UNIVERSITÀ DI PISA
DIPARTIMENTO DI INGEGNERIA CIVILE ED INDUSTRIALE

SOME INFORMATION ABOUT GEOTECHNICAL ASPECTS OF PISA TOWER STABILIZATION

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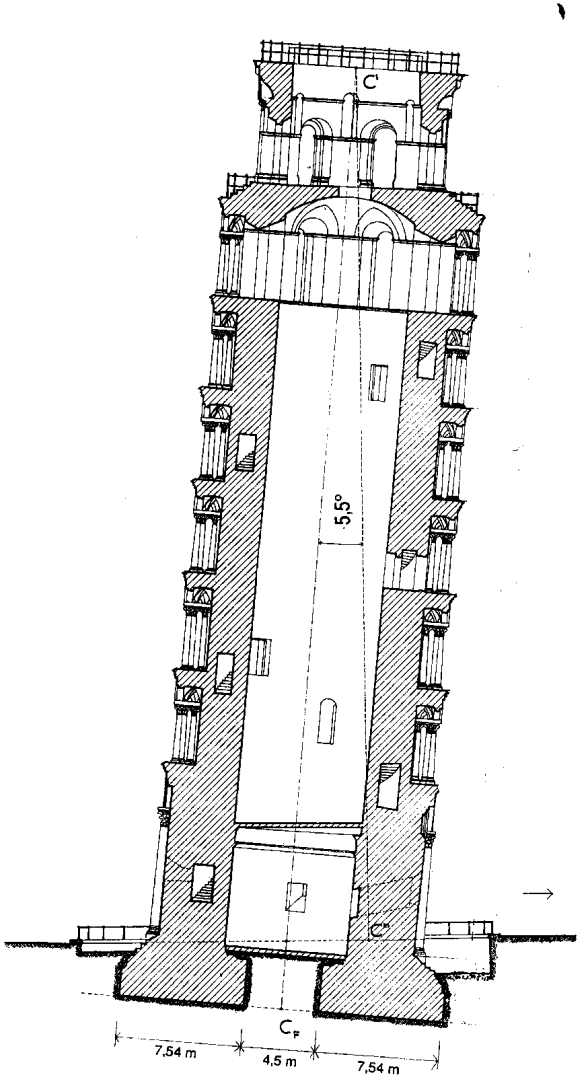
History of construction



Height = 58.4 m

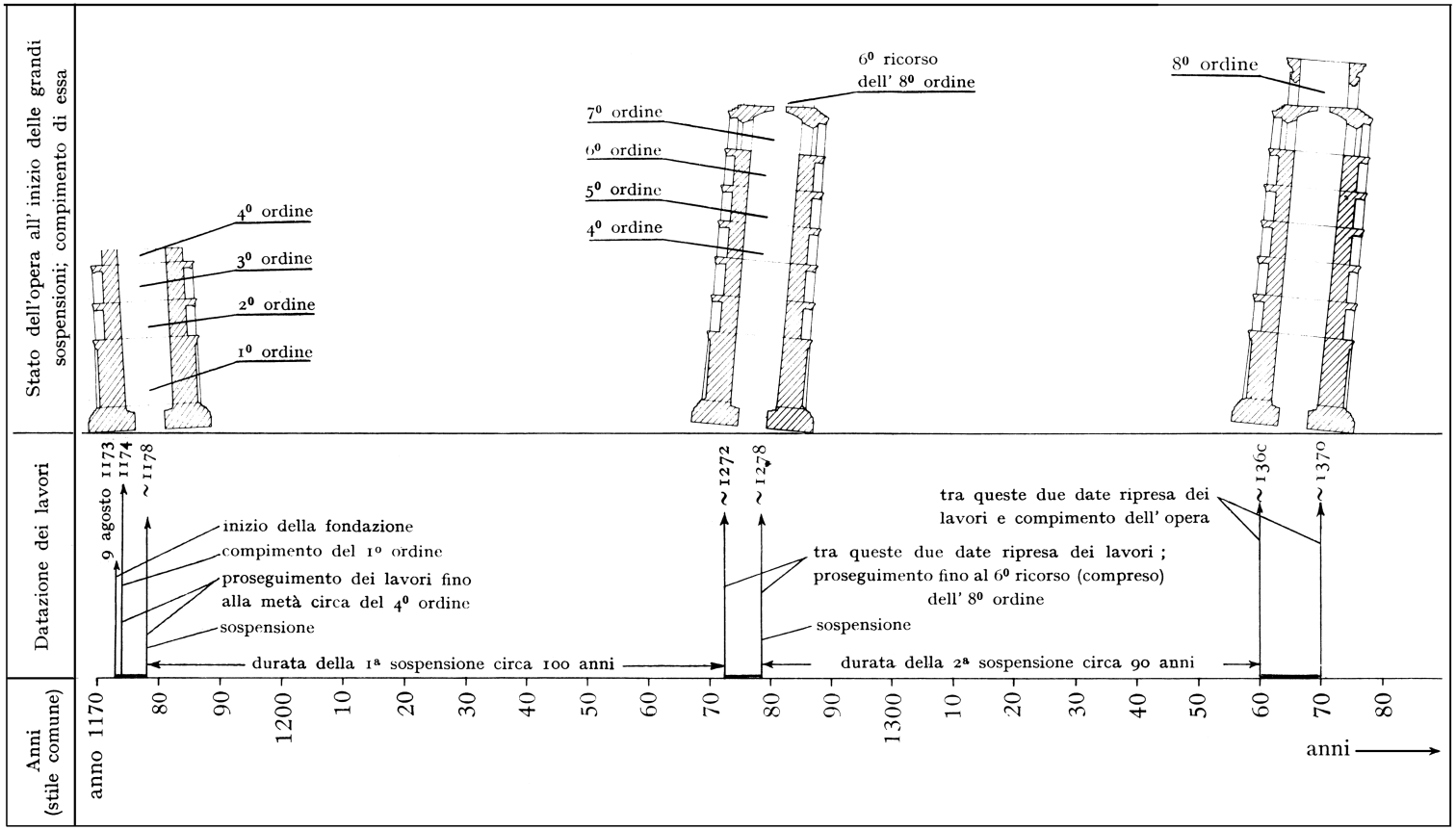
Weight = 142 MN

Diameter of foundation = 19.6 m

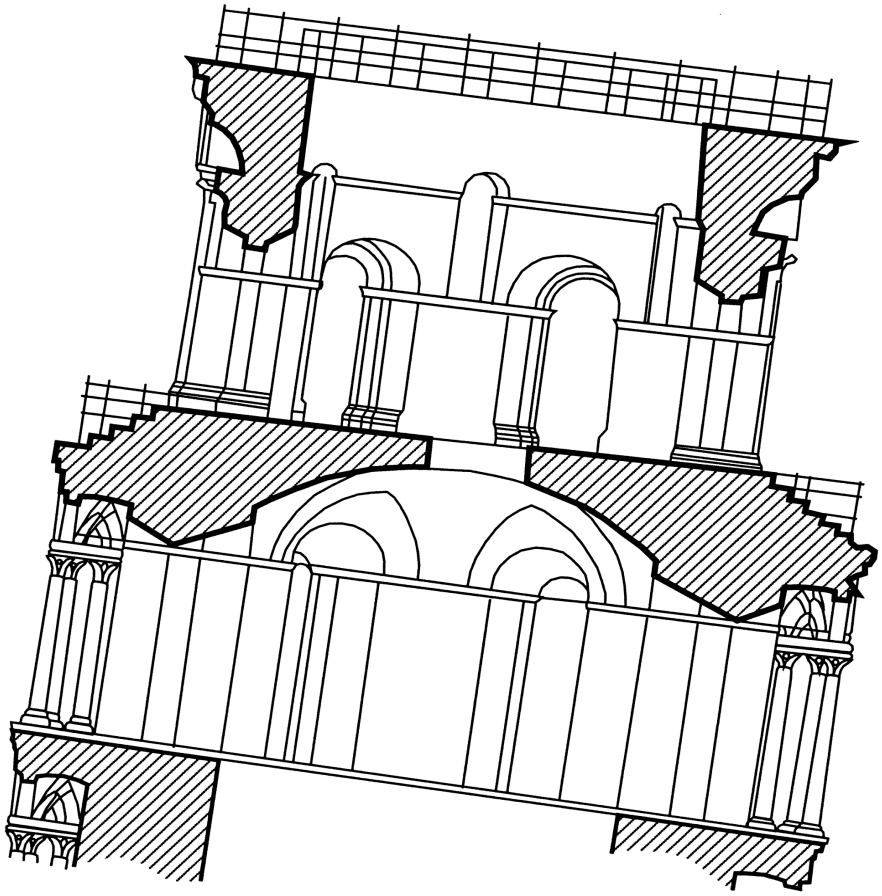
Height of centre of masses = 22.6 m

Average pressure on soil = 497 kPa

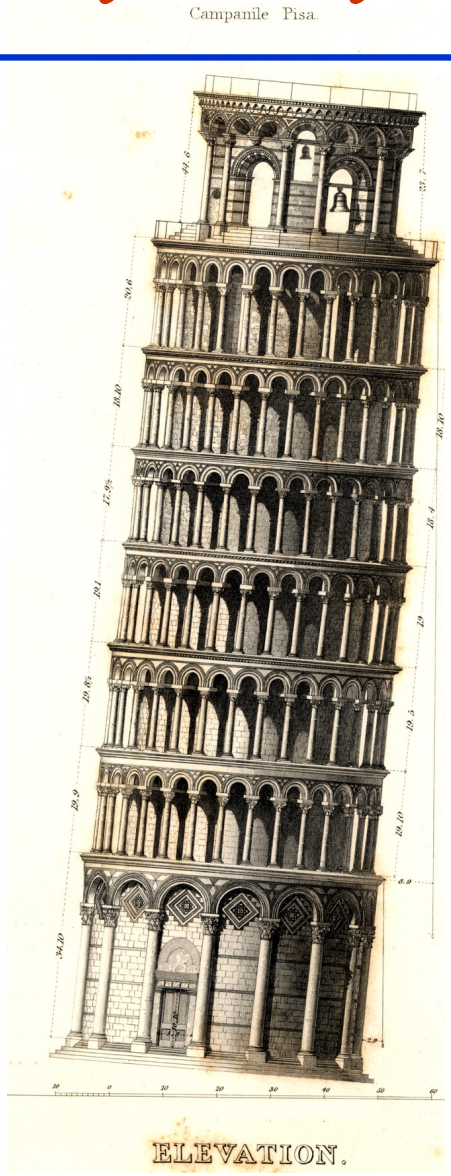
History of construction

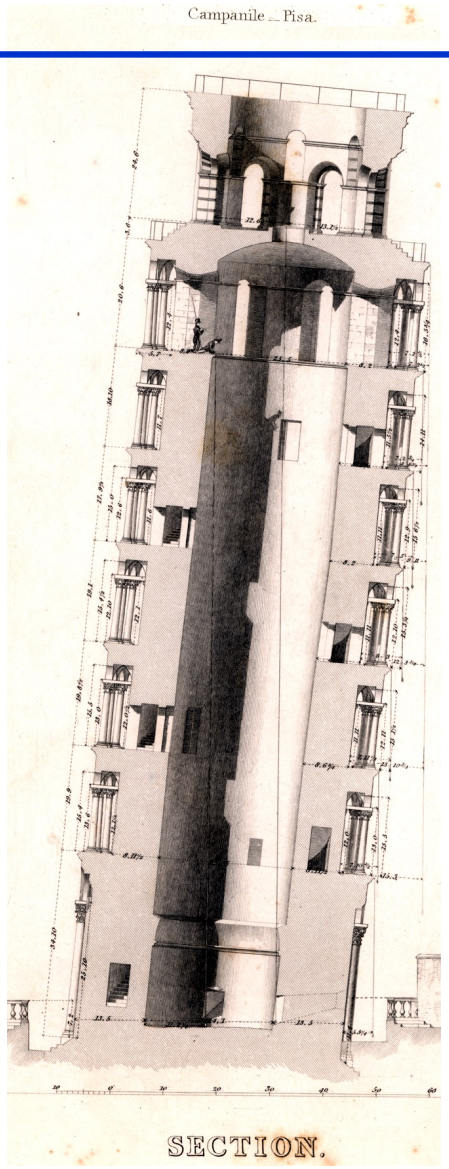


Detail of bell chamber

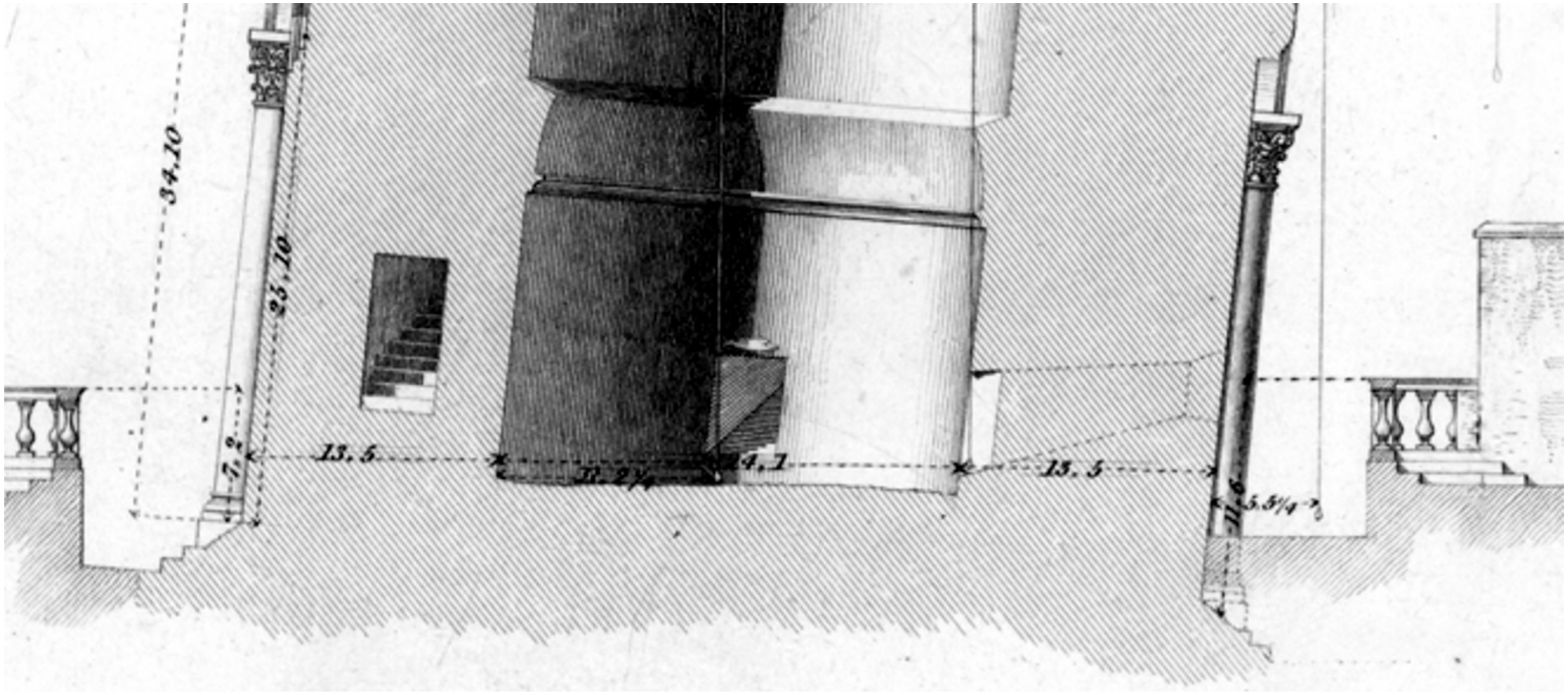


Crasy & Taylor, 1817

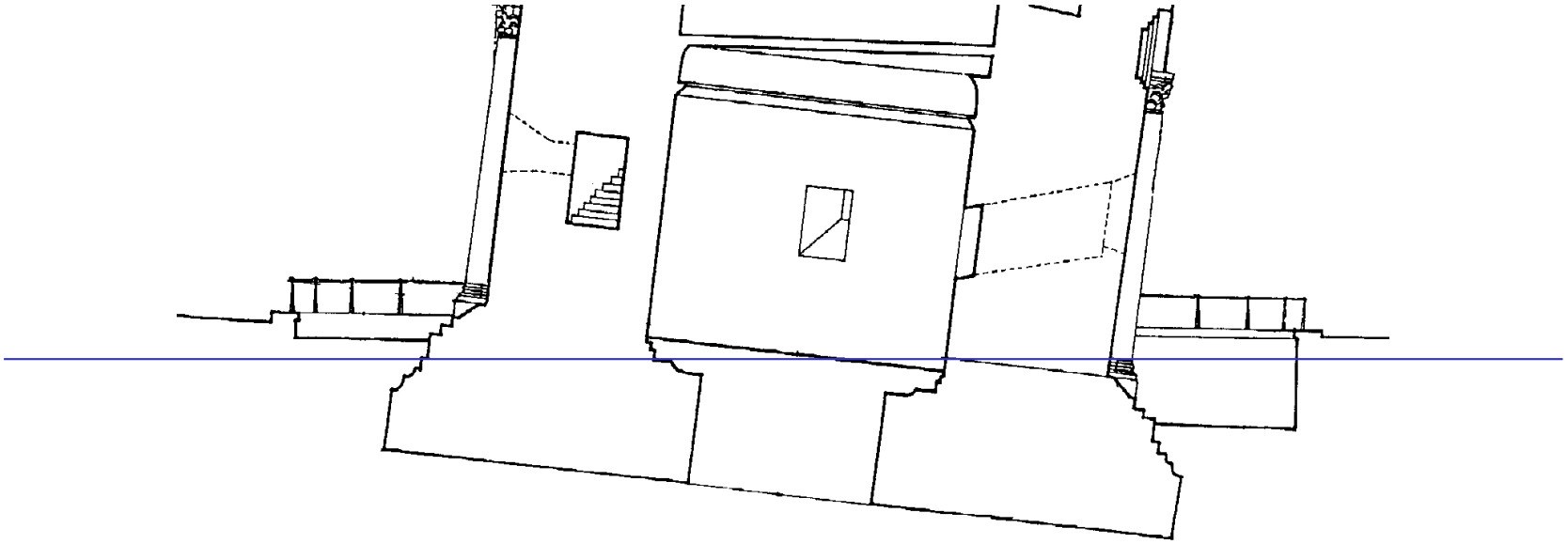




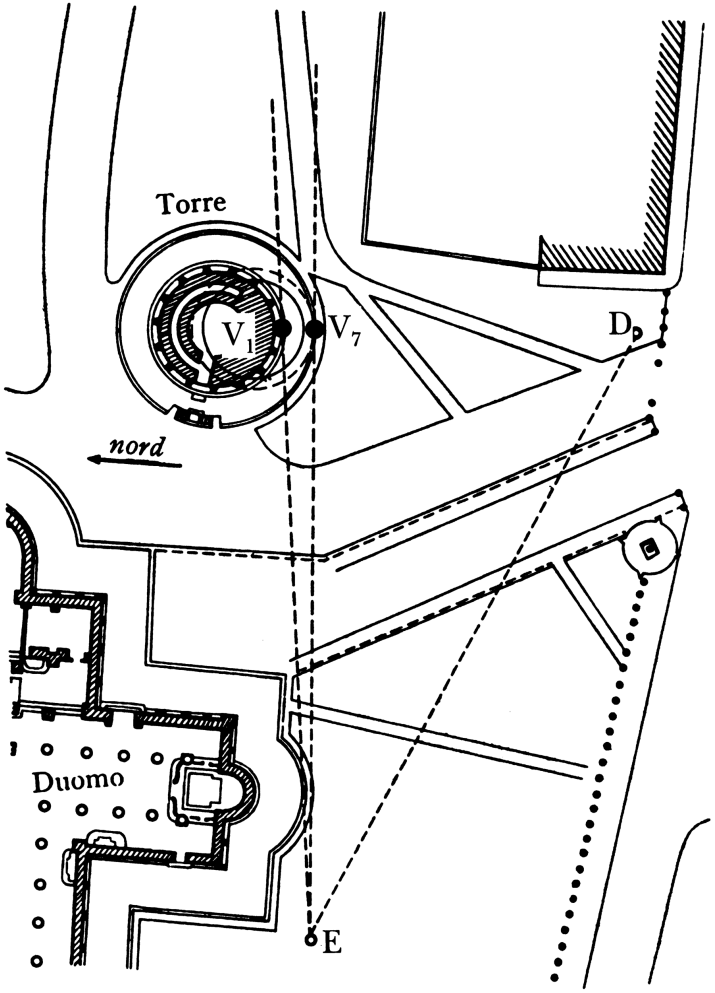
Crasy & Taylor, 1817



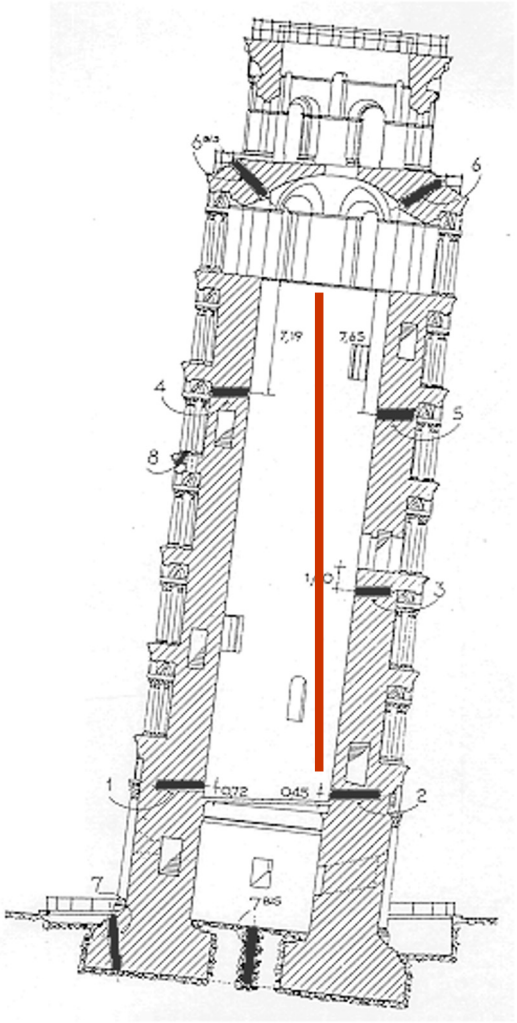
Excavation of “Catino” (Gherardesca, 1835)

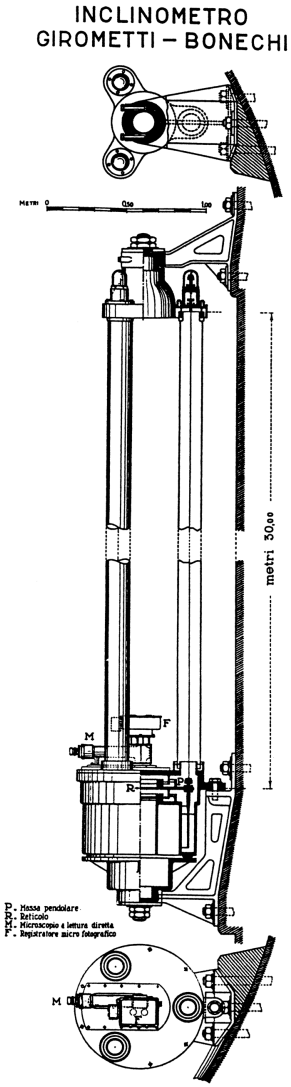


Modern monitoring. Geodetic measurement (since 1911)

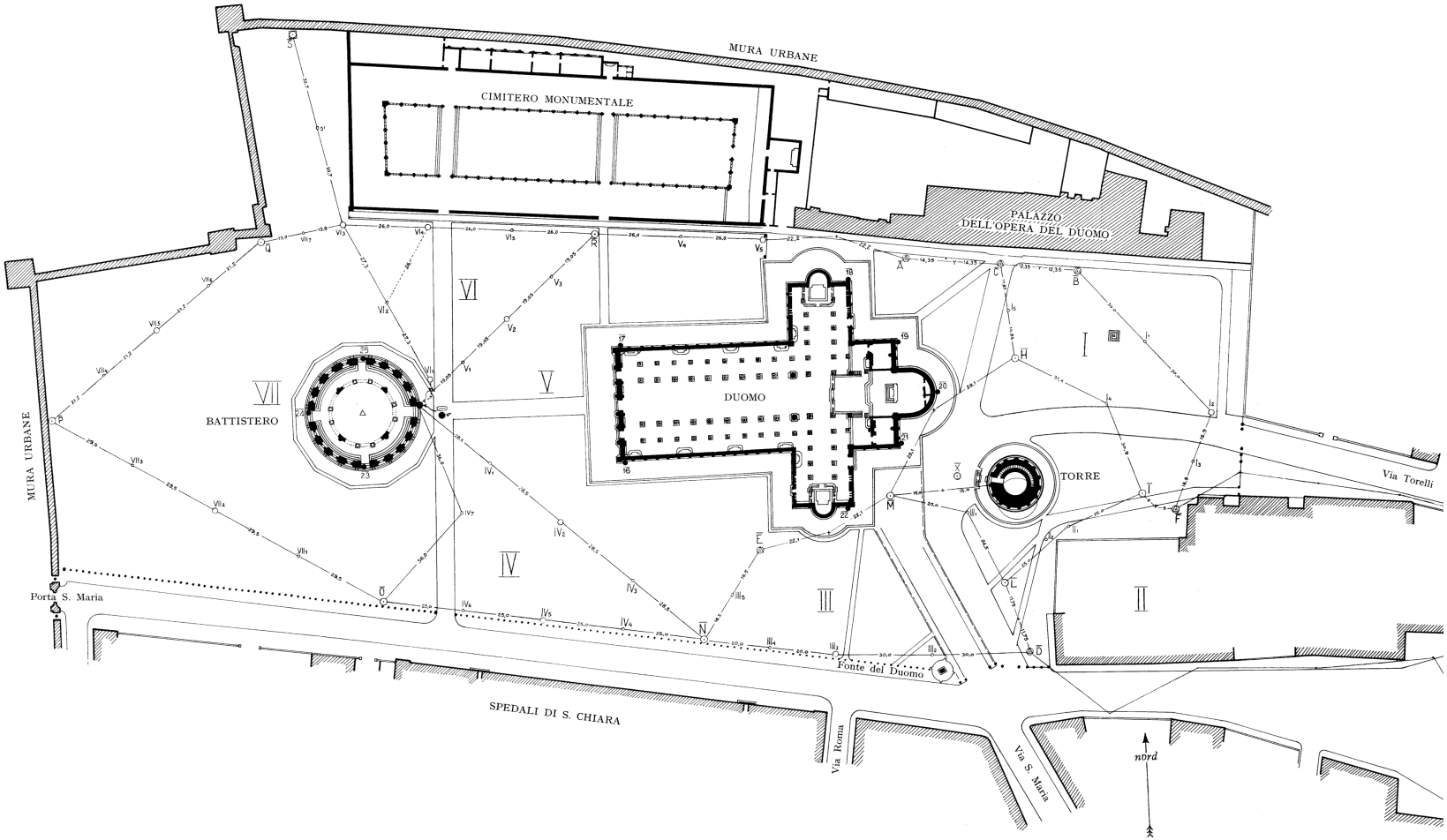


Modern monitoring. GB pendulum (1935)



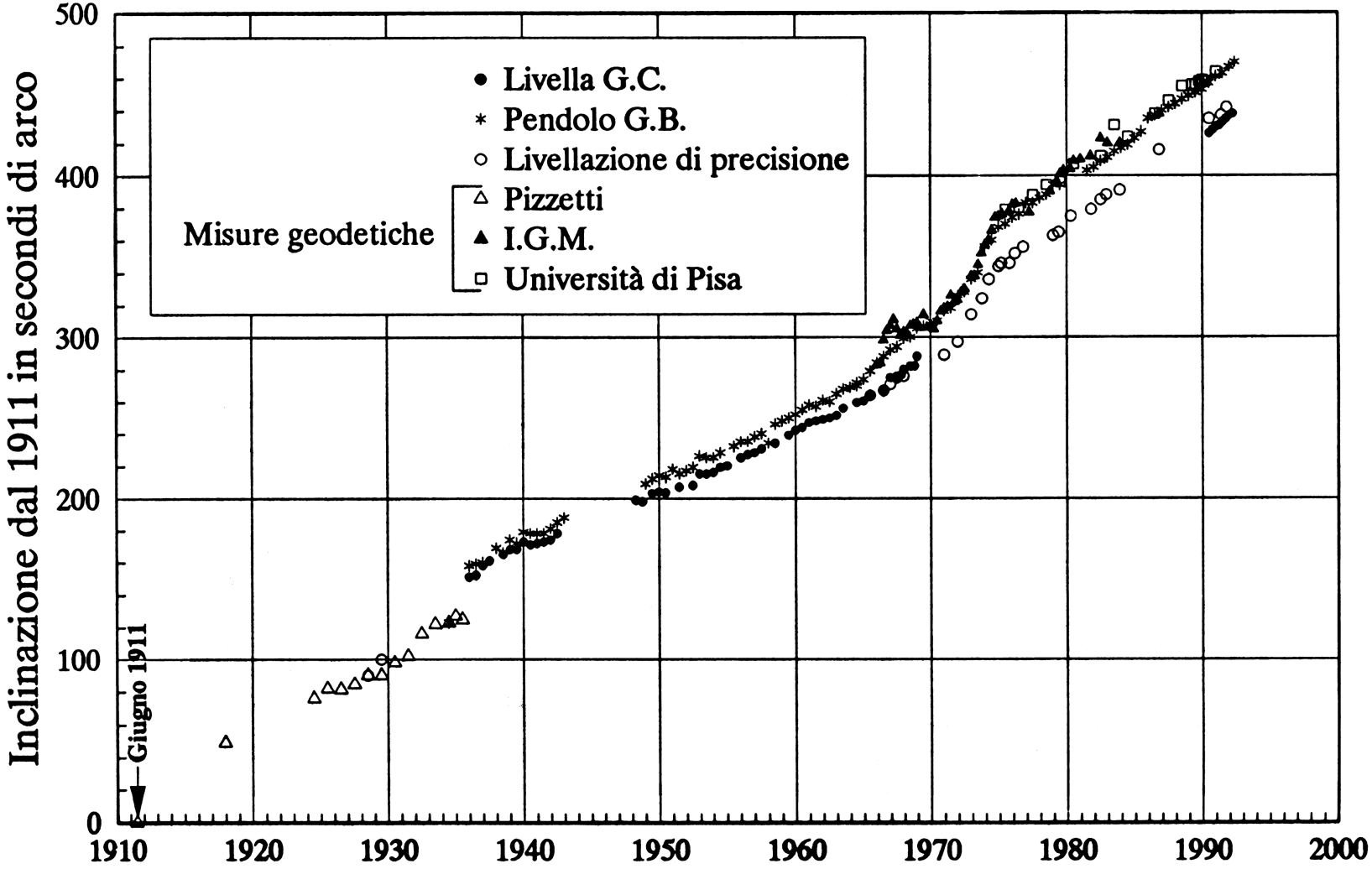


topographic survey of square (since 1965)

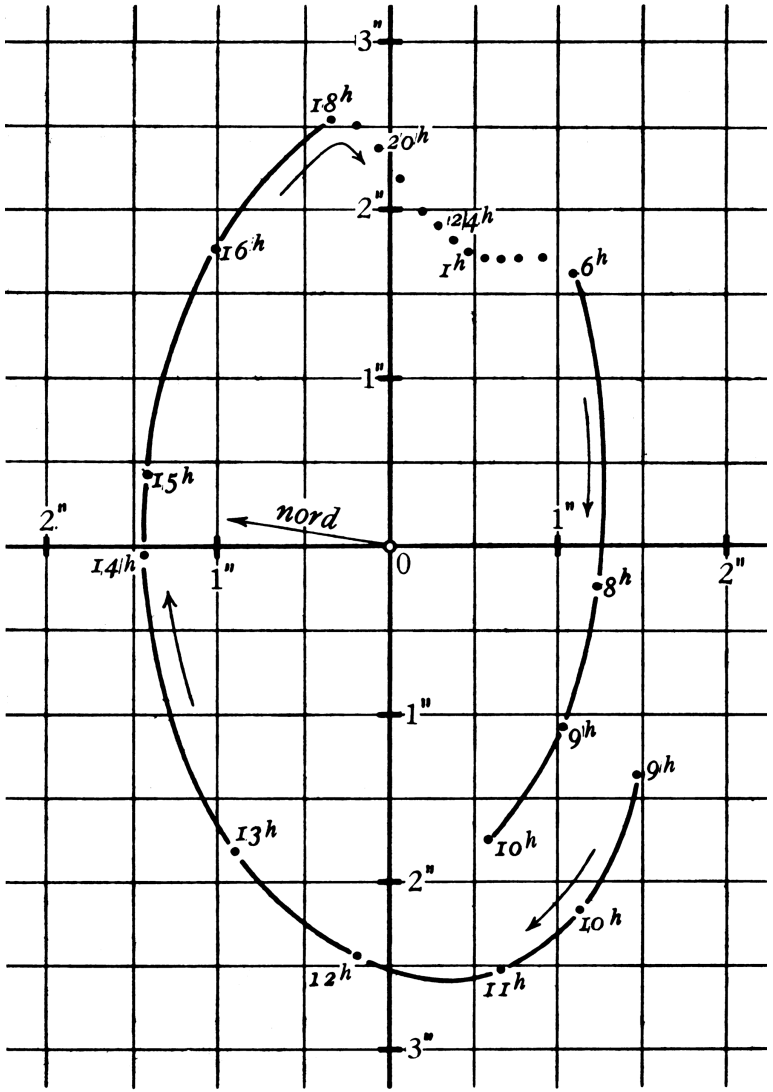


SOME INFORMATION ABOUT GEOTECHNICAL ASPECTS OF PISA TOWER STABILIZATION

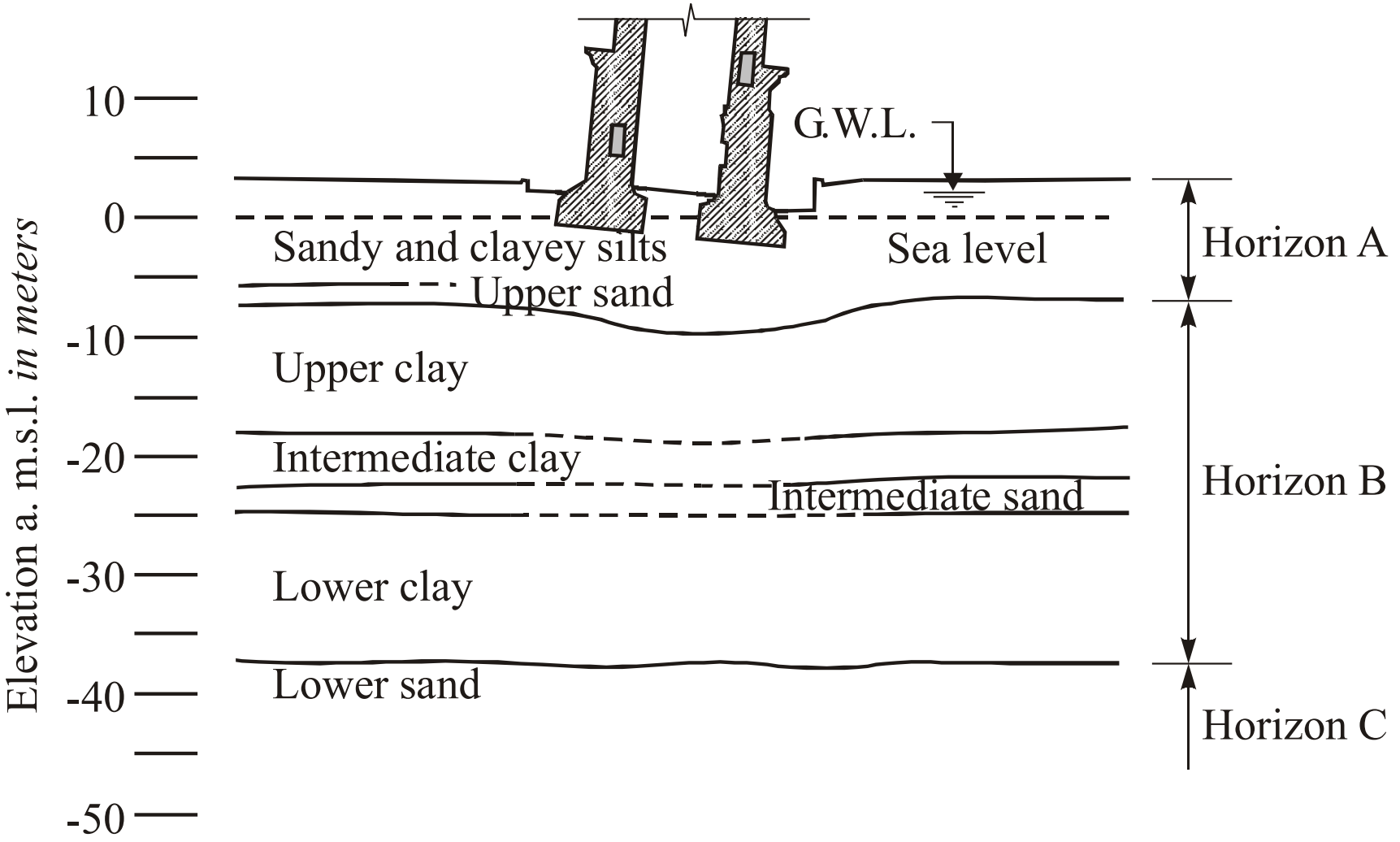
Rotation of tower (1911 – 1993)



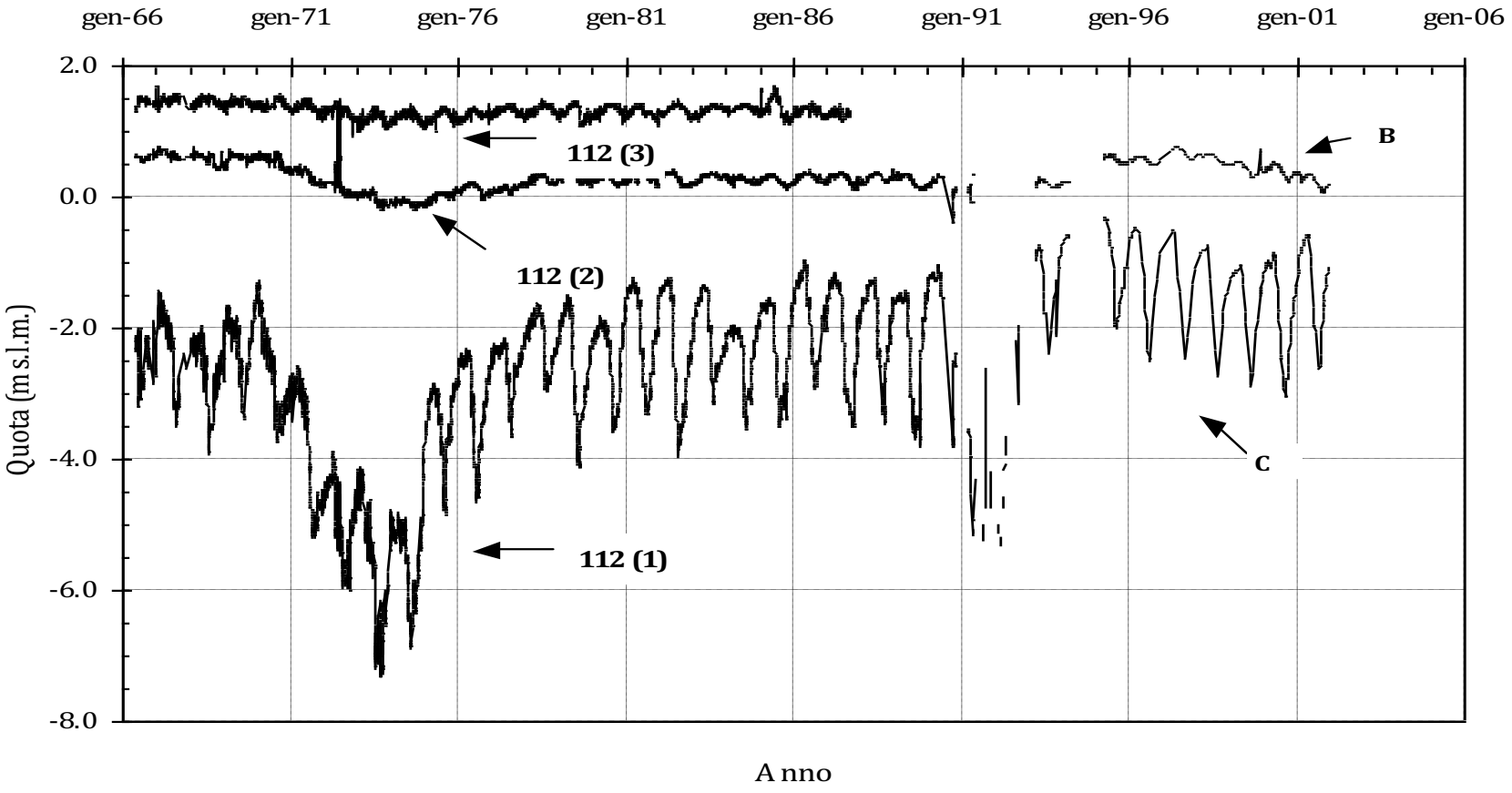
Effects of sun radiation



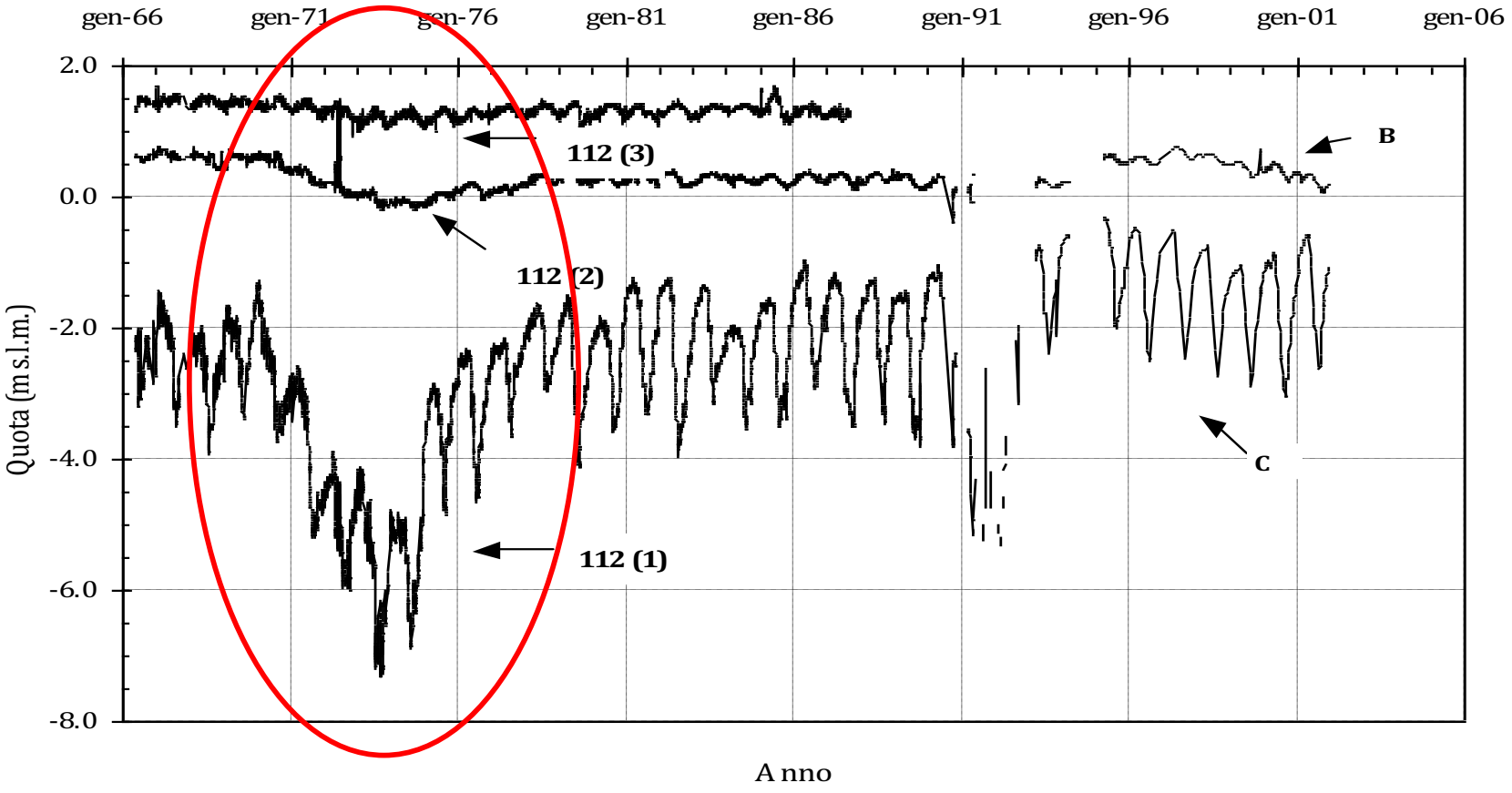
Soil profile (Polvani, 1965)



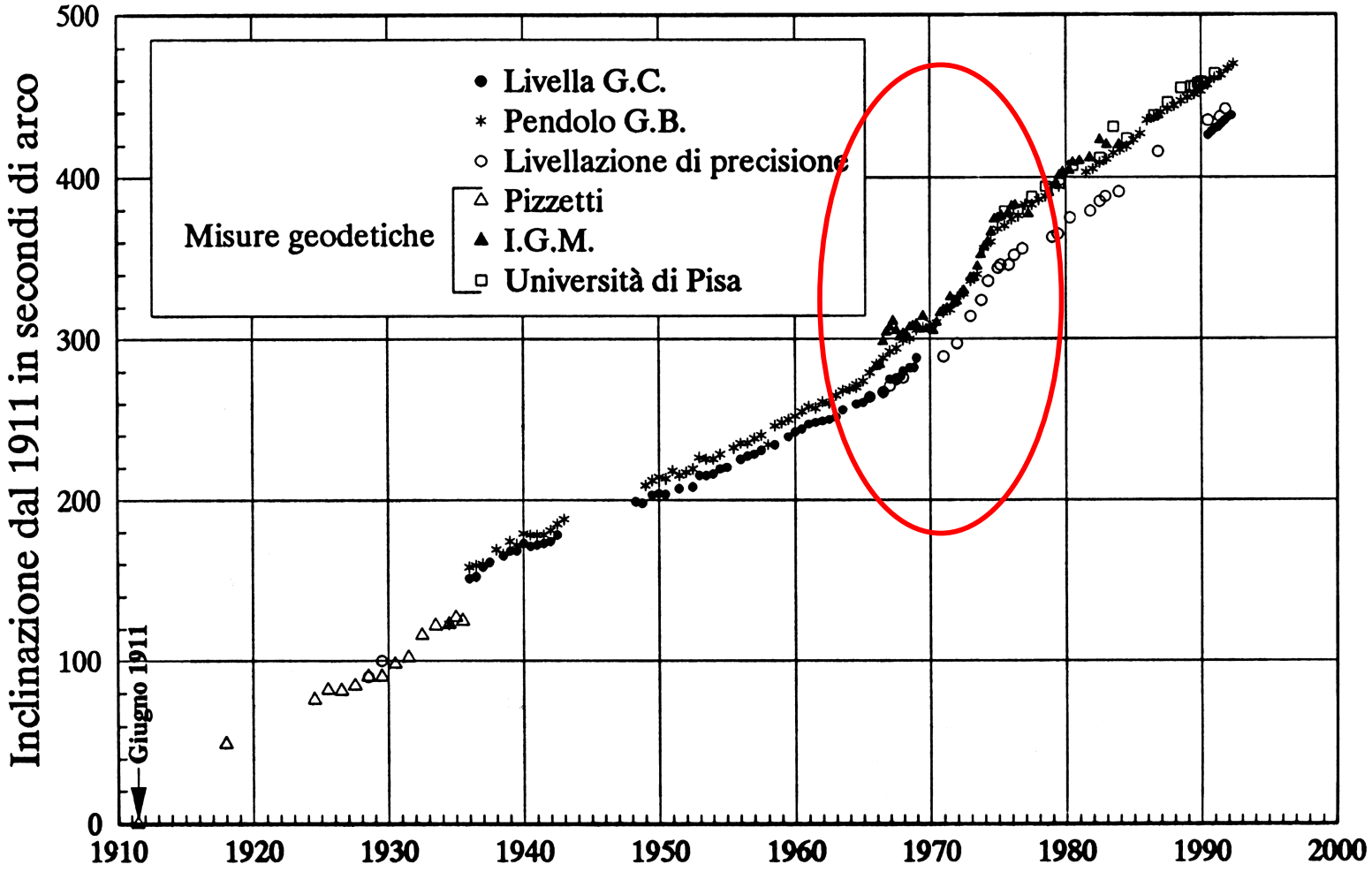
Hydraulic head in the ground



Effect of head variations on the tower



Effect of head variations on the tower



Jamiolkowski Committee appointment

- March 1989: civic tower of Pavia collapsed
- December 1989: Ministry of Public Works declared the tower of Pisa unsafe
- January 1990: The leaning tower was closed to visitors
- May 1990: Appointment of Jamiolkowski commettee

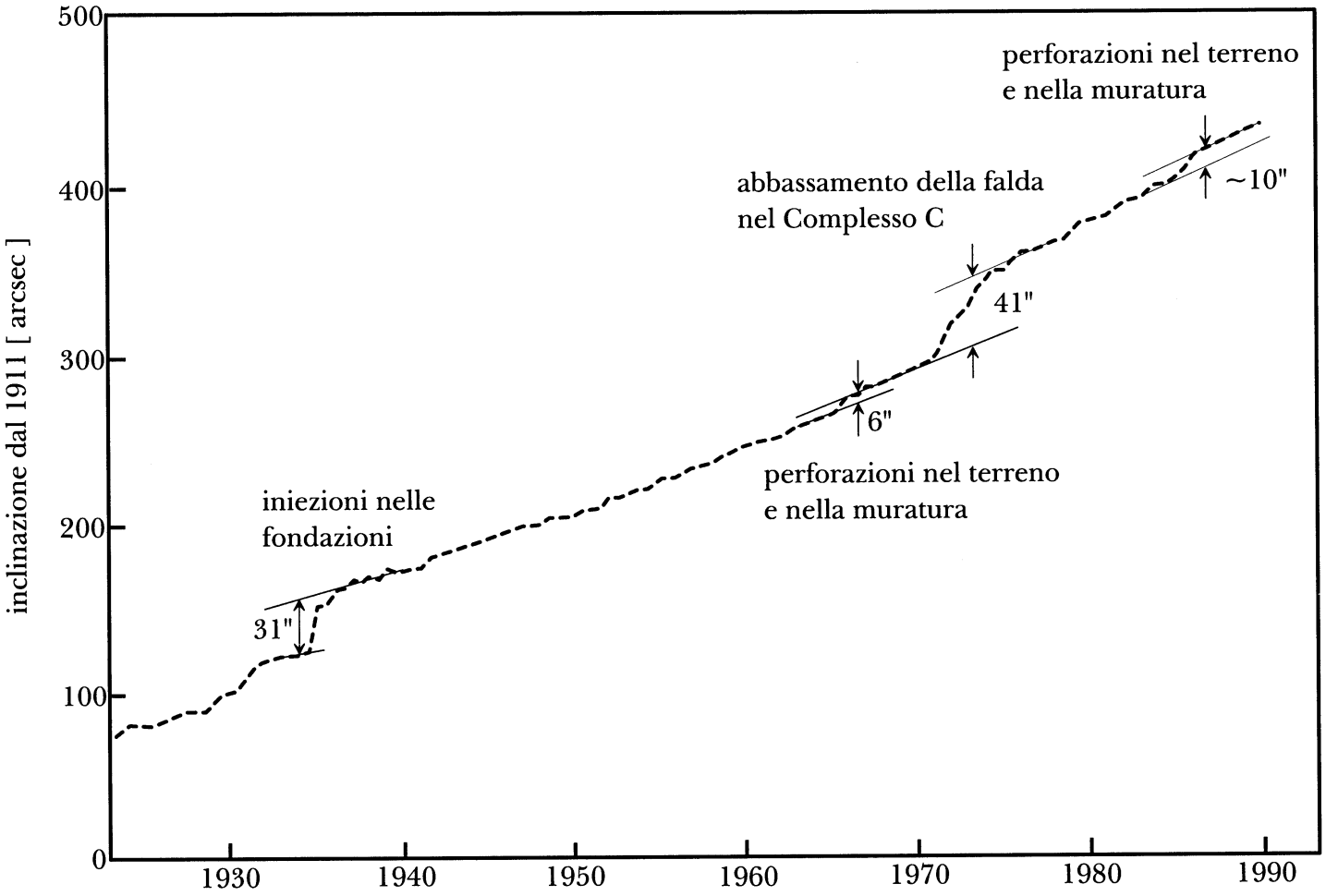
Tasks of Jamiolkowski Commettee

to design and implement structural strenghtening

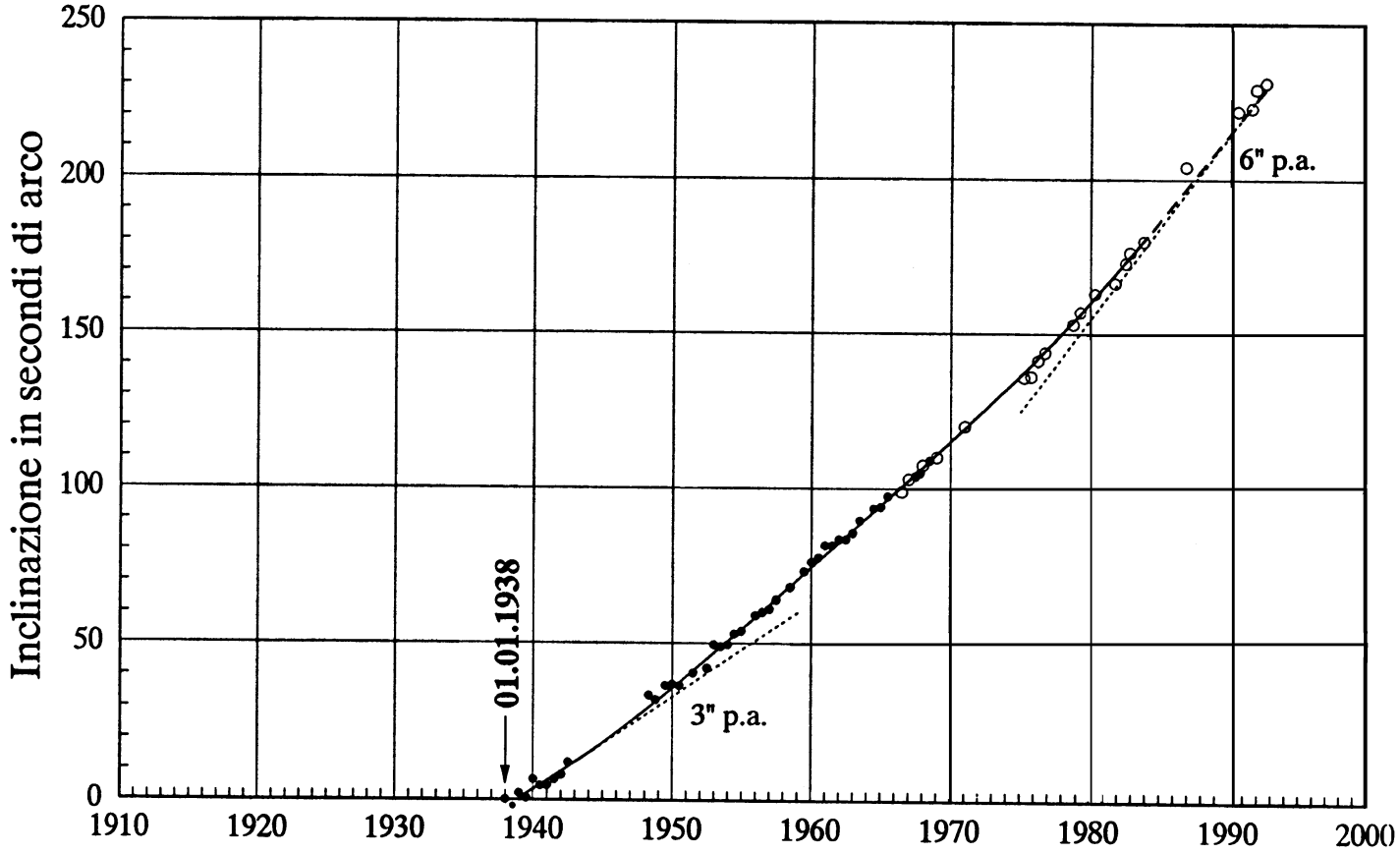
To design and implement geotechnical stabilisation

To design restoration of surfaces

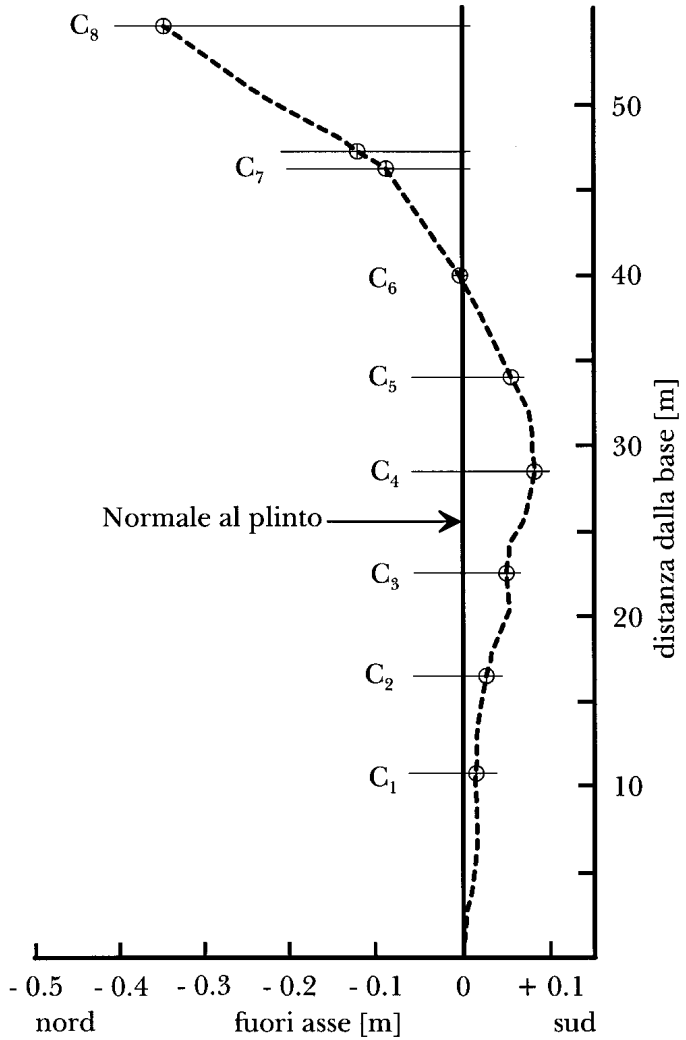
ROTATION OF FOUNDATIONS



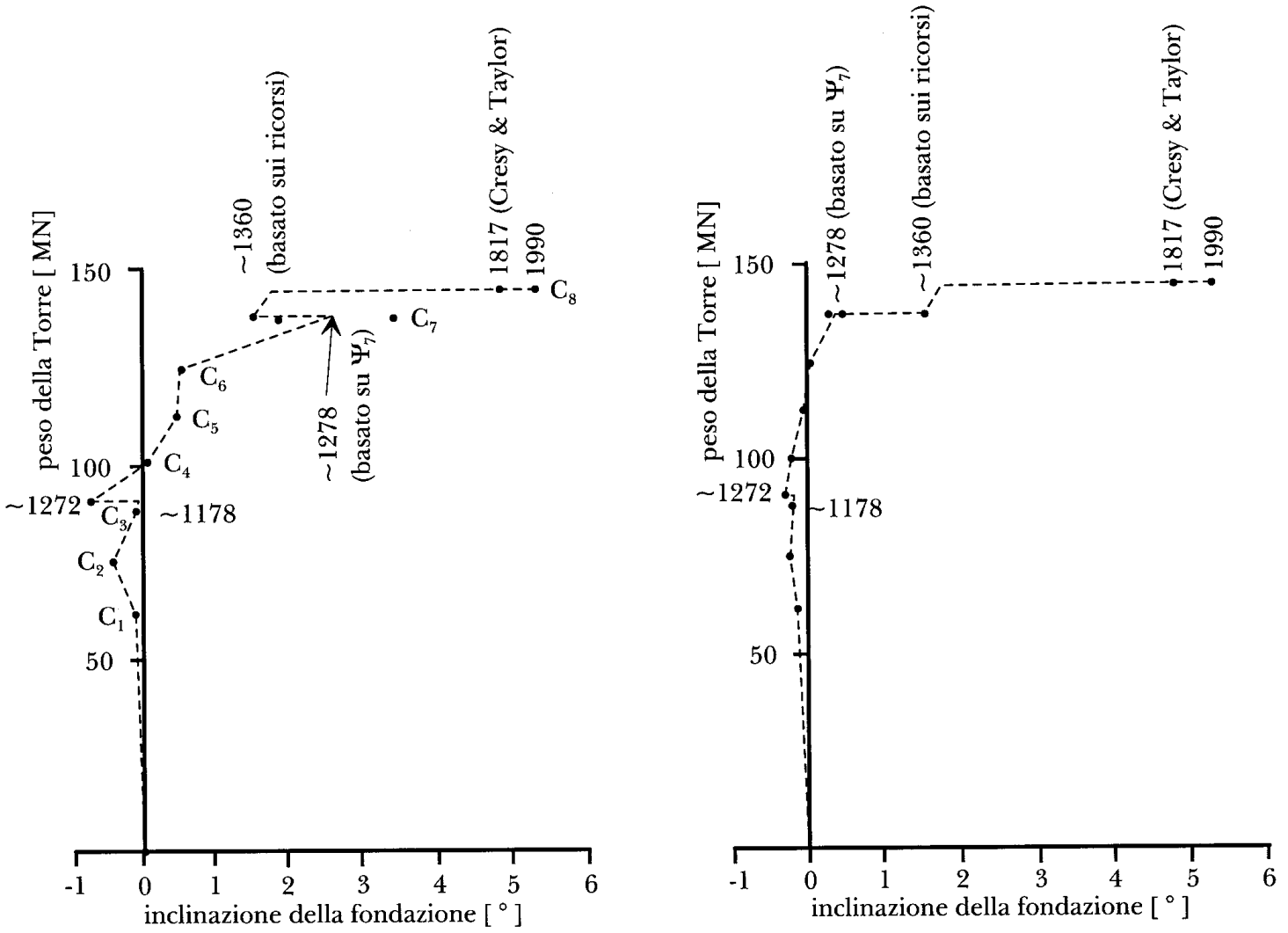
RATE OF ROTATION OF FOUNDATIONS



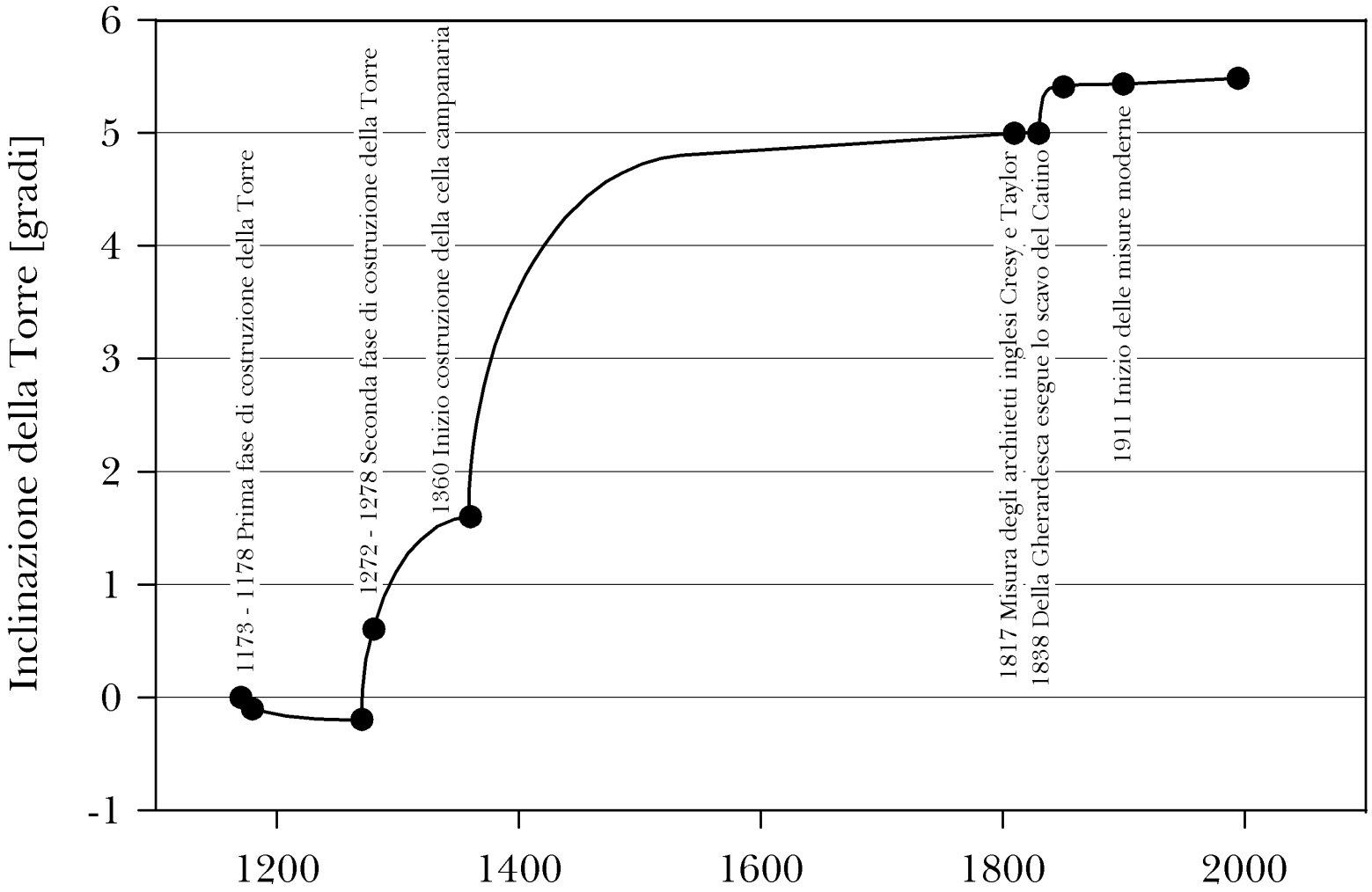
SHAPE OF TOWER AXIS



HISTORY OF INCLINATION



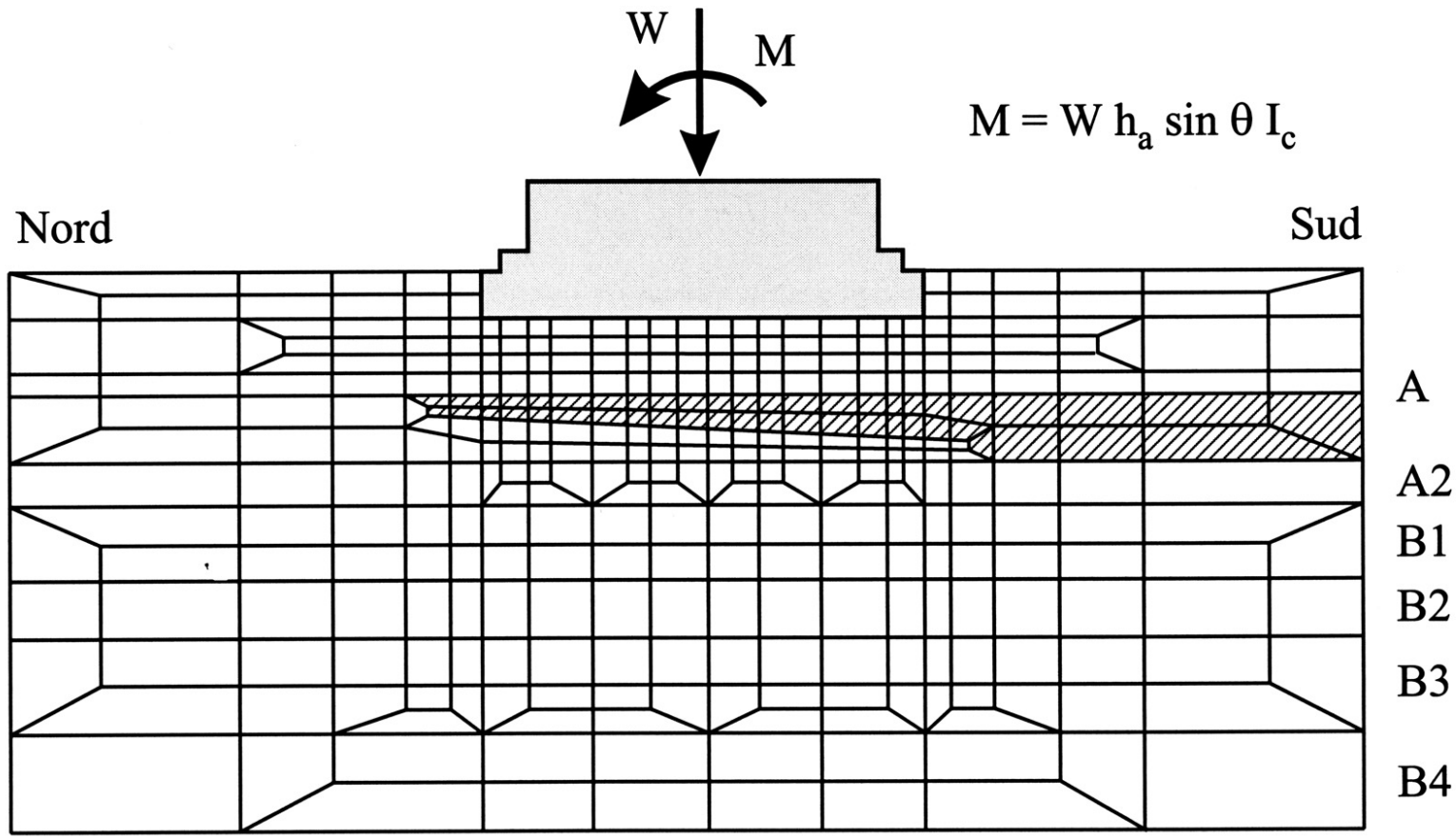
HISTORY OF INCLINATION

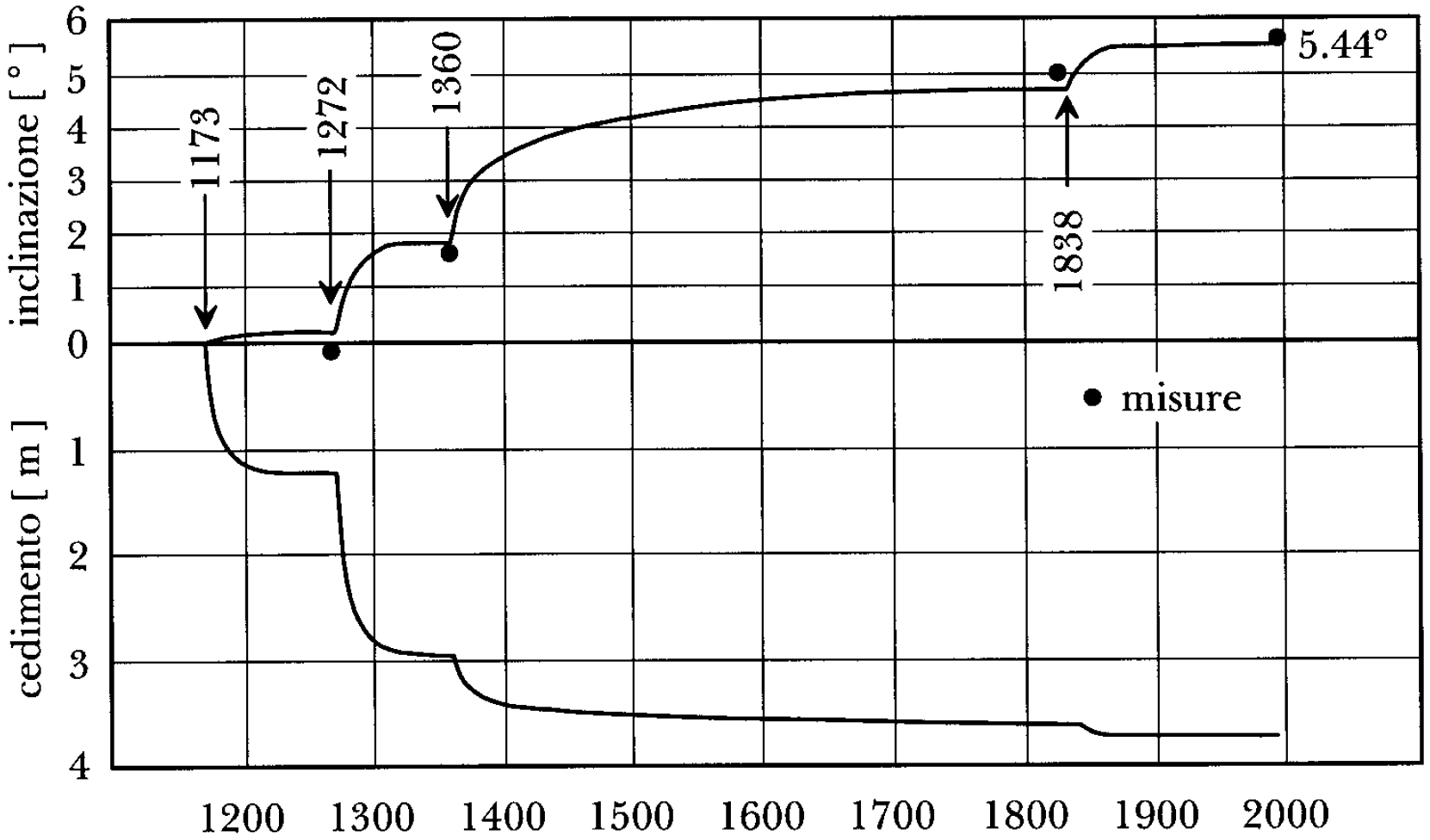


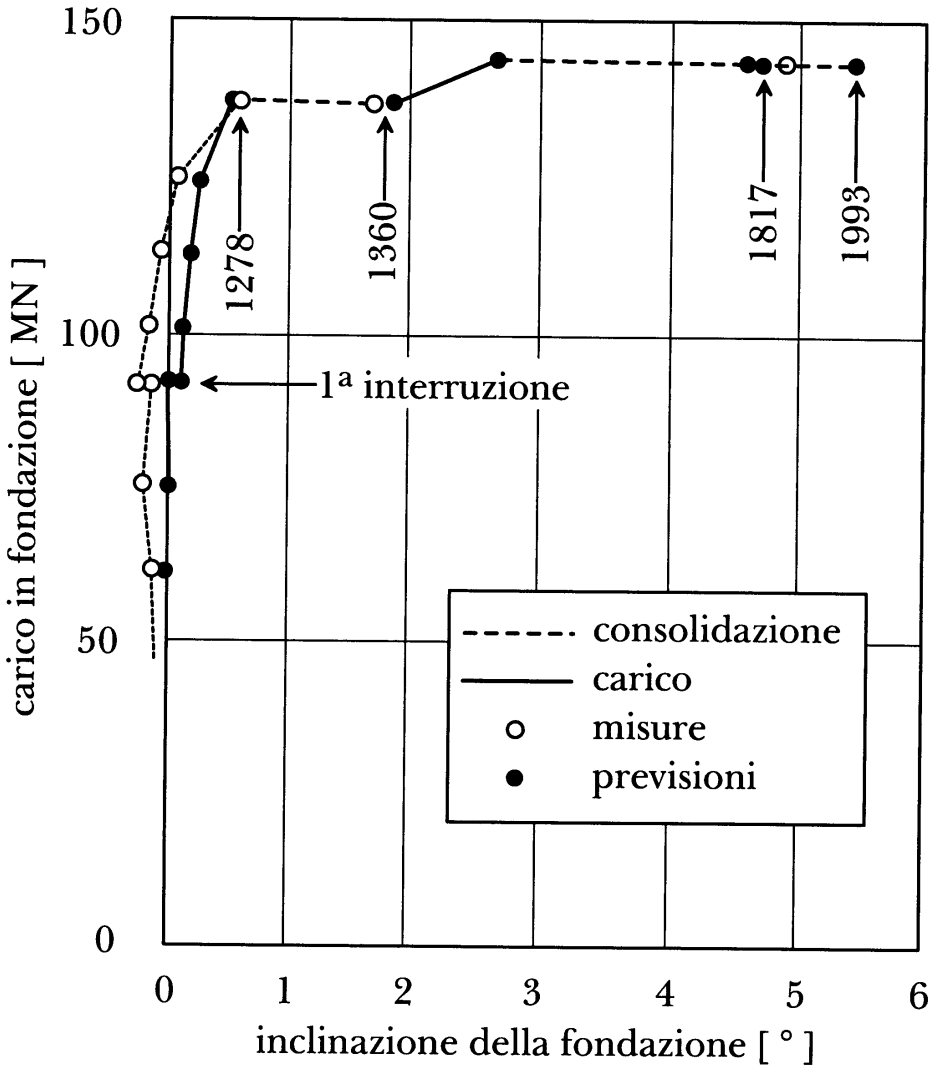
ANALISIS OF HISTORY OF INCLININATION:

- numerical modelling
- physical modelling
- centrifuge testing

Numerical modelling (Burland & Potts, 1992)



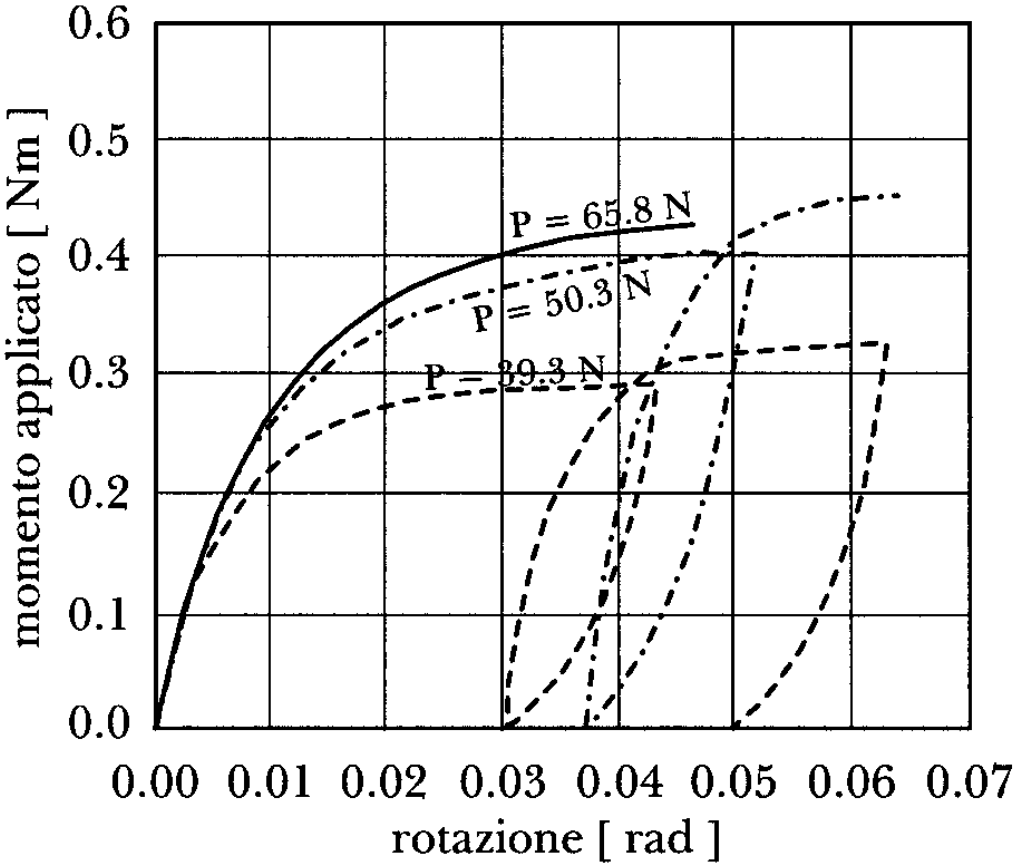

inclinazione [°]
cedimento [m]
6
5
4
3
2
1
0
1
2
3
4
1173
1272
1360
1838
5.44°
misure
1200
1300
1400
1500
1600
1700
1800
1900
2000


150
100
50
0
carico in fondazione [MN]
1278
1360
1817
1993
1ª interruzione
consolidazione
carico
misure
previsioni
0
1
2
3
4
5
6
inclinazione della fondazione [°]

The inclination of the Tower is related to a phenomenon of instability of equilibrium (leaning instability)

Centrifuge tests (Cheney *et Al.*, 1991)

Tests not related to the tower



$$M_r = f(\alpha, N)$$

Two steps strategy

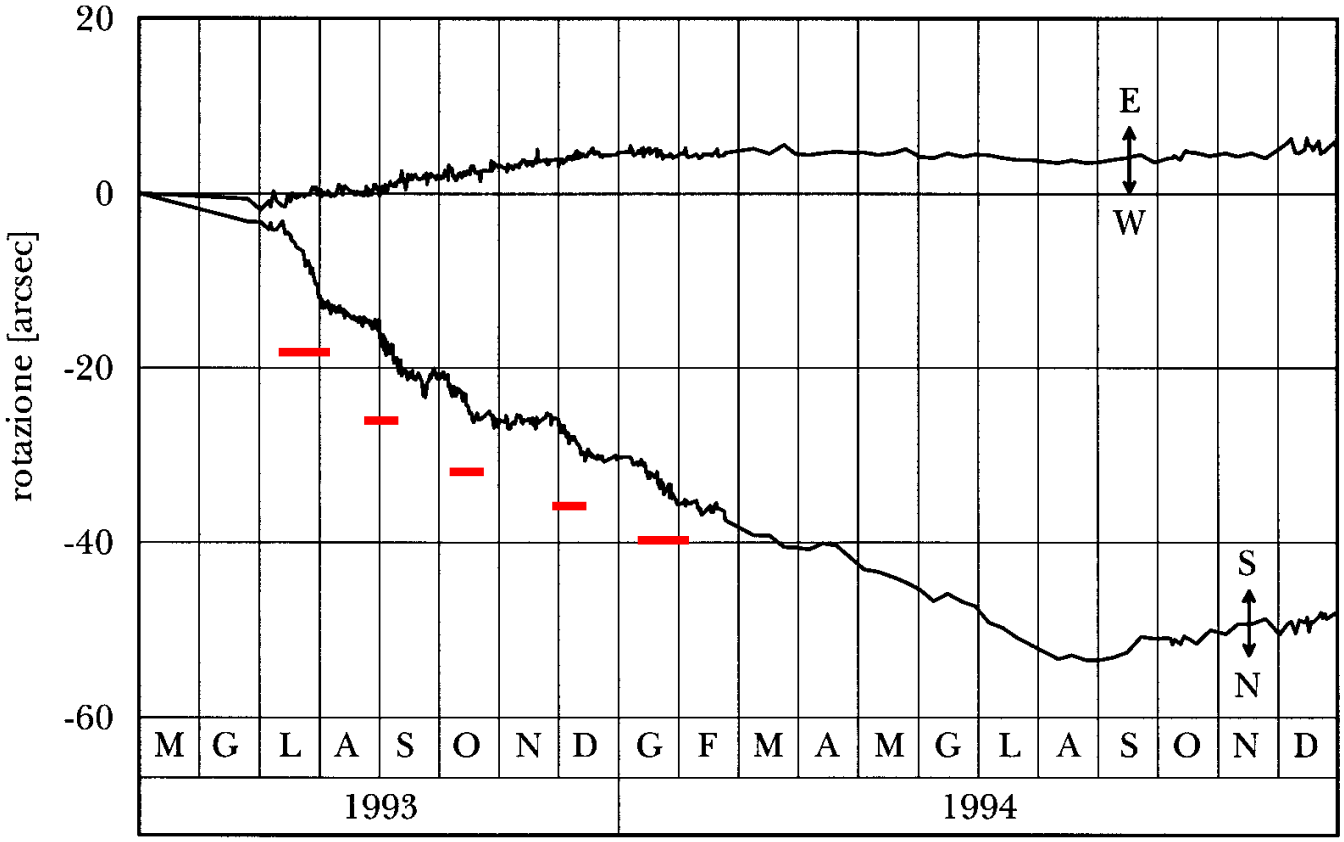
1) Temporarily and reversible actions

2) Long terms actions

Basic requirements of permanent stabilization

- not endagering tower safety
- preserving character of monument
- stopping phenomenon of leaning instability
- based on well understood concepts
- allowing to follow observational approach
- requiring minimum manteinance in time

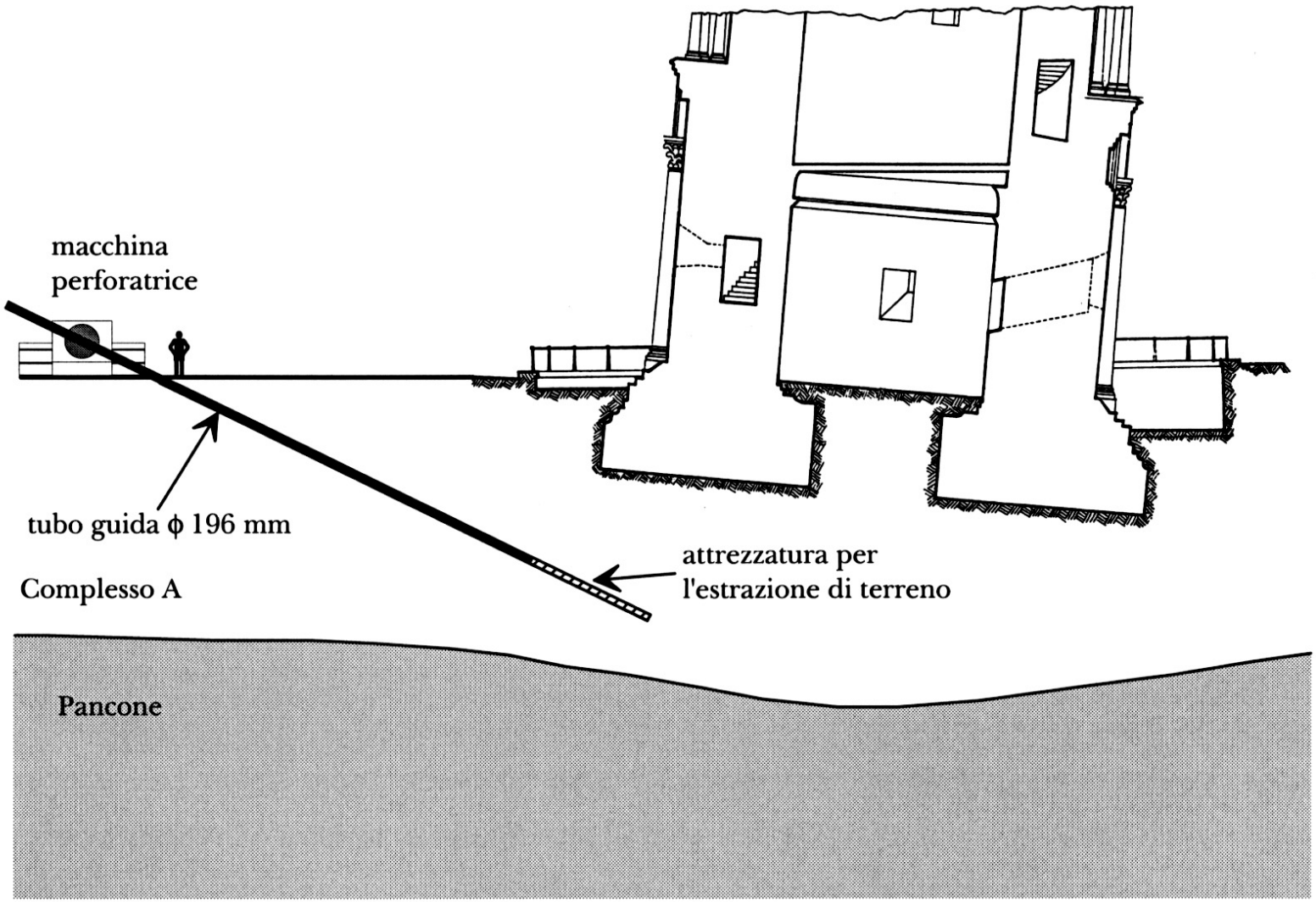
Effects of lead ingots installation



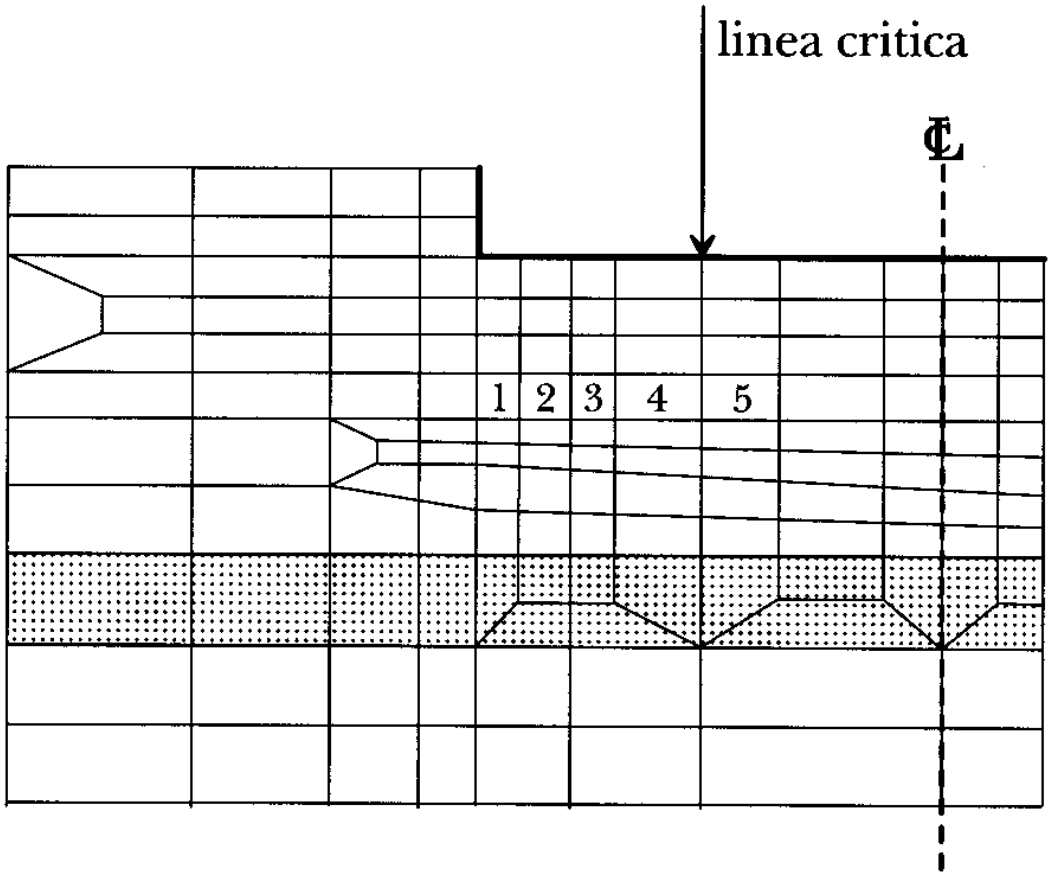
SOME INFORMATION ABOUT GEOTECHNICAL ASPECTS OF PISA TOWER STABILIZATION

Underexcavation

1. Numerical analysis
2. Centrifuge tests
3. Field test

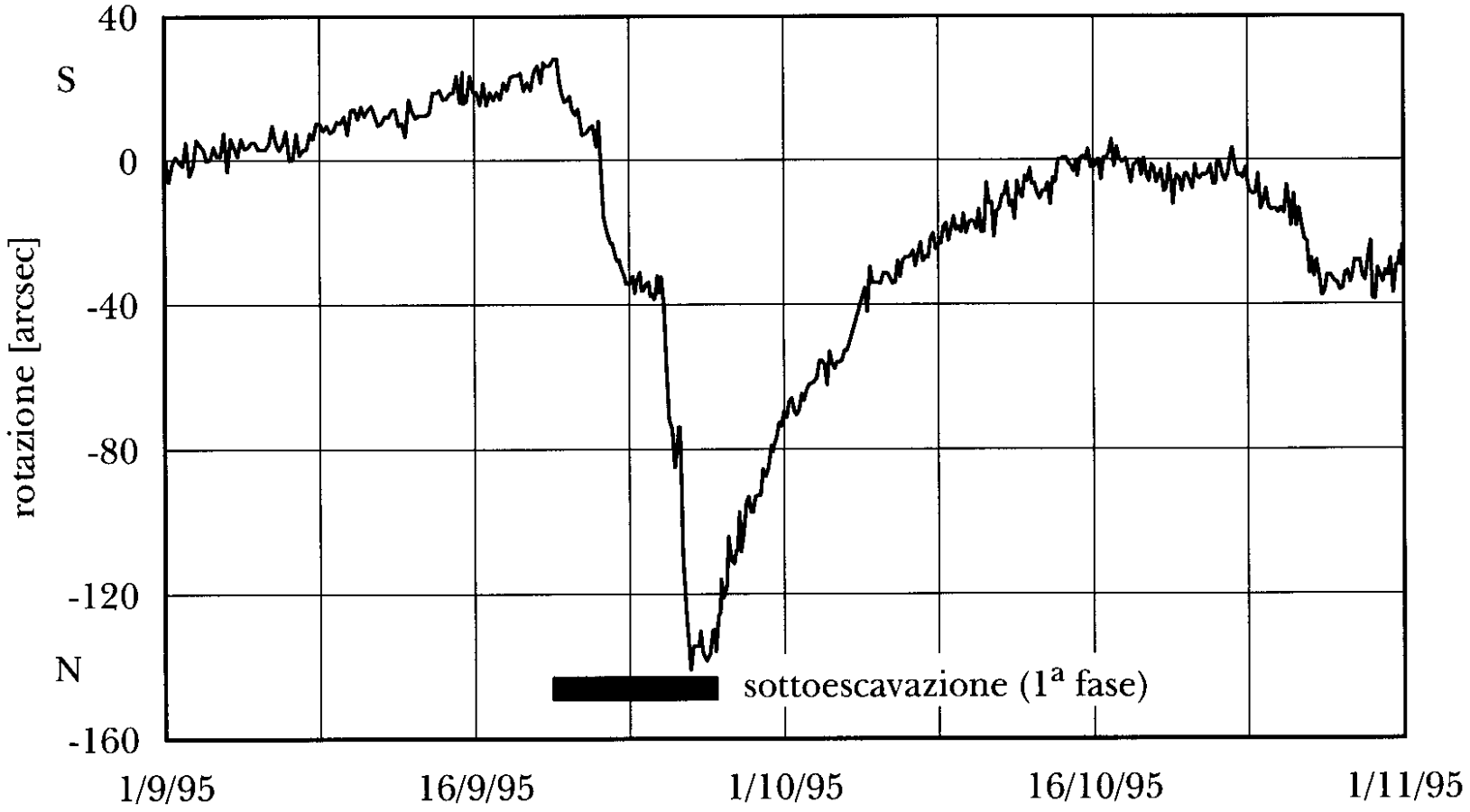

macchina
perforatrice
tubo guida ϕ 196 mm
Complesso A
attrezzatura per
l'estrazione di terreno
Pancone

Numerical analysis – critical line



SOME INFORMATION ABOUT GEOTECHNICAL ASPECTS OF PISA TOWER STABILIZATION

Field test: results



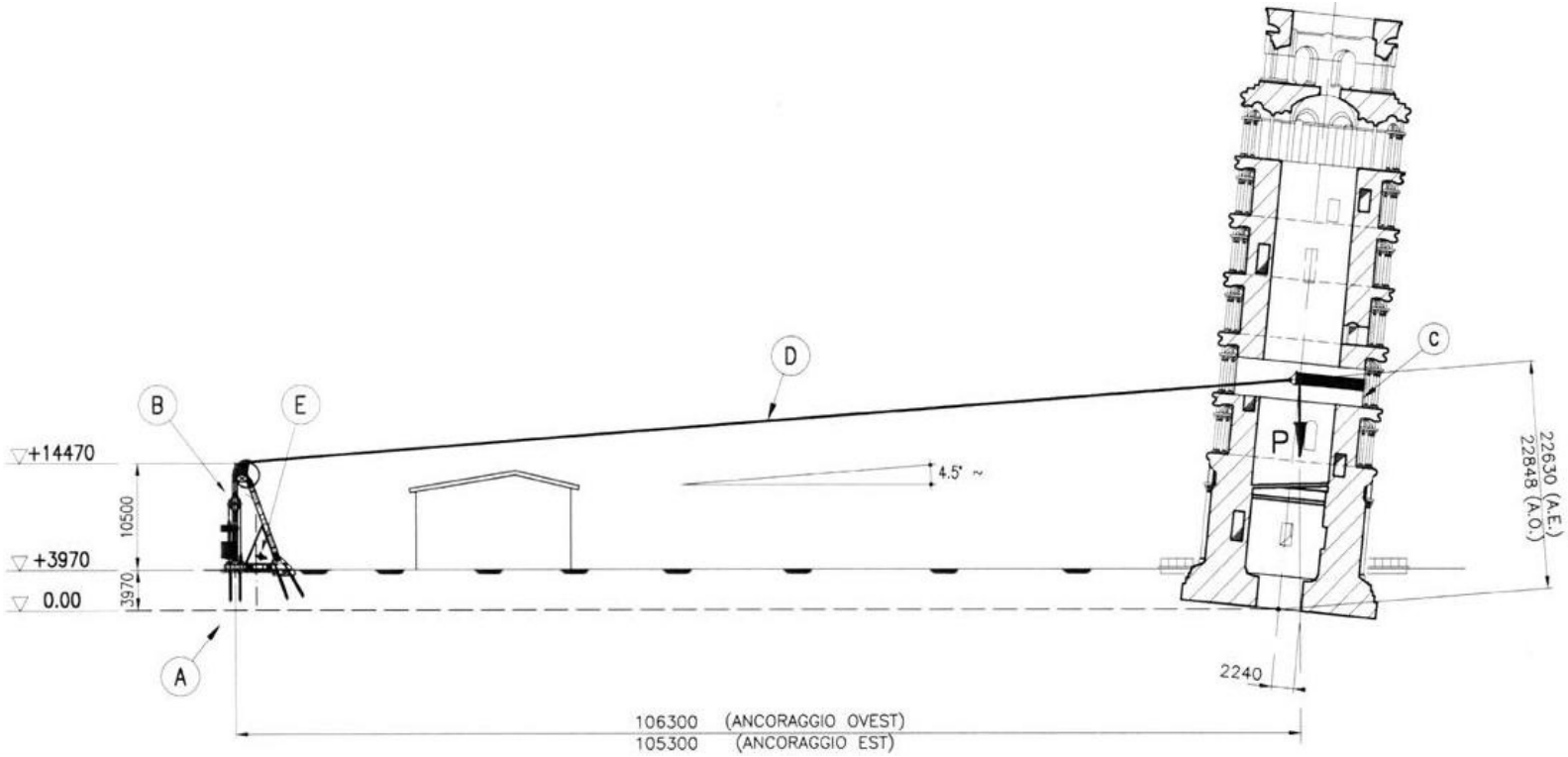
APPLICATION TO THE TOWER

PHASE 0 – SAFEGUARD STRUCTURE

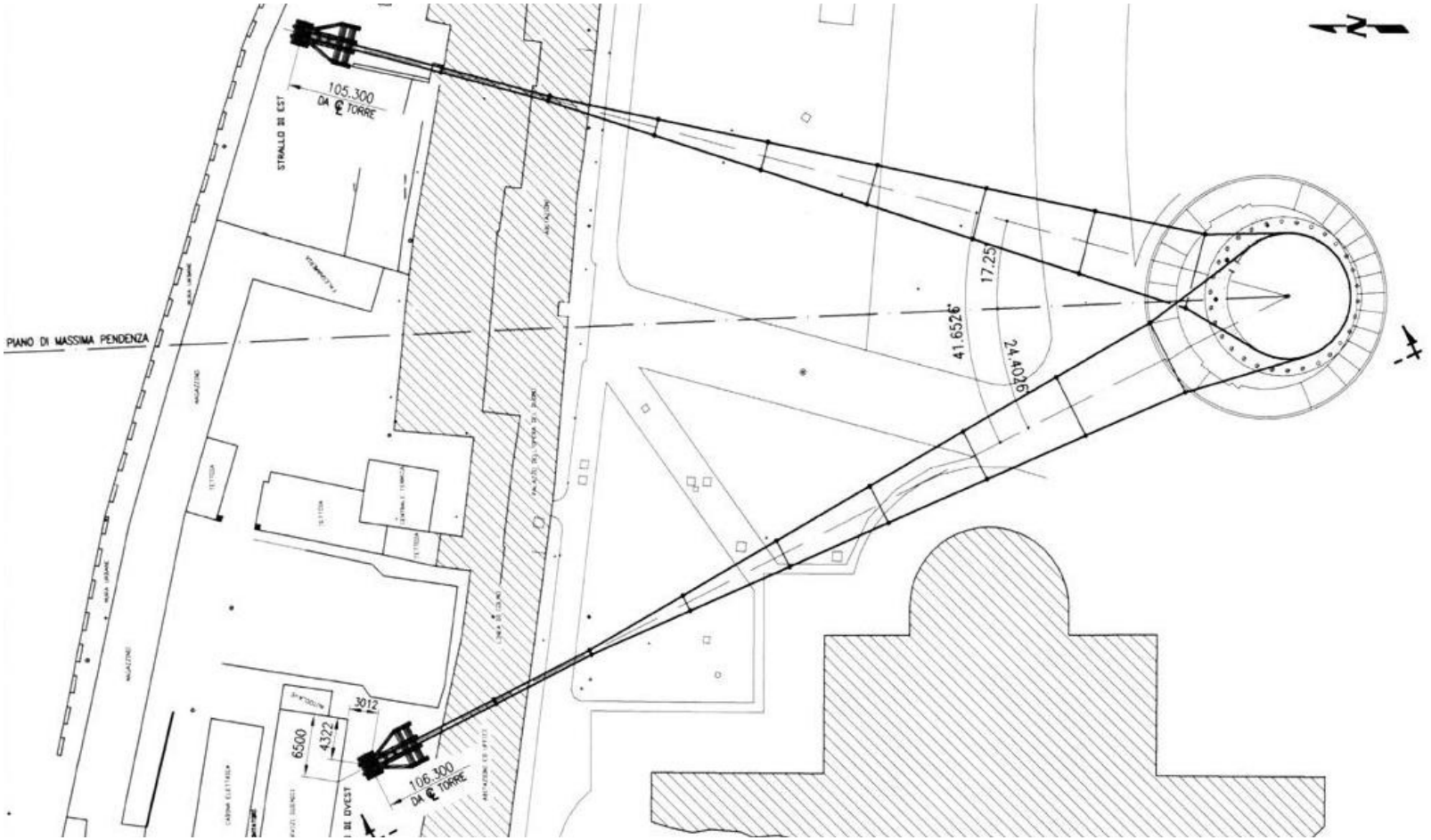
1ST PHASE – PRELIMINARY UNDEREXCAVATION

2ND PHASE – FULL UNDEREXCAVATION

SAFEGUARD STRUCTURE



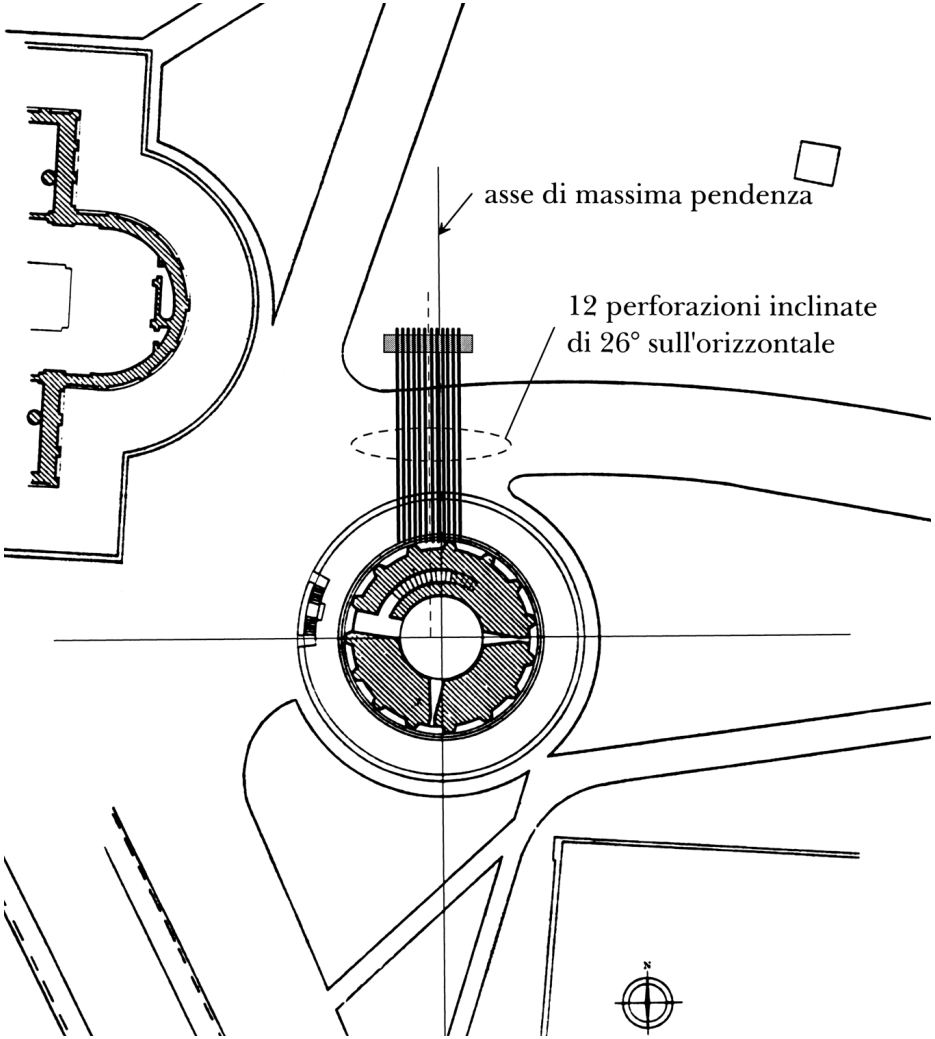
SAFEGUARD STRUCTURE



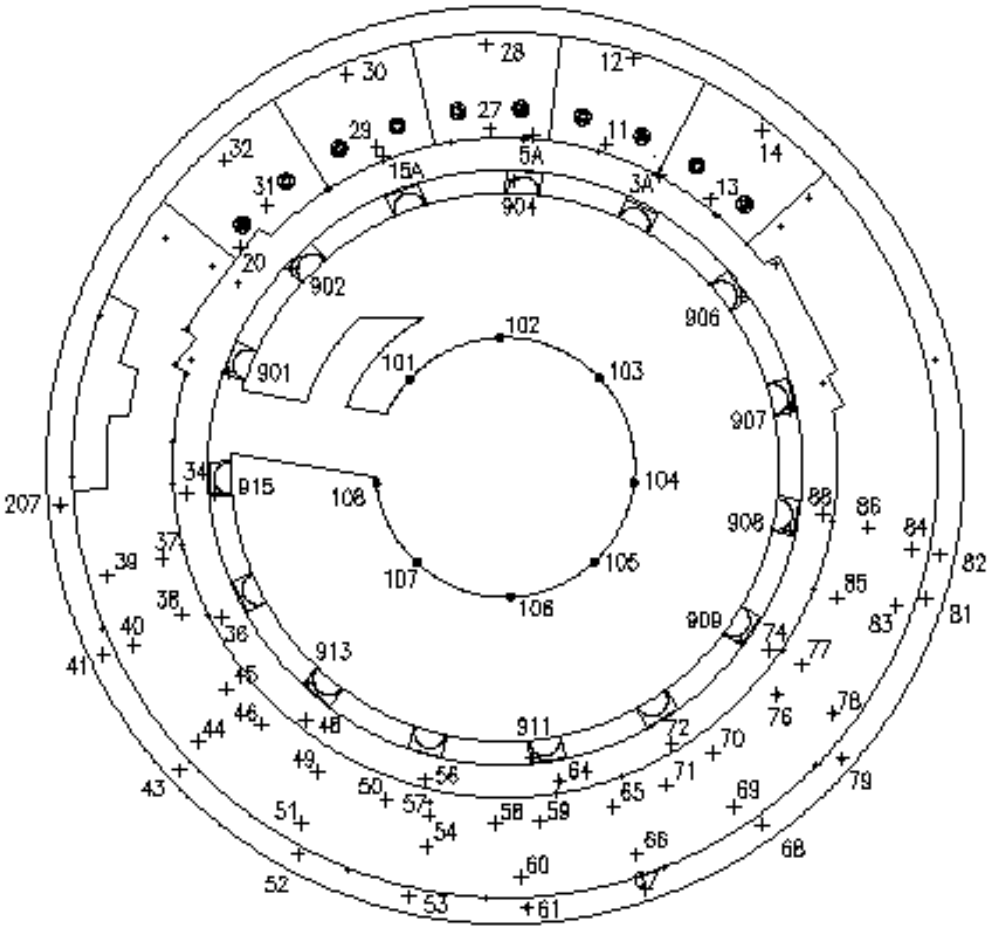
It is conceived as a force, not a restraint

Preliminary underexcavation:

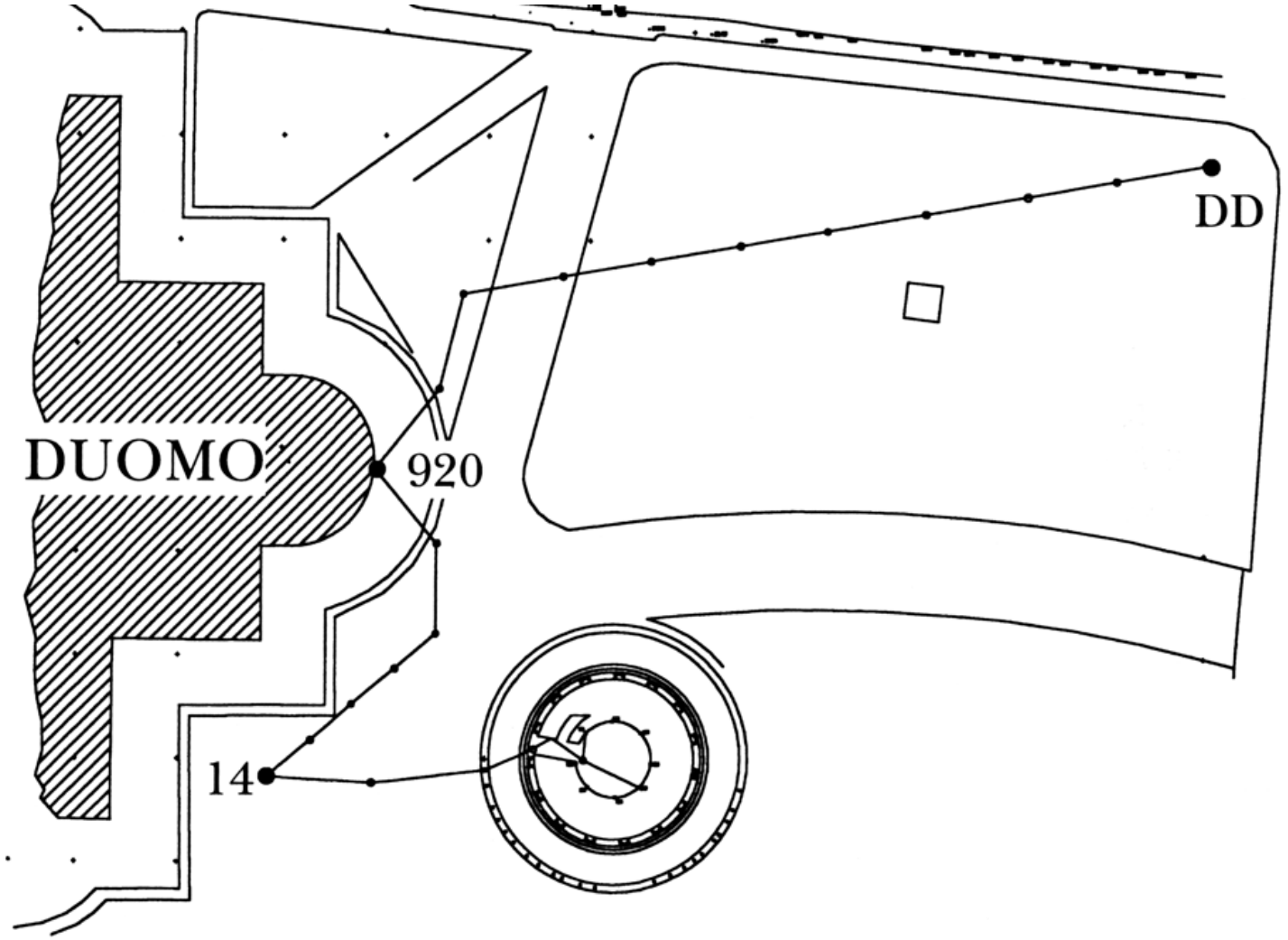
✓ 12 boreholes



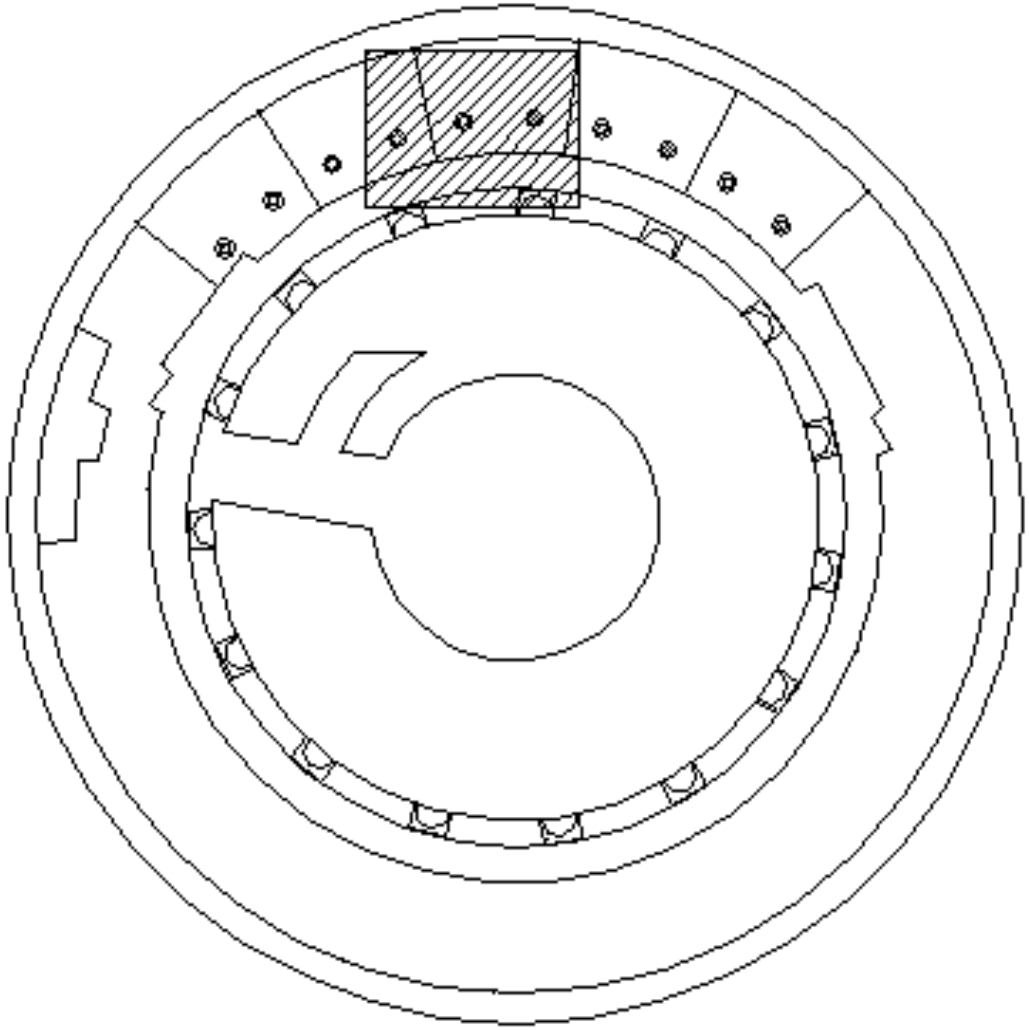
Monitoring of settlements



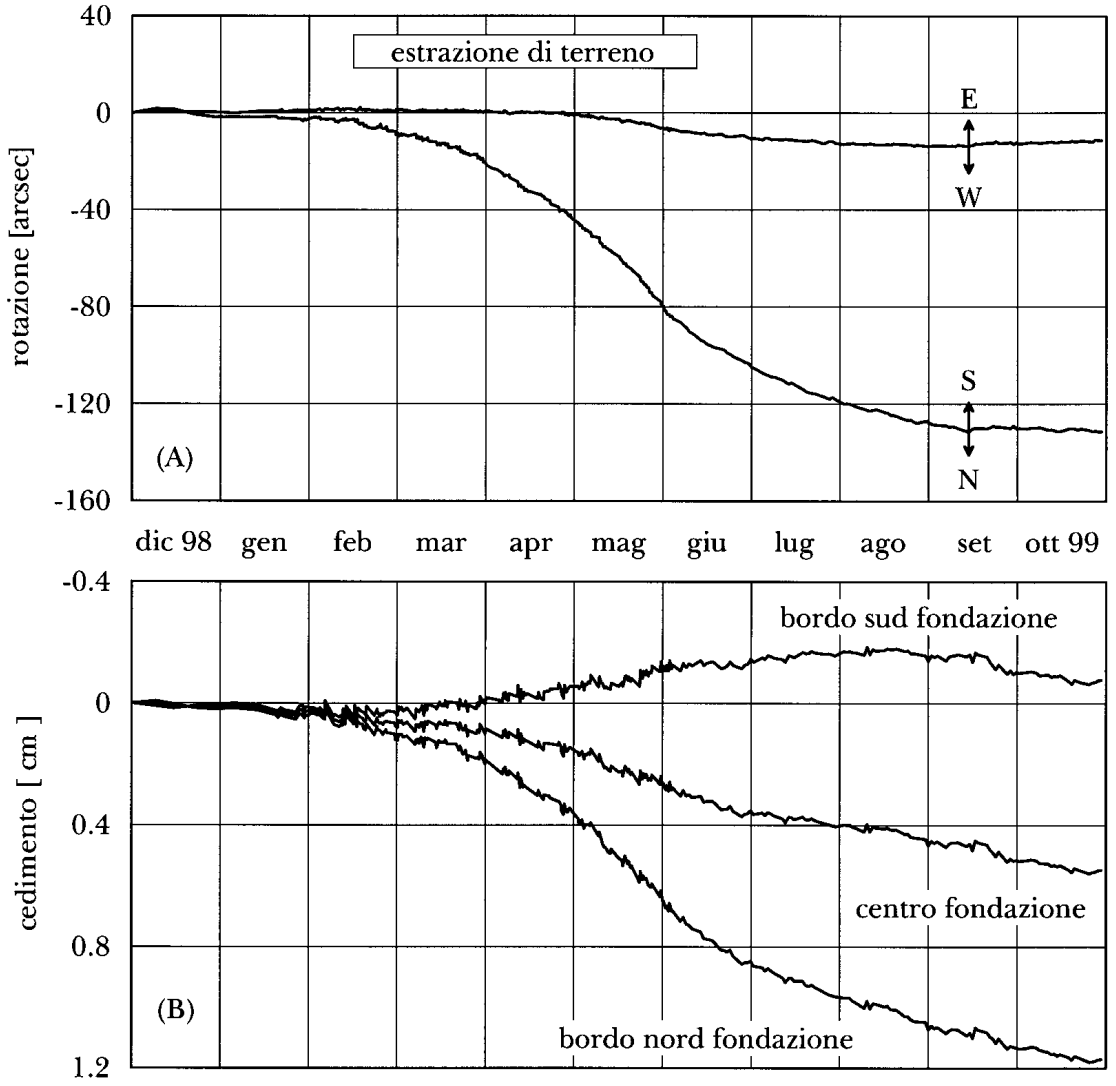
Monitoring of settlements



Localization of extractions



results

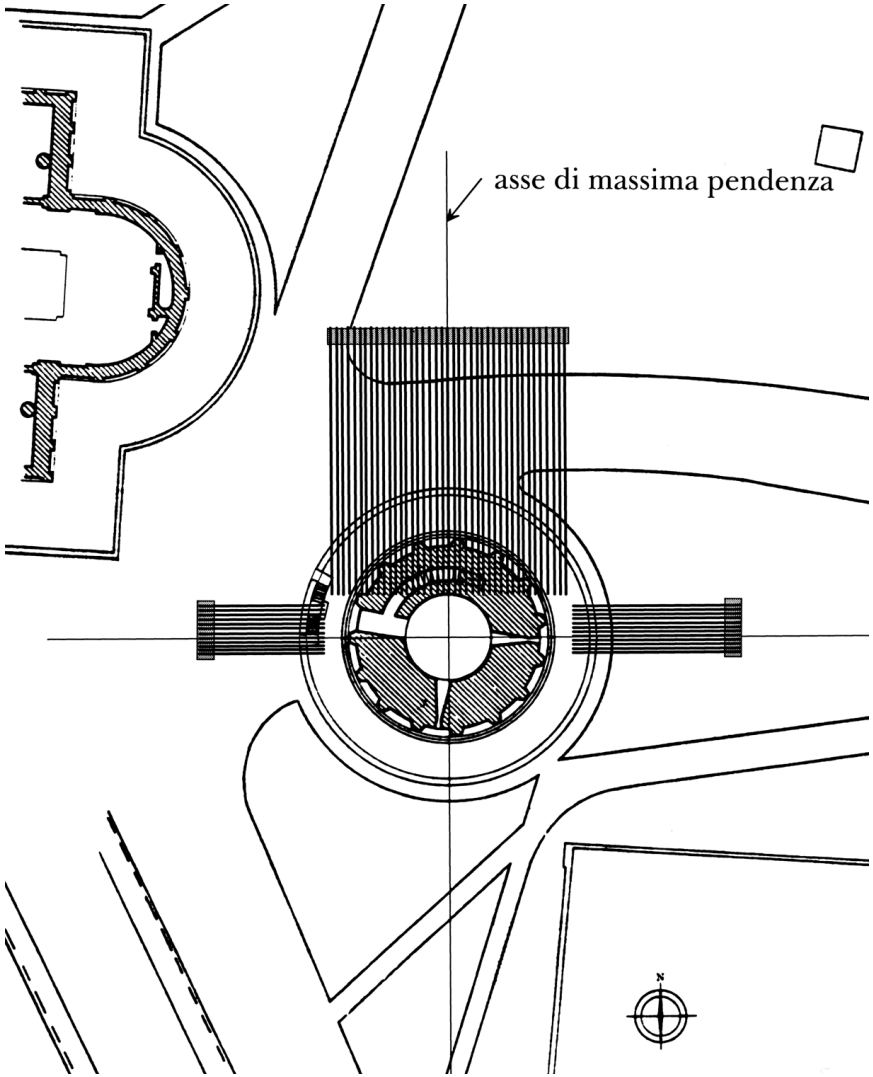

40
0
-40
-80
-120
-160
rotazione [arcsec]
estrazione di terreno
E
W
S
N
(A)
dic 98
gen
feb
mar
apr
mag
giu
lug
ago
set
ott 99
-0.4
0
0.4
0.8
1.2
cedimento [cm]
bordo sud fondazione
centro fondazione
bordo nord fondazione
(B)

Some problem to solve before the second phase:

- topographic survey
  - improve accuracy
  - increase the detail within the Catino
- avoid rupture of catino floor
- improve efficiency of estractions
- improve safety and velocity of extraction operations

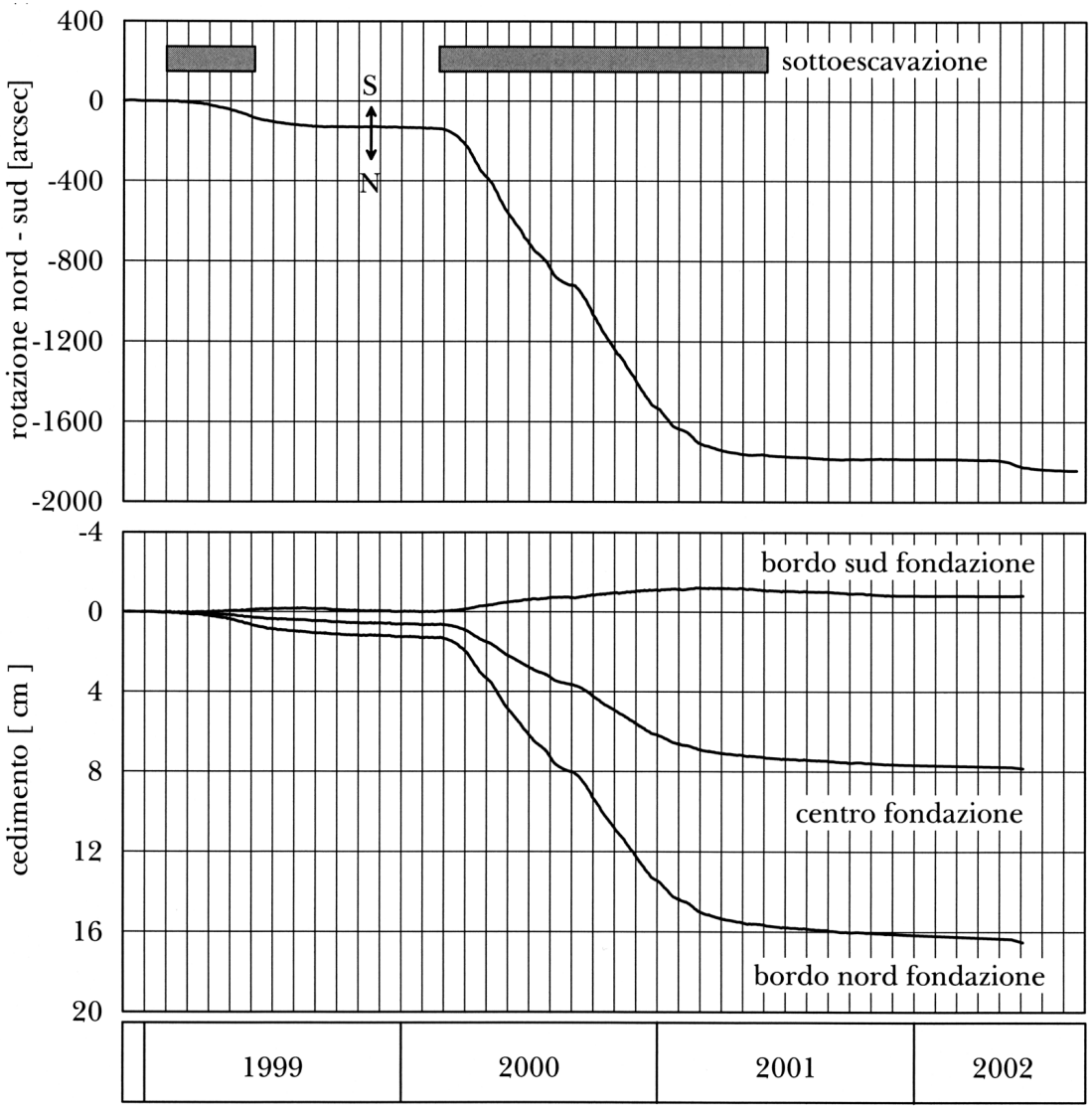
Second phase:

- 41 boreholes
- inclination 20°
- auger always in place
- side extractions



SOME INFORMATION ABOUT GEOTECHNICAL ASPECTS OF PISA TOWER STABILIZATION

results


400
0
-400
-800
-1200
-1600
-2000
rotazione nord - sud [arcsec]
S
N
sottoescavazione
-4
0
4
8
12
16
20
cedimento [cm]
bordo sud fondazione
centro fondazione
bordo nord fondazione
1999
2000
2001
2002

Lead ingots removal

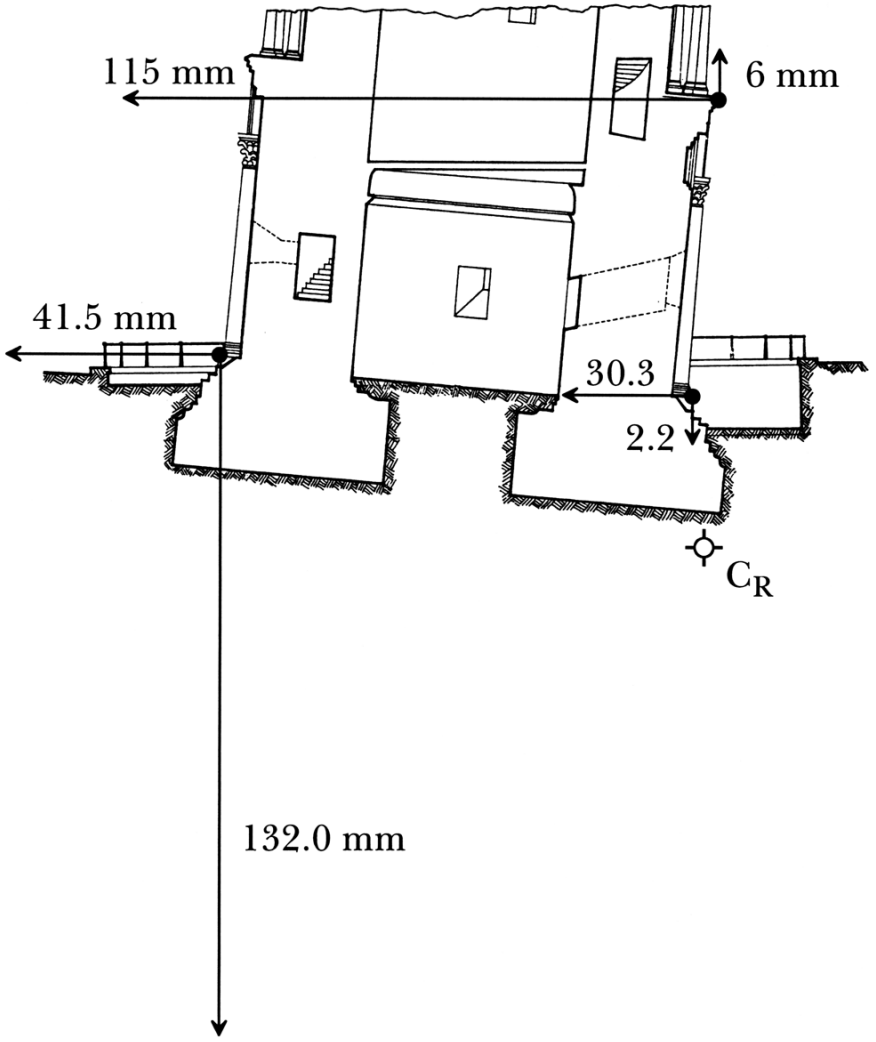
	A	B	C	D	E	F	G	H
13				9375 kg 23.5.2000	9375 kg 23.5.2000	9375 kg 14.9.1999	9375 kg 14.9.1999	9375 kg 14.9.1999
12				9375 kg 30.5.2000	9375 kg 30.5.2000	9375 kg 13.6.2000	9770 kg 6.6.2000	9375 kg 6.6.2000
11			9375 kg 13.6.2000	9375 kg 20.6.2000	9375 kg 27.6.2000	9375 kg 4.7.2000	9375 kg 27.6.2000	9375 kg 20.6.2000
10			9375 kg 4.7.2000	9375 kg 11.7.2000	9375 kg 18.7.2000	9375 kg 25.7.2000	9375 kg 18.7.2000	9375 kg 11.7.2000
9			9375 kg 25.7.2000	9426 kg 1.8.2000	9426 kg 28.8.2000	9426 kg 28.8.2000	9970 kg 28.8.2000	9730 kg 1.8.2000
8		9375 kg 12.9.2000	9750 kg 12.9.2000	9630 kg 19.9.2000	9820 kg 26.9.2000	9890 kg 19.9.2000	9730 kg 19.9.2000	9760 kg 12.9.2000
7		9820 kg 26.9.2000	9860 kg 3.10.2000	9780 kg 3.10.2000	9870 kg 10.10.2000	9830 kg 10.10.2000	9830 kg 3.10.2000	9800 kg 26.9.2000
6		9880 kg 10.10.2000	9810 kg 17.10.2000	9750 kg 24.10.2000	9700 kg 24.10.2000	9770 kg 24.10.2000	9690 kg 17.10.2000	9710 kg 17.10.2000
5	9630 kg 24.10.2000	9770 kg 31.10.2000	9710 kg 31.10.2000	9710 kg 7.11.2000	9670 kg 7.11.2000	9630 kg 7.11.2000	9650 kg 31.10.2000	9760 kg 31.10.2000
4	9680 kg 7.11.2000	9450 kg 14.11.2000	9590 kg 14.11.2000	9530 kg 21.11.2000	9570 kg 21.11.2000	9470 kg 21.11.2000	9440 kg 14.11.2000	9480 kg 14.11.2000
3	9200 kg 21.11.2000	9200 kg 28.11.2000	9200 kg 28.11.2000	9250 kg 5.12.2000	9220 kg 5.12.2000	9150 kg 5.12.2000	9200 kg 28.11.2000	9200 kg 28.11.2000
2	9280 kg 5.12.2000	9140 kg 12.12.2000	9140 kg 12.12.2000	9090 kg 20.12.2000	8950 kg 20.12.2000	9090 kg 20.12.2000	9055 kg 12.12.2000	9340 kg 12.12.2000
1	8170 kg 20.12.2000	8308 kg 9.1.2001	7422 kg 9.1.2001	8232 kg 16.1.2001	7506 kg 16.1.2001	8352 kg 16.1.2001	7414 kg 9.1.2001	8346 kg 9.1.2001

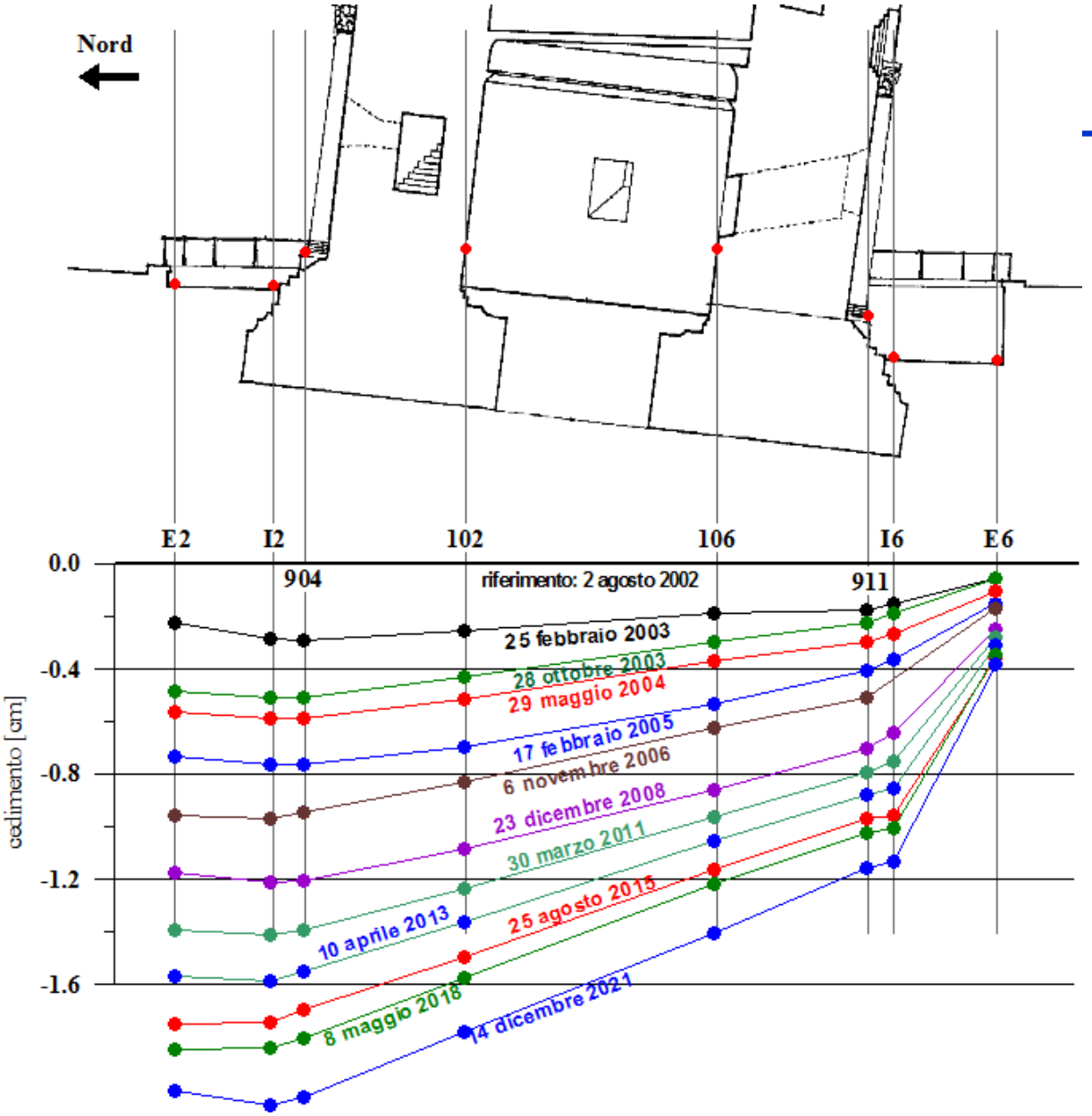
9375 kg <------- peso del lingotto
14.9.1999 <------- data della rimozione

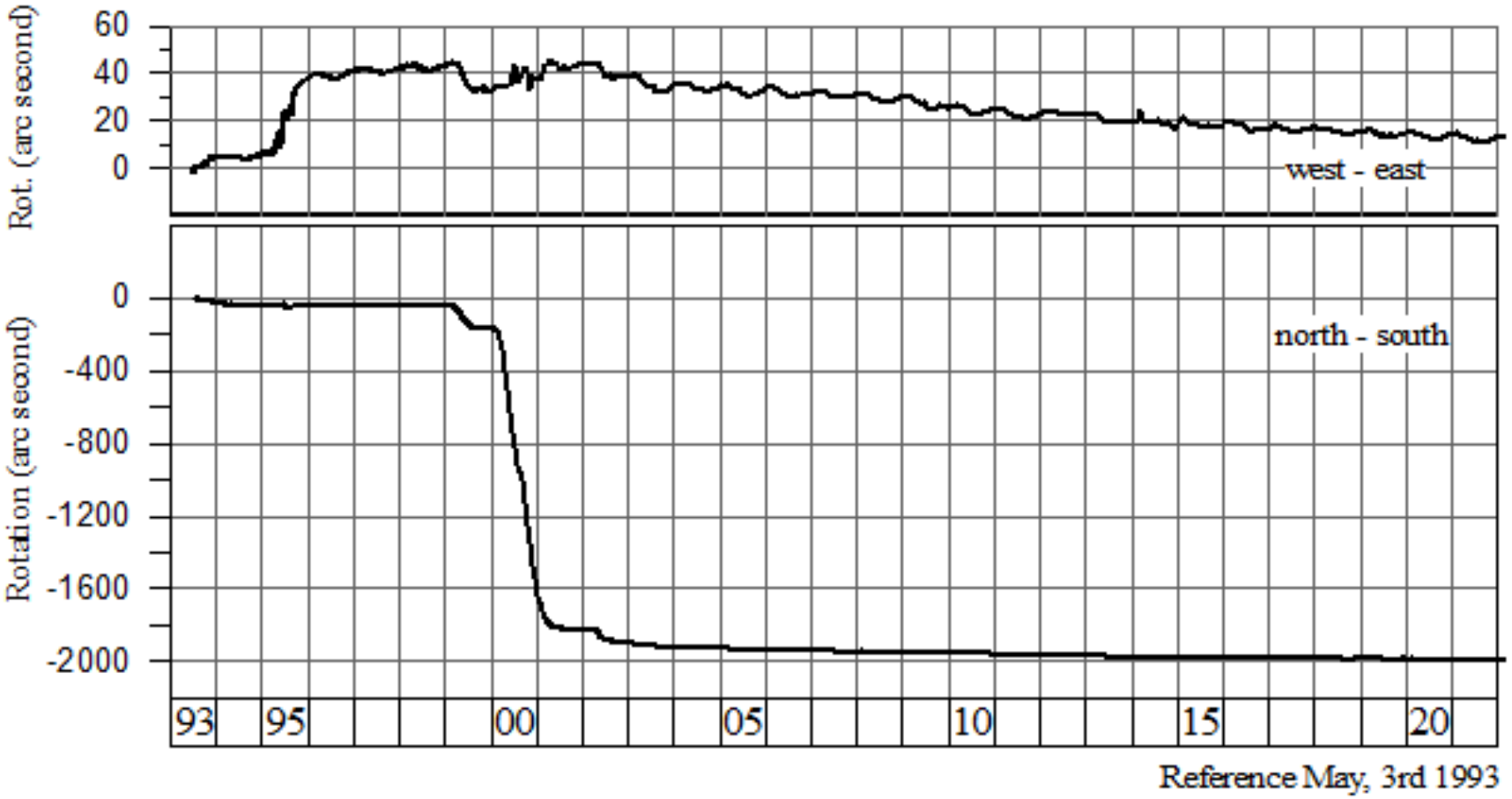
traccia dell'asse di massima pendenza

2C	2B	2A	1A	1B
9375 kg 27.2.2001	9375 kg 20.2.2001	9375 kg 27.2.2001	9375 kg 20.2.2001	9375 kg 27.2.2001

Movements of some points




Nord
E2
I2
102
106
I6
E6
0.0
-0.4
-0.8
-1.2
-1.6
cedimento [cm]
904
riferimento: 2 agosto 2002
911
25 febbraio 2003
28 ottobre 2003
29 maggio 2004
17 febbraio 2005
6 novembre 2006
23 dicembre 2008
30 marzo 2011
10 aprile 2013
25 agosto 2015
8 maggio 2018
14 dicembre 2021


Rot. (arc second)
60
40
20
0
west - east
Rotation (arc second)
0
-400
-800
-1200
-1600
-2000
north - south
93
95
00
05
10
15
20
Reference May, 3rd 1993

AT PRESENT THE TOWER IS STILL ROTATING NORTHWARDS AT A RATE OF 2” PER YEAR

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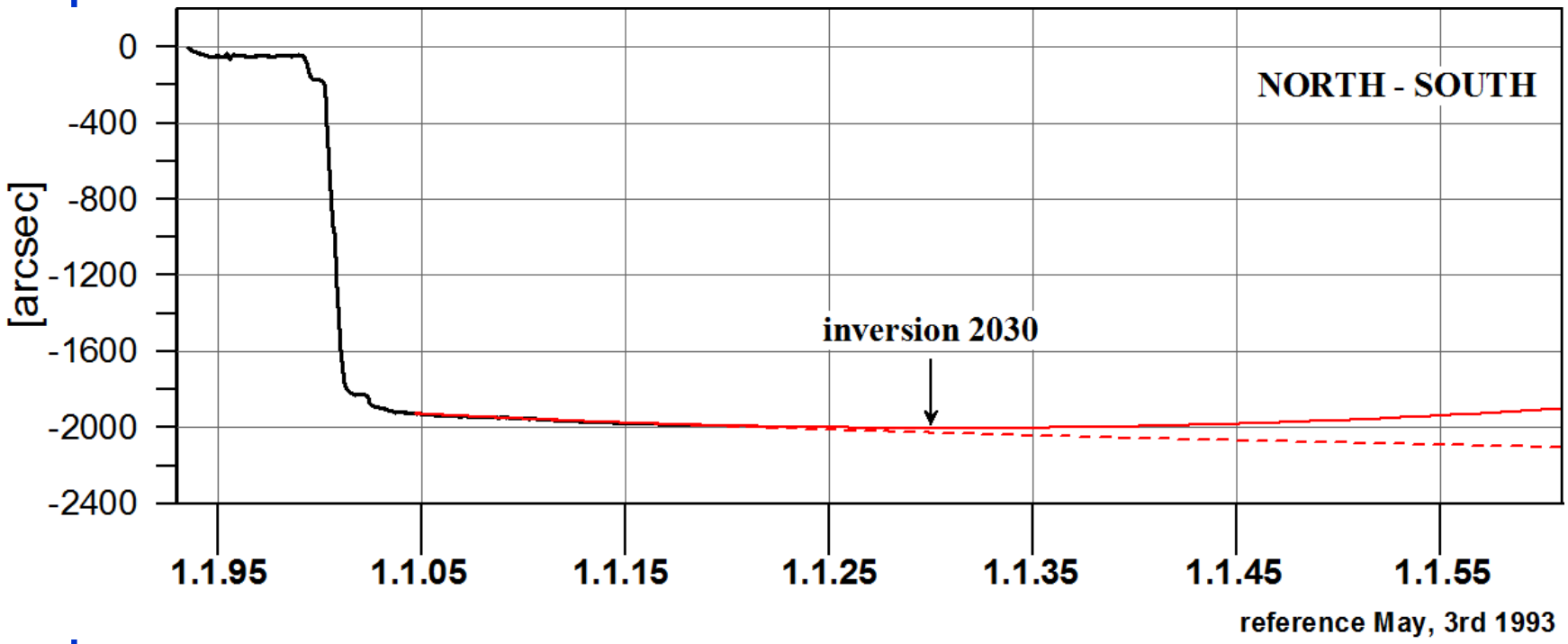
What will happen?

Extrapolation of measures



Finite Element Model