Archimedes

Archimedes: 6. Techniker / Juristen Dialog Frühjahr 2015

"Nationaler und europäischer Schutz geistiger Leistungen dargestellt am Beispiel der Architektur und des Spezialtiefbaus„

Pisa Tower

Dr. Ing. Marco Ziller

07.05.2015, Hotel STEIGENBERGER, Linz

PISA TOWER

CONSOLIDATION AND RESTORATION

Linz, 07 May 2015

Consorzio Progetto Torre di Pisa

BONIFICA – ENEL.HYDRO – ITALSONDA – RODIO – TREVI

Dr. Eng. Marco Ziller

Technical Director of the Consortium

History

Piazza dei Miracoli

Ideal unity of religious · spiritual · political power

Beginning of construction

Cathedral – 1064

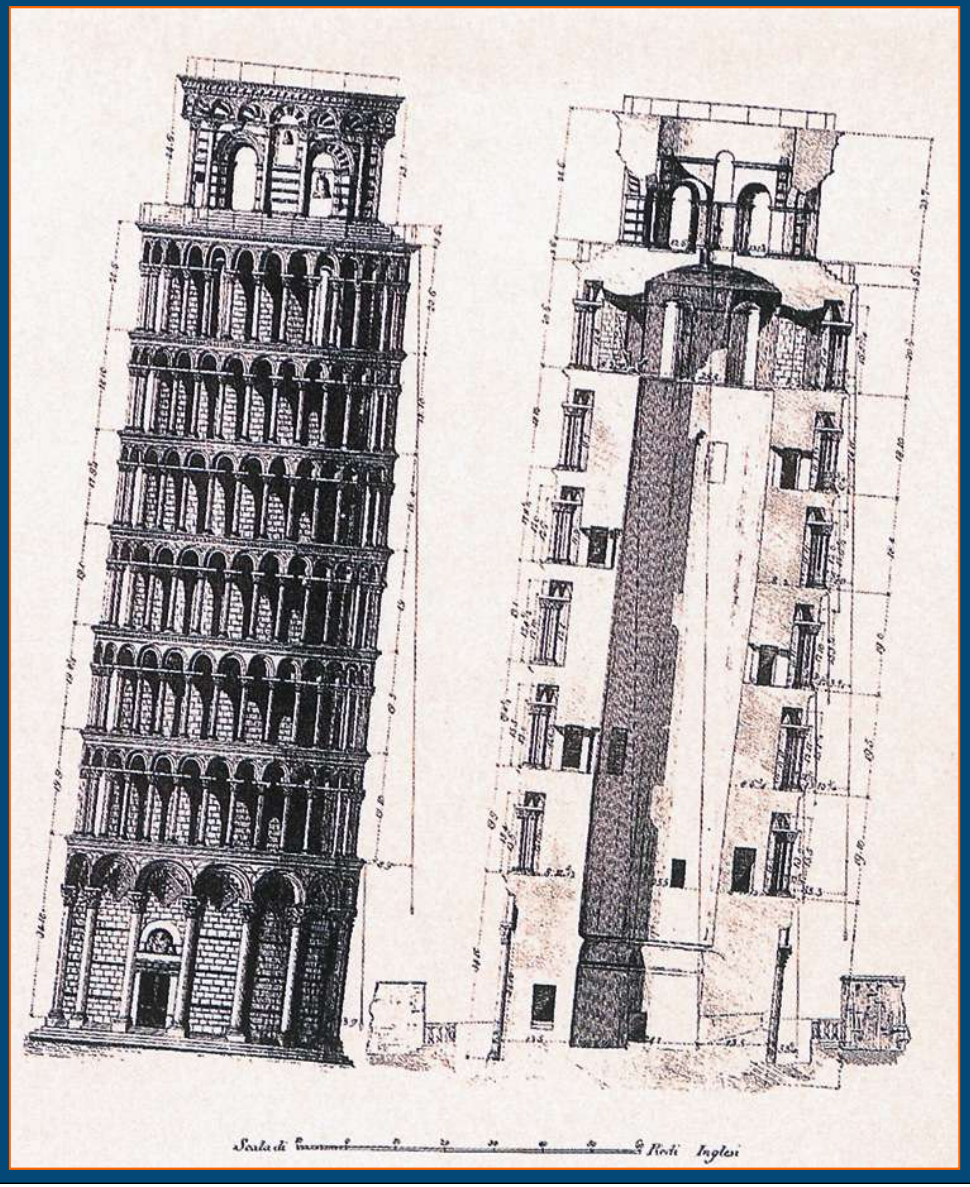
Baptistery – 1152

Tower – 1173

Construction features

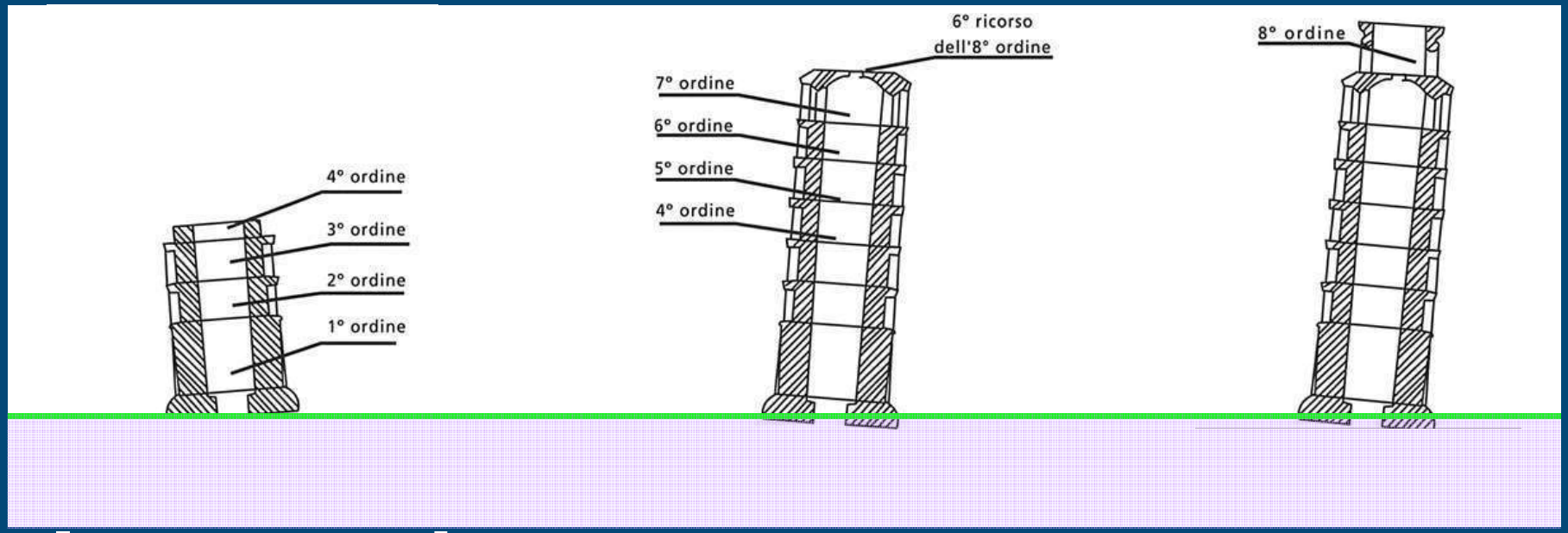
The structure is made of a hollow cylinder surrounded by 6 archades with columns (30 per level) and by vaults emerging from the cylinder at the base

Final high = 58.4 m



Construction phases

1st: 1173-1178 **2nd: 1272-1278** **3rd: 1360-1370** **Tot 21**

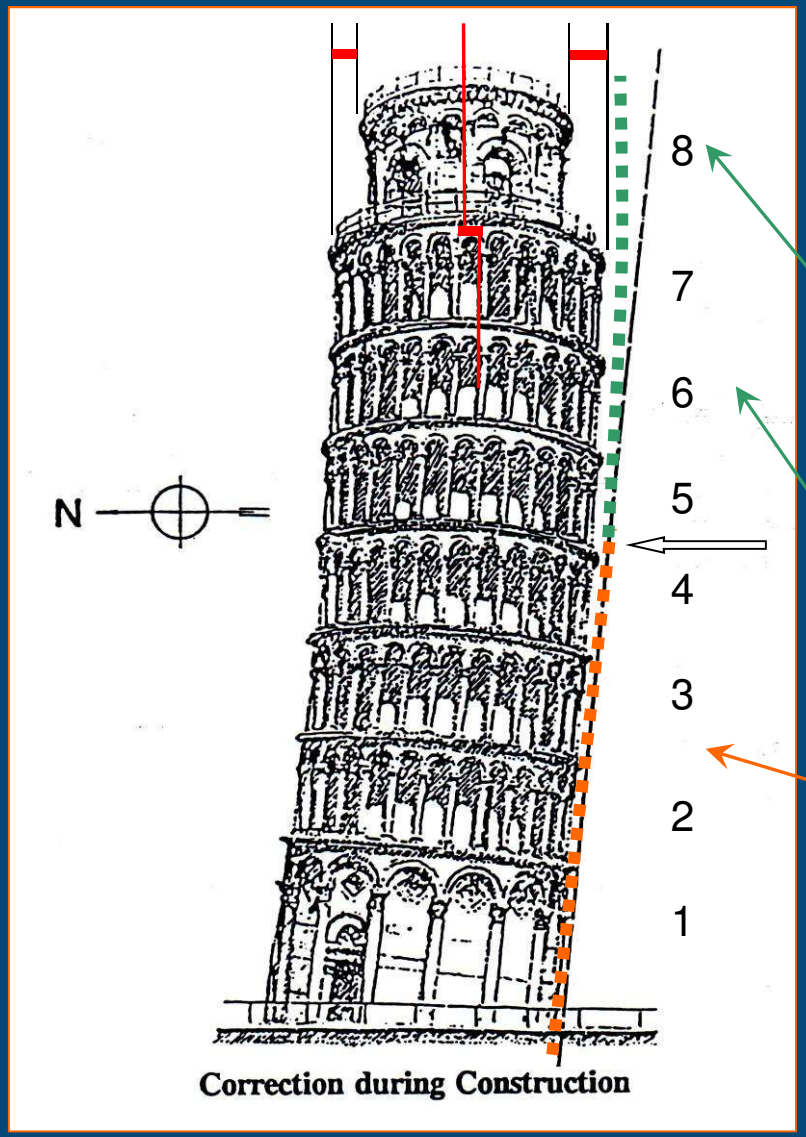


Interruptions

1st: 94 years **2nd: 82 years** **Tot 176**

Total time **197 years**

Construction features



Correction during Construction

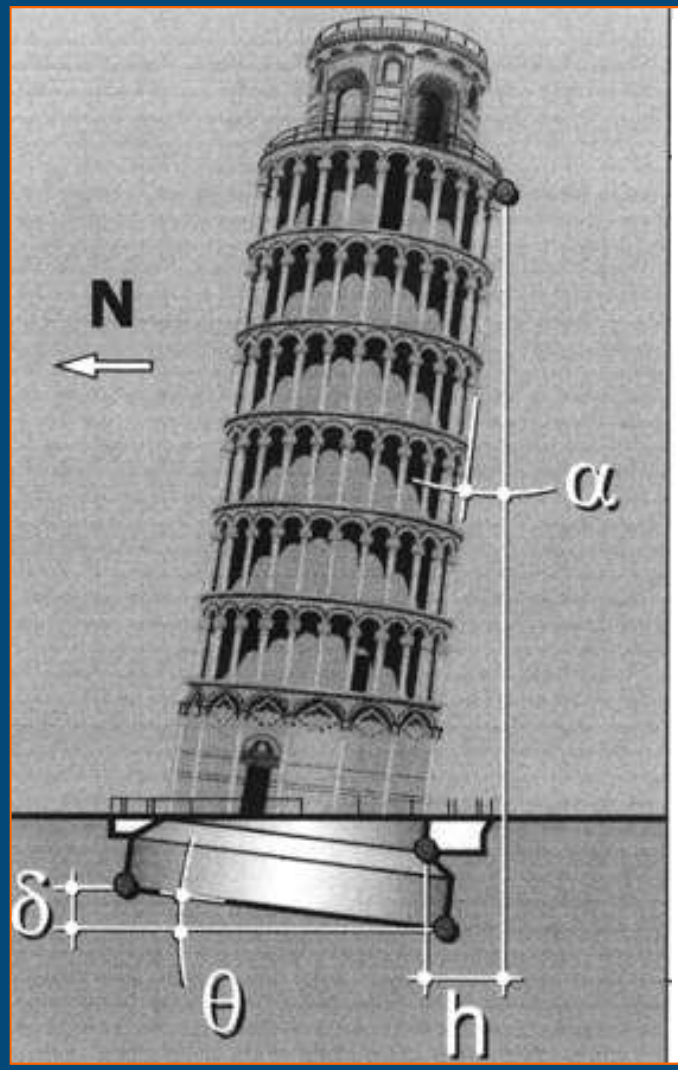
During the second building phase, the direction of the axis – that continued to ineluctably lean – began to be noticeable.

Bell chamber: element 8 center shifted to the North

Axis of the Tower
bended line: elements 5 → 7
straigth line: elements 1 → 4

Construction features

Historic re-construction of the Tower's rotations



Maximum inclination before the application of the lead counterweigth in May 1993/1995

$\theta = 5° 33' 36''$ $h = 4.47$ m

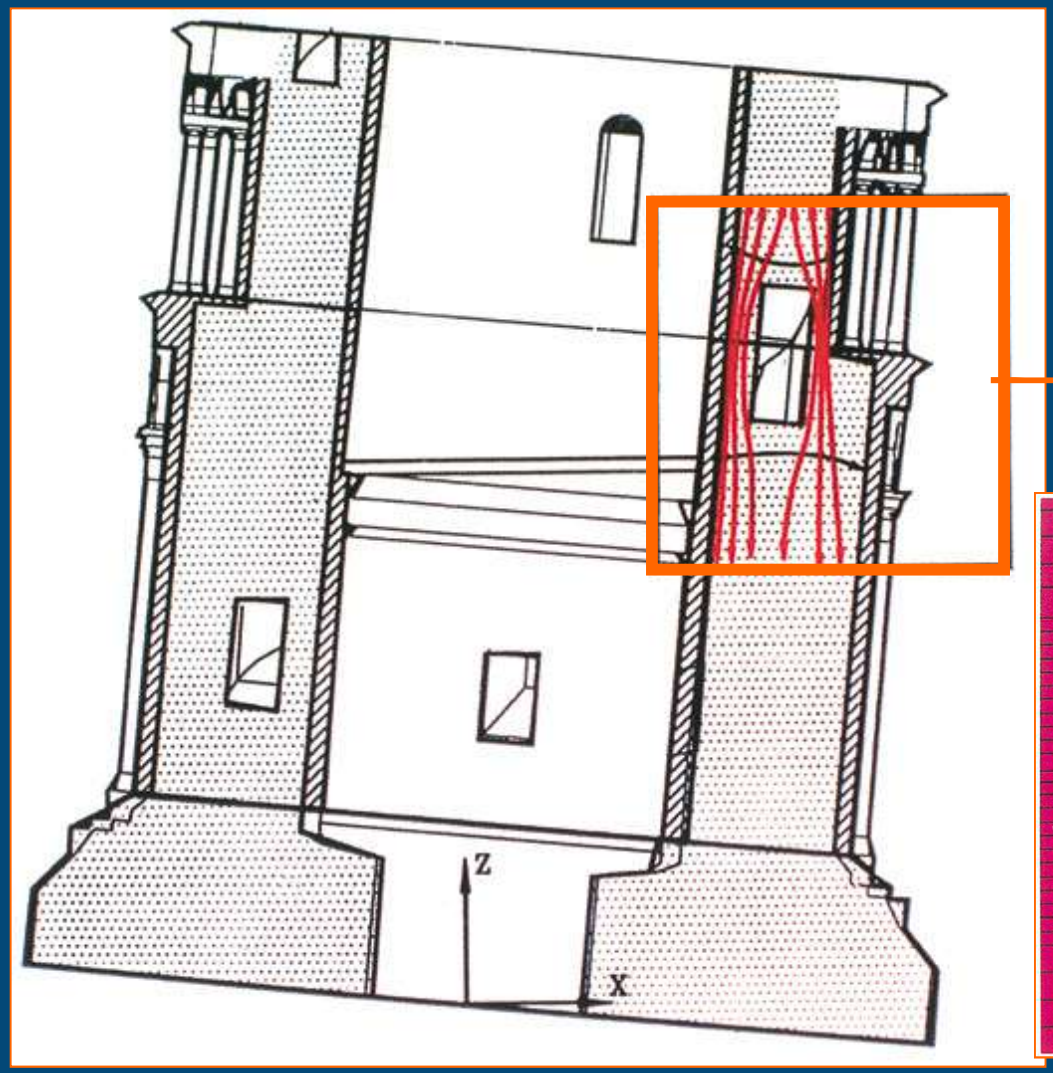
α = axis inclination

θ = basis inclination

δ = differential settlement of the base ~1.95m

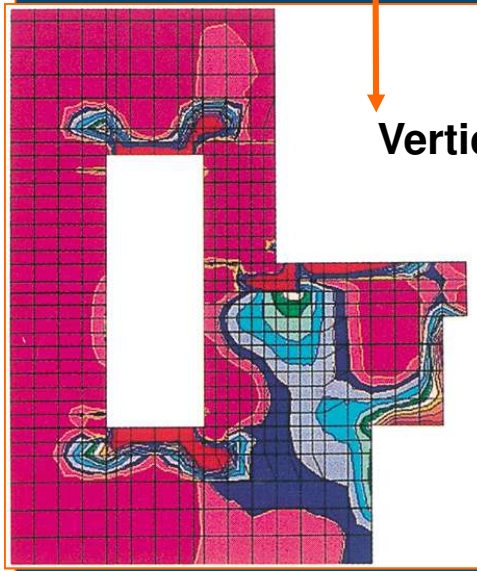
h = horizontal displacement of the tower at the 7° level =4.47m

Dangerous Situations



Structural Analysis
Tomography

Fear of a brittle failure of the masonry:
Max pressure 8MPa = 80 Kg/cm²



Vertical fissures and cracks

Institution of the Committee 1990

Members: Jamiolkowski,
Burland, D'Elia, Desideri, Di Stefano,
Gurrieri, Lemaire, Leonards, Leonhardt, Veniale, Viggiani.

Duty: Updated acquisition of knowledge of the complex tower/soil
Individuation of possible solutions for the safety of the Tower
Final design

Institution of the Consortium:

1989 Consorzio Torre di Pisa for the execution of geotechnical and structural drillings, integration of the monitoring system for the Tower and the surrounding soil.

1990 Consorzio Progetto Torre di Pisa:

Members: bonifica S.p.A. Enel.Hydro IS ITALSONDA RODIO TREVI

Duty: Executive design and implementation of the solutions

Intermediate statement: 1990 the Committee acknowledges:

- Physical and mechanical features of the Leaning Tower and of the ground were are known in a sufficient manner.

- The analyses of the movements of the Leaning Tower, resulting from the instrumental monitoring carried out since the 1900, had led to the acquisition of a thorough knowledge of its behaviour.

- The Leaning Tower of Pisa was affected by leaning instability linked to the insufficient rigidity (and not to the insufficient resistance) of the ground.

- It was difficult to quantify the safety margin possessed by the Tower in 1990 in terms of the risk of collapse by overturning, but all the analyses performed indicated that the safety margin was low – and the risk of overturning high.

- The structure of the Tower was, at some locations, subject to very high stresses; creating a high risk of local brittle failure of the masonry, which could have triggered the immediate collapse of the Tower without any forewarning.

The existence of these risks made it imperative to take rapid temporary and reversible measures to improve safety; with implementation of these temporary schemes the Commission gained the time needed to complete its studies and analyses prior to conceiving, planning and finally implementing permanent stabilisation actions.

Intermediate statement: 1990 the Committee takes decisions:

1. To reduce the inclination of the Tower by one-half of one degree (about 10% of the inclination in 1990) by inducing a controlled settlement at the north side of the foundation.

This could be achieved through different actions:

A. Reinforced concrete pressing slab on the ground surface north of the Tower.

B. Reduction of the volume (shrinking) of the upper clays, north of the Tower, by means of vacuum pumping or electro-osmosis.

C. Controlled extraction of volumes of soil below the foundation level (underexcavation).

Note:
The last method had been recently applied for the mitigation of the differential settlements of the Metropolitan Cathedral of Mexico City.

Decisions

Closure of the Tower 7th January 1990

	Structural risk	Geotechnical risk
Temporary interventions	Safety belt by means of prestressed steel cables	Lead counterweights, anchors, backstays.
Definitive interventions	Safety belt by means of prestressed steel cables Local reinforcements by means of grouting and steel bars	Inclination decrease by means of the induced differential settlement

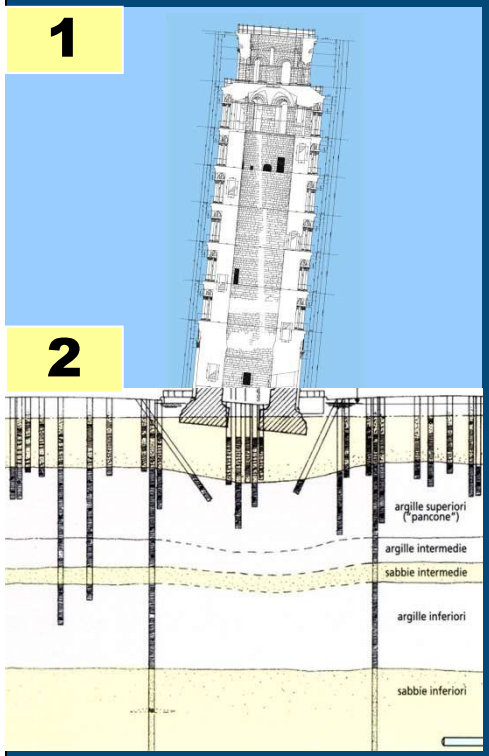
Interventions

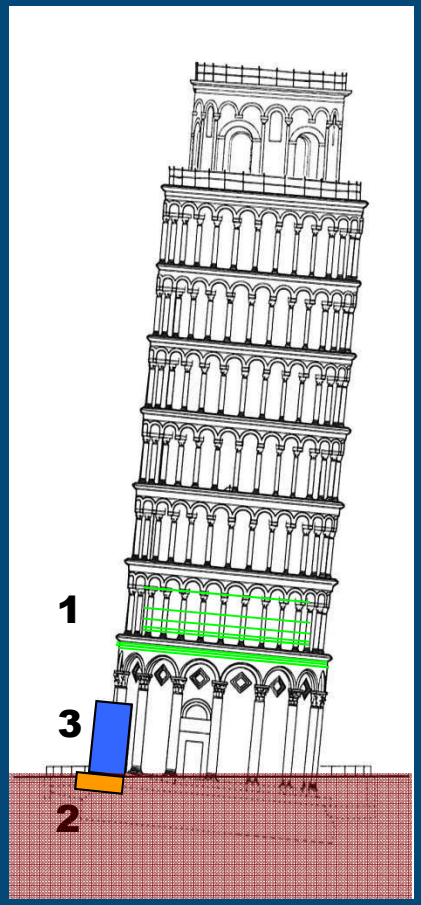
Investigations
1. Tower Instrumentation and Photogrammetry
2. Soil investigation

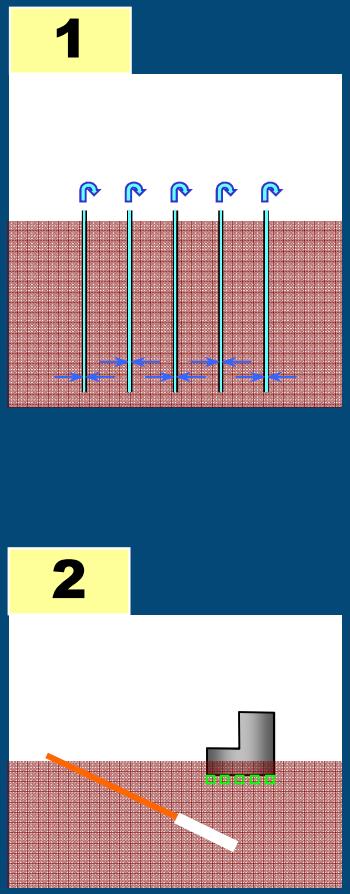
Termporary interventions
1. Safety belt
2. Lead-bearing beam
3. Lead counterweight

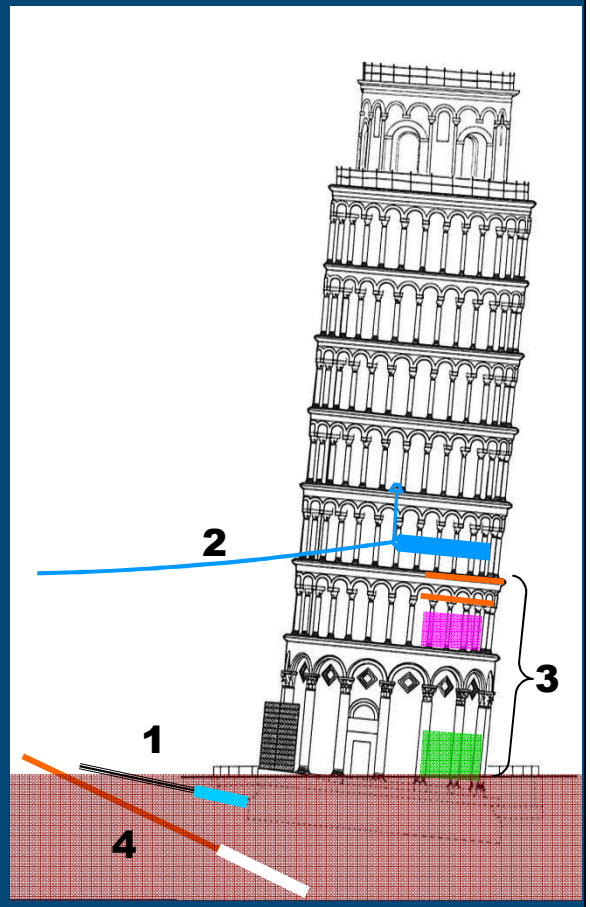
Field tests
1. Electro-osmosis
2. Underexcavation

Final interventions
1. Beam in the catino connected to the Tower and freezing
2. Temporary stays
3. Structural reinforcement
4. Underexcavation







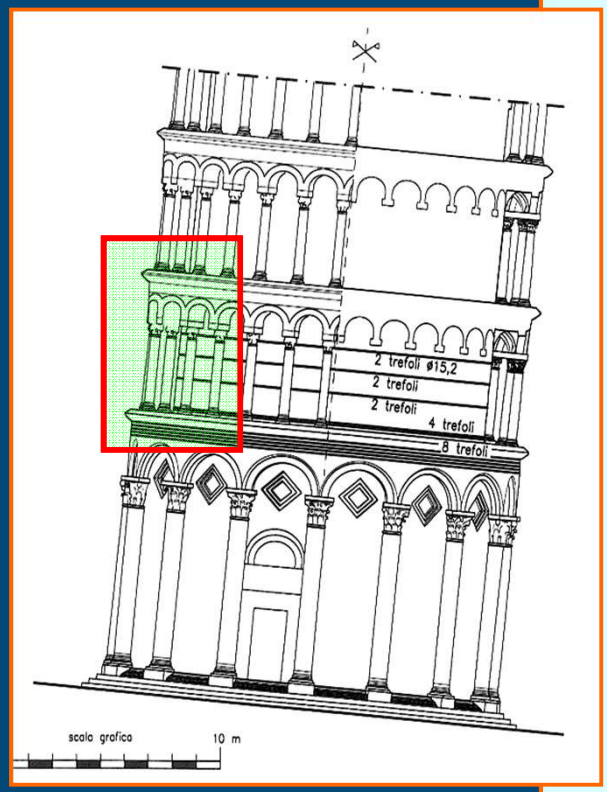


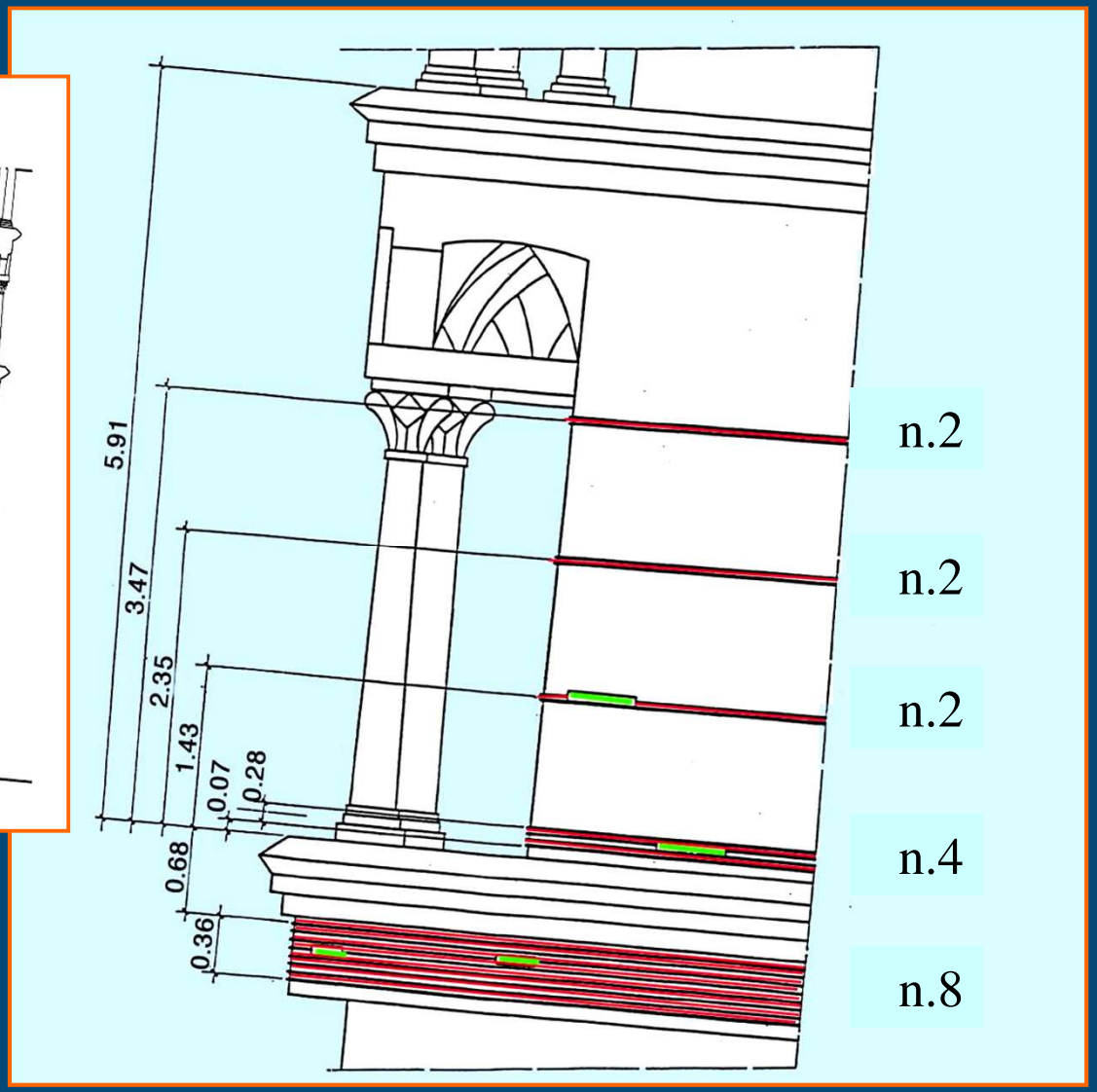
Instrumentation

Instruments installation inside the Tower

Temporary interventions

Circular belts of steel strands





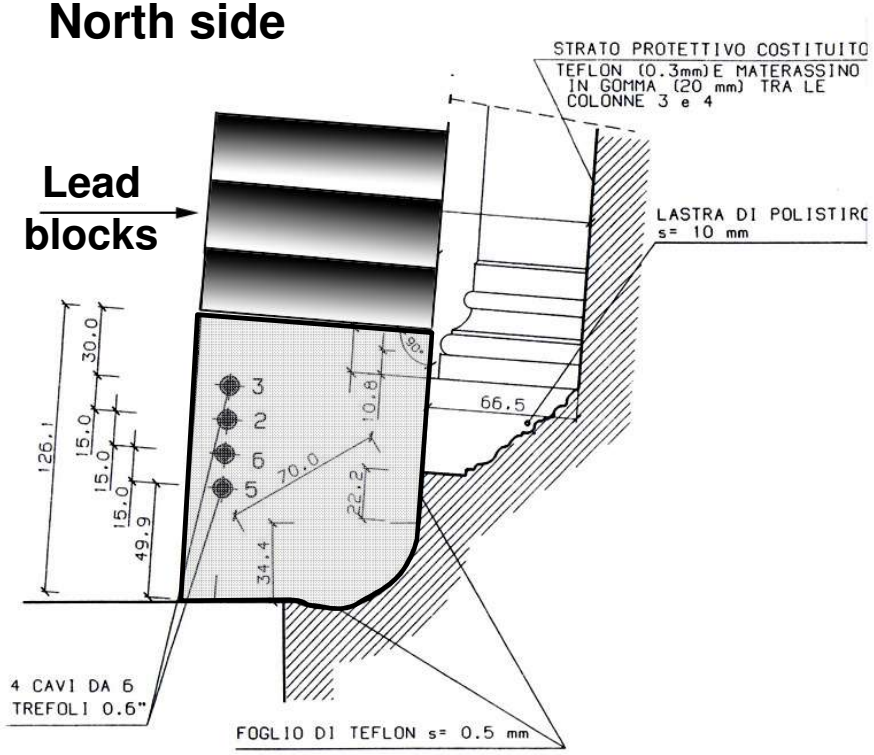
Position of the prestressed cables

Lead counterweigth with beam

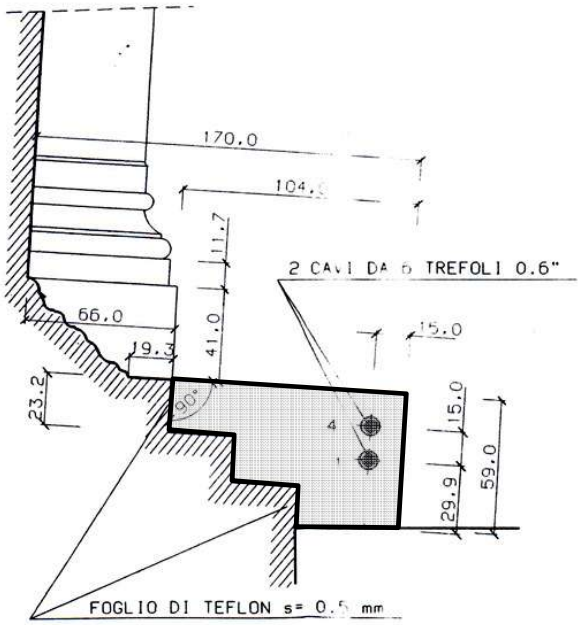
Temporary interventions

North – South Section

North side



South side



Layout of the lead-bearing beam

Temporary interventions

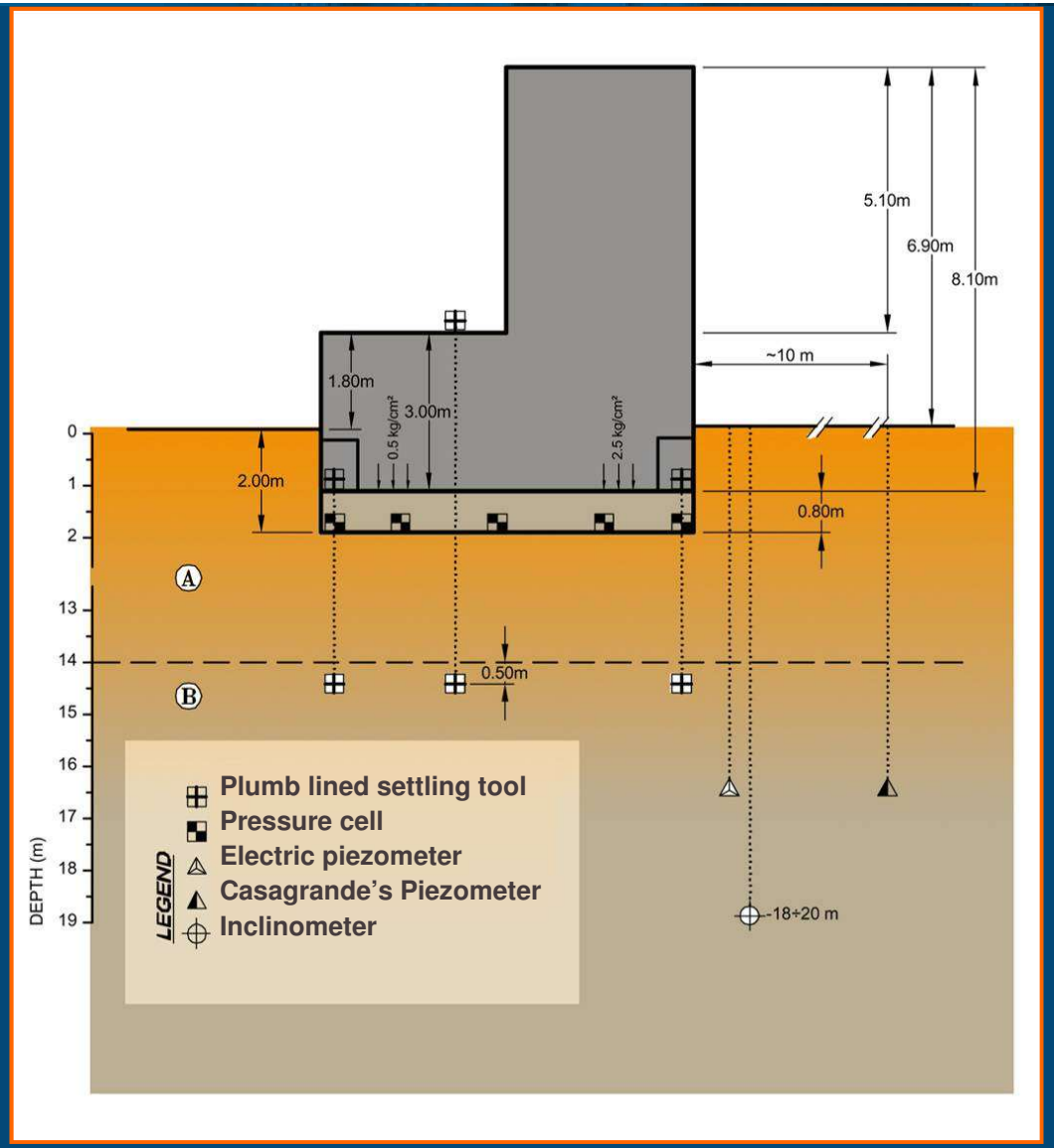
Counterweight wall under construction

Trial test for underexcavation

Concrete asymmetric structure with instrumentation

Monitoring of:

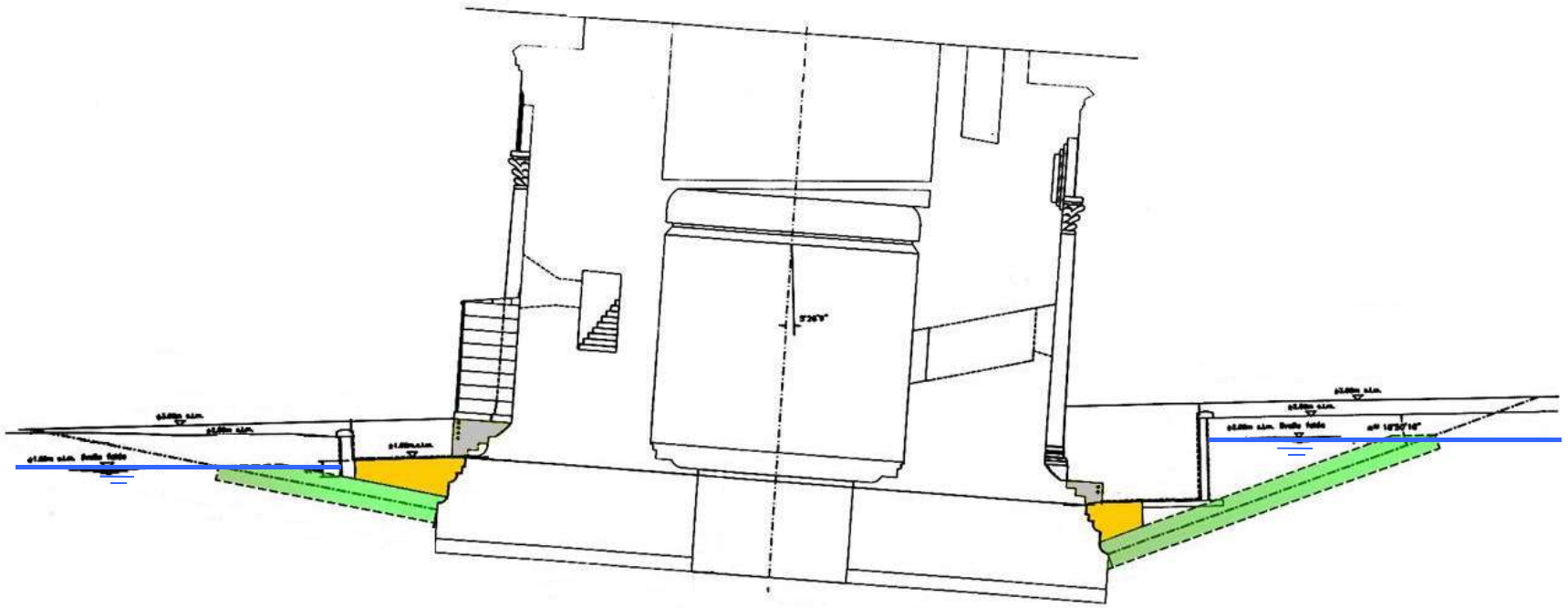
1. **Settlements**
2. **Rotations**
3. **Contact pressure**
4. **Pore pressure**



Beam under the catino

Final interventions

North - South



- Lead-bearing beam
- Beam
- Frozen soil

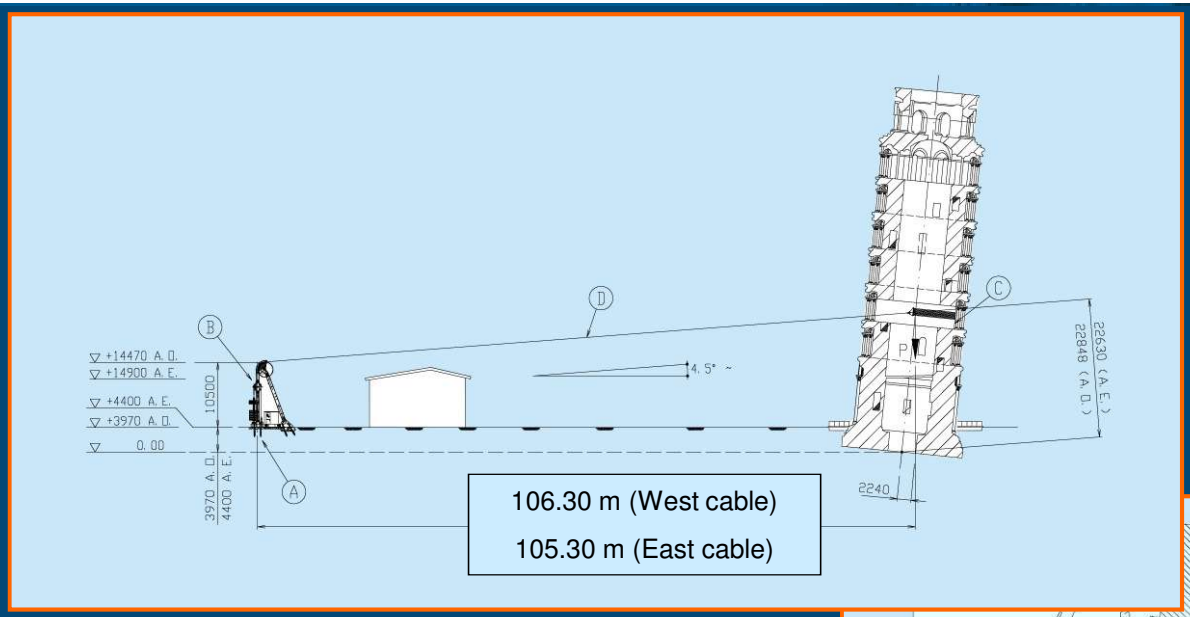
Freezing

Final interventions

Freezing in operation with exausted nitrogen

Safeguard system: N.2 stays

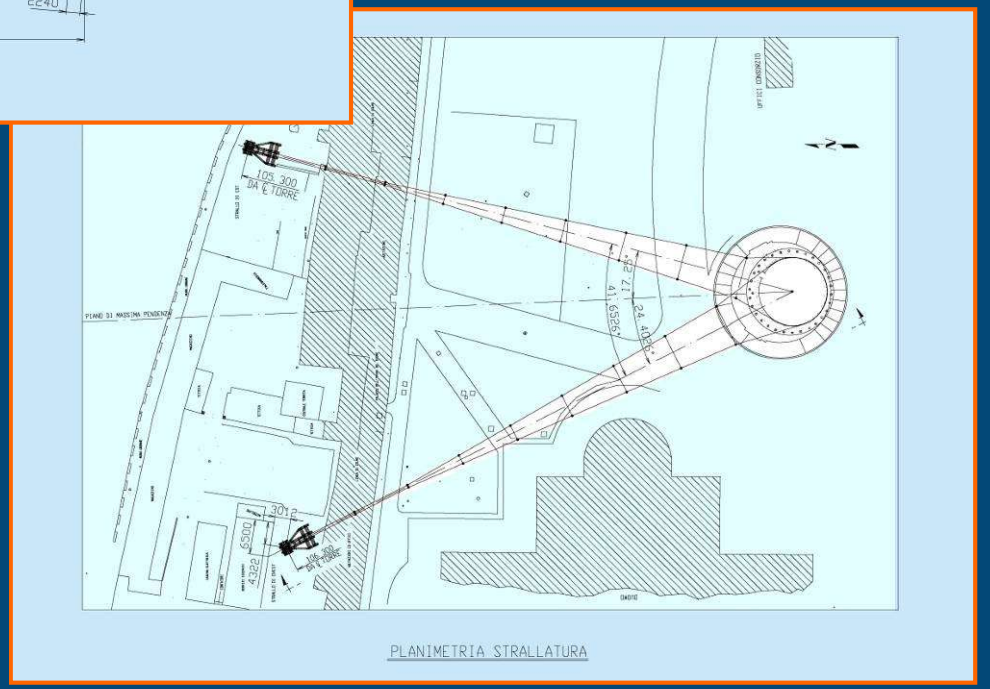
Final interventions



Temporary safety stays

Side view

Max possible traction each stay = 1500KN



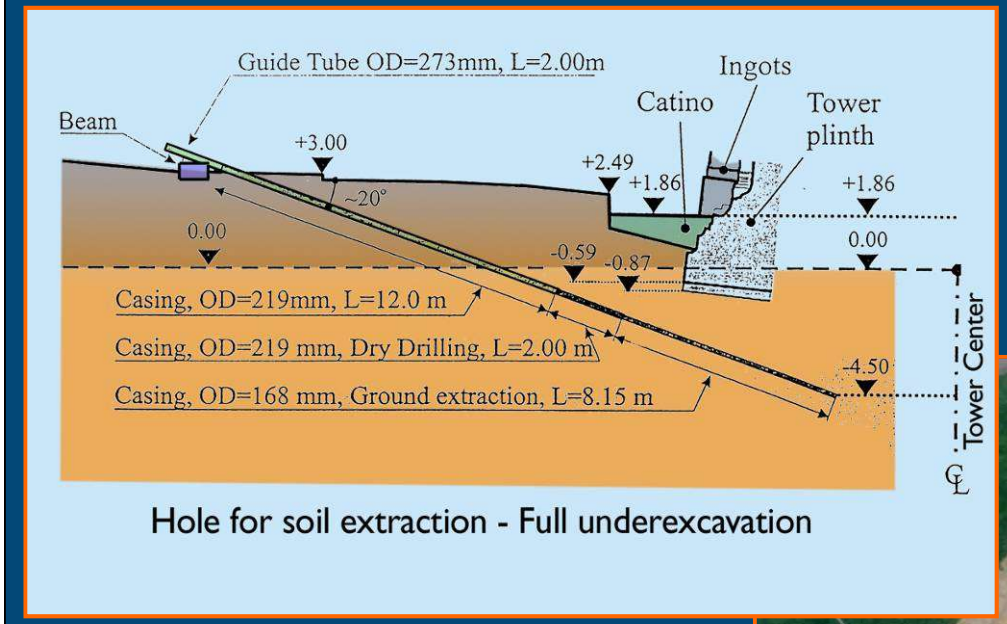
Structural reinforcement

Final interventions

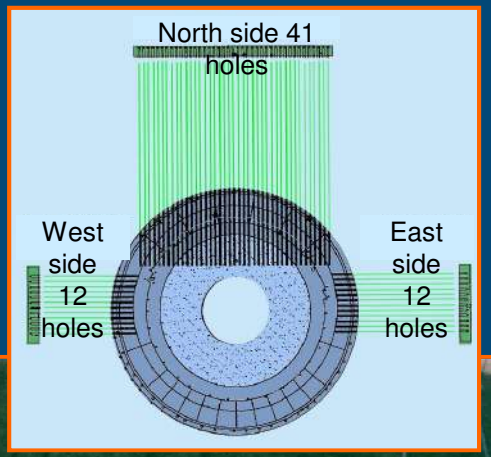
- Grouting
- Installation of stainless steel bars and chemical pegs

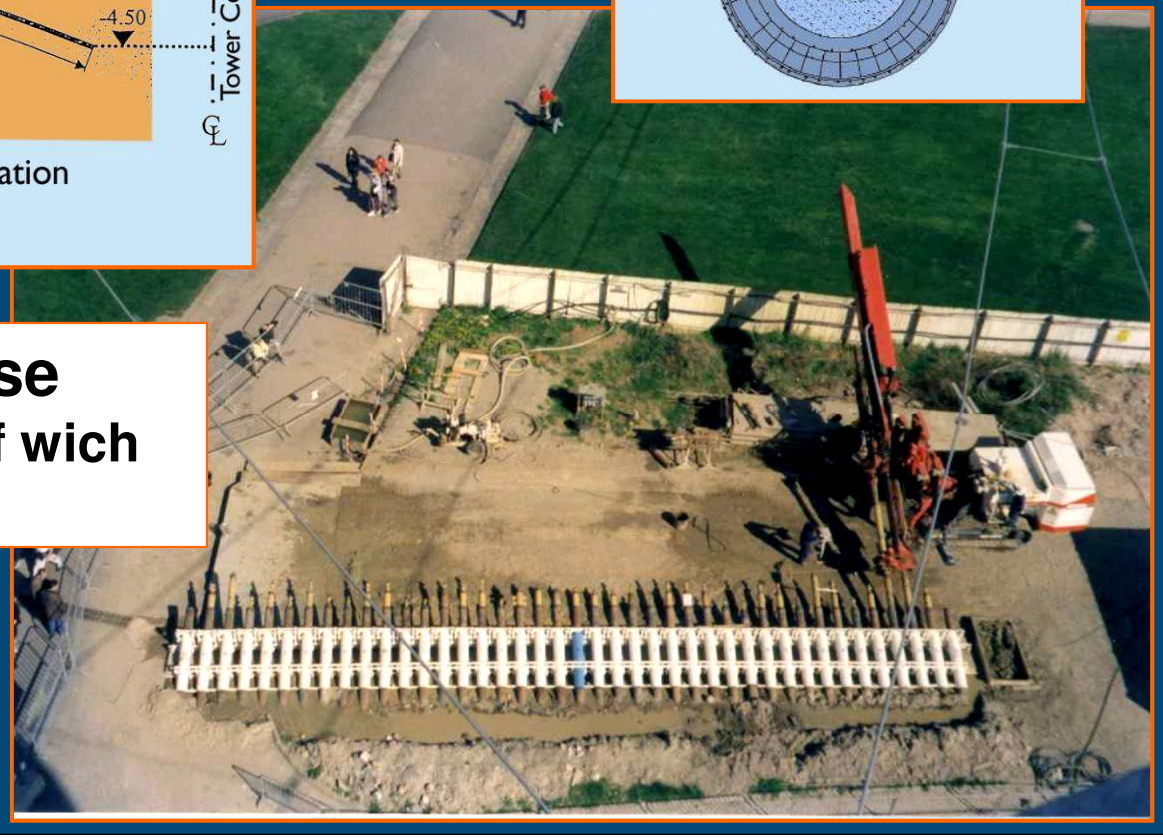
Underexcavation

Final interventions



Hole for soil extraction - Full underexcavation





2000-2001 Second phase

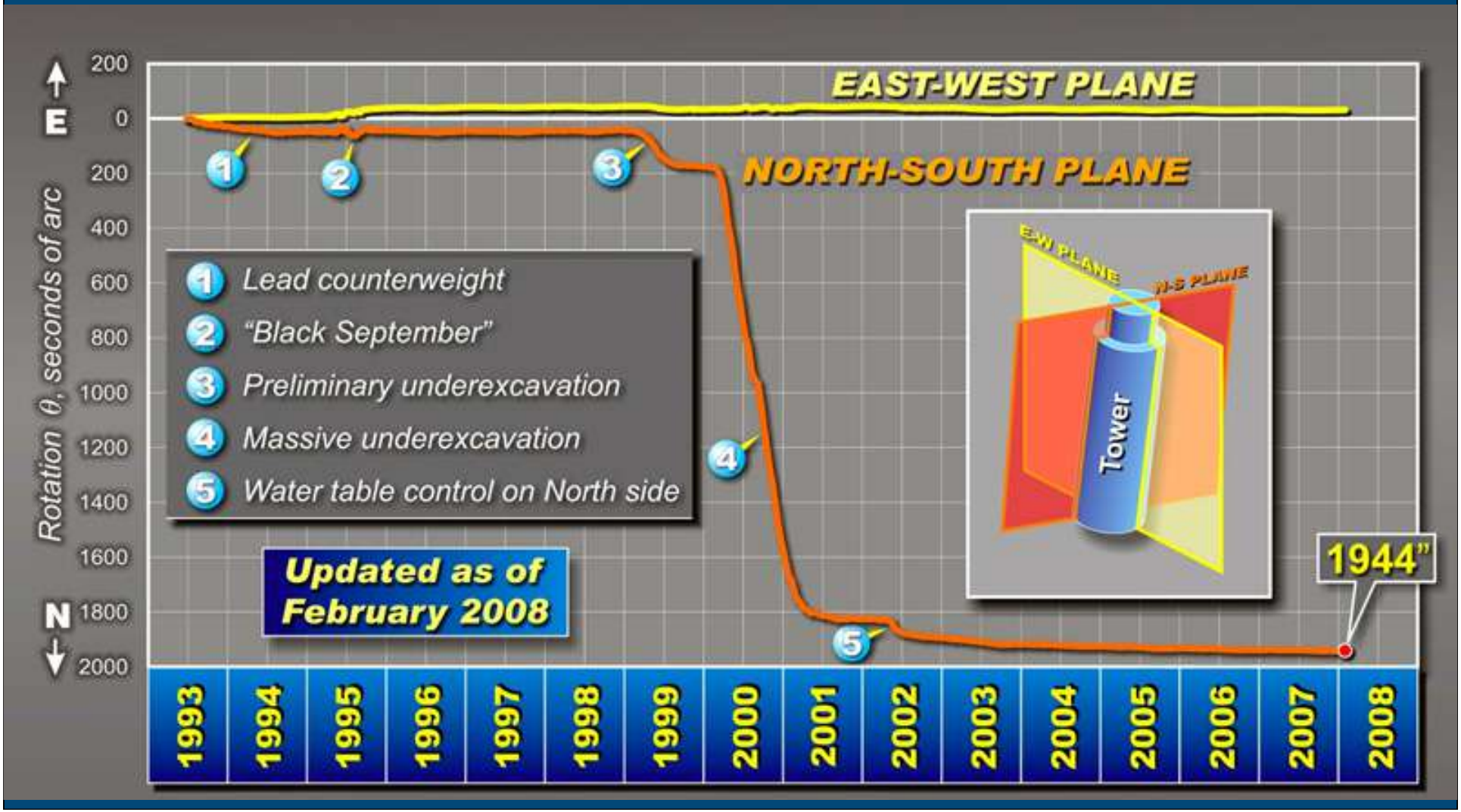
41 holes – 38mc soil extr. of wich 11mc under the foundation

Restoration of the catino

Reconstruction of the floor of the catino

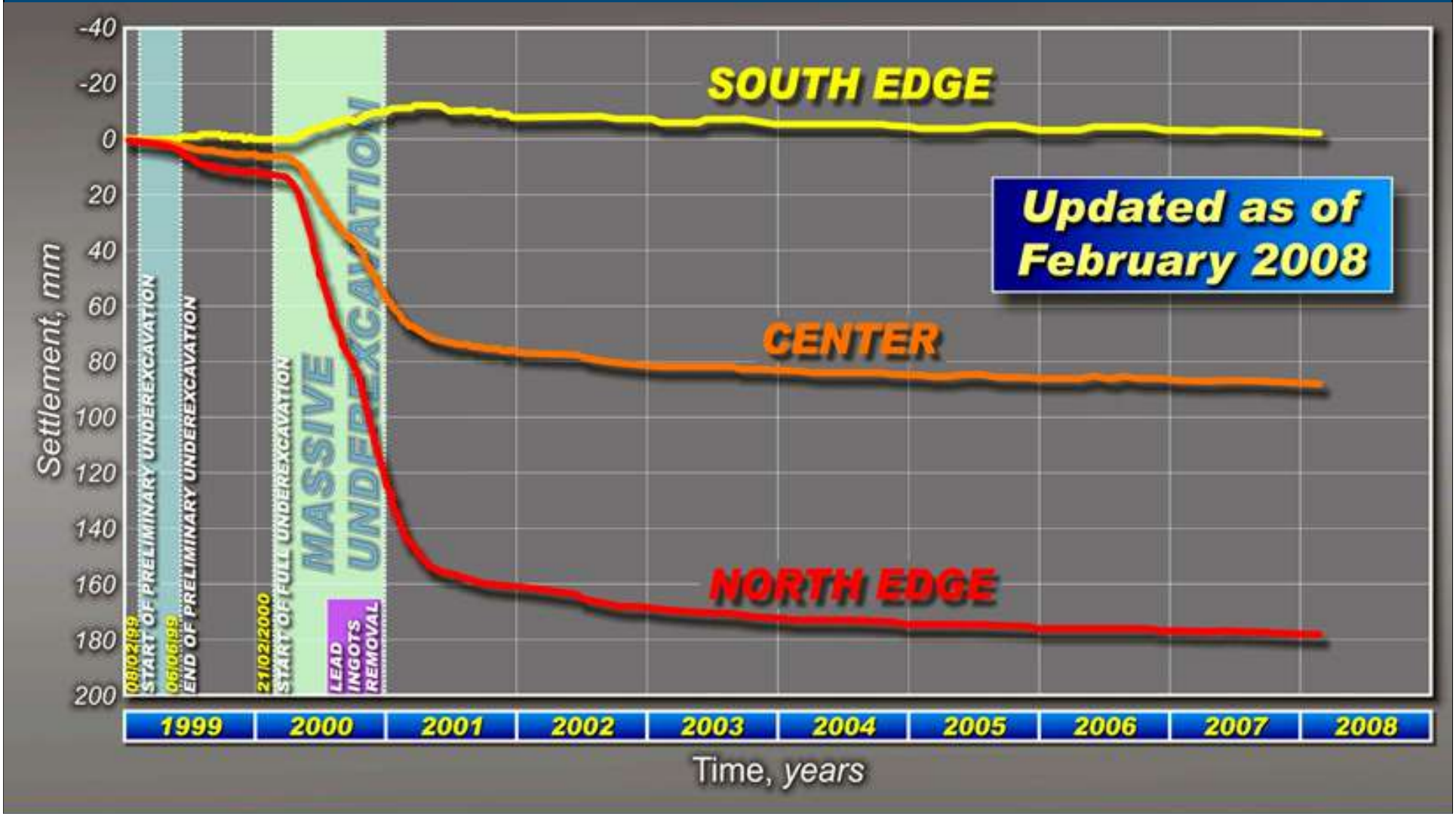
The Tower is stable: 2008

Rotations



The Tower is stable: 2008

Settlements

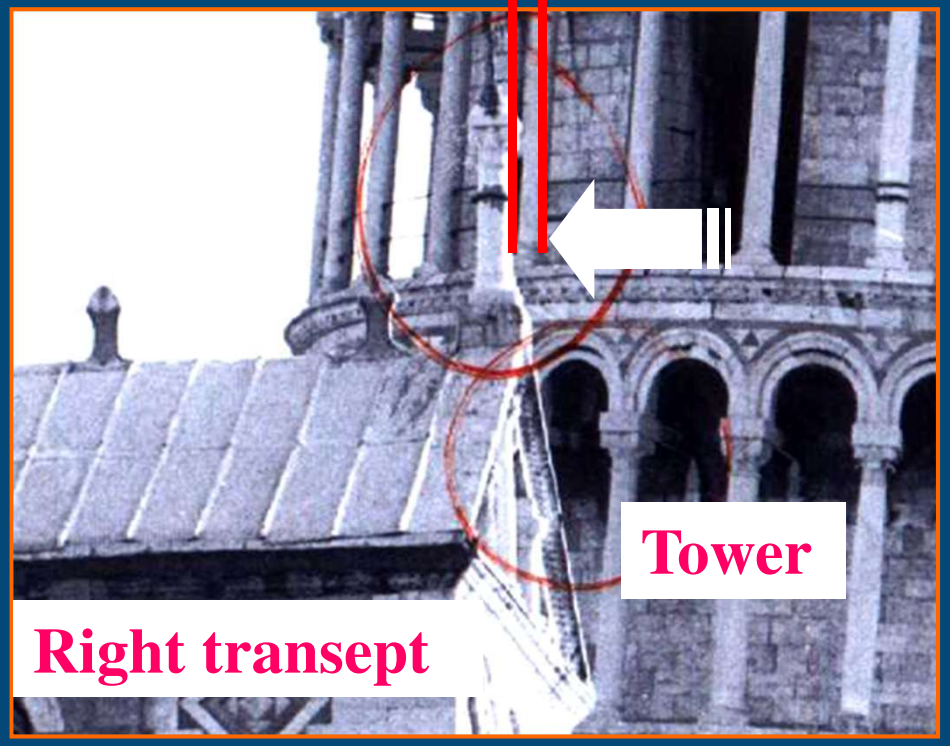


The Tower has returned northwards

Distance between pinnacle and column C d = 43.3cm

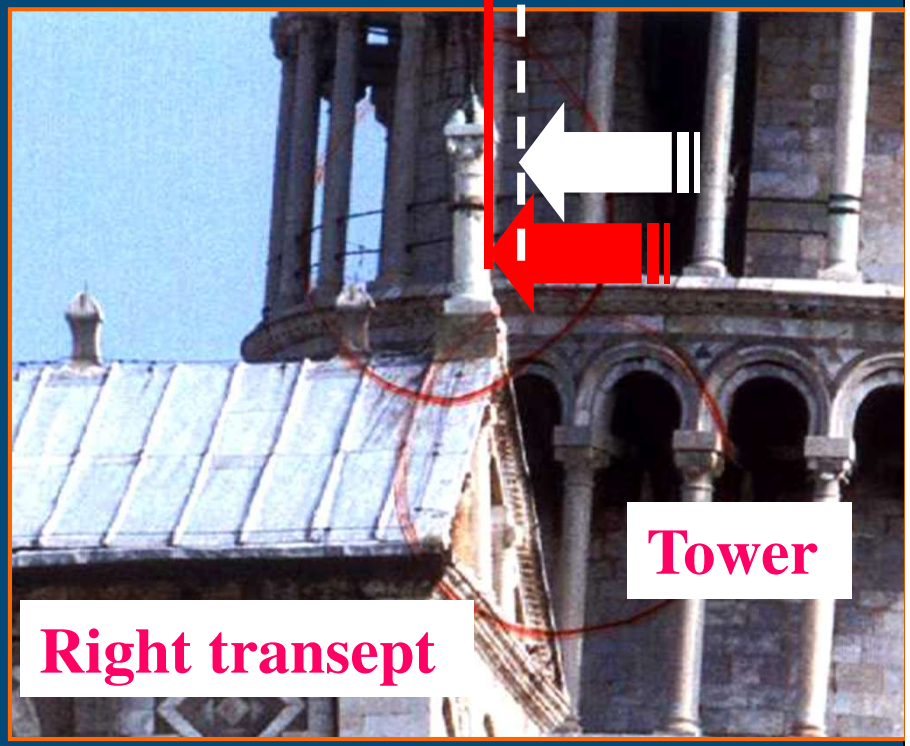
Before

Pinnacle ⟶ ⟵ Base of the column C



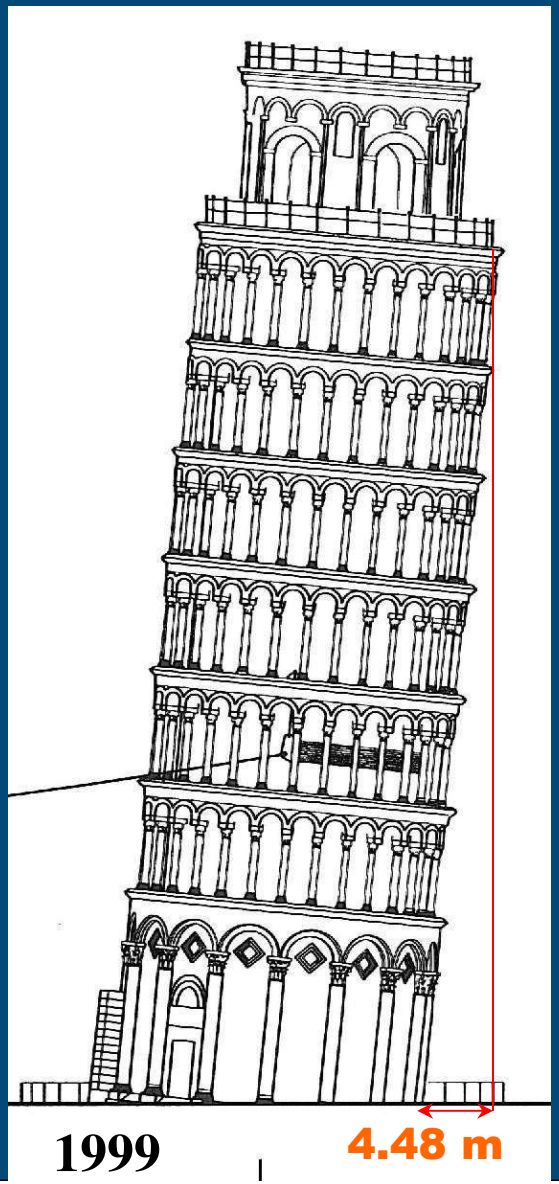
Distance between pinnacle and column C d=0

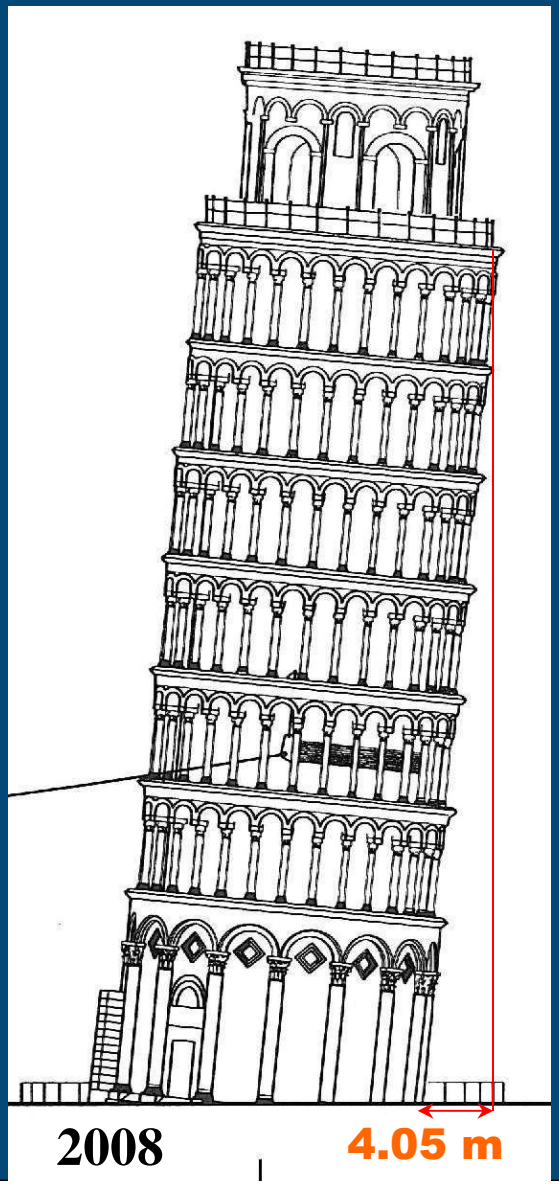
After



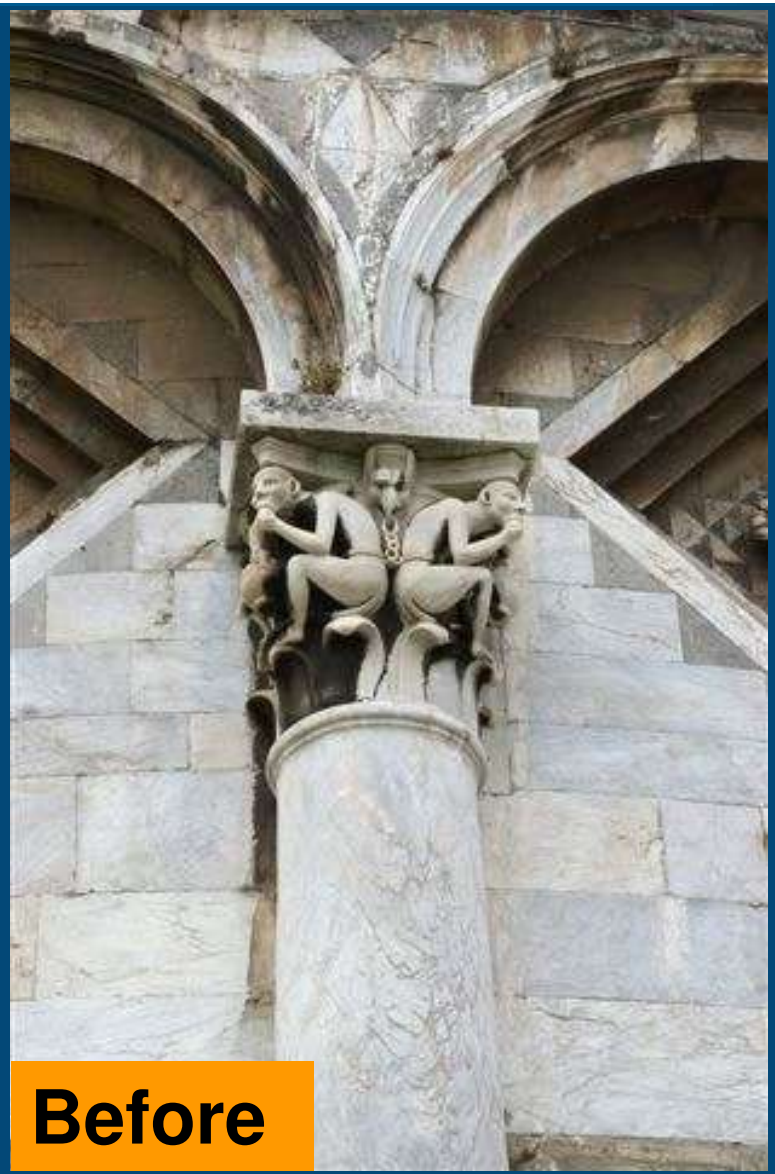
The Tower has been stabilized

Return of the Tower to the North
R = 0,43 m





Final restoration of the marble



Before

After

Final restoration of the marble

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