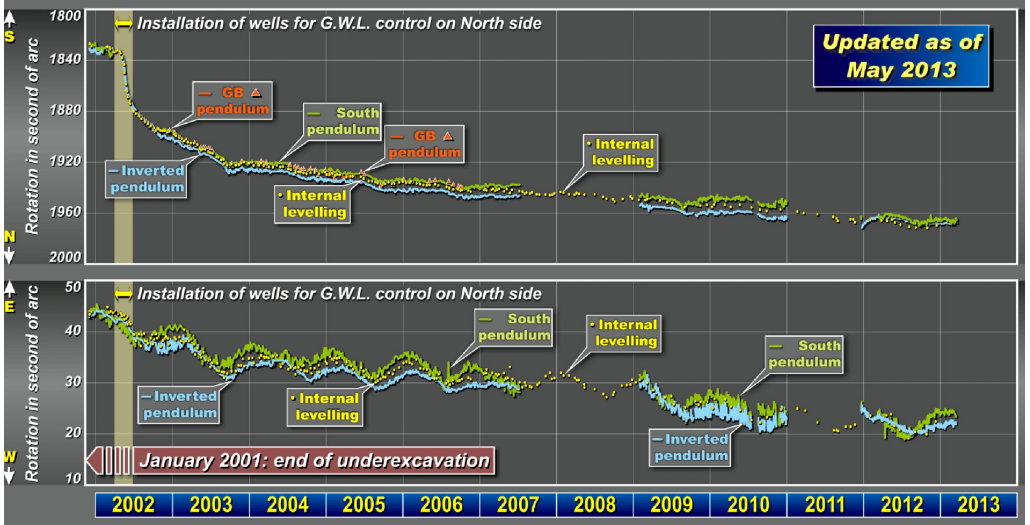
CONTROL OF PERCHED WATER TABLE ON NORTH SIDE

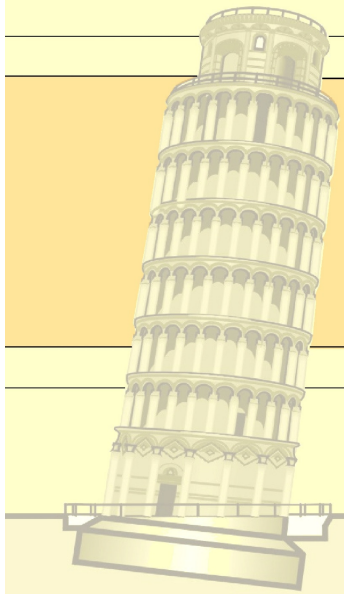


PERCHED GROUND WATER TABLE IN HORIZON "A"



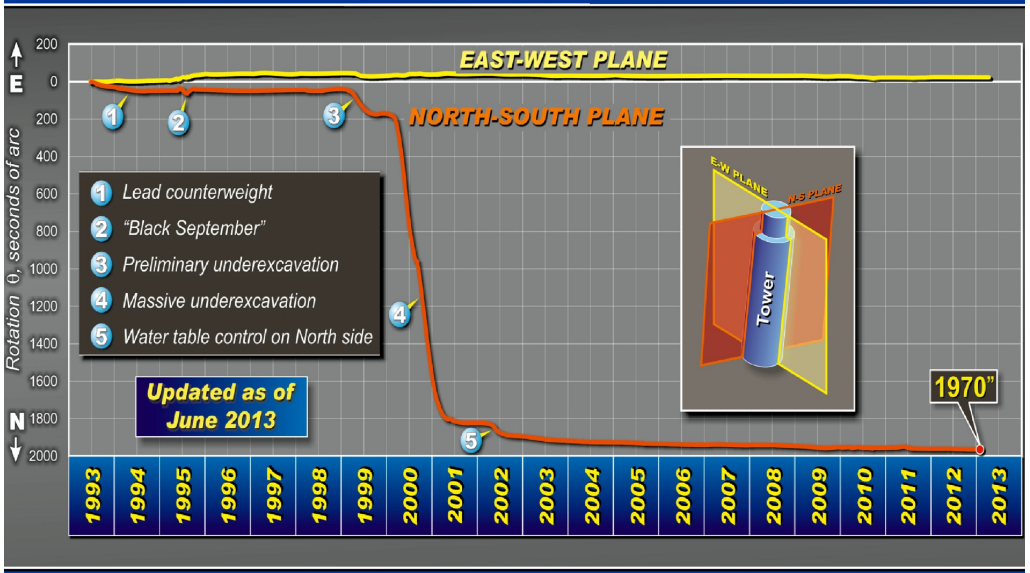
ROTATION OF TOWER AFTER STABILIZATION WORKS



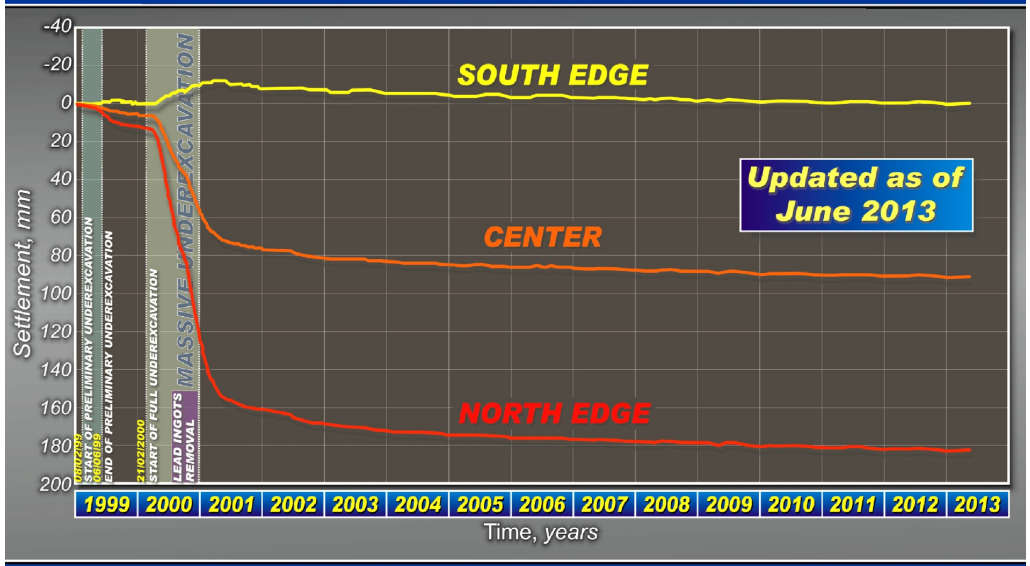


CLOSING REMARKS

ROTATION OF TOWER PLINTH AFTER STABILIZATION WORKS

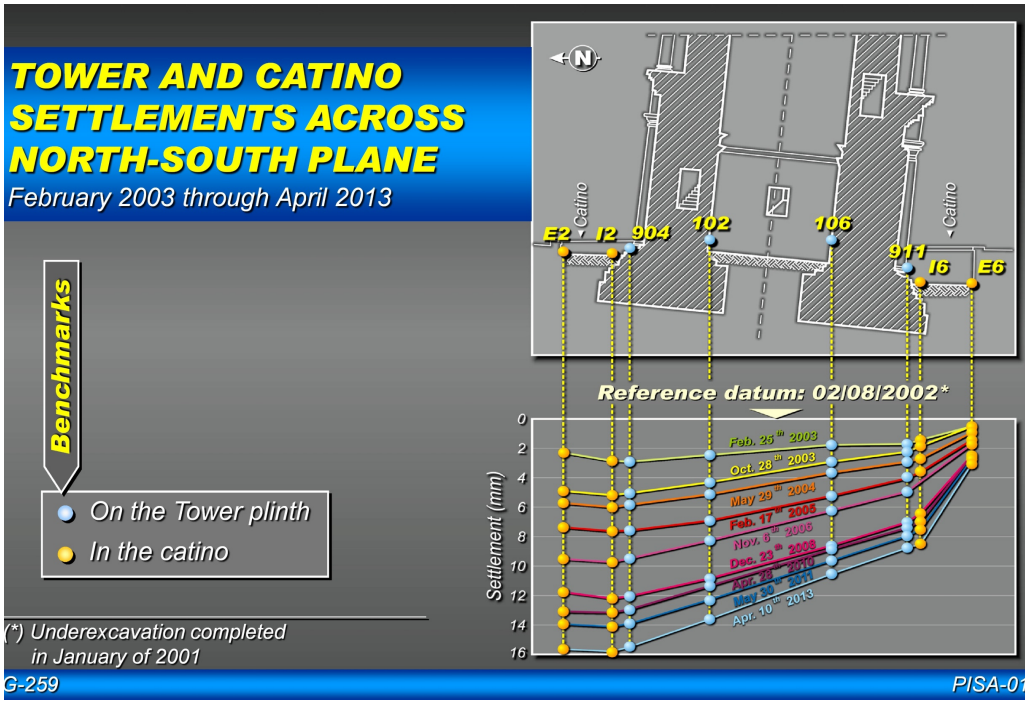


SETTLEMENTS OF TOWER PLINTH AFTER STABILIZATION WORKS



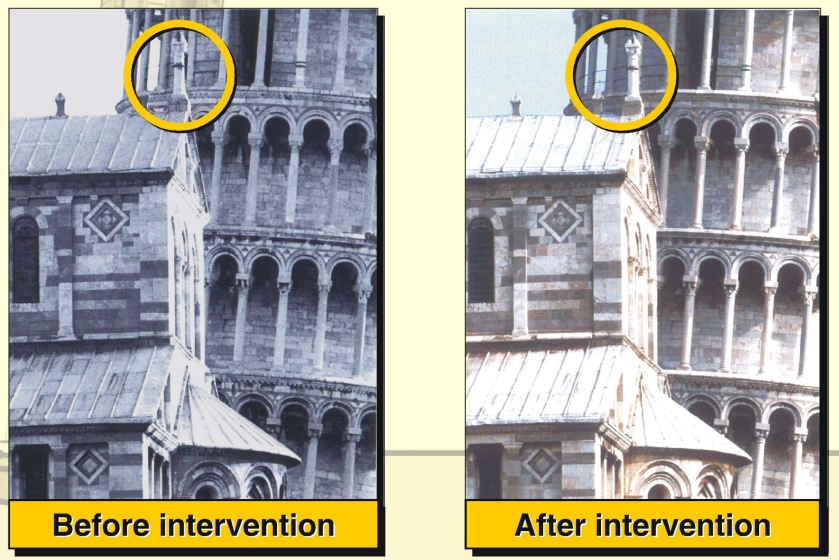
TOWER AND CATINO SETTLEMENTS ACROSS NORTH-SOUTH PLANE

February 2003 through April 2013



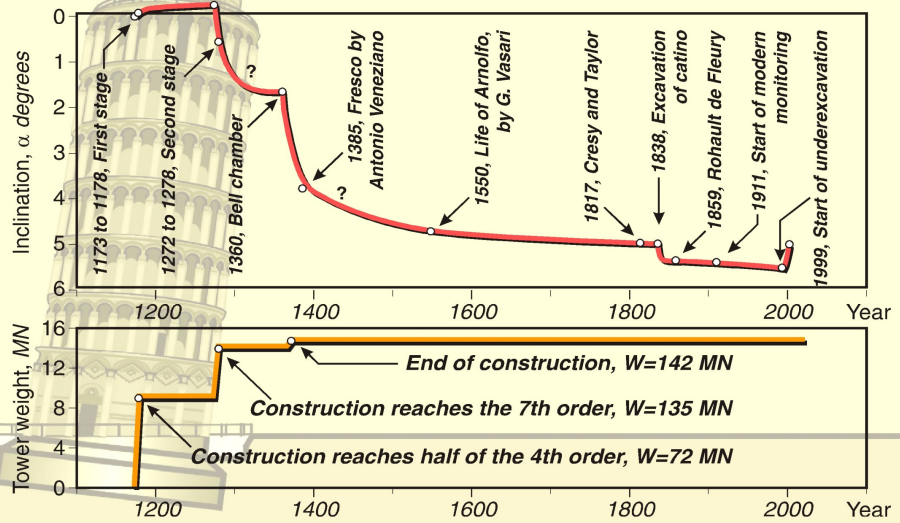
Leaning Tower of Pisa

Reduction of Tower's inclination



Leaning Tower of Pisa

History of the Tower's inclination



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THE GEOTECHNICAL TEAM

1 - M. JAMIOLKOWSKI

2 - J.B. BURLAND

3 - C. VIGGIANI

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HOW WILL THE TOWER BEHAVE IN FUTURE ?

TWO SCENARIOS CAN BE ENVISAGED:

- **PESSIMISTIC:**

  Tower will remain stable for a period of time, followed by resumption of rotation at a much reduced rate, granted at least 300 years of life.

- **OPTIMISTIC:**

  Leaning instability phenomenon has been stopped, continuing rotation will cease.*

(*) except for minor cyclic rotations induced by seasonal phenomena and ground water oscillations

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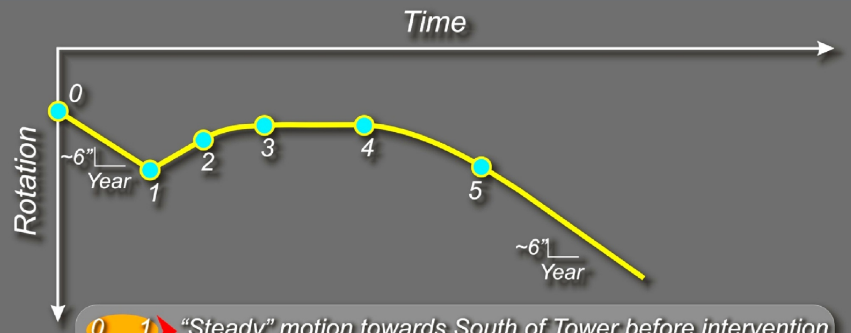
LEANING TOWER OF PISA
EXPECTED FUTURE BEHAVIOUR



0 1	"Steady" motion towards South of Tower before intervention
1 2	Reduction of inclination during intervention
2 3	"Delayed" effect of intervention
3 4	Tower motionless
4 5	Southward rotation resumed
5	Rotation rate as before intervention

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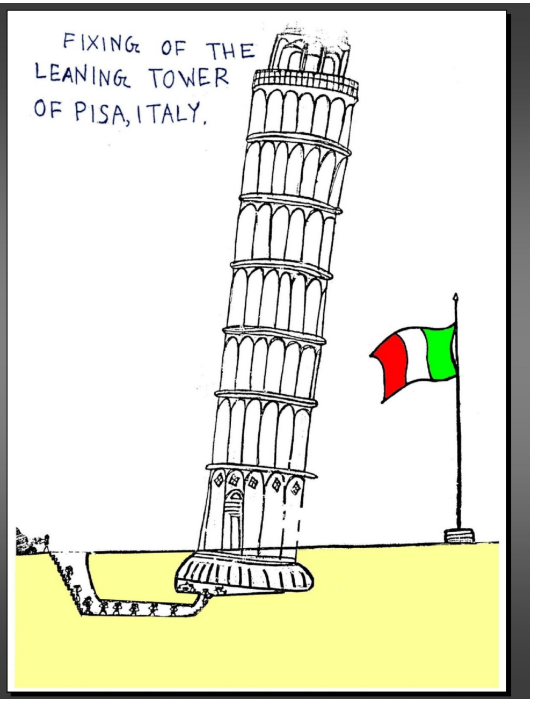
By Chumki Bhaban,
9 years old girl
from Bangladesh



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