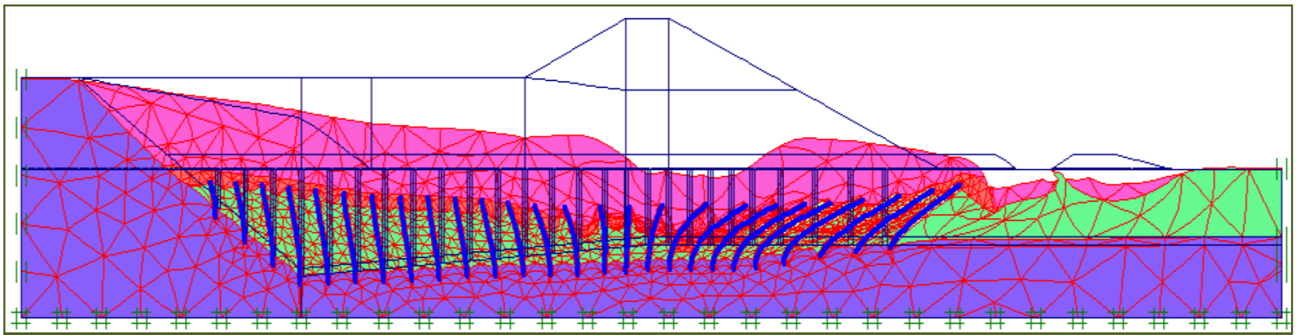
INTERNATIONAL SYMPOSIUM & SHORT COURSES

TC 211 IS-GI Brussels 2012

SHORT COURSE 4: COMPENSATION GROUTING & JET GROUTING



Recent Research, Advances & Execution Aspects of

GROUND IMPROVEMENT WORKS

30 May 2012, Brussels, BELGIUM

Organised by:

ISSMGE Technical Committee TC 211 Ground Improvement

Belgische Groepering voor Grondmechanica en Geotechniek
Groupement Belge de Mécanique des Sols et de la Géotechnique

Comité Français de Mécanique des Sols

SIMSG ISSMGE

GBMS BGGG

CFMS

SIMSG ISSMGE

TC 211

SHORT COURSE 4 – COMPENSATION GROUTING AND JET GROUTING

Date: *Sunday 1 September 2013* ***Place:*** *Terrasol, Immeuble Central Seine 42-52 Quai de la Râpée, Paris, France*	***Coordinators:*** *R. Essler, RD Geotech Ltd., UK* *J. Maertens, Jan Maertens bvba, Belgium*

PROGRAMME

SC4 - COMPENSATION GROUTING

09h30 – 10h15 : Design of compensation grouting for TBMs,
R. Essler, RD Geotech Ltd, United Kingdom
10h15 – 11h00 : Compensation grouting - numerical modelling simulations,
T. O'Brien, Mott Mc Donald, United Kingdom

11h00 – 11h15 : Coffee Break

11h15 – 11h45 : Experience from CrossRail project in UK,
M. Black, Crossrail, United Kingdom
11h45 – 12h15 : Shumann Josaphat project in Brussels,
Y. Stevens, Denys, Belgium
12h15 – 12h45 : Monitoring during compensation grouting,
J.G. La Fonta, Sol-Data, France
12h45 – 13h00 : Discussion

13h00 – 14h30 : Lunch

SC4 - JET GROUTING

14h30 – 15h00 : Probability analysis to determine jet grout cut off design,
R. Essler, RD Geotech Ltd, United Kingdom
15h00 – 15h30 : Recent aspect in jet grouting development,
Tsutomu Tsuchiya, Chemical Grouting Co., Ltd, Japan
15h30 – 16h00 : Design of jet grout base plugs and strength of jet grout elements,
W. Sondermann, Keller Grundbau, Germany

16h00 – 16h15 : Coffee break

16h15 – 16h45 : Design issues for jet grouted structures,
A. Flora, Università di Napoli Frederico II, Italy
16h45 – 17h15 : Sandwich wall beneath Amsterdam Central Station,
O. Langhorst, Movares, The Netherlands
17h15 – 17h45 : Quality assurance of jet grouting,
B. Lecomte, Solétanche-Bachy, France
17h45 – 18h00 : Discussion

18h00 : Reception

IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Design of compensation grouting for TBMs

R. Essler, RD Geotech Ltd, United Kingdom

Design of Compensation Grouting For Tunnel Boring Machines

RD Essler
RD Geotech Ltd

1st September 2013

RD GEOTECH LTD

The Progression from Concept to Execution

- Concept Design
- Detailed Design
- Execution Design

Concept Design

- Deals with estimation of settlement
  - Is grouting needed?
  - Where is grouting needed?
- Where should the grout tubes be positioned?
- How much settlement will take place and will there be sufficient grouting resources?

Concept Design
Estimation of Settlement

- Generally it is common to adopt a three stage approach to settlement mitigation:
  - Stage 1 Greenfield settlement estimation using empirical methods
    - (O'REILLY & NEW, 1982)
    - (ATTEWELL & WOODMAN, 1982).
  - Stage 2 Greenfield strain estimates for buildings etc subjected to more than 10mm settlement
    - Use of Burland Table

BURLAND DAMAGE CLASSIFICATION

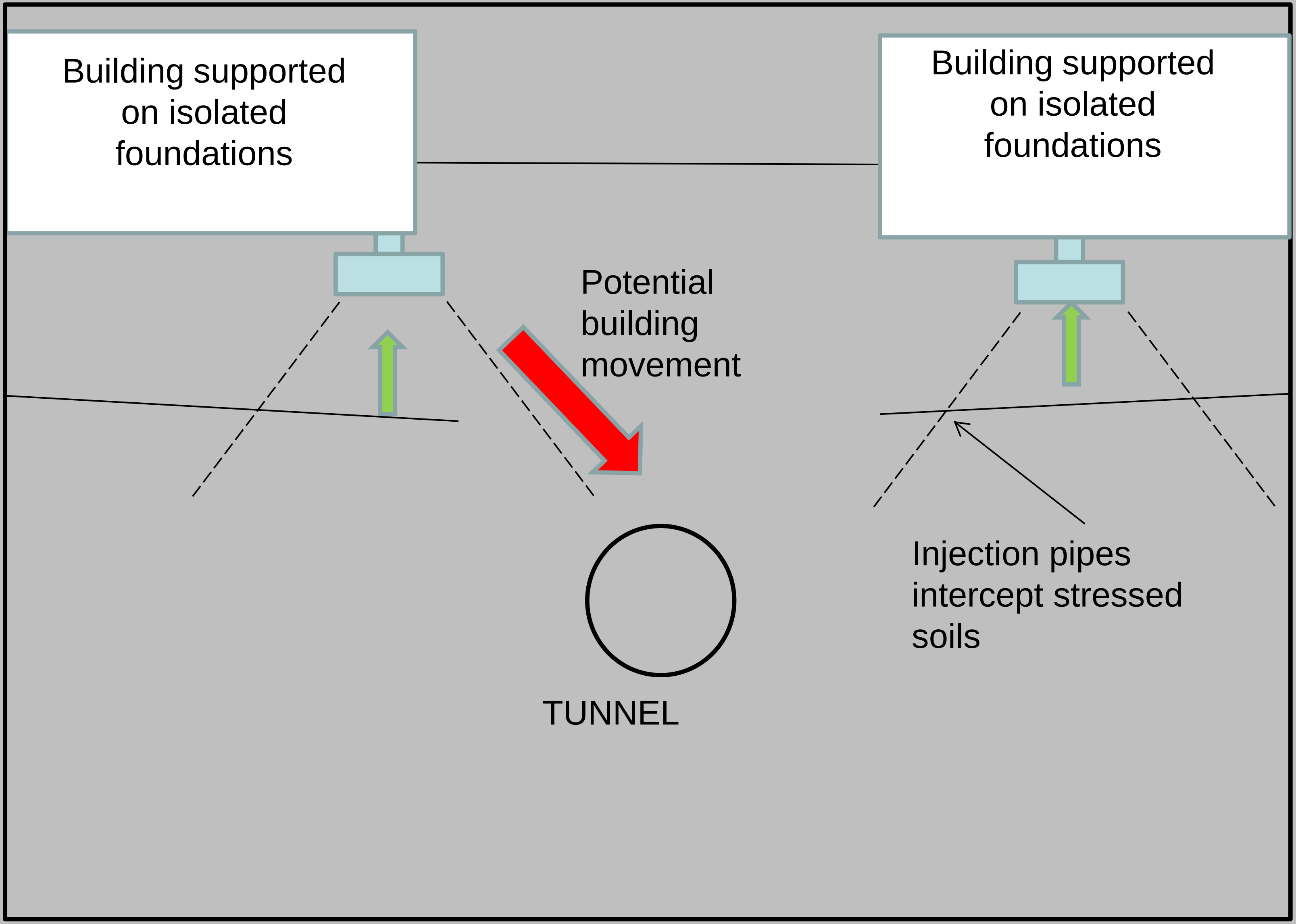
1 Risk Category	2 Max Tensile Strain %	3 Description of Degree of Damage	4 Description of Typical Damage and Likely Form of Repair for Typical Masonry buildings	5 Approx[1] Crack Width (mm)
0	0.05 or less	Negligible	Hairline cracks.	
1	More than 0.05 and not exceeding 0.075	Very Slight	Fine cracks easily treated during normal redecorations. Perhaps isolated slight fracture in building. Cracks in exterior brickwork visible upon close inspection.	0.1 to 1
2	More than 0.075 and not exceeding 0.15	Slight	Cracks easily filled. Redecoration probably required. Several slight fractures inside building. Exterior cracks visible; some repointing may be required for weather-tightness. Doors and windows may stick slightly.	1 to 5
3	More than 0.15 and not exceeding 0.3	Moderate	Cracks may require cutting out and patching. Recurrent cracks can be masked by suitable linings. Repointing and possibly replacement of a small amount of exterior brickwork may be required. Doors and windows sticking. Utility services may be interrupted. Weather tightness often impaired.	5 to 15 or a number of cracks greater than 3
4	More than 0.3	Severe	Extensive repair involving removal and replacement of sections of walls, especially over doors and windows required. Windows and door frames distorted. Floor slopes noticeably. Walls lean or bulge noticeably, some loss of bearing in beams. Utility services disrupted.	15 to 25 but also depends on number of cracks
5		Very Severe	Major repair required involving partial or complete reconstruction. Beams lose bearing, walls lean badly and require shoring. Windows broken by distortion. Danger of instability.	Usually greater than 25 but depends on number of cracks

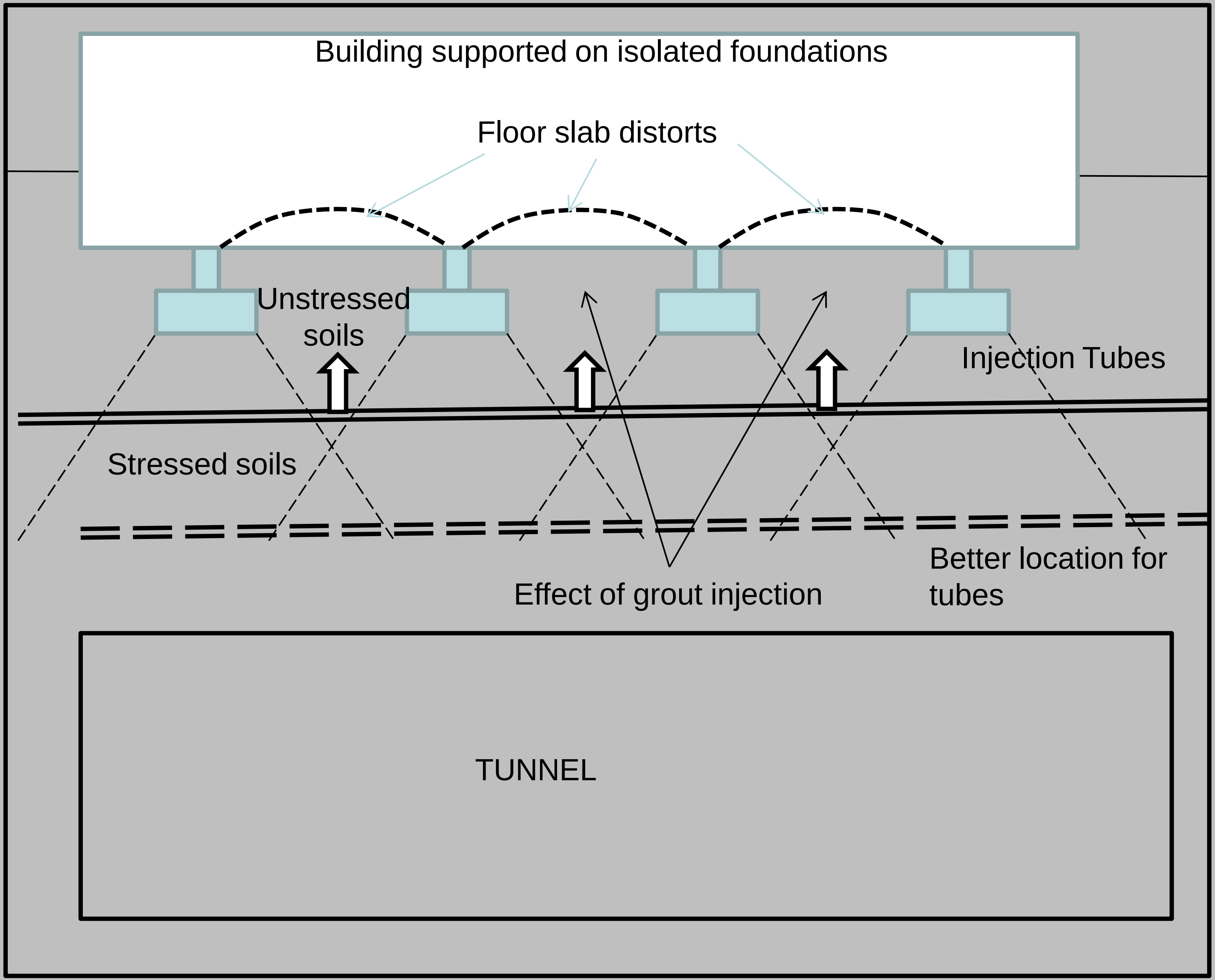
Concept Design

- Stage 3
  - Detailed structural analysis of building to determine soil/structure interaction
- Following Stage 3 all buildings requiring mitigation are identified an if necessary initial compensation grouting design concept applied

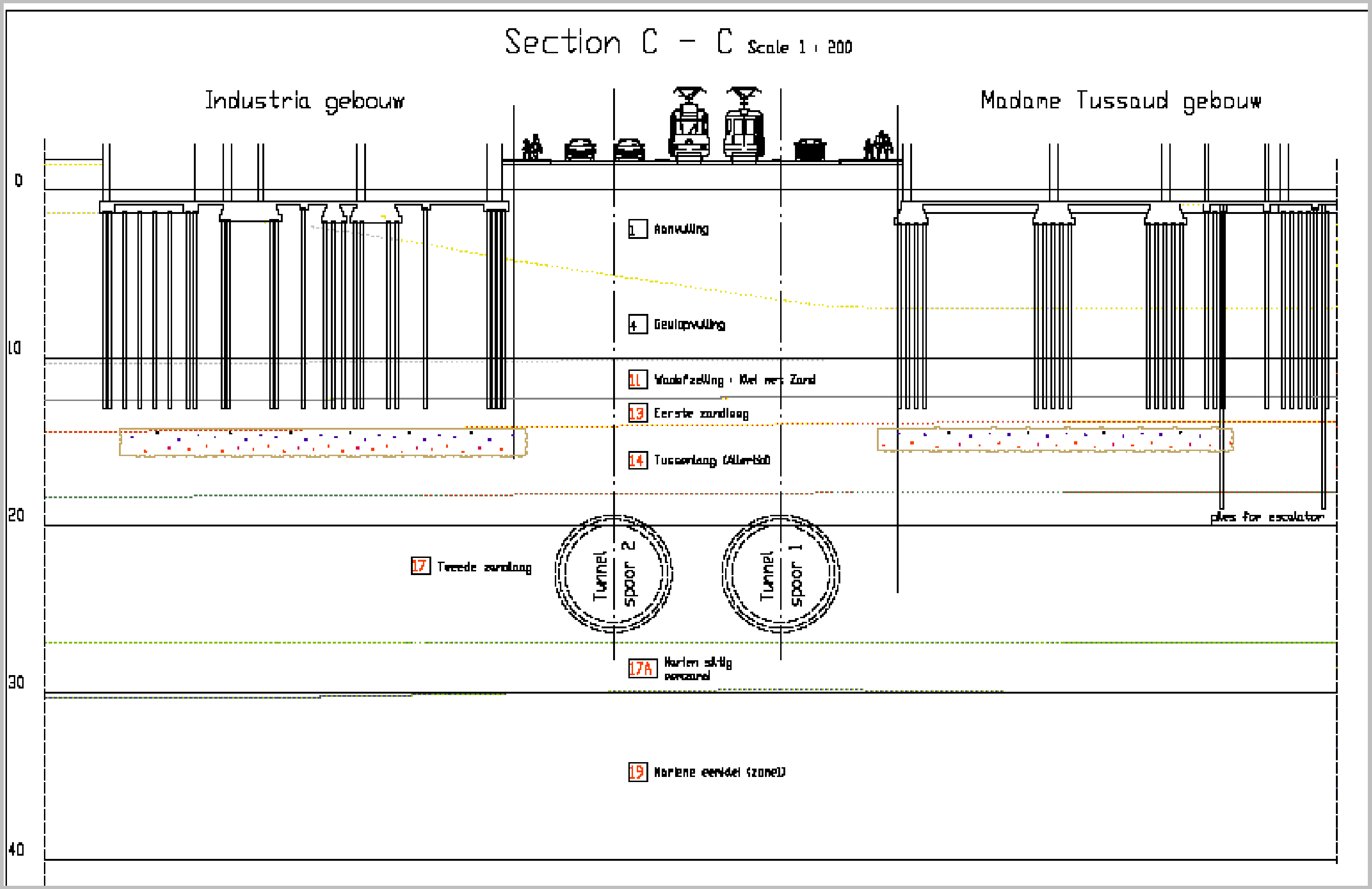
Concept Design

- Position of grout tubes is critical
  - To ensure that uneven movement is not generated
  - To ensure that the full foundation is protected
  - To reduce the risk of grout entering the tunnel or causing overstress

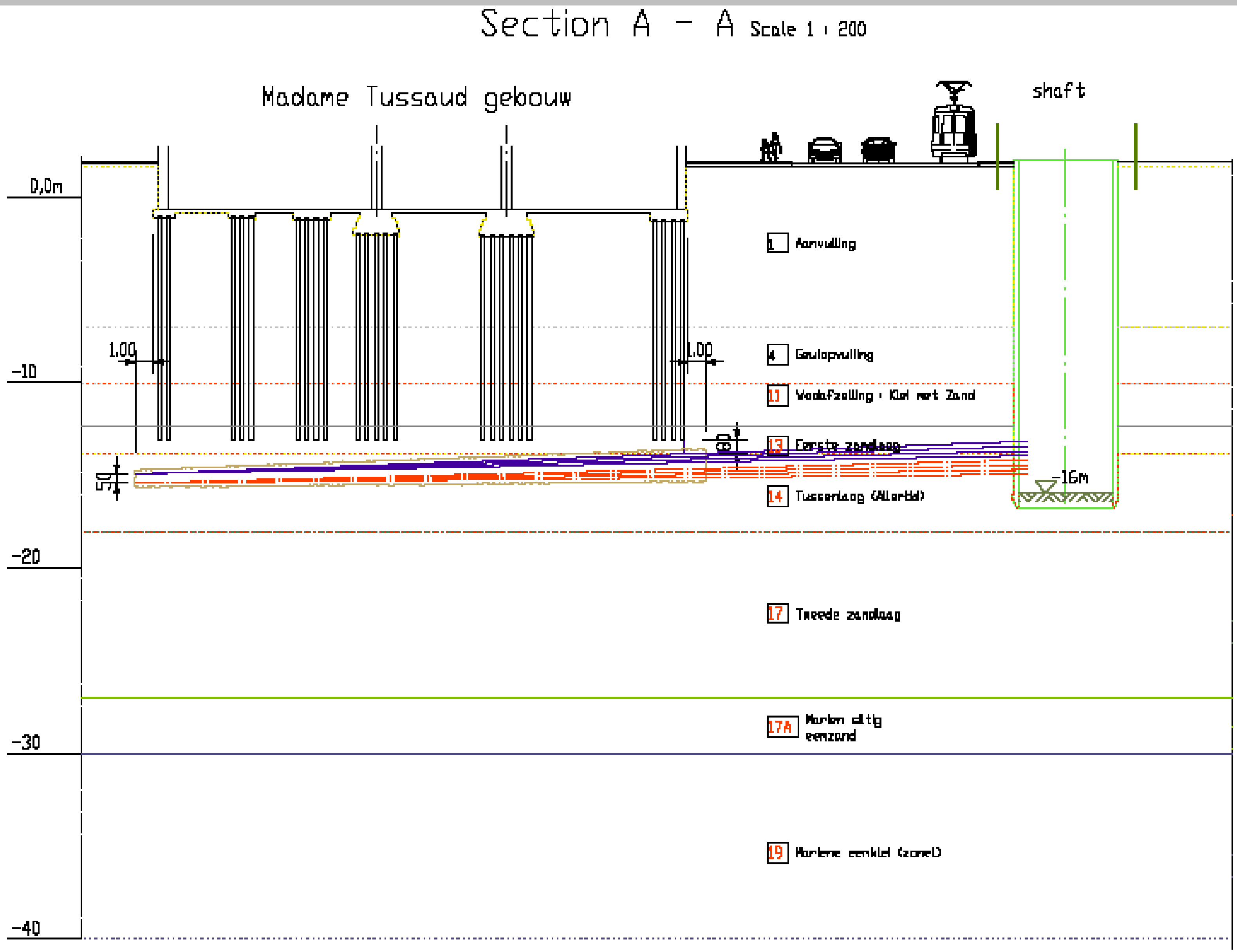

Building supported on isolated foundations
Building supported on isolated foundations
Potential building movement
Injection pipes intercept stressed soils
TUNNEL


Building supported on isolated foundations
Floor slab distorts
Unstressed soils
Injection Tubes
Stressed soils
Better location for tubes
Effect of grout injection
TUNNEL

Example of Concept Design Amsterdam North-South Line Original Design Cross-Section



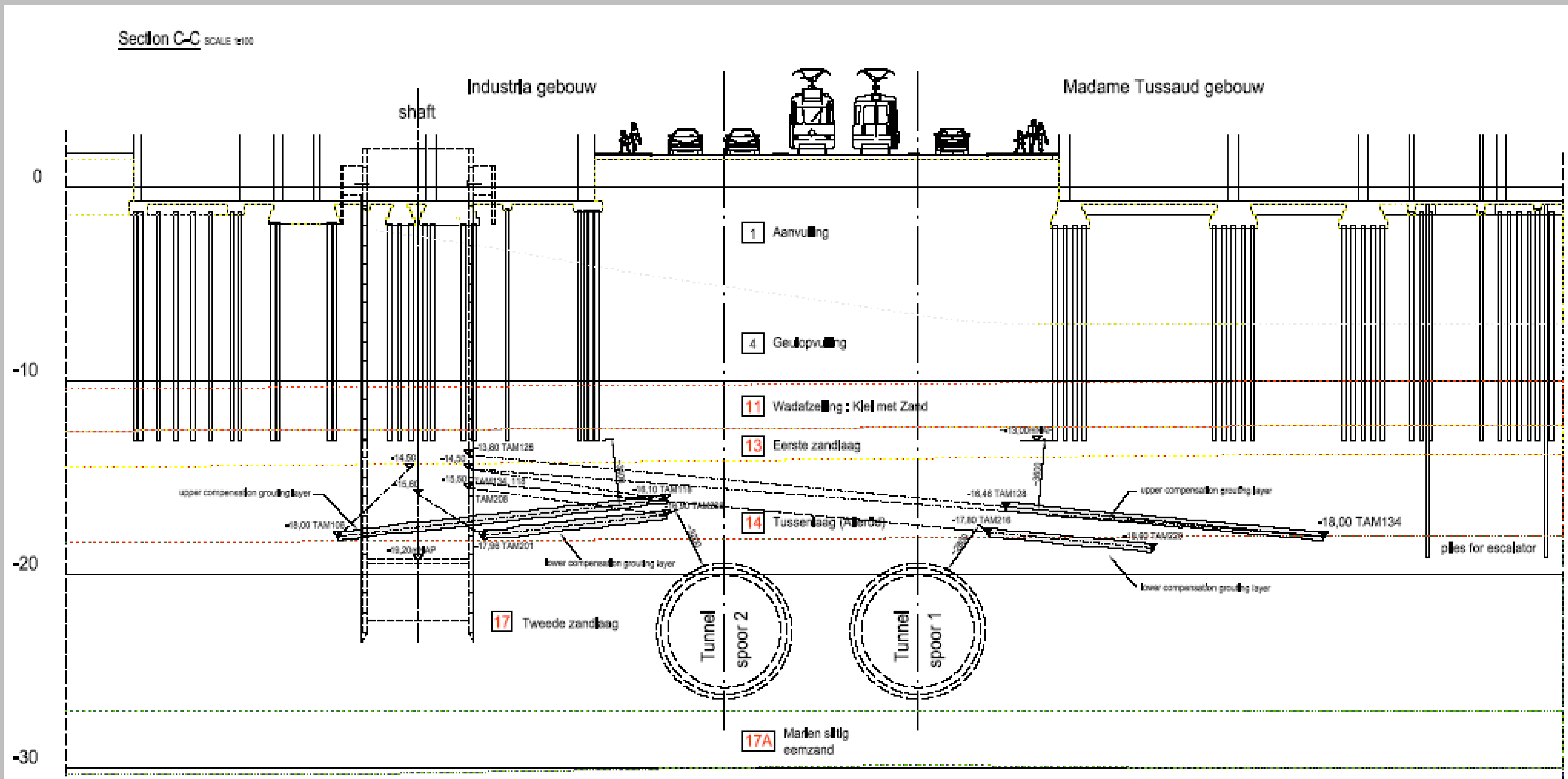
Original Design Cross-Section



Design Principles

- Intercept contours using a sloping grout zone to increase coverage efficiency
- Position grout zone a minimum of 3m from pile toes and preferably midway between the pile toes and tunnel crown
- Coverage to 5mm contour line only
- One layer of pipes only

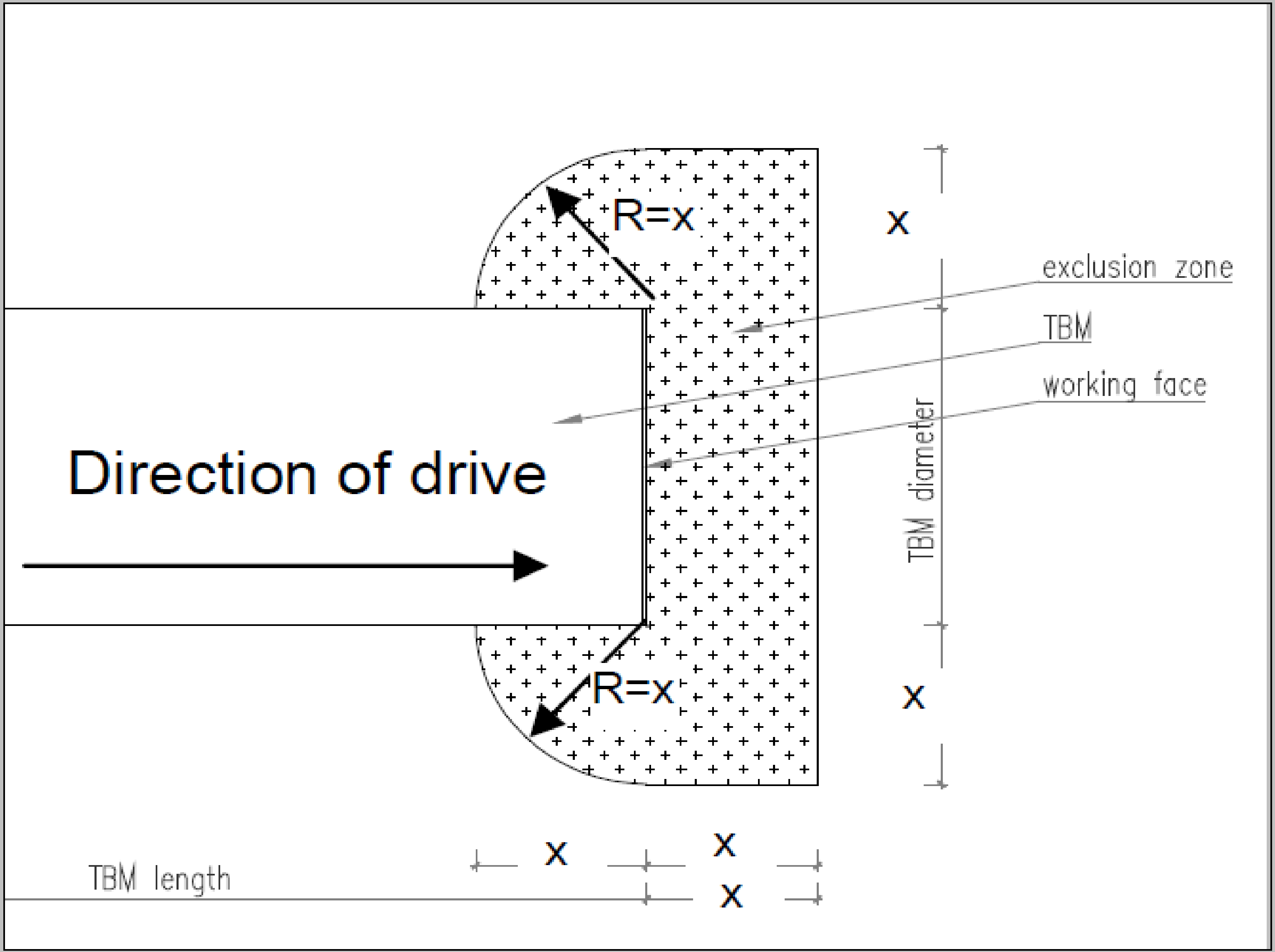
Redesign Cross-Section



TBM Exclusion Zones

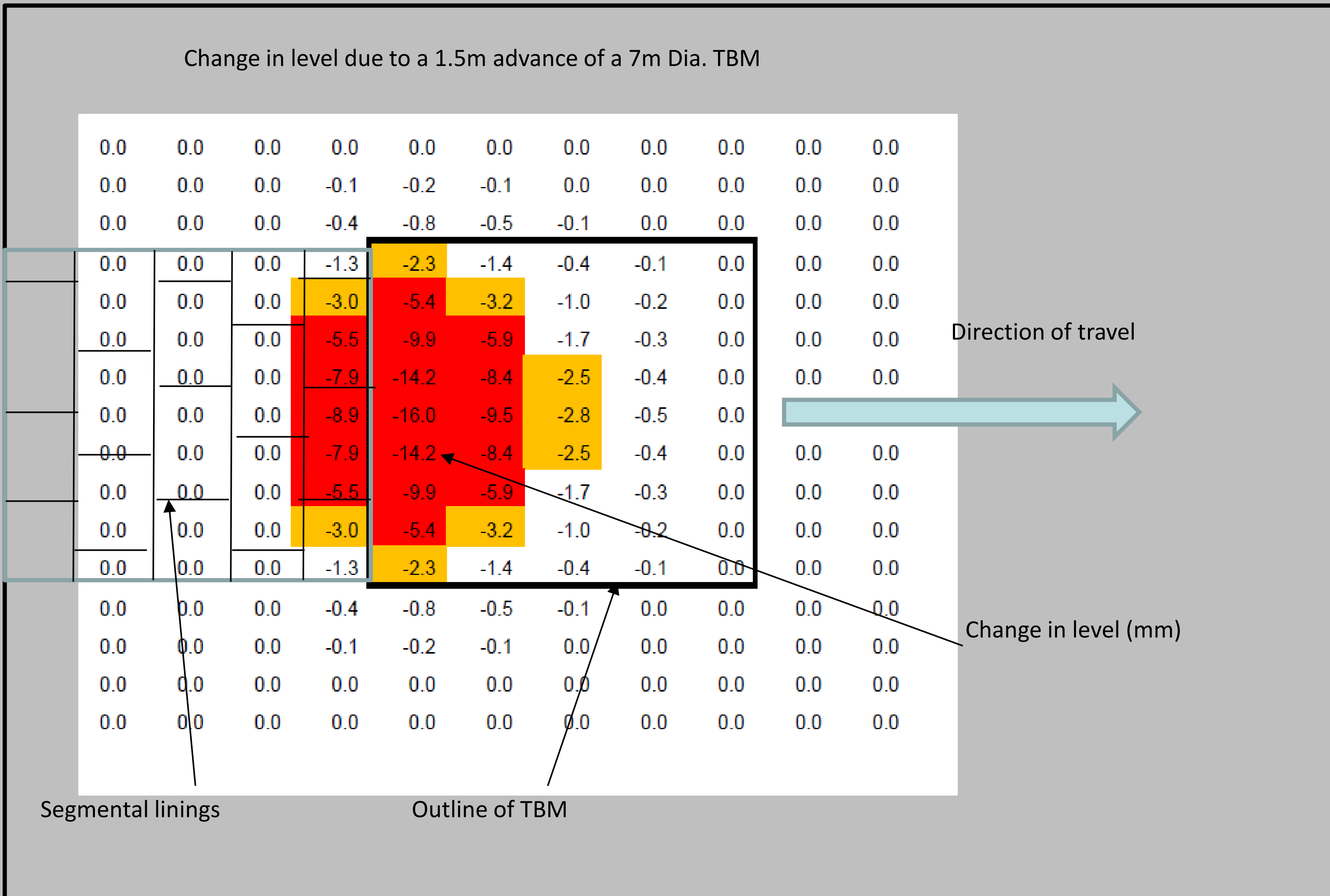
- Exclusion zones needed:
  - Prevent overpressurization at face
  - Leakage of grout to face
    - Contamination of slurry
    - Loss of grouting efficiency

TBM Exclusion Zones



(North-South Line, Amsterdam)

Settlement resulting from advance of TBM by 1.5m for 1% volume loss



0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	-0.1	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	-0.4	-0.8	-0.5	-0.1	0.0	0.0	0.0	0.0
0.0	0.0	0.0	-1.3	-2.3	-1.4	-0.4	-0.1	0.0	0.0	0.0
0.0	0.0	0.0	-3.0	-5.4	-3.2	-1.0	-0.2	0.0	0.0	0.0
0.0	0.0	0.0	-5.5	-9.9	-5.9	-1.7	-0.3	0.0	0.0	0.0
0.0	0.0	0.0	-7.9	-14.2	-8.4	-2.5	-0.4	0.0	0.0	0.0
0.0	0.0	0.0	-8.9	-16.0	-9.5	-2.8	-0.5	0.0		
0.0	0.0	0.0	-7.9	-14.2	-8.4	-2.5	-0.4	0.0	0.0	0.0
0.0	0.0	0.0	-5.5	-9.9	-5.9	-1.7	-0.3	0.0	0.0	0.0
0.0	0.0	0.0	-3.0	-5.4	-3.2	-1.0	-0.2	0.0	0.0	0.0
0.0	0.0	0.0	-1.3	-2.3	-1.4	-0.4	-0.1	0.0	0.0	0.0
0.0	0.0	0.0	-0.4	-0.8	-0.5	-0.1	0.0	0.0	0.0	0.0
0.0	0.0	0.0	-0.1	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

depth to axis 15.5 Time from start 200 hours Red -4
half trough width 23.25 Position 8.3 m Amber -2
Y increment 1.5
X increment 1.458

	0	1.458	2.917	4.375	5.833	7.292	8.75	10.21	11.67	13.13	14.58	16.04	17.5	18.96	20.42	21.88	23.33	24.79	26.25	27.71	29.17	30.63	32.08	33.54	35	36.46	37.92	39.38	40.83	42.29	43.75	45.21	46.67	48.13
28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.0	-0.7	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.5	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.2	-2.8	-2.0	-1.2	-0.6	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	-7.7	-7.7	-7.7	-7.7	-7.7	-7.7	-7.6	-6.6	-4.8	-2.9	-1.5	-0.6	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.5	-14.9	-14.9	-14.9	-14.9	-14.9	-14.9	-14.8	-12.8	-9.3	-5.6	-2.9	-1.2	-0.4	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	-24.0	-24.0	-24.0	-24.0	-24.0	-24.0	-23.8	-20.7	-15.0	-9.1	-4.6	-1.9	-0.7	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5	-31.9	-31.9	-31.9	-31.9	-31.9	-31.9	-31.7	-27.5	-19.9	-12.1	-6.1	-2.6	-0.9	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0	-35.1	-35.1	-35.1	-35.1	-35.1	-35.1	-34.8	-30.2	-21.9	-13.3	-6.7	-2.8	-1.0	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.5	-31.9	-31.9	-31.9	-31.9	-31.9	-31.9	-31.7	-27.5	-19.9	-12.1	-6.1	-2.6	-0.9	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-3	-24.0	-24.0	-24.0	-24.0	-24.0	-24.0	-23.8	-20.7	-15.0	-9.1	-4.6	-1.9	-0.7	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-4.5	-14.9	-14.9	-14.9	-14.9	-14.9	-14.9	-14.8	-12.8	-9.3	-5.6	-2.9	-1.2	-0.4	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-6	-7.7	-7.7	-7.7	-7.7	-7.7	-7.7	-7.6	-6.6	-4.8	-2.9	-1.5	-0.6	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-7.5	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.2	-2.8	-2.0	-1.2	-0.6	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-9	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.0	-0.7	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-10.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-12	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 1 Settlements at tunnel advance at 8.3m

depth to axis	15.5	Time from start	224	hours	Red	-4
half trough width	23.25	Position	9.8	m	Amber	-2
Y increment	1.5					
X increment	1.458					

	0	1.458	2.917	4.375	5.833	7.292	8.75	10.21	11.67	13.13	14.58	16.04	17.5	18.96	20.42	21.88	23.33	24.79	26.25	27.71	29.17	30.63	32.08	33.54	35	36.46	37.92	39.38	40.83	42.29	43.75	45.21	46.67	48.13
28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.0	-0.7	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.5	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.2	-2.8	-2.0	-1.2	-0.6	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	-7.7	-7.7	-7.7	-7.7	-7.7	-7.7	-7.7	-7.6	-6.6	-4.8	-2.9	-1.5	-0.6	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.5	-14.9	-14.9	-14.9	-14.9	-14.9	-14.9	-14.9	-14.8	-12.8	-9.3	-5.6	-2.9	-1.2	-0.4	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	-24.0	-24.0	-24.0	-24.0	-24.0	-24.0	-24.0	-23.8	-20.7	-15.0	-9.1	-4.6	-1.9	-0.7	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5	-31.9	-31.9	-31.9	-31.9	-31.9	-31.9	-31.9	-31.7	-27.5	-19.9	-12.1	-6.1	-2.6	-0.9	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0	-35.1	-35.1	-35.1	-35.1	-35.1	-35.1	-35.1	-34.8	-30.2	-21.9	-13.3	-6.7	-2.8	-1.0	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.5	-31.9	-31.9	-31.9	-31.9	-31.9	-31.9	-31.9	-31.7	-27.5	-19.9	-12.1	-6.1	-2.6	-0.9	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-3	-24.0	-24.0	-24.0	-24.0	-24.0	-24.0	-24.0	-23.8	-20.7	-15.0	-9.1	-4.6	-1.9	-0.7	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-4.5	-14.9	-14.9	-14.9	-14.9	-14.9	-14.9	-14.9	-14.8	-12.8	-9.3	-5.6	-2.9	-1.2	-0.4	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-6	-7.7	-7.7	-7.7	-7.7	-7.7	-7.7	-7.7	-7.6	-6.6	-4.8	-2.9	-1.5	-0.6	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-7.5	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.2	-2.8	-2.0	-1.2	-0.6	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-9	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.0	-0.7	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-10.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-12	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 2 Settlements at tunnel advance at 9.8m

depth to axis	16	Time from start	224	hours	Red	-4
half trough width	23	Position	9.8	m	Amber	-2
Y increment	1.5	Preheave applied	0	mm		
X increment	1.5					

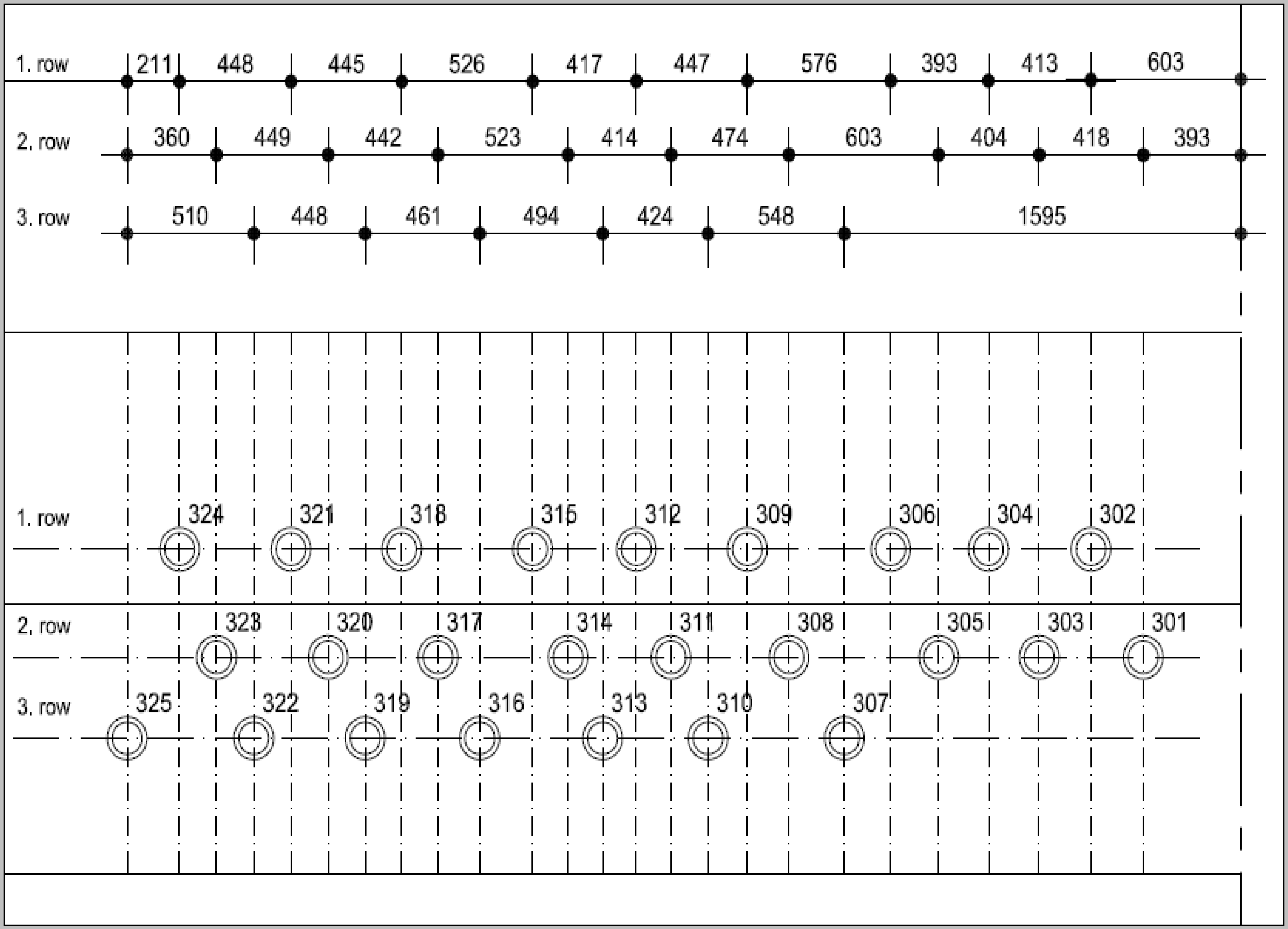
	0	1.5	2.9	4.4	5.8	7.3	8.8	10	12	13	15	16	18	19	20	22	23	25	26	28	29	31	32	34	35	36	38	39	41	42	44	45	47	48
28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.4	-0.8	-0.8	-0.6	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-1.0	-1.8	-1.9	-1.4	-0.8	-0.4	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-1.9	-3.5	-3.7	-2.8	-1.7	-0.8	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-3.1	-5.7	-5.9	-4.5	-2.7	-1.3	-0.5	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-4.2	-7.5	-7.9	-6.0	-3.5	-1.7	-0.6	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	-4.6	-8.3	-8.6	-6.6	-3.9	-1.8	-0.7	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-4.2	-7.5	-7.9	-6.0	-3.5	-1.7	-0.6	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-3	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-3.1	-5.7	-5.9	-4.5	-2.7	-1.3	-0.5	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-4.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-1.9	-3.5	-3.7	-2.8	-1.7	-0.8	-0.3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-6	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-1.0	-1.8	-1.9	-1.4	-0.8	-0.4	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.4	-0.8	-0.8	-0.6	-0.4	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.3	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

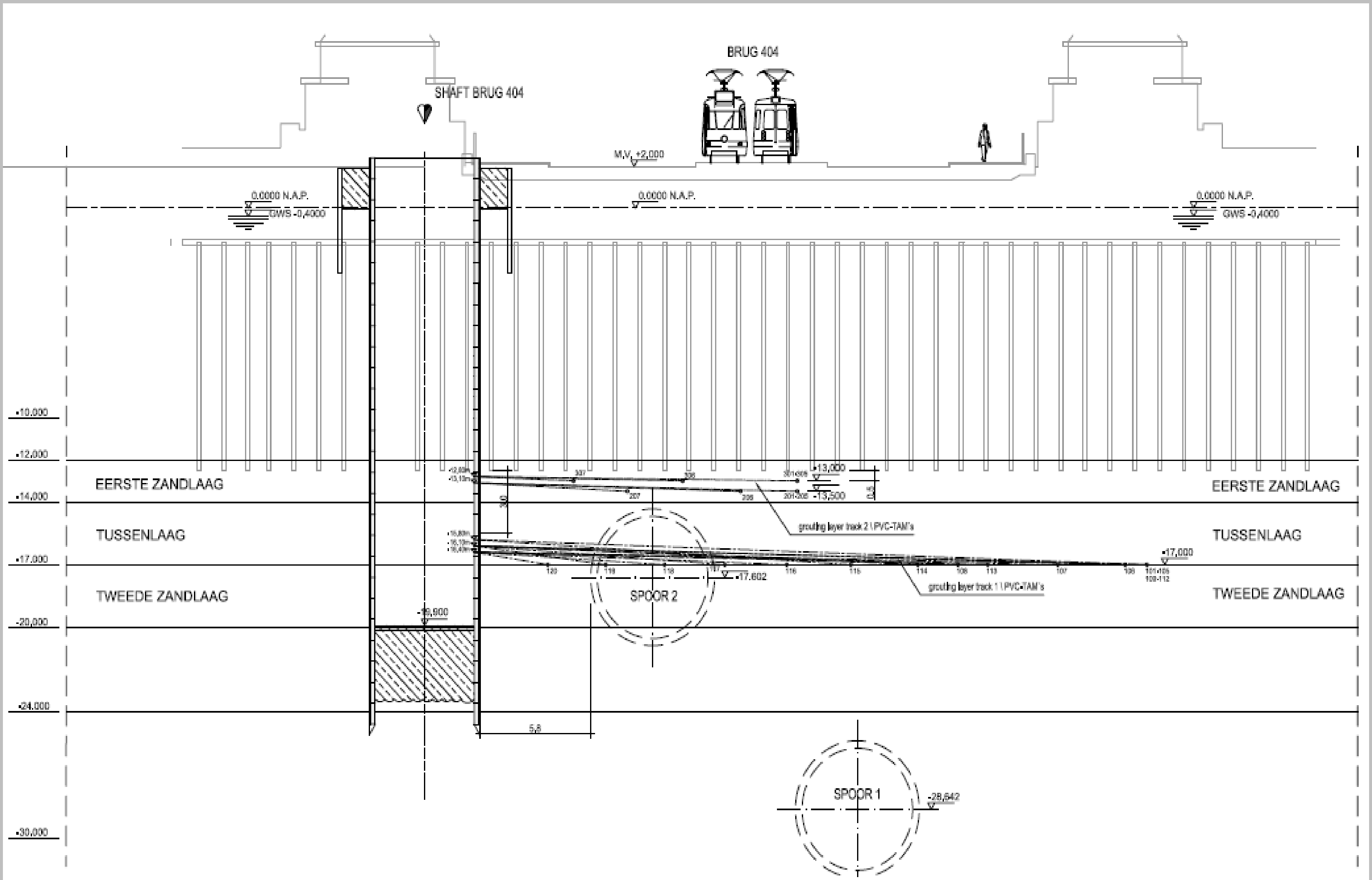
Figure 3 Additional settlement resulting from 1.5m tunnel advance

Detailed Design

- Detailed design has three components:
  - The initial layout and positioning of the grout tubes;
  - The initial grouting or “conditioning“ of the ground; and
  - The compensation grouting during settlement mitigation

Layout of pipes at detailed design stage

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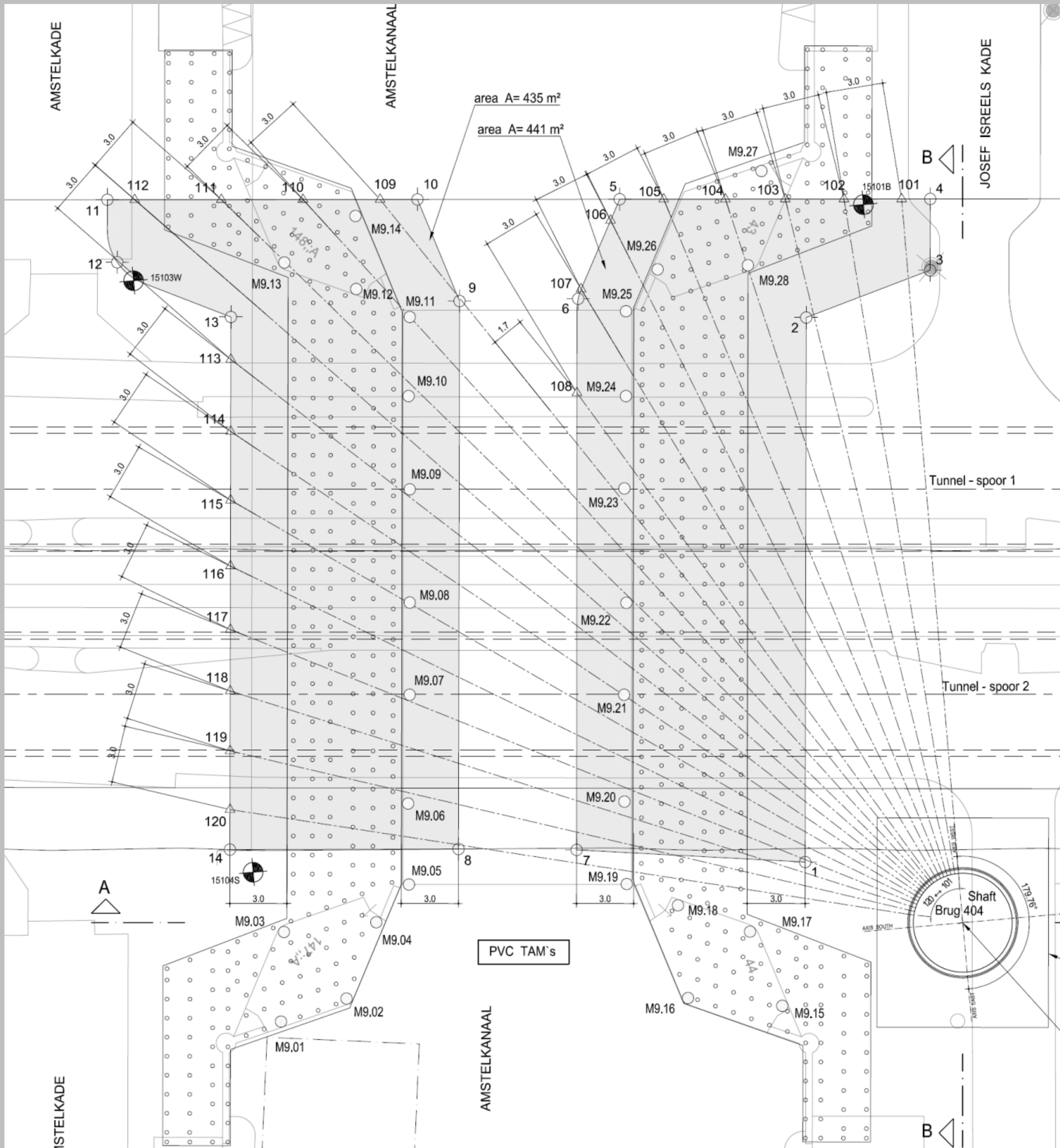
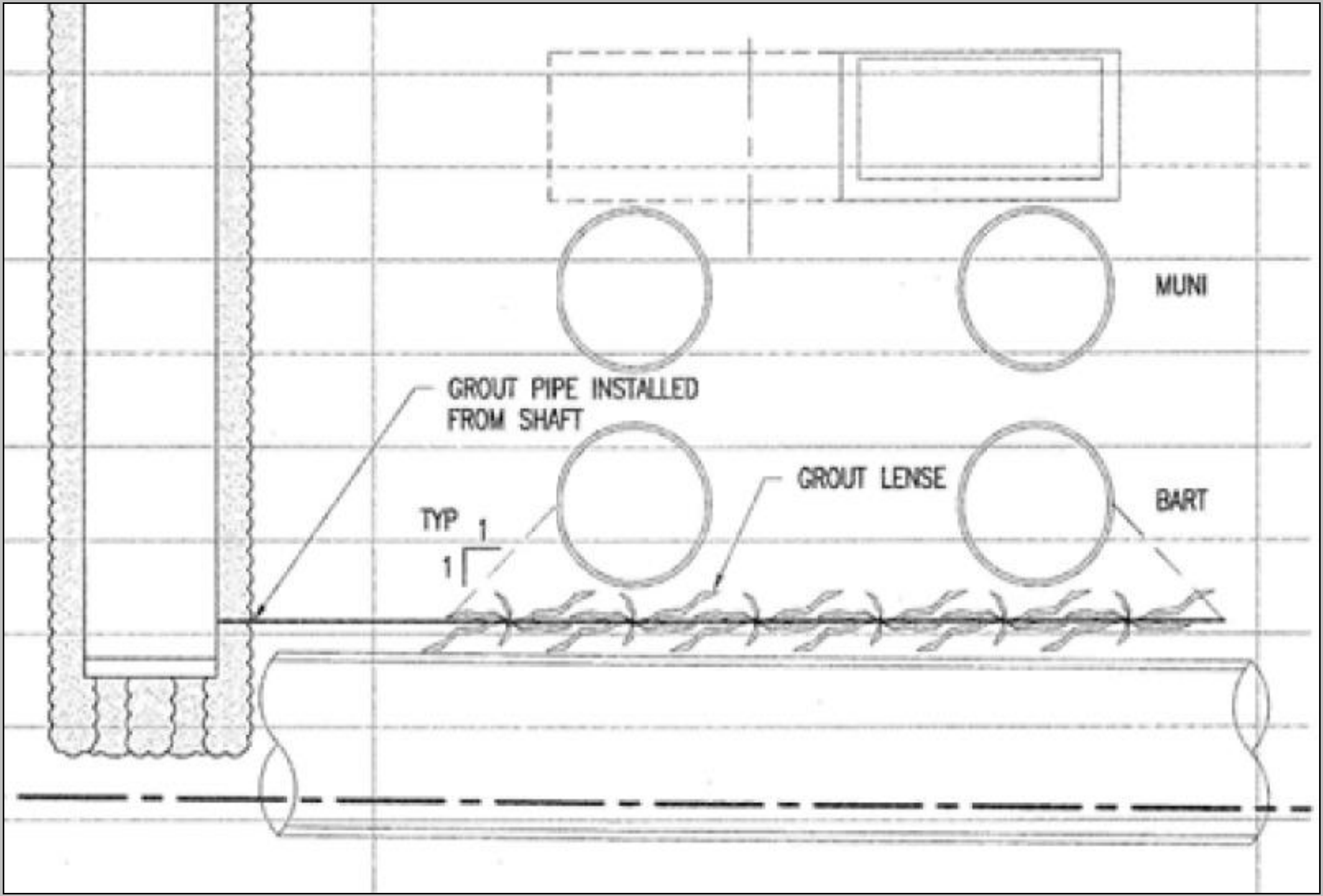
SHAFT BRUG 404
M.V. +2,000
0.0000 N.A.P.
GWS -0,4000
-10,000
-12,000
-14,000
-17,000
-20,000
-24,000
-30,000
EERSTE ZANDLAAG
TUSSENLAAG
TWEEDE ZANDLAAG
-13,000
-13,500
grouting layer track 2 \ PVC-TAM's
-17,000
-17,602
grouting layer track 1 \ PVC-TAM's
SPOOR 2
-19,600
5,8
SPOOR 1
-28,642



Only one level of pipes was possible because of the geometry

Pipe spacing varied in accordance with the pipe length as the pipe spacing at the shat was fixed to the minimum possible

Example where concept design does not consider practical issues



Initial Grouting

- Important to carry out initial pre-injections in advance of settlement correction (TBM etc)
  - Stiffen ground to ensure good response
  - Assess efficiency for compensation grouting phase

Grouting Efficiency

- Ratio of ground volume change to grout volume injected
- Varies from site to site due to ground conditions

Grouting Efficiency

Project	Soil-type	Grout Range (l/m²)	Grout Average (l/m²)	Foundation Load (kN/m²)
Antwerp 1	Sand	42–46	45	60
Antwerp 2	Sand	87–115	100	800
Essen, AEG	Silt	35–55	45	80
Bielefeld	Clay	56–64	60	280
Dortmund 1	Silt	65–75	70	200
Dortmund 2	Silt	84–96	90	200
Düsseldorf	Gravel/Sand	42–52	50	500
Hamburg [4]	Sand/Silt	31–70	45	50

Table 2: Amount of injected Grout in Phase I

(CHAMBOSSE & OTTERBEIN, 2001)

Grouting Efficiencies

Soil Type	Grouting Efficiency (%)
Sands and Gravels	5% to 15%
Silts	15% to 25%
Soft Clays	0% to 10%
Firm Clays	15% to 25%
Stiff Clays	30% to 50%

RD Essler 2012

Compensation Grouting

TBM v Sprayed Concrete

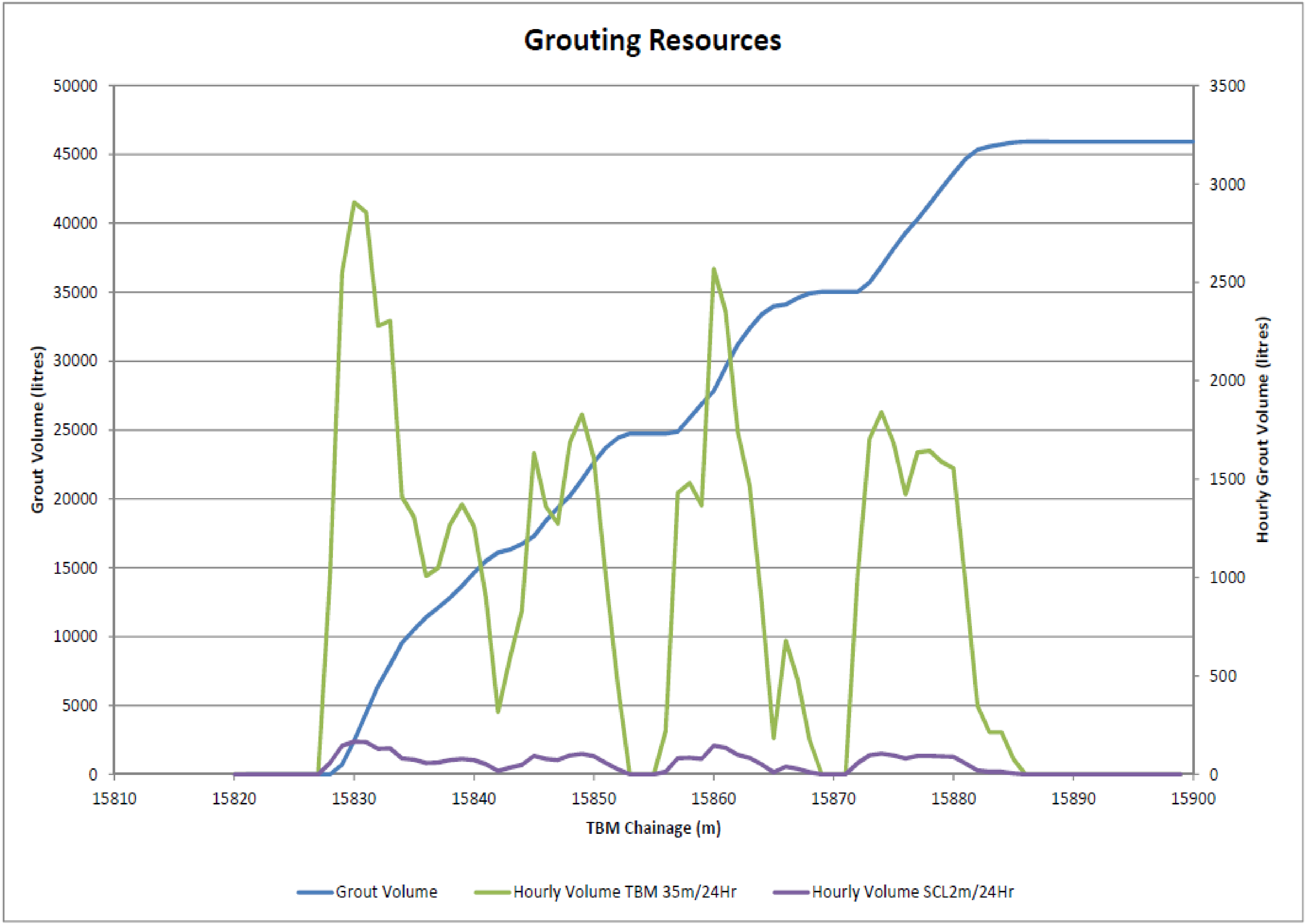
- Compensation grouting for a TBM is completely different to compensation grouting for Sprayed Concrete Linings (SCL)
  - TBM can advance at 20m a day compared to SCL works at 1m per day

TBM v SCL

- Consider a tunnel being advanced with a diameter of 7m and assuming a volume loss of 0.5%
  - TBM would advance at 20m per 24 hours
    - Volume loss is 3,850 litres/24 hours
  - SCL would advance at 1m per 24 hours
    - Volume loss is 195 litres/24 hours

TBM v SCL

- Considering a TBM operating in sands with an efficiency of 15%
  - Required grout volume per 24 hours would be 25,650 litres
- Considering a SCL construction operating in a stiff clay with an efficiency of 30%
  - Required grout volume per 24 hours would be 650 litres



Grouting Resources
Grout Volume (litres)
Hourly Grout Volume (litres)
TBM Chainage (m)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
3500
3000
2500
2000
1500
1000
500
0
15810
15820
15830
15840
15850
15860
15870
15880
15890
15900
Grout Volume
Hourly Volume TBM 35m/24Hr
Hourly Volume SCL2m/24Hr

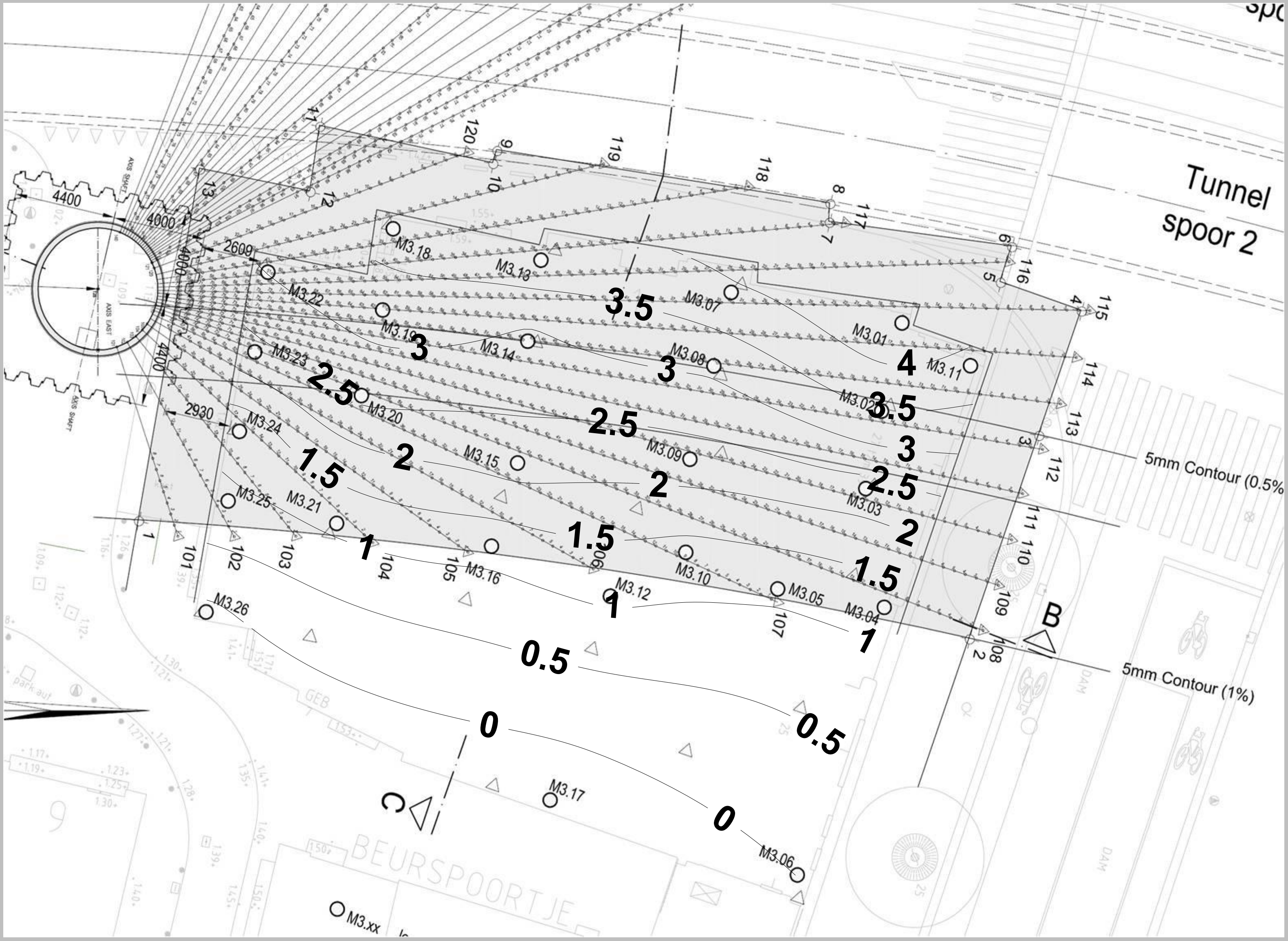
Conclusions from TBM v SCL

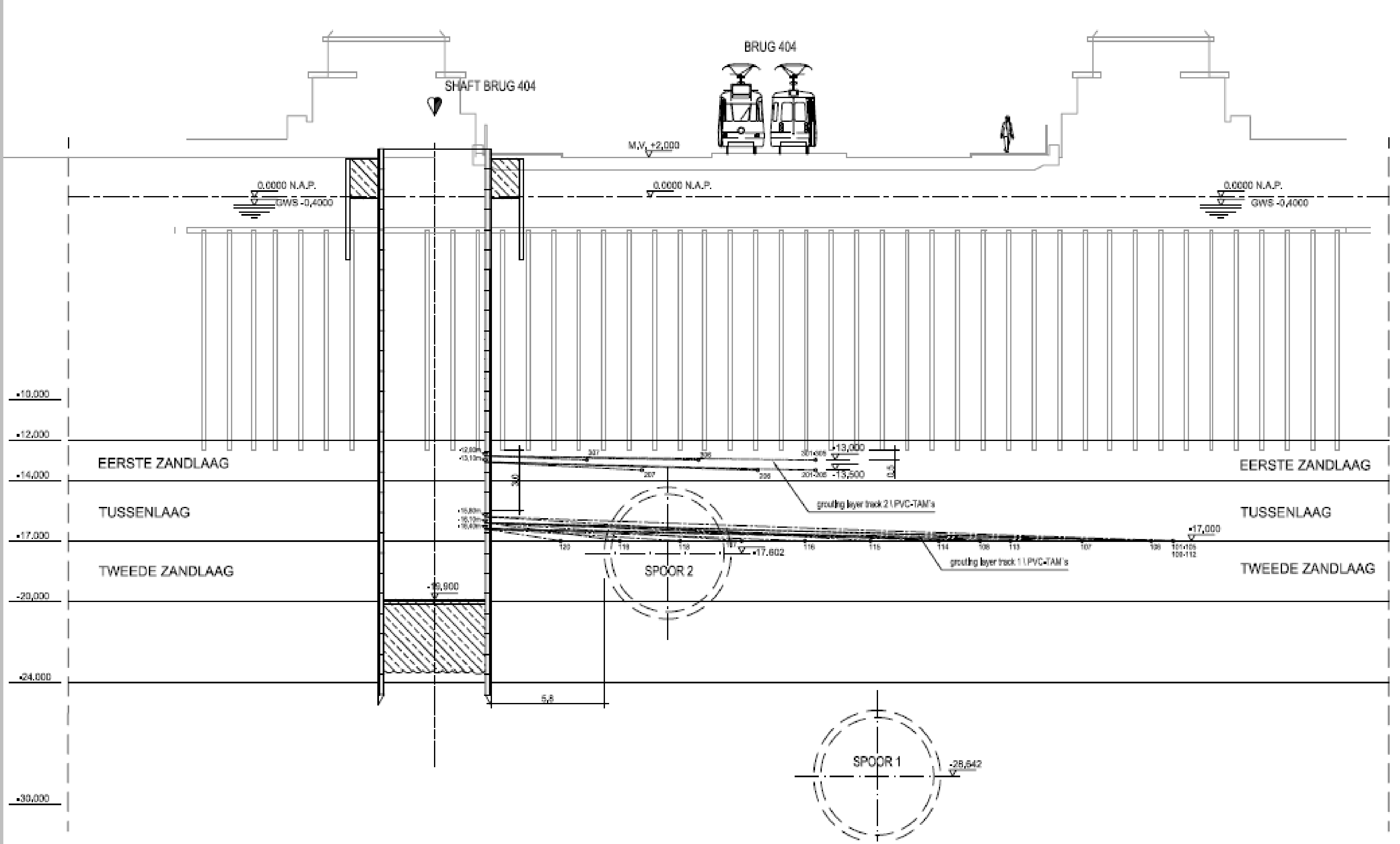
- For the TBM, the grouting crew are very busy!
- May need 3-4 injection crew working as fast as possible
- Grouting software may struggle to keep up with movements and work correctly
- Recommend that injections are sequenced with lining construction and based on a nominal volume loss
- Injections needed on a 24 hour basis

Conclusions from TBM v SCL

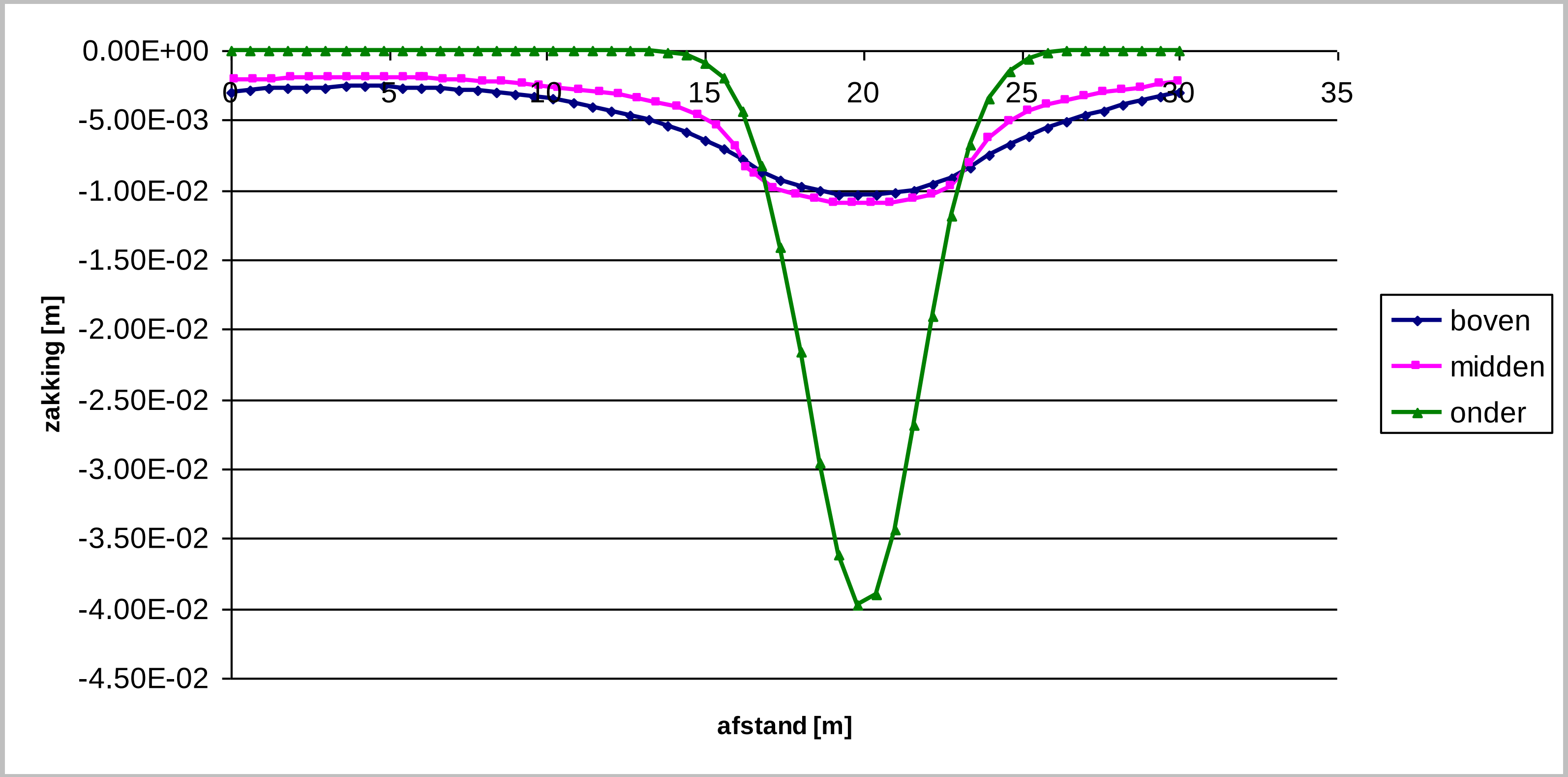
- For SCL works
- Grouting is part time, maybe 3-4 hours per day
- Pre-injections can be carried out in advance of the tunnel in this period with very little additional cost
- Possible to operate during day time only

Example of Pre-Heave for Tunnel Transit

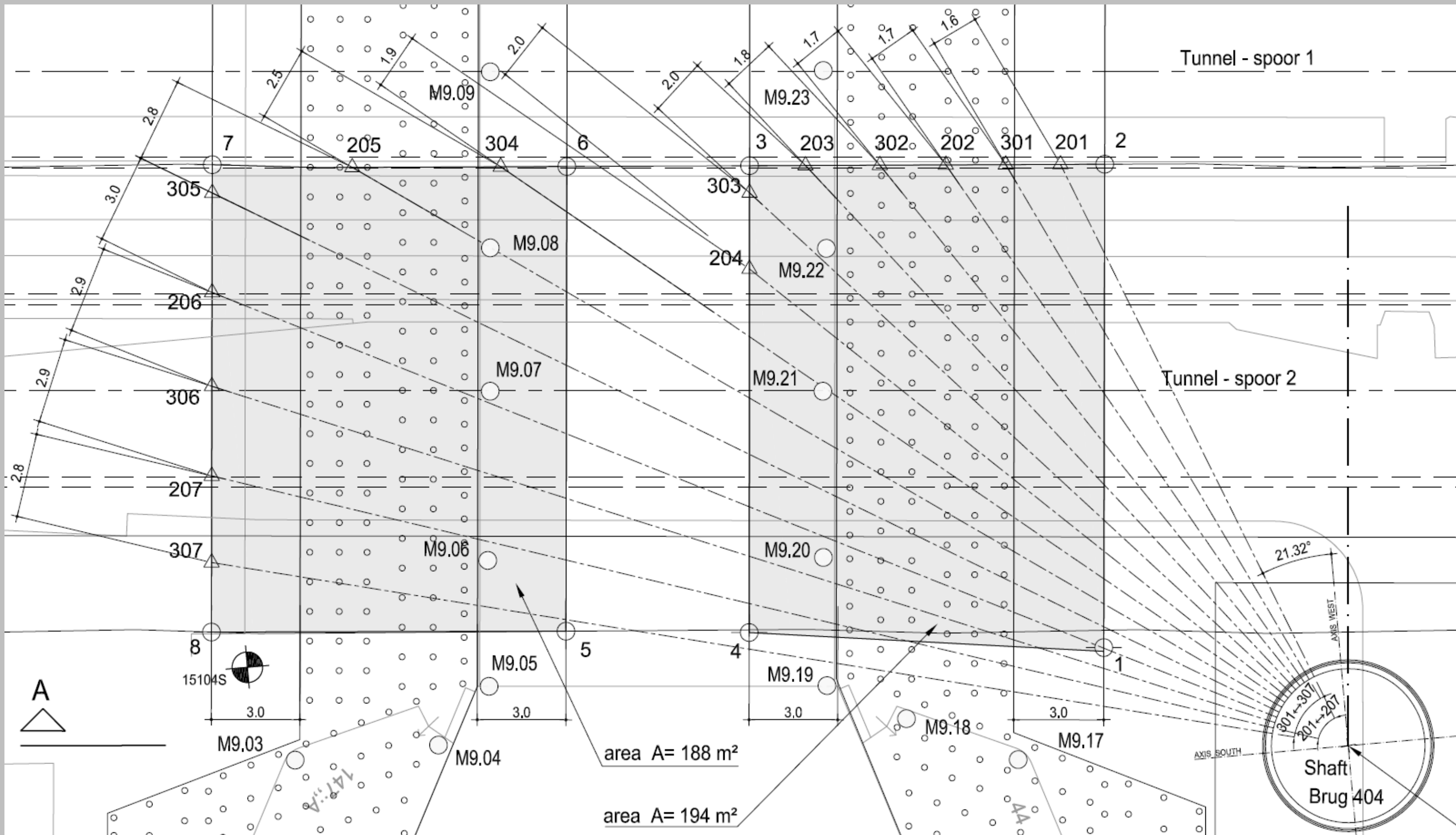




BRUG 404
SHAFT BRUG 404
M.V. +2,000
0,0000 N.A.P.
GWS -0,4000
-10,000
-12,000
-14,000
-17,000
-20,000
-24,000
-30,000
EERSTE ZANDLAAG
TUSSENLAAG
TWEEDE ZANDLAAG
-13,000
-13,500
grouting layer track 2 \ PVC-TAM's
grouting layer track 1 \ PVC-TAM's
-17,000
-17,602
SPOOR 2
-19,900
5,8
SPOOR 1
-28,642

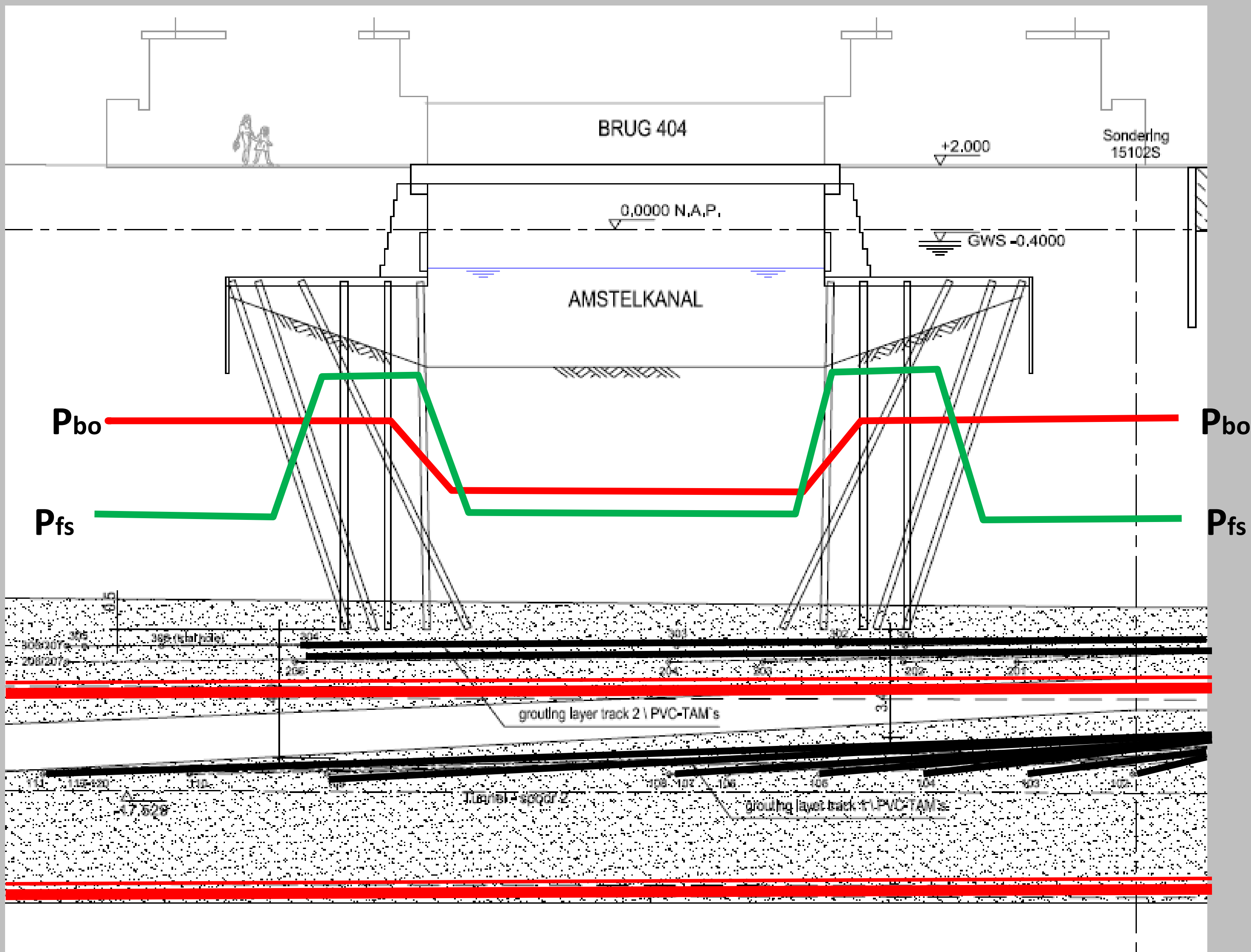


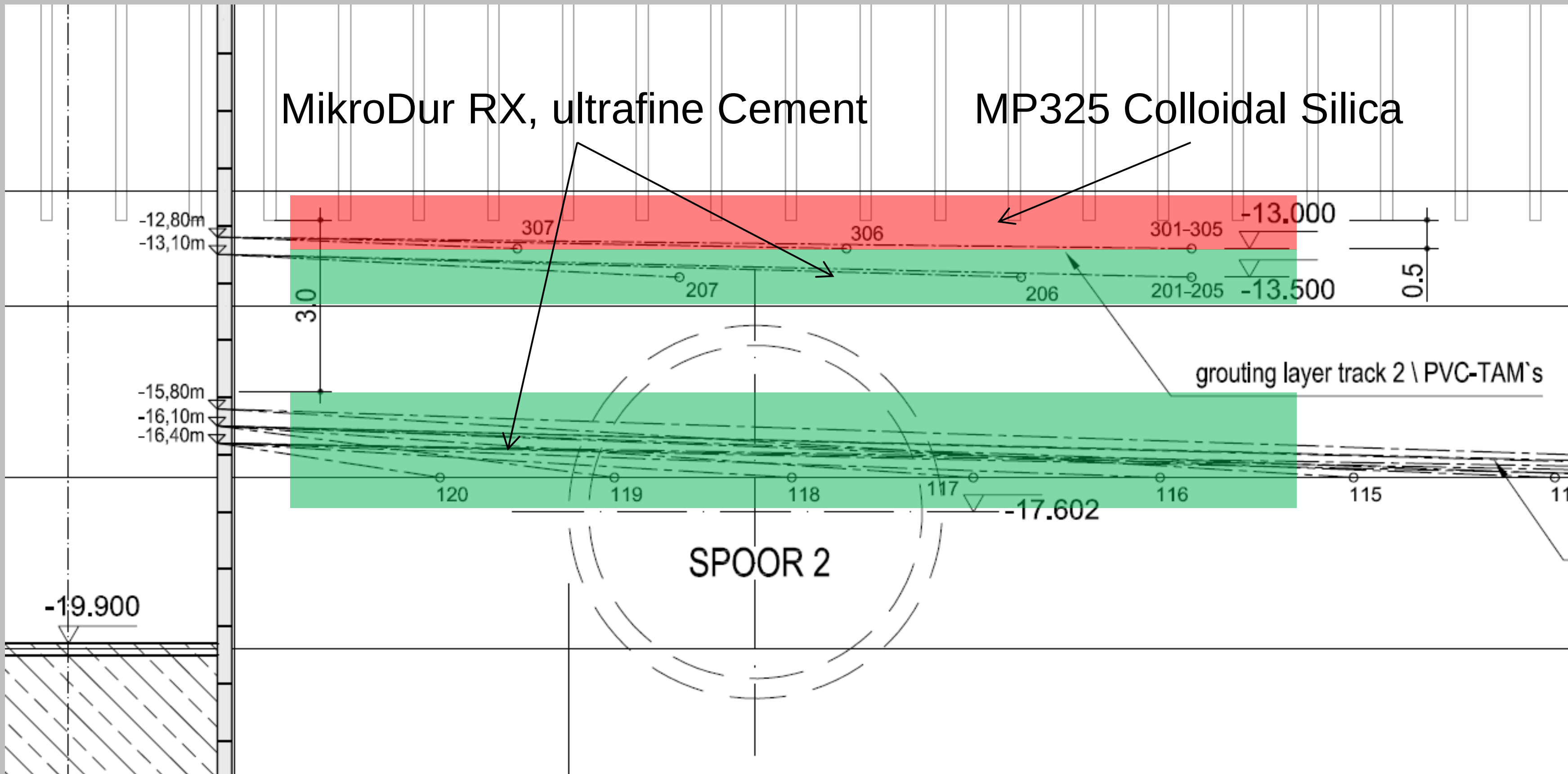
0.00E+00
-5.00E-03
-1.00E-02
-1.50E-02
-2.00E-02
-2.50E-02
-3.00E-02
-3.50E-02
-4.00E-02
-4.50E-02
0
5
10
15
20
25
30
35
zakking [m]
afstand [m]
boven
midden
onder



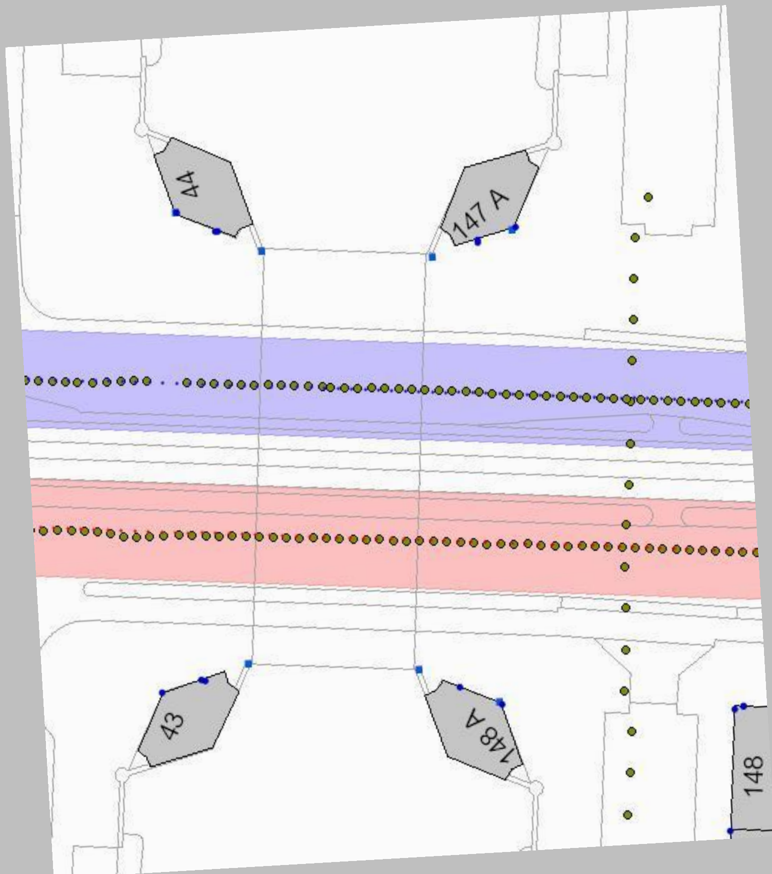
Tunnel - spoor 1
Tunnel - spoor 2
M9.09
M9.23
M9.08
M9.22
M9.07
M9.21
M9.06
M9.20
M9.05
M9.19
M9.04
M9.18
M9.03
M9.17
7
205
304
6
3
203
302
202
301
201
2
305
303
204
206
306
207
307
8
5
4
1
15104S
A
3.0
21.32°
area A= 188 m²
area A= 194 m²
Shaft
Brug 404

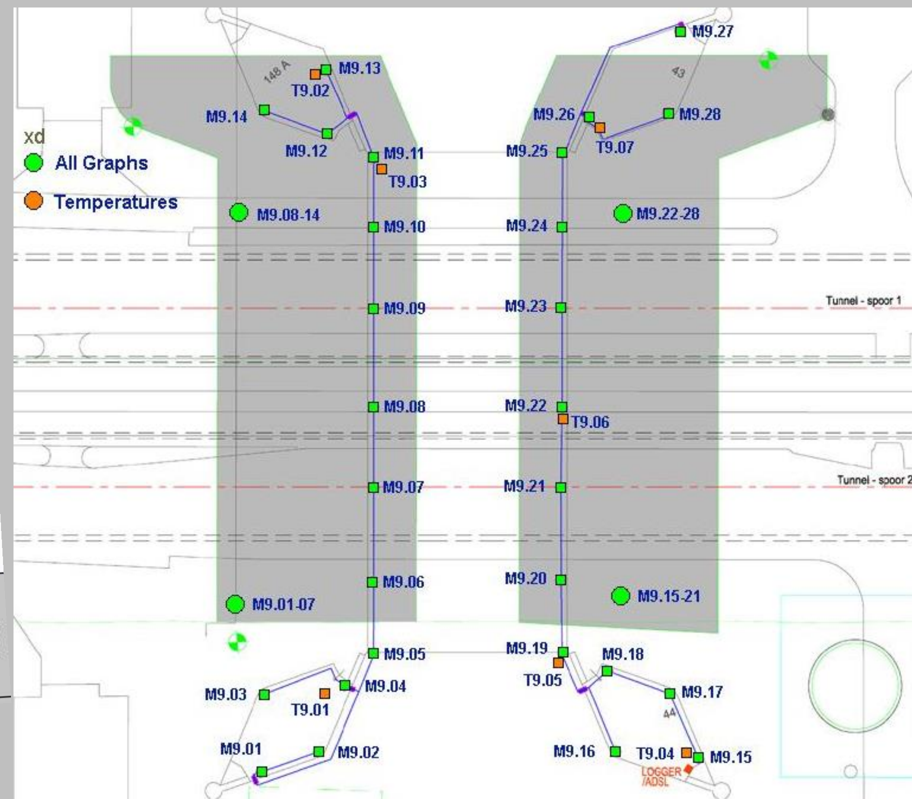
Brug 404 - Amsterdam

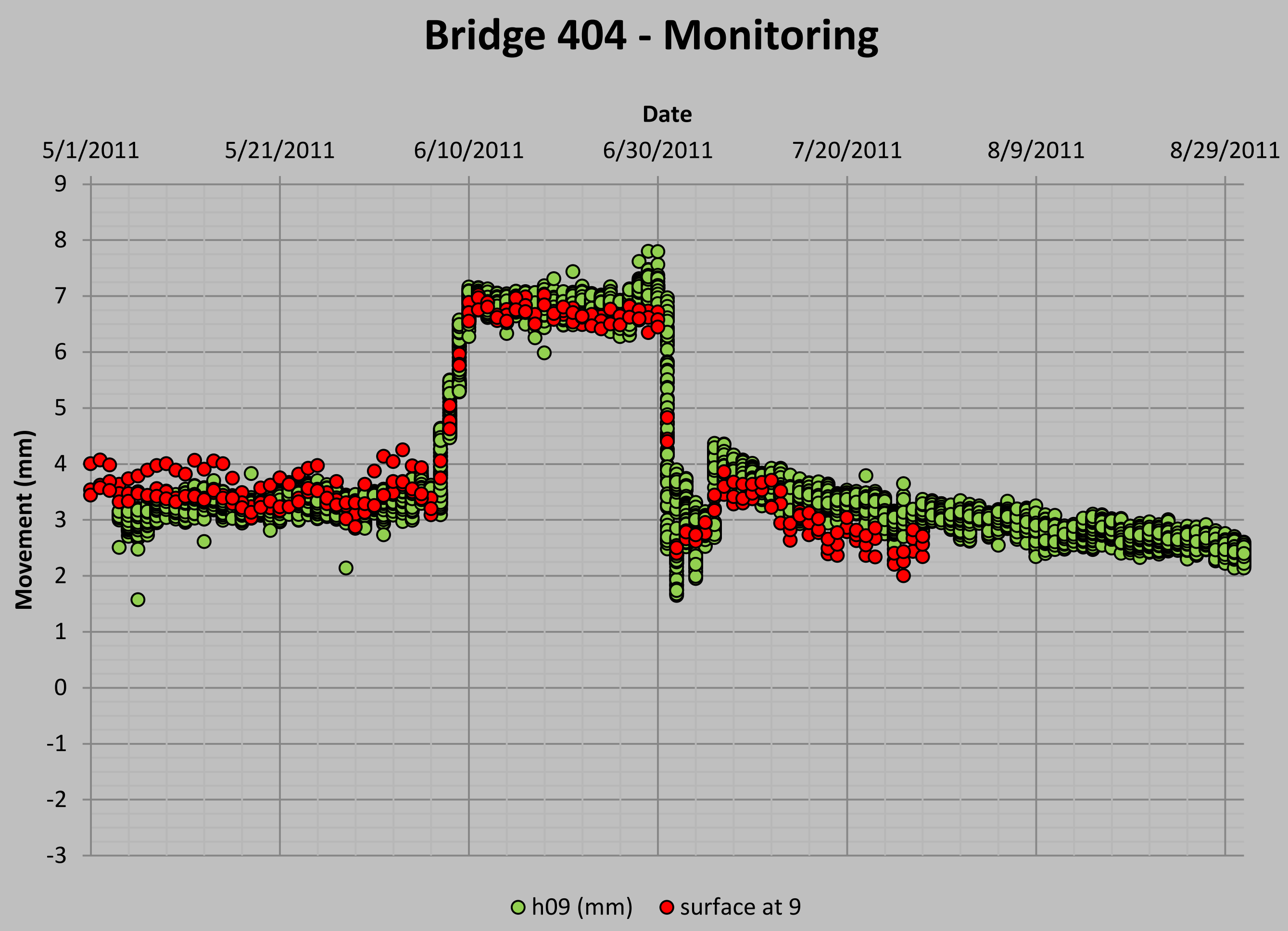




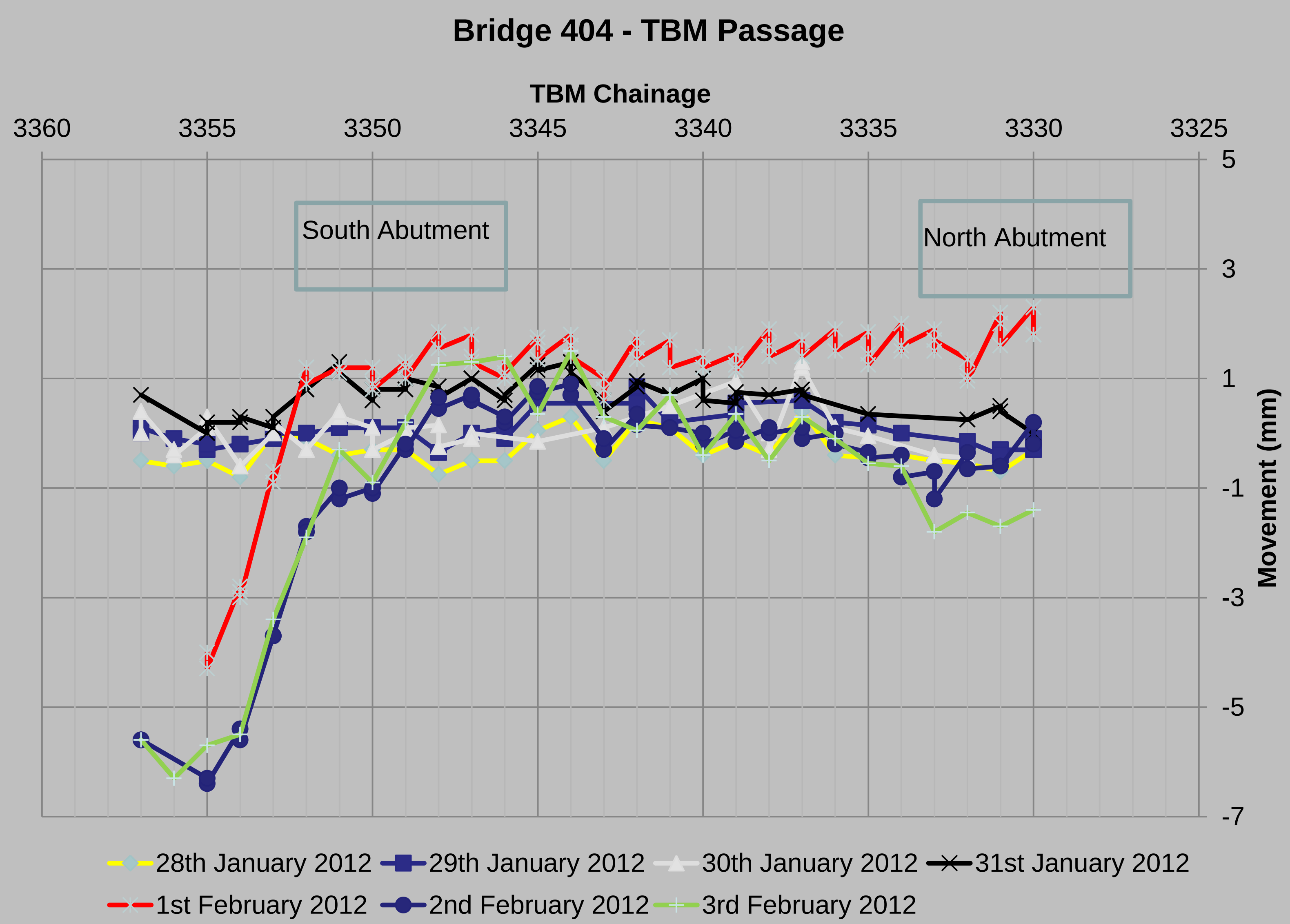
MikroDur RX, ultrafine Cement
MP325 Colloidal Silica
-12,80m
-13,10m
-15,80m
-16,10m
-16,40m
307
306
301-305
-13.000
207
206
201-205
-13.500
0.5
3.0
grouting layer track 2 \ PVC-TAM`s
120
119
118
117
116
115
114
-17.602
SPOOR 2
-19.900


44
147 A
43
148 A
148


xd
All Graphs
Temperatures
M9.27
M9.13
T9.02
148 A
43
M9.14
M9.12
M9.11
T9.03
M9.26
T9.07
M9.28
M9.25
M9.08-14
M9.10
M9.24
M9.22-28
M9.09
M9.23
Tunnel - spoor 1
M9.08
M9.22
T9.06
M9.07
M9.21
Tunnel - spoor 2
M9.06
M9.20
M9.01-07
M9.15-21
M9.05
M9.19
T9.05
M9.18
M9.03
T9.01
M9.04
M9.17
44
M9.01
M9.02
M9.16
T9.04
M9.15
LOGGER /ADSL



Bridge 404 - Monitoring
Date
5/1/2011
5/21/2011
6/10/2011
6/30/2011
7/20/2011
8/9/2011
8/29/2011
Movement (mm)
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
h09 (mm)
surface at 9



Bridge 404 - TBM Passage
TBM Chainage
3360
3355
3350
3345
3340
3335
3330
3325
5
3
1
-1
-3
-5
-7
Movement (mm)
South Abutment
North Abutment
28th January 2012
29th January 2012
30th January 2012
31st January 2012
1st February 2012
2nd February 2012
3rd February 2012

IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Compensation grouting - numerical modelling simulations

T. O'Brien, Mott Mc Donald, United Kingdom

Compensation Grouting - Numerical Modelling Simulations

(too may factors to consider?)

Professor Tony O'Brien,

Geotechnics Practice Leader, Mott MacDonald

Visiting Professor, Southampton University

Mott MacDonald

Numerical Modelling - key questions

Specific issues

- Type of grouting
  - grout jacking
  - "true" compensation grouting
- Soil behaviour
  - hysteresis
  - non-linearity
- Geometry
  - 2D or 3D?

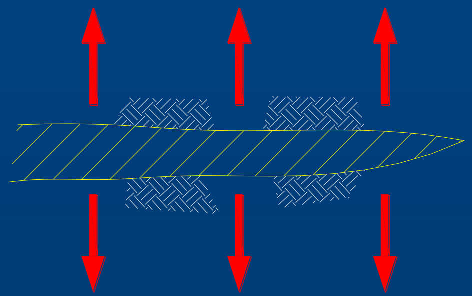
Generic issues

Issues	Comments
1. Key objective of numerical modelling; e.g. vertical or horizontal movements, structural forces/stresses?	Numerical model can produce plethora of different outputs. Intrinsic limitations of most constitutive models mean that different outputs, will be of variable reliability.
2. What relevant case histories are available, for calibration of model?	The use of uncalibrated models is poor practice, and can provide highly misleading results.
3. Is the ground investigation adequate for providing appropriate parameters?	There is no value in carrying out sophisticated modelling in the absence of good quality ground investigation. Specific testing may be needed to provide appropriate input parameters.
4. How will key input parameters be checked, e.g. strength, compressibility, (more important as stress-strain model becomes more complex)	Important to run computer simulations of “element” behaviour under relevant drainage conditions and stress paths, e.g. undrained or drained strength in triaxial compression or extension, compression/swelling of oedometer; and compare against laboratory data.
5. Will groundwater flow/seepage influence behaviour (“undrained” analyses may be unrealistic)	Below water table, in permeable horizons, local drainage/consolidation may have a marked effect on behaviour, necessitating coupled analyses.
6. Construction sequence, miscellaneous effects	Construction sequence can significantly influence many ground-structure interaction problems, hence realistic sequences need to be developed. Construction effects, such as vibration, may be important in cohesionless soils.

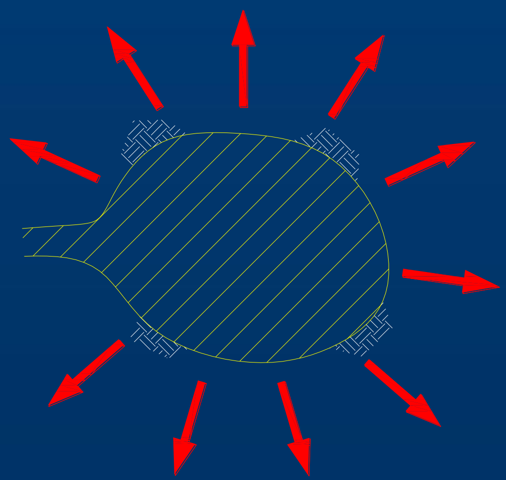
Compensation Grouting and Numerical Modelling - grouting mechanism

Fracture grouting or cavity expansion

- Fracture pressure ⇒ Grout injected via Hydrofracture

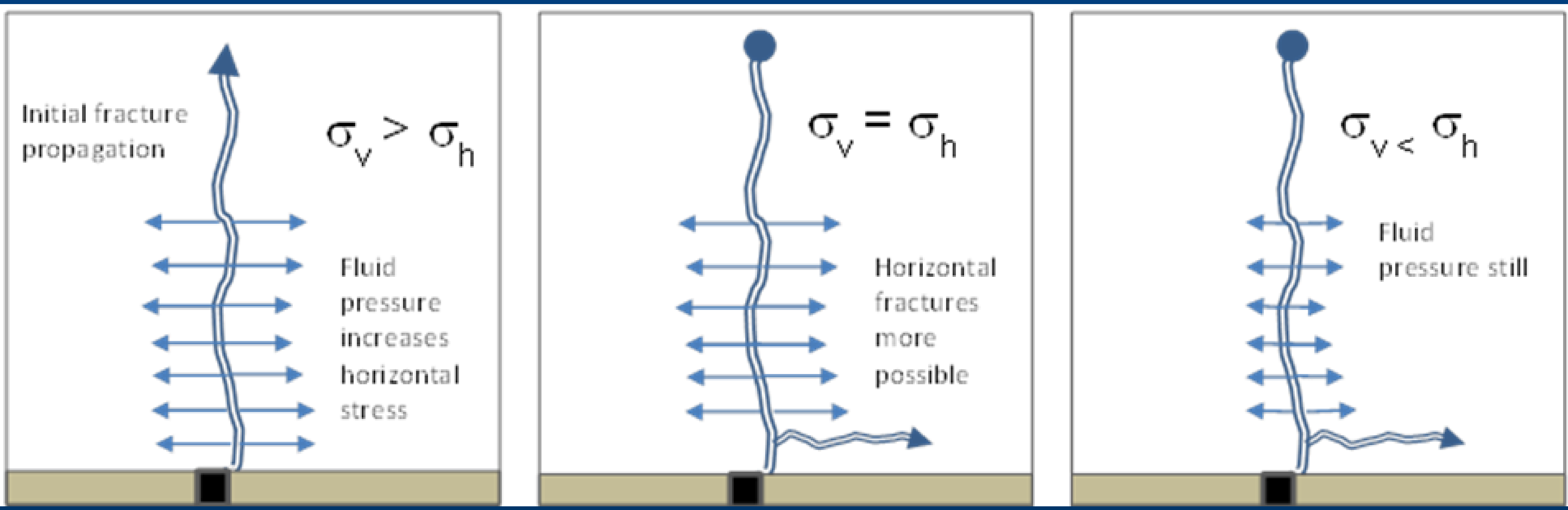


- Cavity expansion pressure ⇒ Grout injected via Plastic shearing of ground around a grout bulb



Simulation of grout injection
Hydrofracture - Fracture propagation

Function of principal stresses

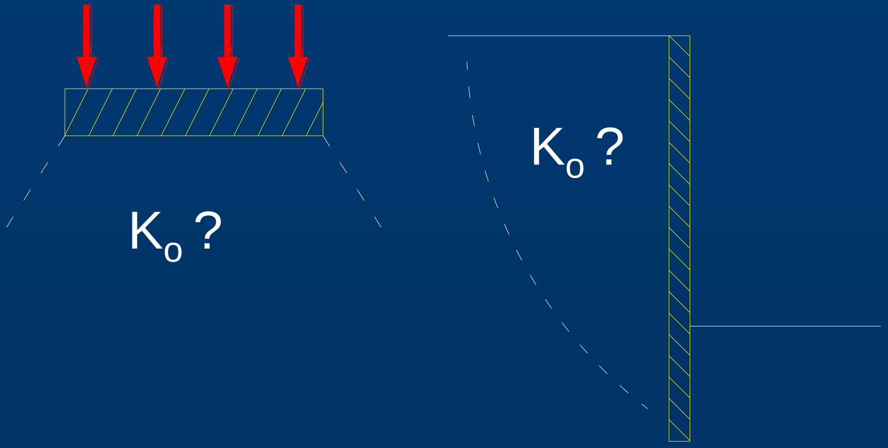


- Influence of K_o is critical

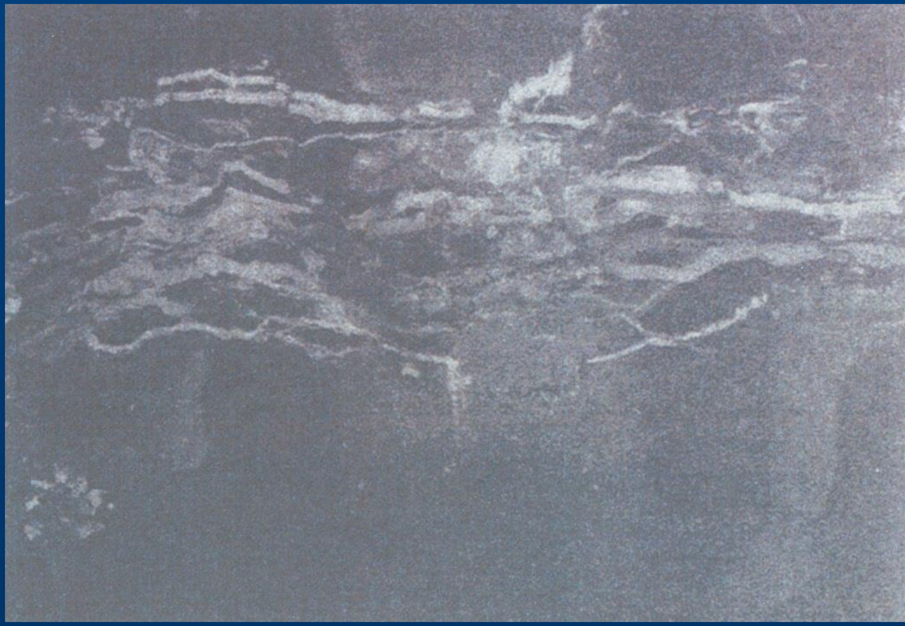
Simulation of grout injection Hydrofracture

- Adjacent to existing building foundations and basements -

  complex variations in K_o principal stress rotations



- Hence, fracture propagation - will be complex



Numerical modelling ⇒ Grout injection - highly idealised + simplified

Fracture grouting vs. Cavity expansion

Grouting induced stress changes

fn. of overburden stress; stress history; shear strength of ground

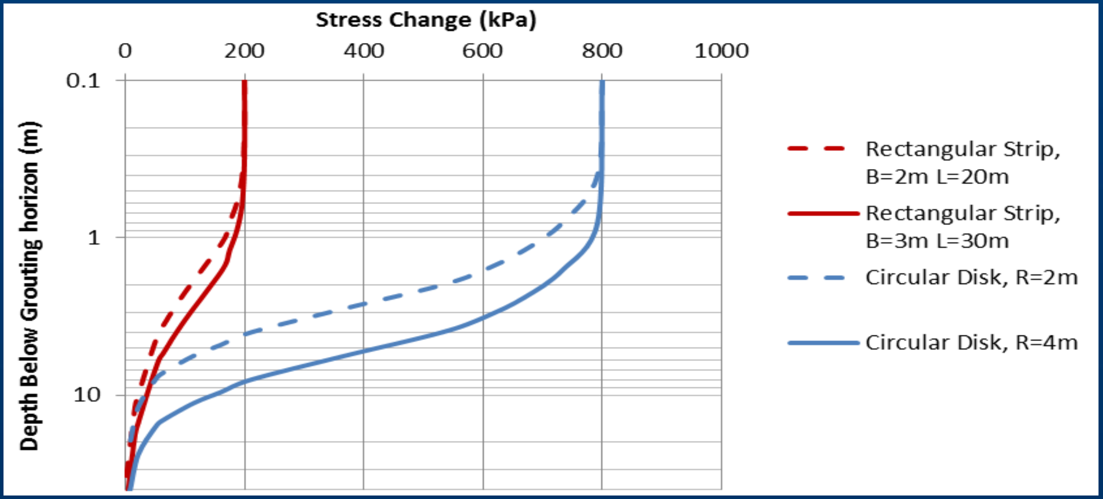
- Fracture grouting (compensation grouting)
  - fluid grout
  - concurrent with tunnelling ⇒ relatively low induced stresses in the ground
- Cavity expansion (grout jacking)
  - thick viscous grout pastes
  - post tunnelling ⇒ relatively high induced stresses in the ground
- Simulation of concurrent grouting is difficult in 2D models (dummy "soft" tunnel invert)

Fracture grouting vs. Cavity expansion

Example:

10m to 15m depth, O/C clay urban area (udl ~50 to100kN/m^2)

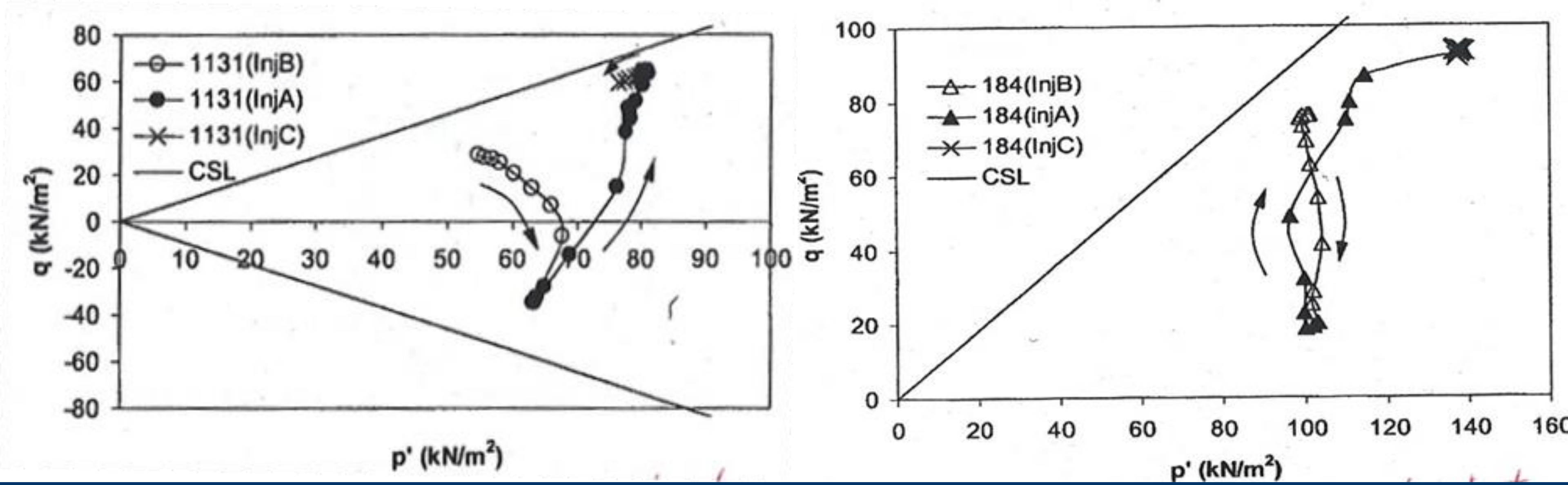
- Fracture grouting - $\Delta\sigma$ ~ 350 to 600kN/m^2 (ie. 150 to 250 kN/m^2 above overburden)
- Cavity expansion - $\Delta\sigma$ ~ 1000 to 3000kN/m^2 (ie. 800 to 2600 kN/m^2 above overburden)



- if model assumes a wide 2D "sheet" of grout, then $\Delta\sigma$ ~ overburden stress. Hence, UNDERESTIMATE grout induced stress changes

Soil behaviour - Hysteresis

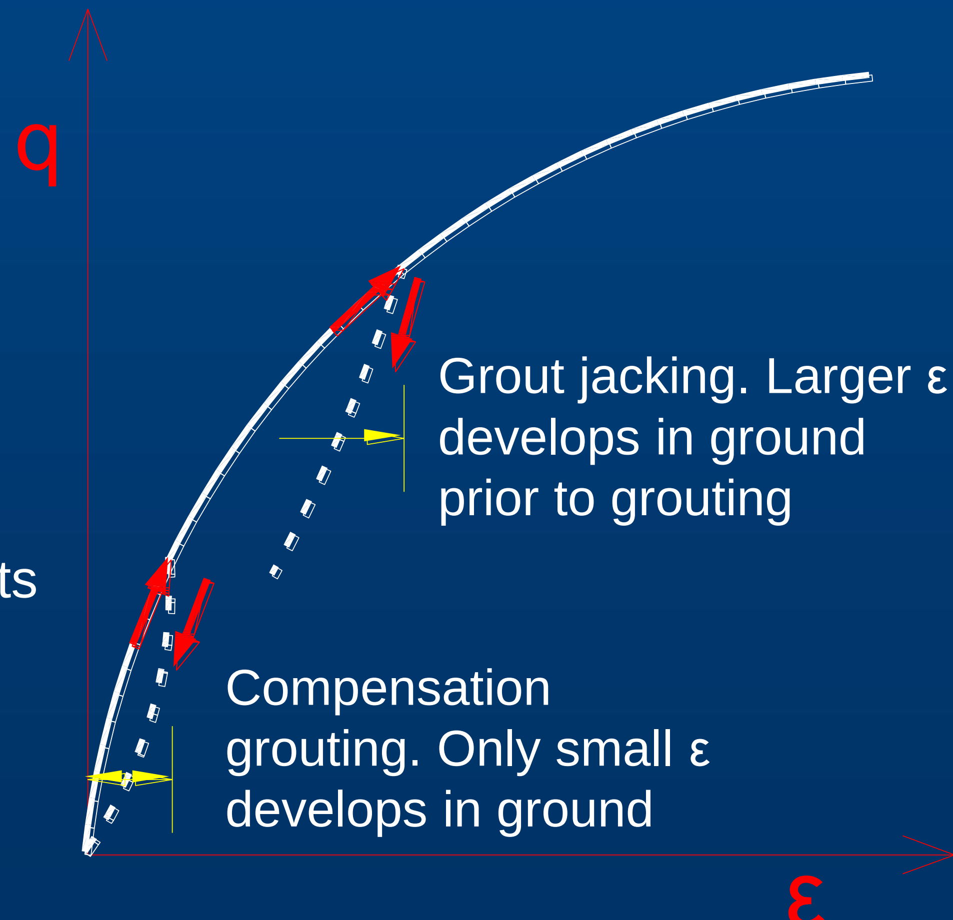
- Physical models and numerical models (Au et al, 2003; Lee et al, 2002)



⇒ Soil elements between grouting and tunnel experience complex changes in stress path direction

Soil behaviour - (1) Non-linear stress strain behaviour

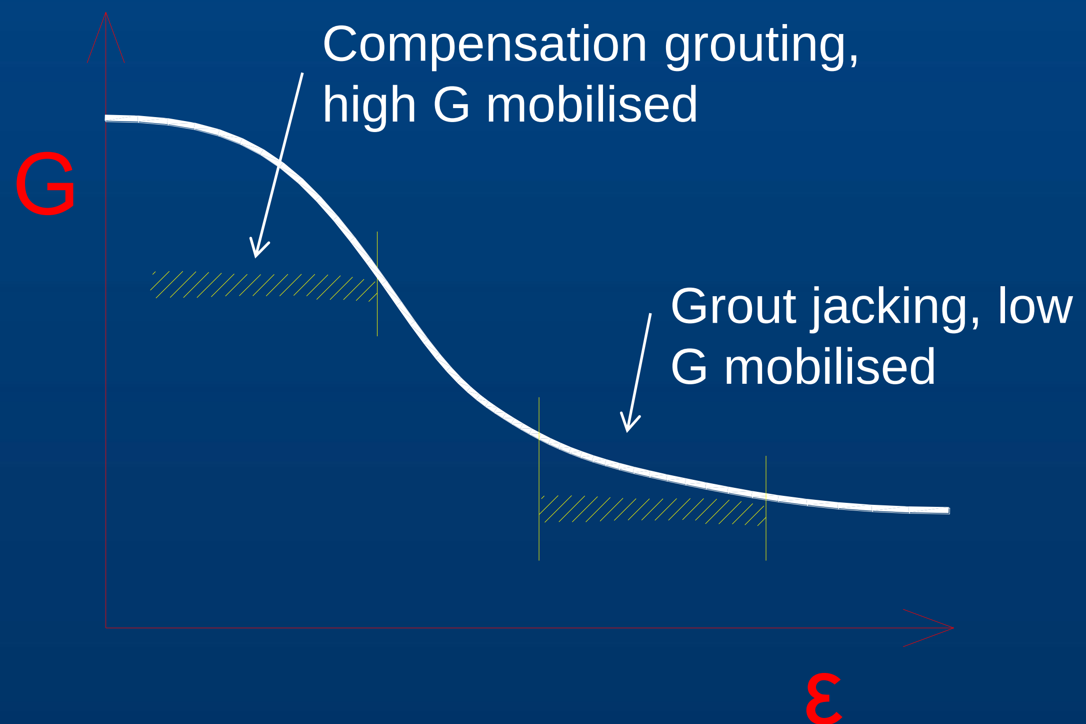
Well known that soil behaviour ⇒ very non-linear. Small strain G ~ 10 x large strain G



Soil behaviour - (2) Non-linear stress strain behaviour

Stress in tunnel lining is sensitive to G mobilised in ground adjacent to lining

Due to (1) + (2), many soil models in commercial modelling software are inadequate!!



2D vs. 3D

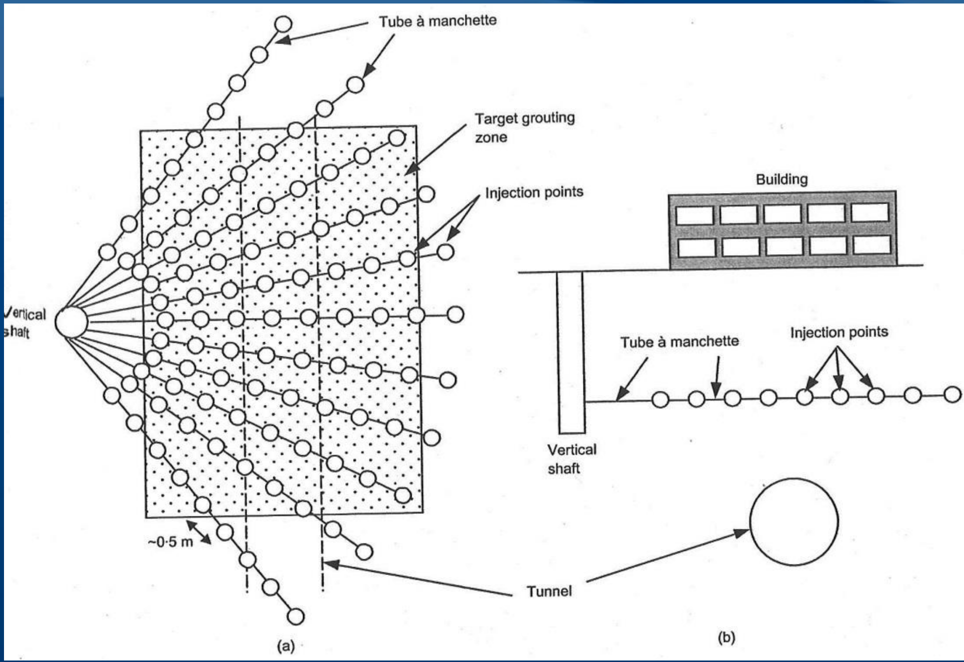
Both

Tunnelling process

and

Compensation grouting

are 3D



- Numerical modelling usually 2D
  - cheaper and quicker
  - simpler to understand output
  - is 2D ok?

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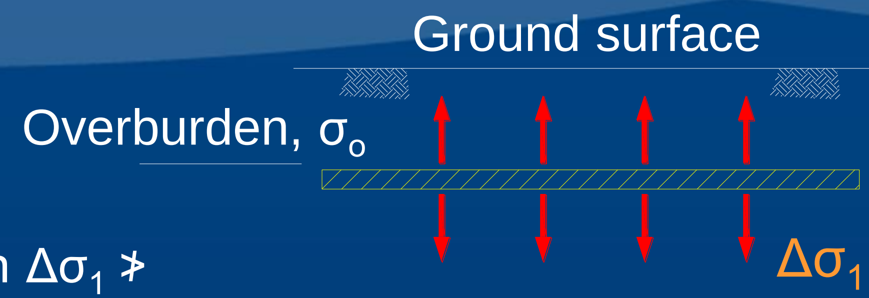
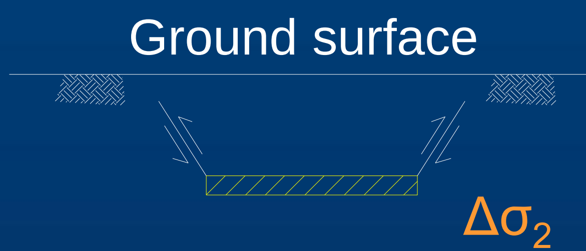
Is 2D ok? - Consider maximum grouting pressure, $\Delta\sigma$, in model

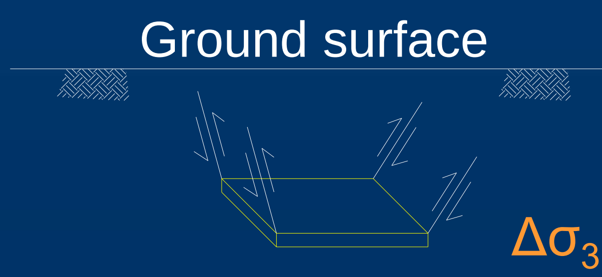
- $\Delta\sigma_1$ - 2D wide sheet
  - if modelled as a wide sheet then $\Delta\sigma_1 \ngtr$ overburden, due to vertical equilibrium



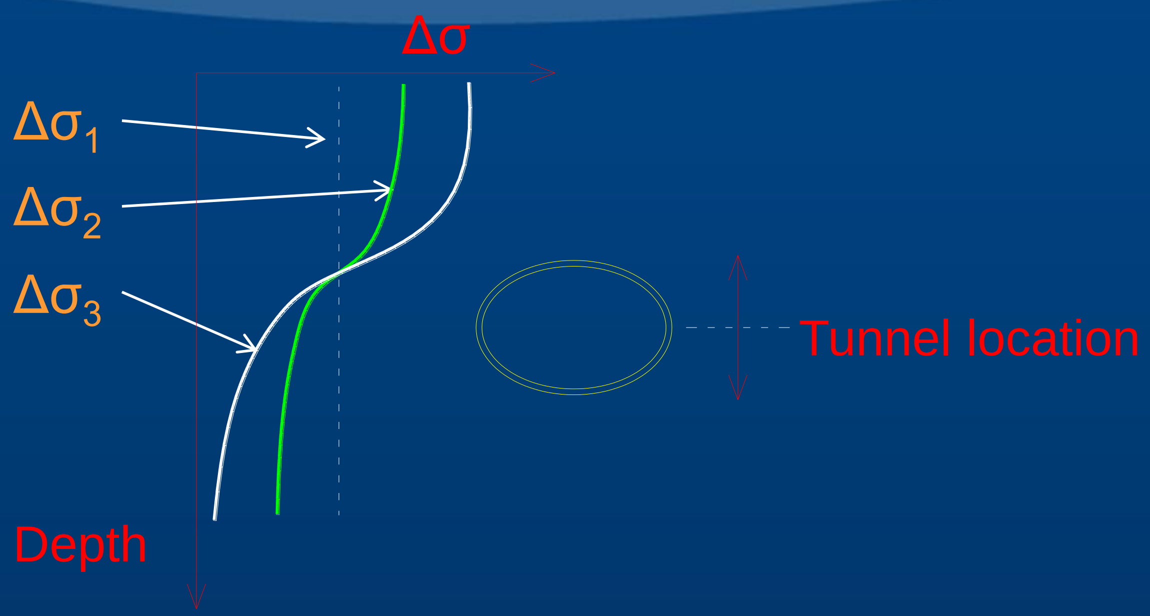
- $\Delta\sigma_2$ - 2D narrow sheet
  - if modelled as a series of narrow sheets then $\Delta\sigma_2$ > overburden, but $\Delta\sigma$ still limited



- $\Delta\sigma_3$ - 3D narrow 'footing'
  - if modelled in 3D, then $\Delta\sigma_3$ >> overburden $\Delta\sigma_3 > \Delta\sigma_2 > \Delta\sigma_1$



Is 2D ok?



- if grouting close to tunnel - 2D models likely to underestimate Δσ close to tunnel lining
- if grouting remote from tunnel - 2D models likely to overestimate Δσ close to the tunnel lining

Recent numerical modelling studies

Influence of

- Grout zone geometry
- Soil behaviour
- 2D vs. 3D
- Grout jacking (post-tunnelling) vs. Compensation grouting (concurrent with tunnelling)

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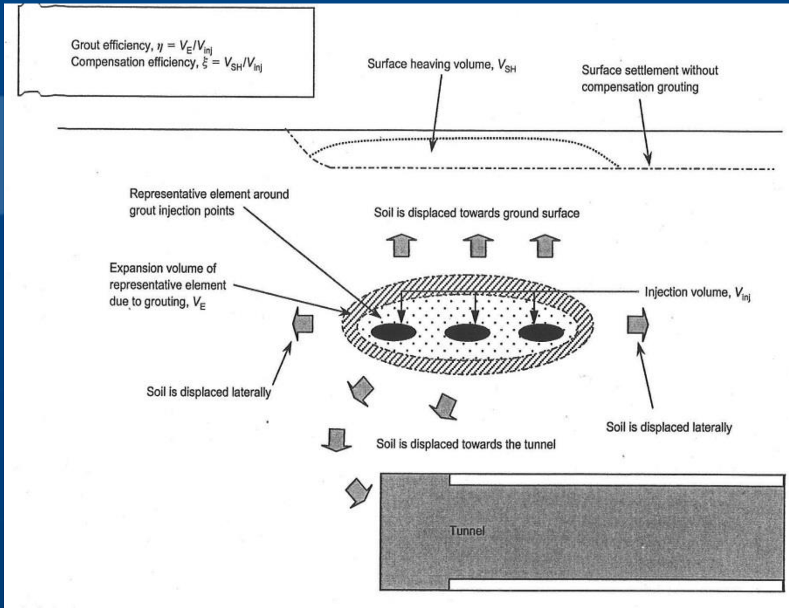
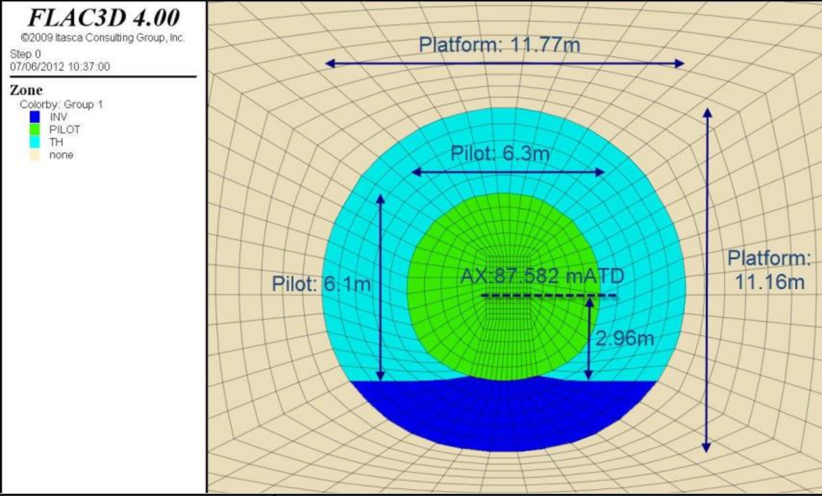
Objectives of numerical modelling

1) Surface settlement?
2) Sub-surface ground movements?
3) Damage to surface buildings?
4) Tunnel face stability?
5) Tunnel lining stresses? → Focus for the modelling discussed here

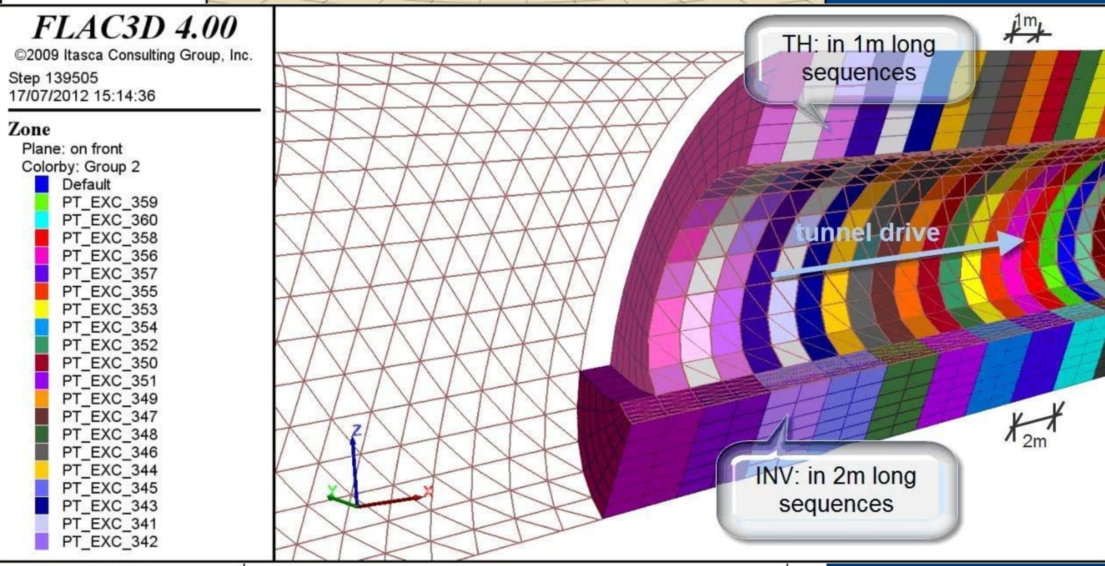


Each of the above would need ⇒ different modelling requirements

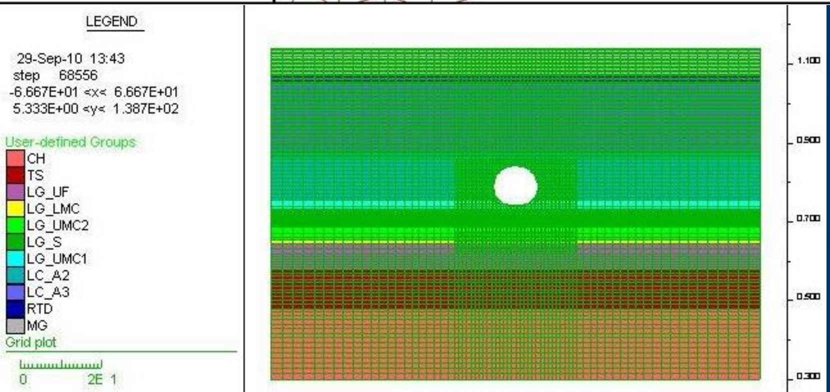
- Mesh geometry
- Construction sequences
- modelling of structure
- Soil behaviour
- Grouting simulation



Mesh geometry



- Large model required
- Boundaries
  - 10D - transverse
  - 5D - base
- V fine mesh needed close to tunnel lining

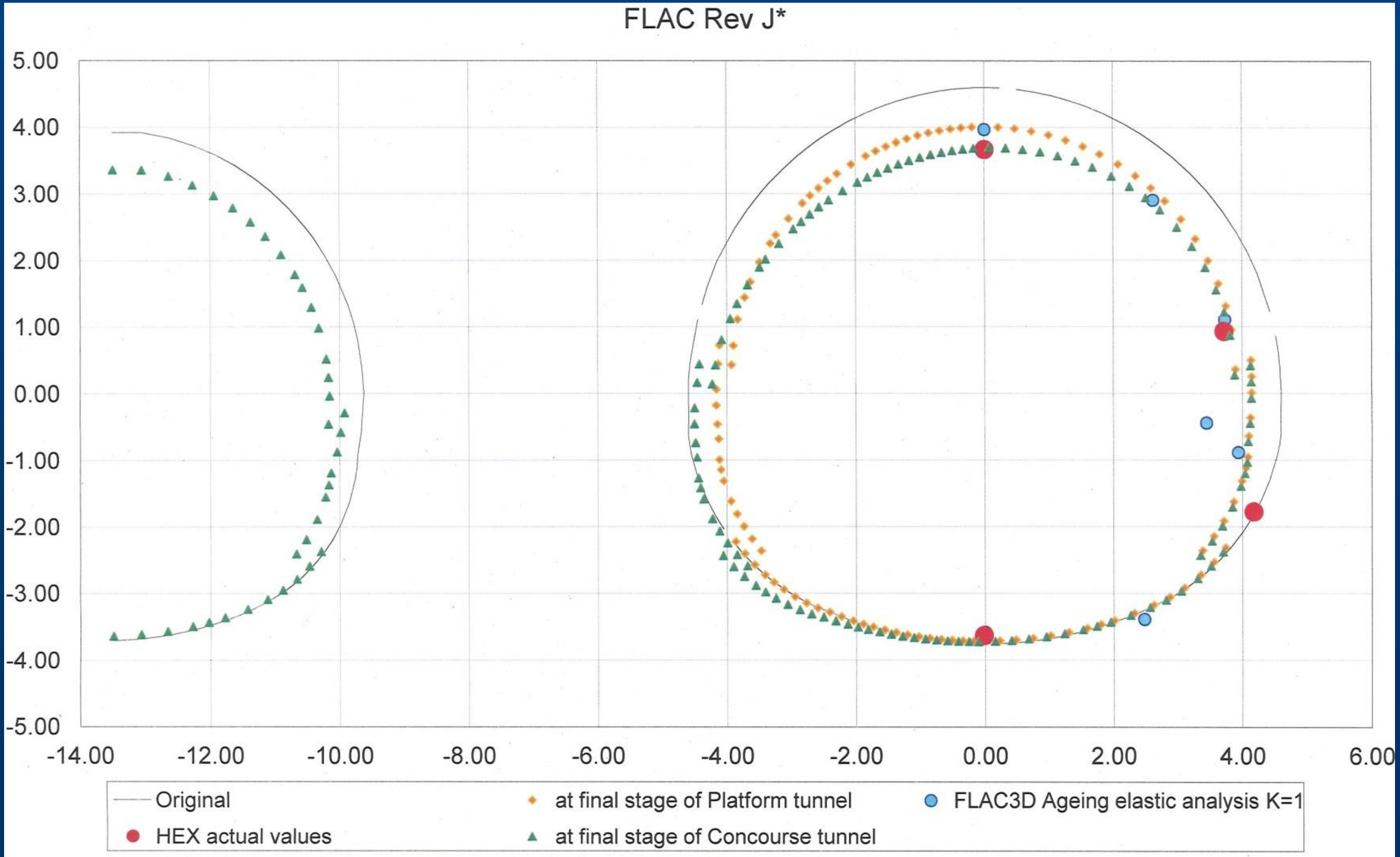


Input parameters and calibration

- Soil behaviour
  - (a) Non-linear stiffness, A*
  - (b) Non-linear stiffness, with hysteresis, A* H
- Shotcrete
  - non-linear time dependent gain in strength/stiffness - CRITICAL!
- Calibration
  - observed deflection/stresses, Heathrow Express Tunnel

Input parameters and calibration - Lining distortion

- Concourse tunnel built after platform tunnel



Input parameters and calibration - Lining stresses and volume loss

Model	Platform tunnel			Concourse Tunnel		
A*	M_{max} 43 to 65	N_{max} 887 to 967	V_L (%) 0.59	M_{max} 42 to 45	N_{max} 599 to 851	V_L (%) 0.71
A*H	41 to 59	864 to 1007	0.64	29 to 34	589 to 898	0.70
Observed	20 to 30	1100 to 1400	0.85	-	-	0.60

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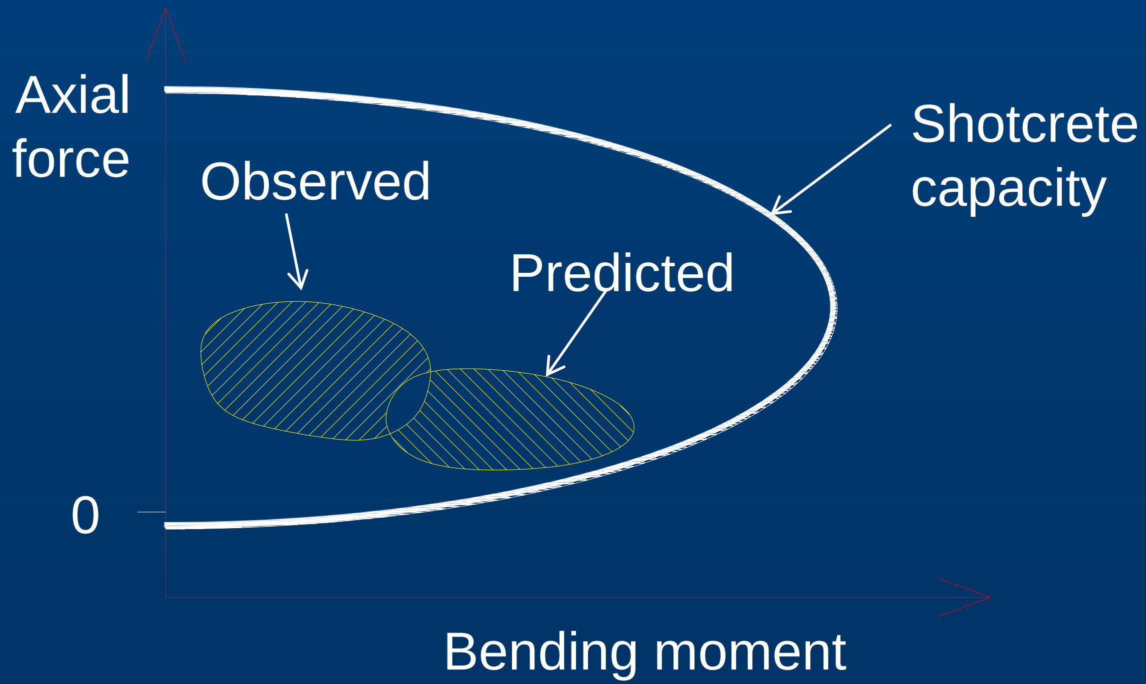
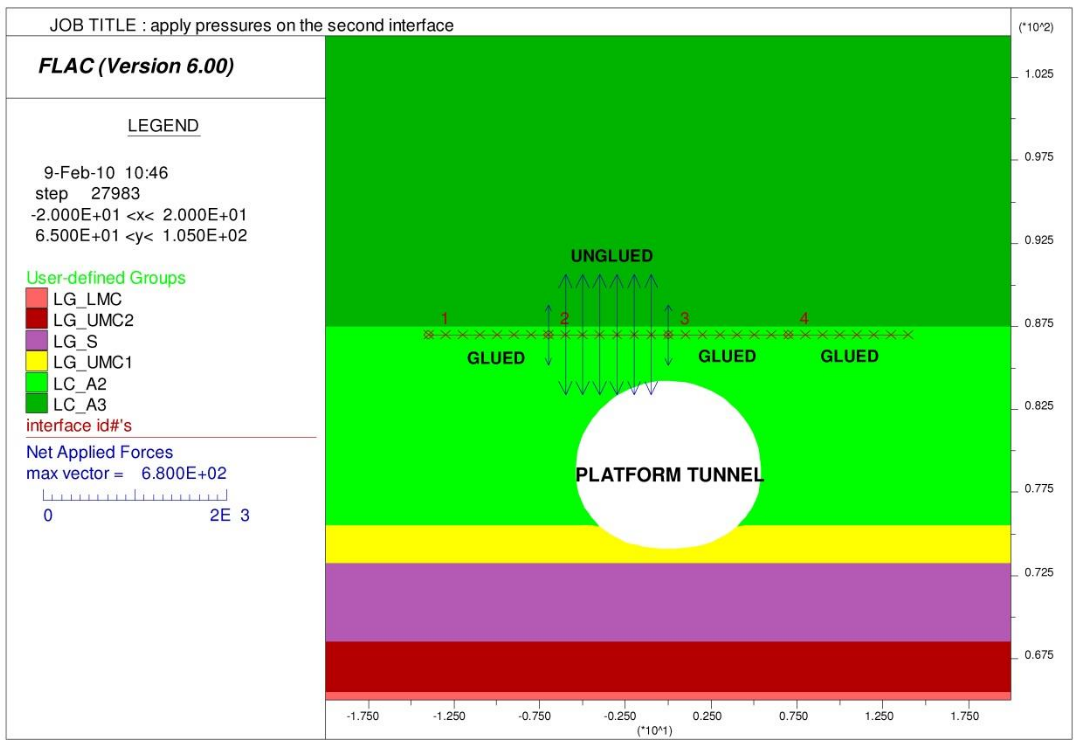
Input parameters and calibration - Interaction curve

- Due to location of stresses on interaction curves underprediction of axial force is conservative in this case

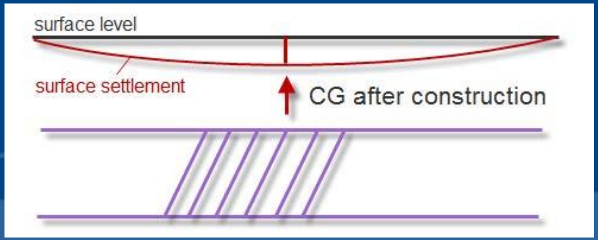


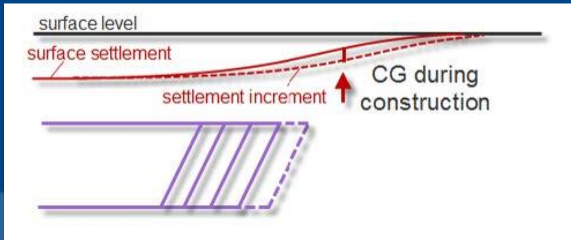
Grout simulations

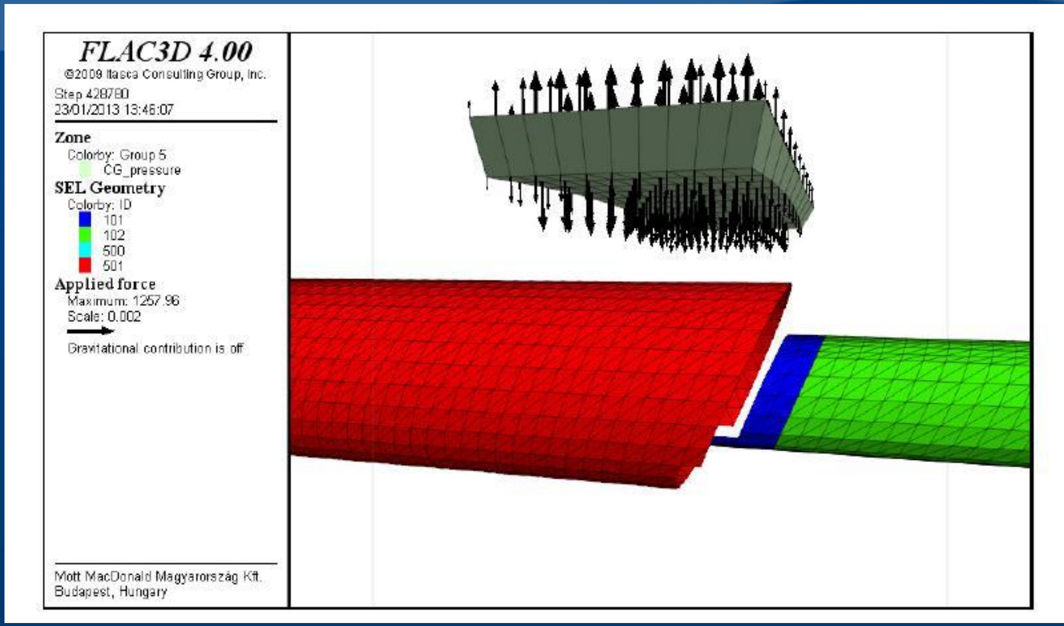


- Effect of geometry
  - Patches vs. Wide strip
- Effect of timing/sequence
  - concurrent with tunnelling
  - after tunnelling
- Grout planes
  - interface elements at appropriate levels in mesh
  - grout injection, apply as equal + opposite internal pressure to sides of interface
  - grout pressure increased to approximately nullify surface settlement
  - once equilibrium achieved, interface "re-glued"

Grout simulations







- Effect of geometry
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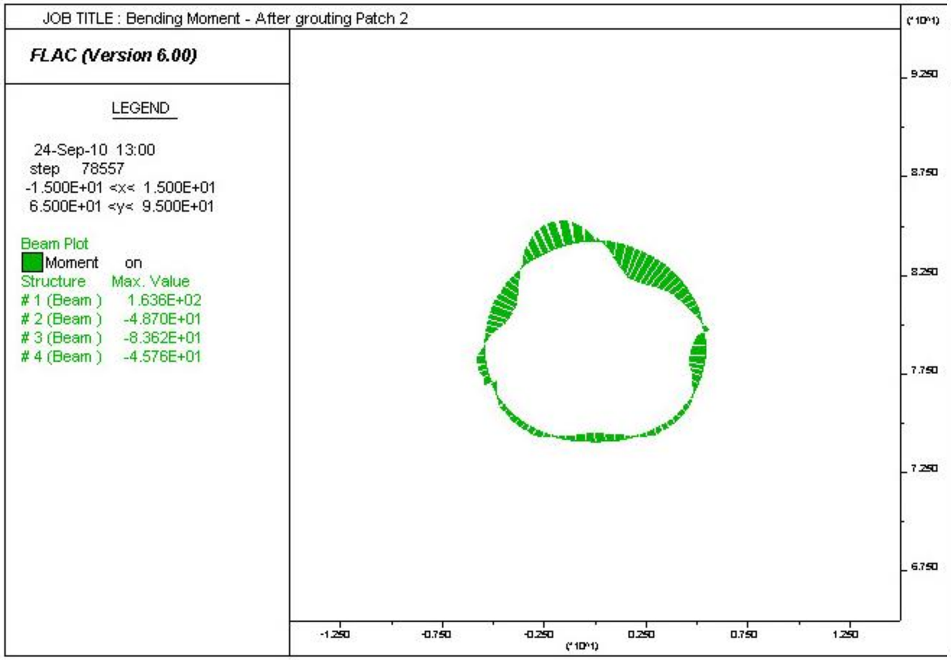
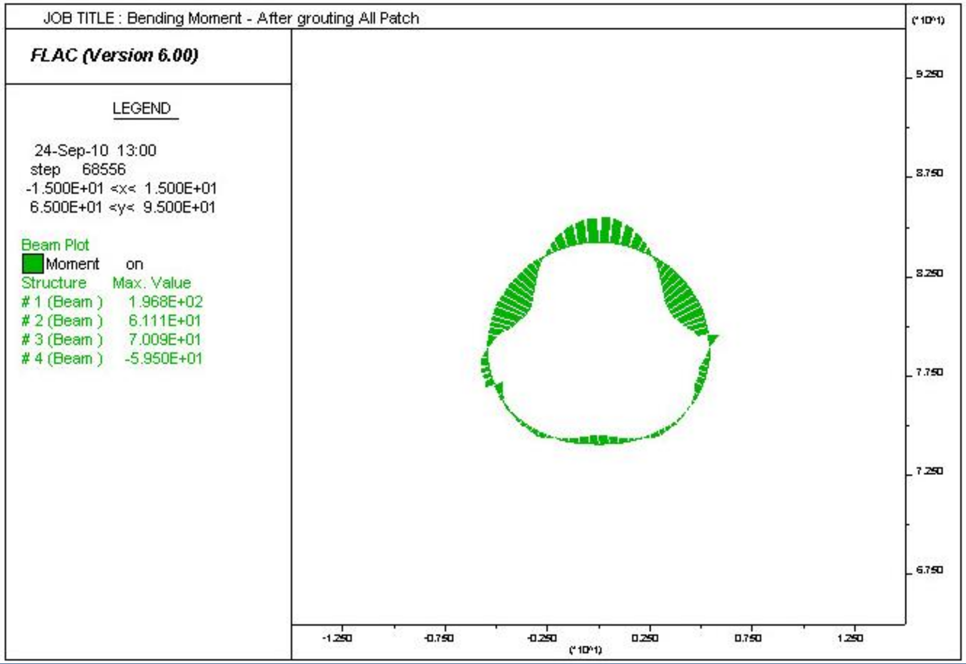
Results from 2D models

- Lining stress increments
  - vary significantly around tunnel lining

Local patch



Wide strip

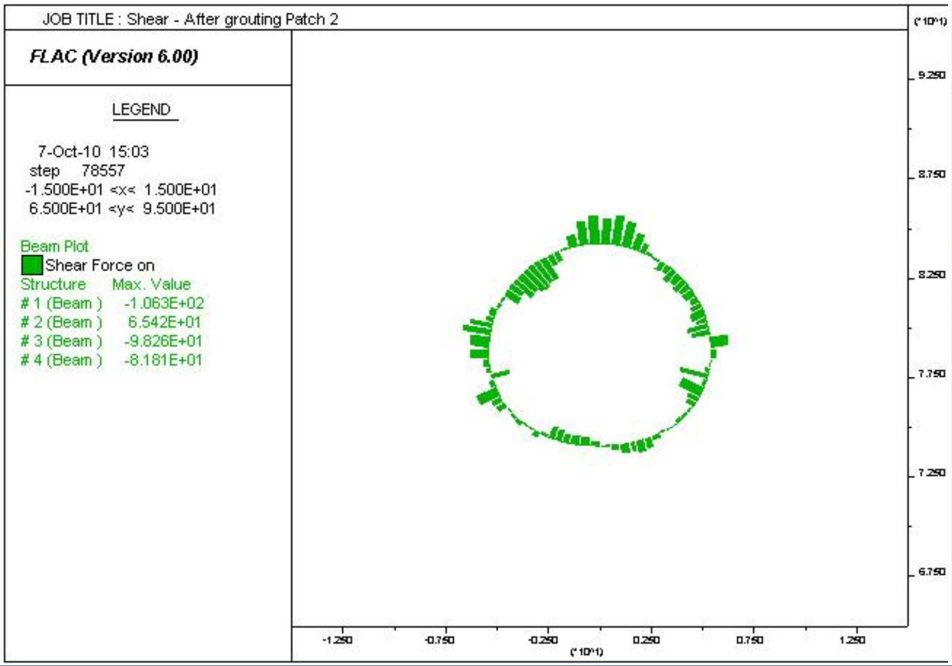


Bending moment

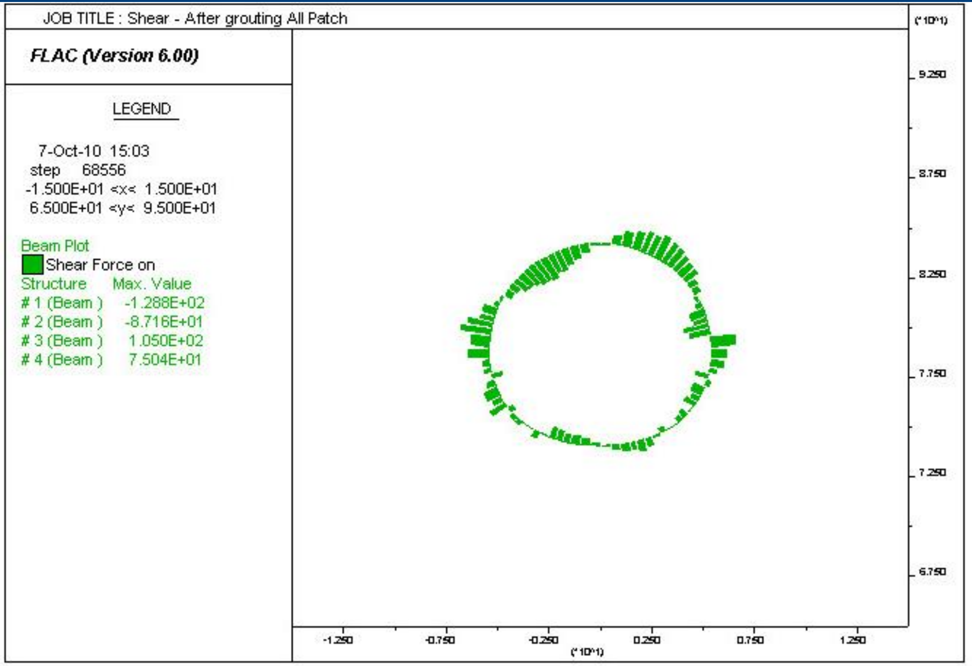
Results from 2D models

- Lining stress increments
  - vary significantly around tunnel lining

Local patch



Wide strip

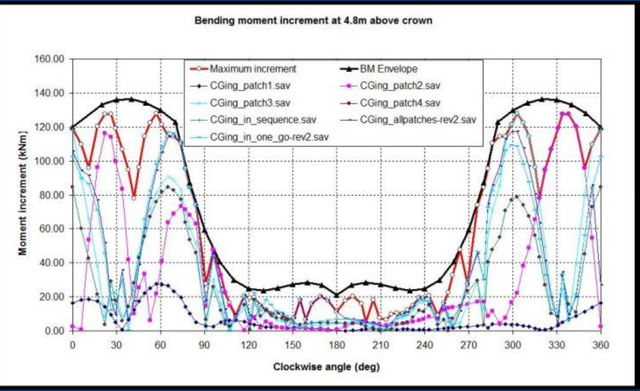


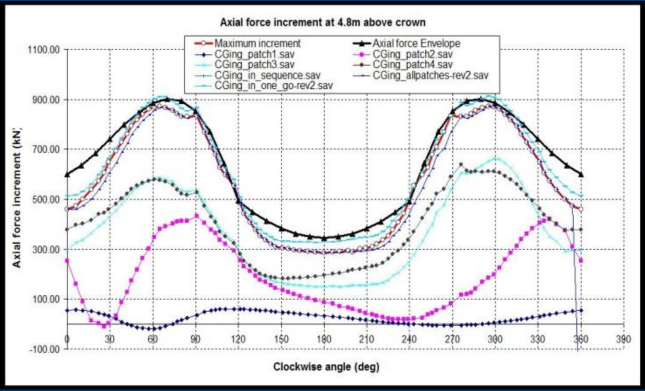
Shear Force

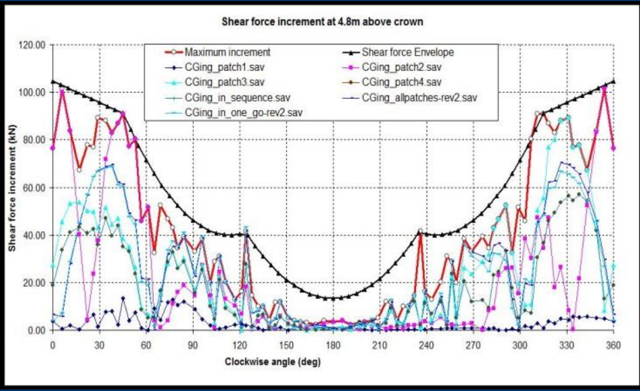
Local patches v. Wide strip

- Local patch
  - higher BM + SF
  - lower AF
  - more onerous structural loads

Geometry	ΔBM (%)	ΔSF (%)	ΔAF (%)
Wide	17	2	22
Local	32	20	23



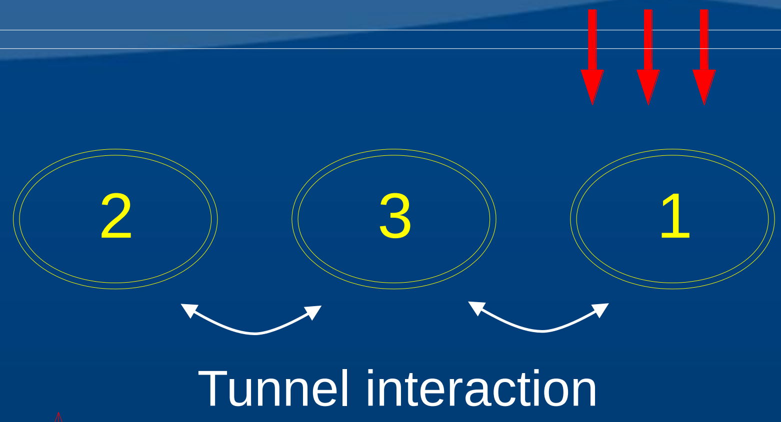


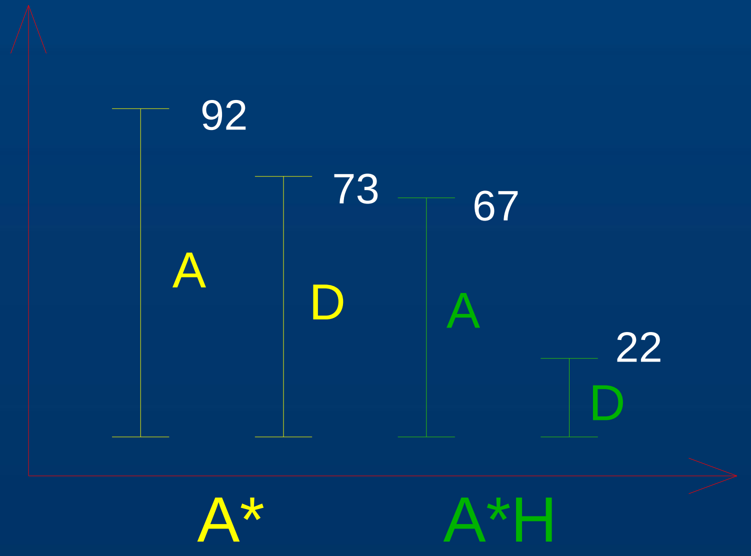


NB.
- wide variation in lining stresses around lining
- location of maximum BM ≠ location of max AF

Multiple tunnel interaction and soil hysteresis

Timing	Tunnel	Hysteresis	ΔBM (%)
After	1	No	108
	3	No	92
During	1	No	106
	3	No	73
After	1	Yes	88
	3	Yes	67
During	1	Yes	73
	3	Yes	22





Soil hysteresis

- significant influence
- lower BM (+SF)
- most significant if several tunnels in close proximity

3D Models

- Effect of geometry
  - Patches vs. Wide strip
- Effect of timing/sequence
  - concurrent with tunnelling
  - after tunnelling
- Grout planes
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  - grout injection, apply as equal + opposite internal pressure to sides of interface
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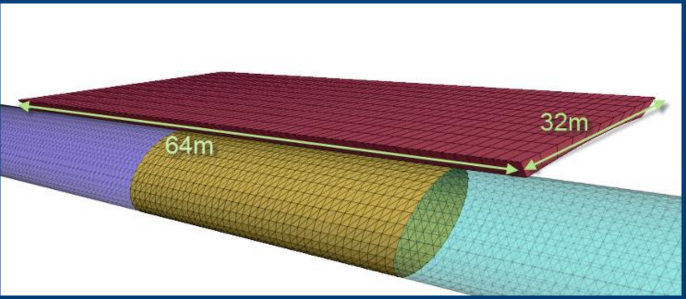
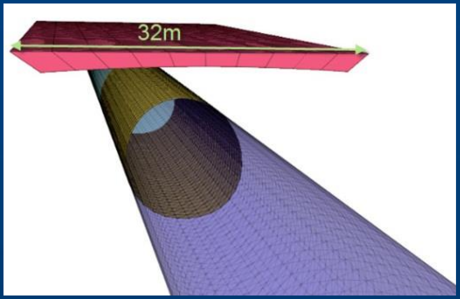
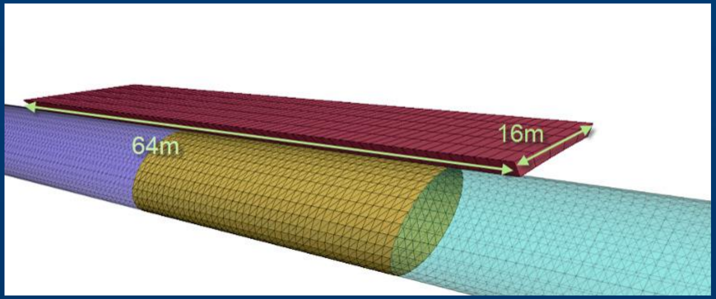
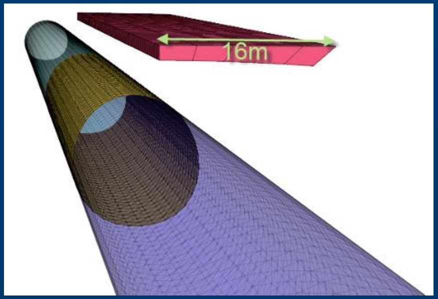
3D Models

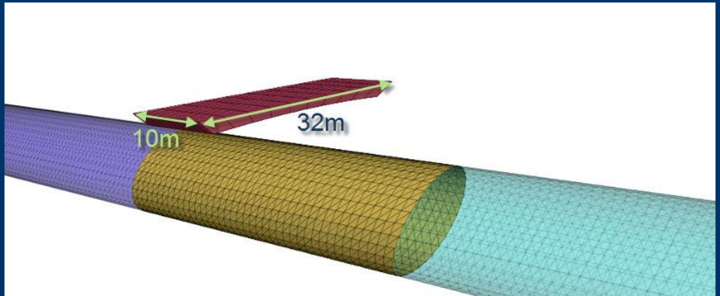
- Patches vs. Wide strip
  - Effect of geometry

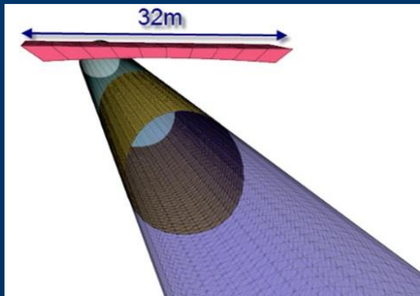










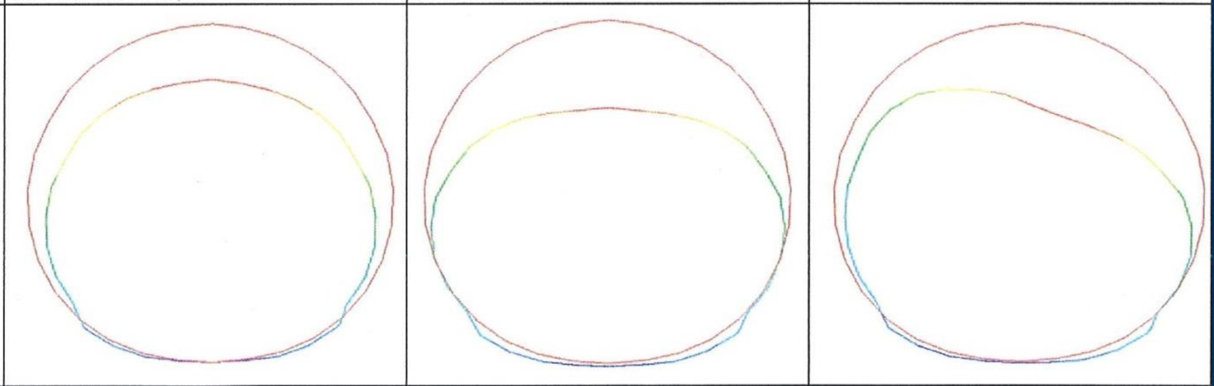


3D Models - influence of geometry and grout timing

Geometry	Timing	ΔBM (%)	ΔSF (%)	ΔAF (%)
Wide	After	135	83	68
Local, Shoulder	After	156	174	53
Wide	During	37	89	65
Local, Shoulder	During	24	116	43
Local, transverse	After	53	100	33
Local, transverse	During	17	67	54

Stiffness degradation during tunnel construction a major issue. Hence, grout jacking far more onerous than compensation grouting.

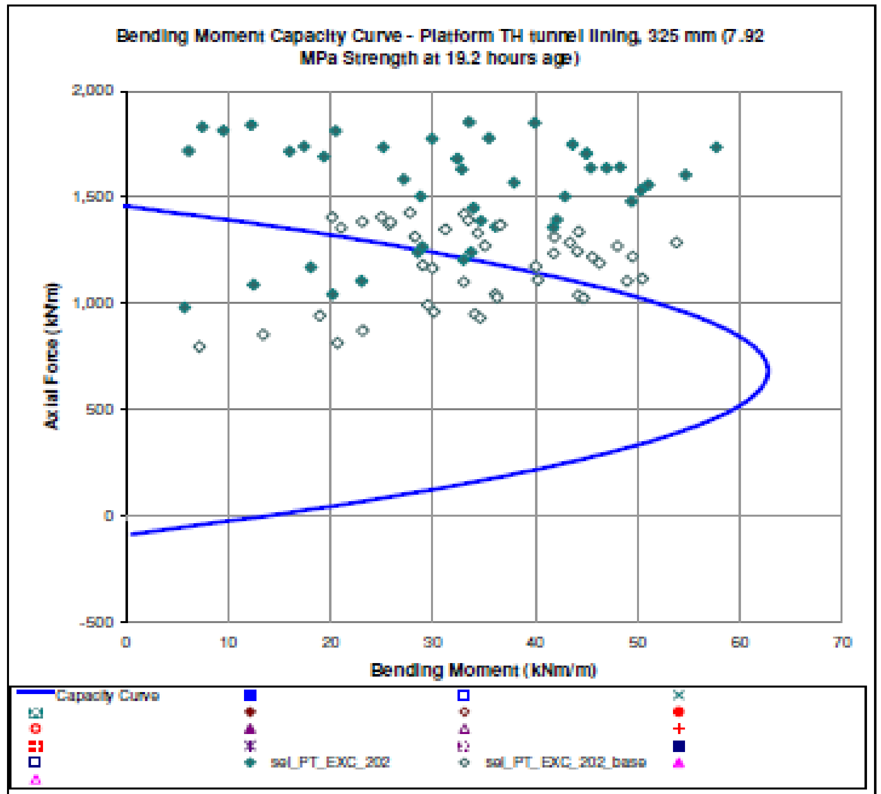
Case histories support these findings.

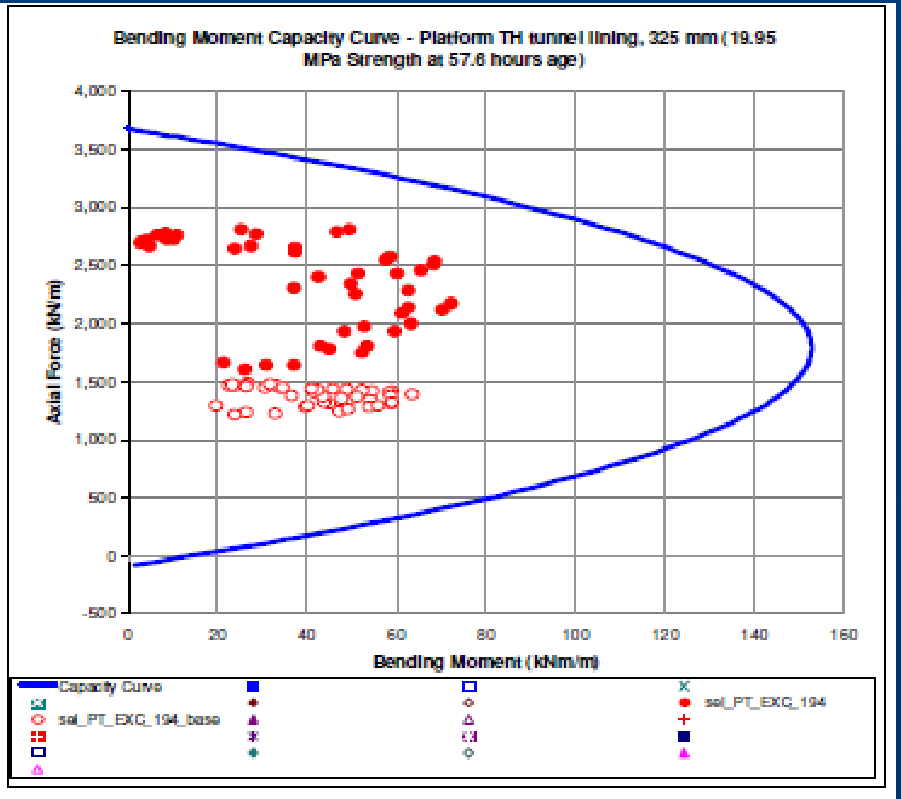
Model	A (no CG)	C03 (full panel CG)	C07 (shoulder panel CG)
Max. displ.	21mm	31mm	28mm
Deformed cross-section			

Influence of shotcrete age

For one scenario

- < 24hrs shotcrete overstressed
- > 48hrs shotcrete stresses OK





Conclusions

- Many factors to consider!
- Parametric studies are essential to assess plausible range of loads
- Calibration is necessary, but little data on impact of grouting on Bending Moment + Shear Force in tunnel lining
- 2D modelling - may underpredict stresses, especially when grouting close to tunnel
- Grout type and parameters are critical - stresses due to "true" compensation grouting << grout jacking
- Grout jacking (post tunnelling) - more onerous than compensation grouting (concurrent or during tunnelling)
- Soil behaviour - hysteresis effects are significant, especially if multiple tunnels
- Shotcrete age - if grout too early, the lining may fail

IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Experience from Crossrail project in UK

M. Black, Crossrail, United Kingdom

Compensation grouting on the Crossrail Project, London

- Mike Black
- Crossrail Ltd

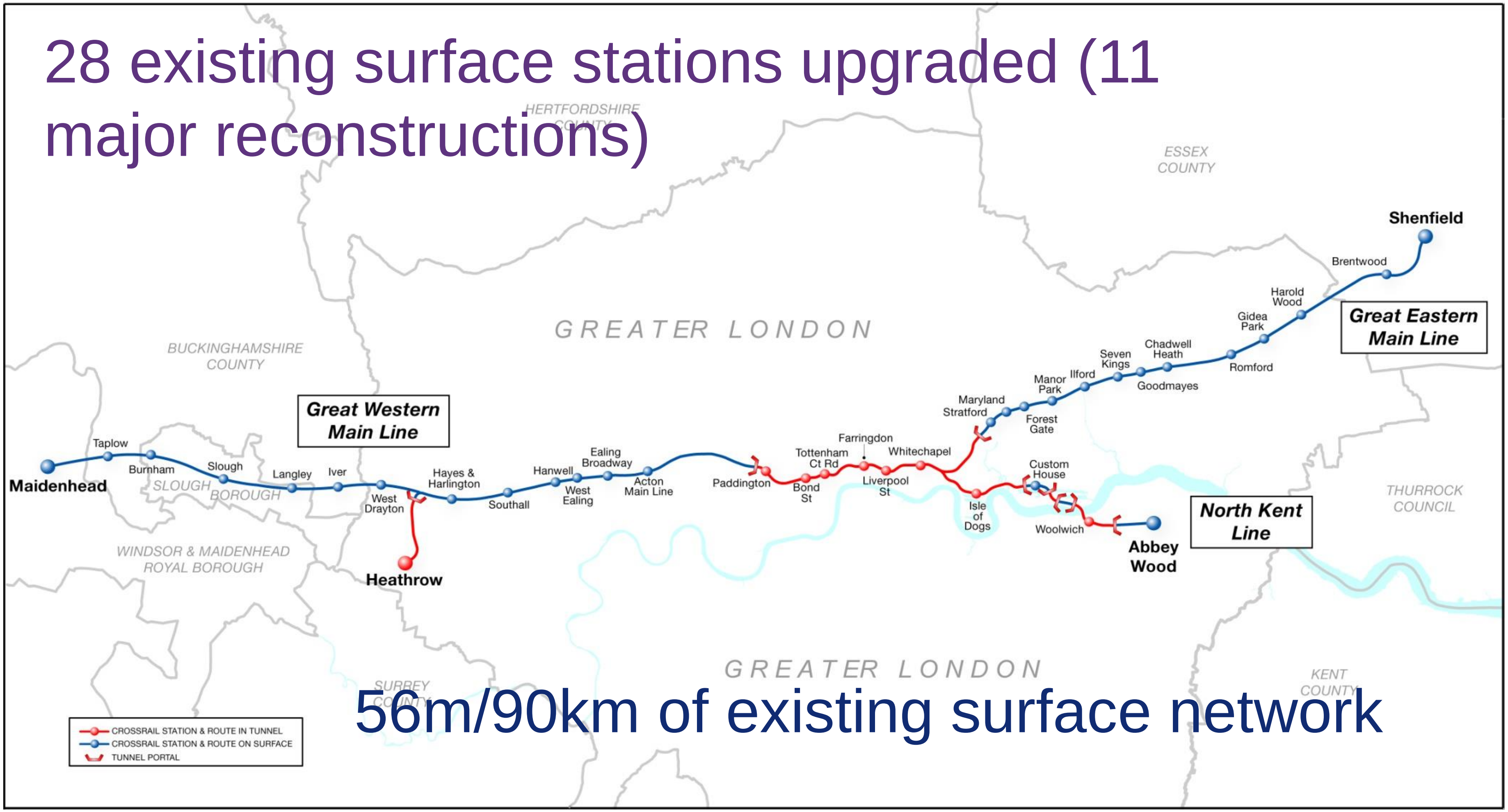
Contents

- Introduction to the Crossrail Project
- CG design philosophy
- Shaft sinking and TAM drilling
- Instrumentation and Monitoring
- CG Implementation

Introduction to the Crossrail Project

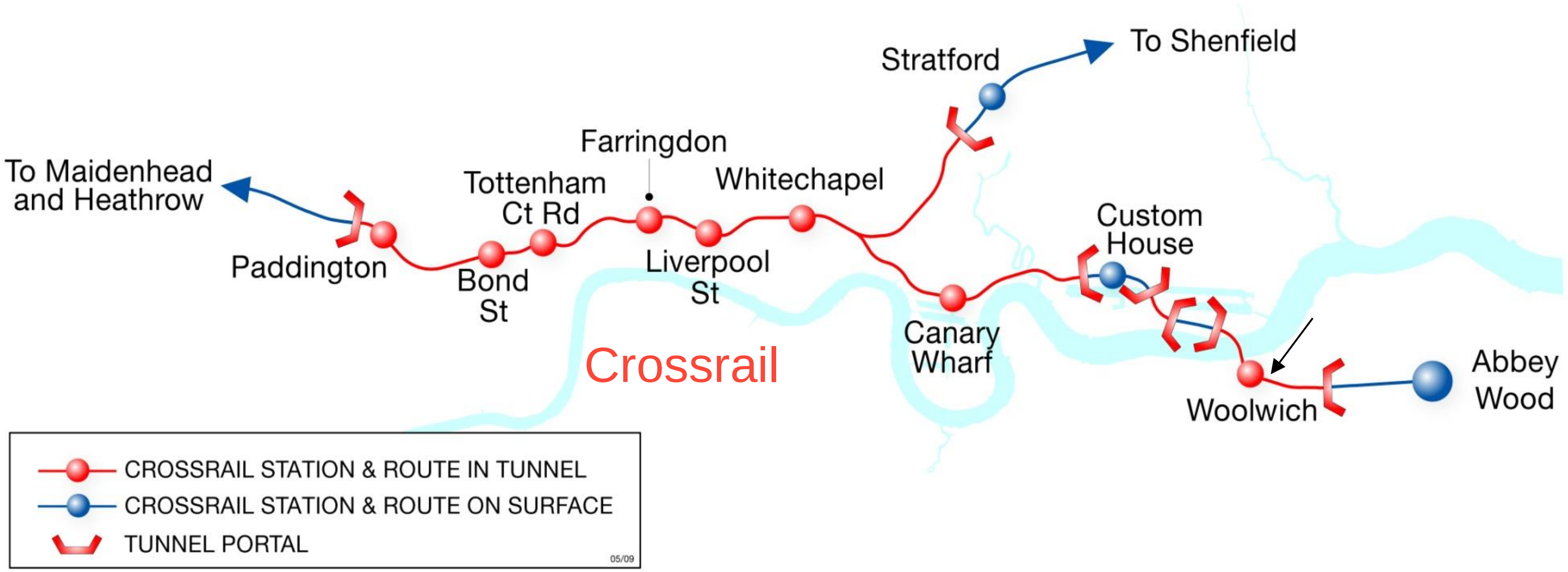
Crossrail

28 existing surface stations upgraded (11 major reconstructions)



56m/90km of existing surface network

13m/21 km of new sub-surface twin-bore railway through London



8 sub-surface stations

Programme

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

15th May 2009
Construction begins at Canary Wharf

2012

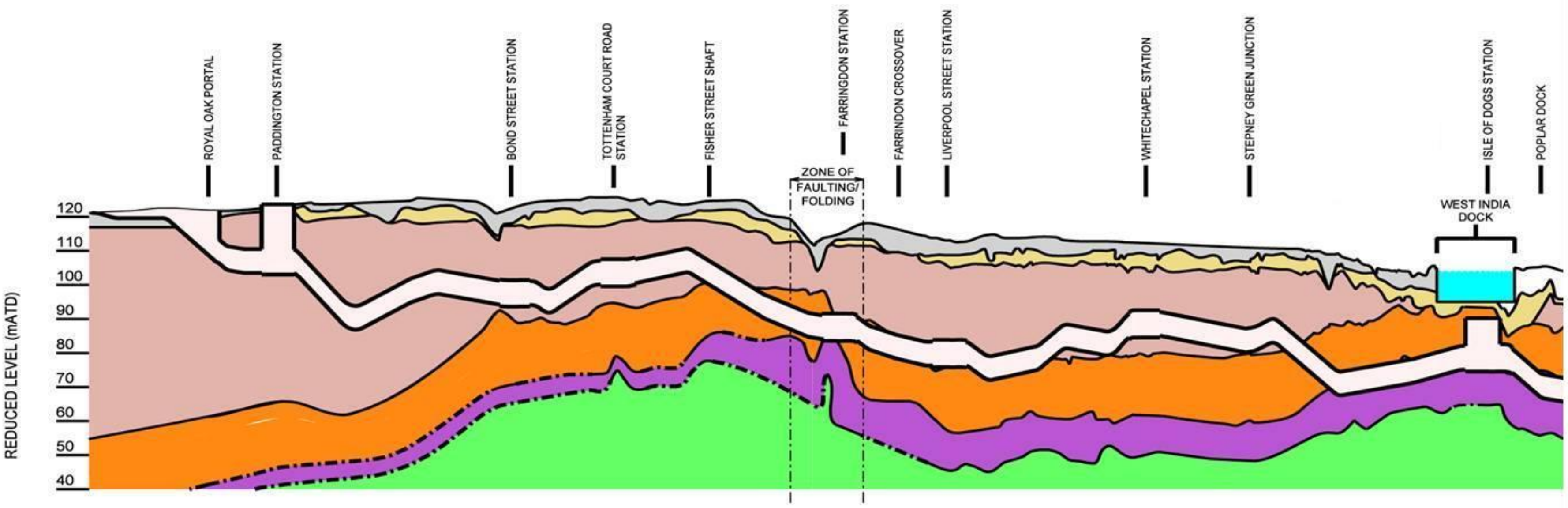
Launch first TBM

2014 - 2018

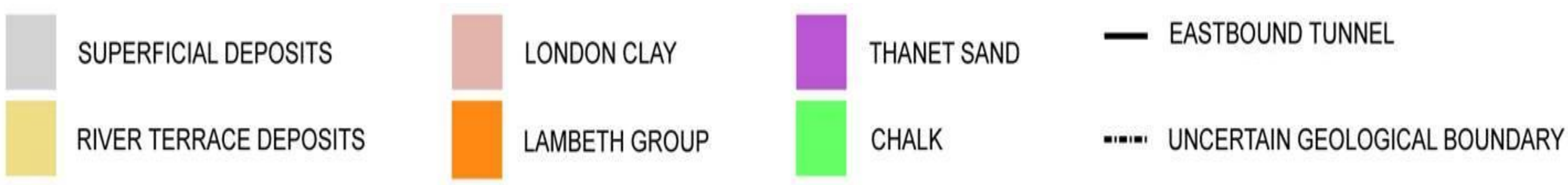
Systems Install

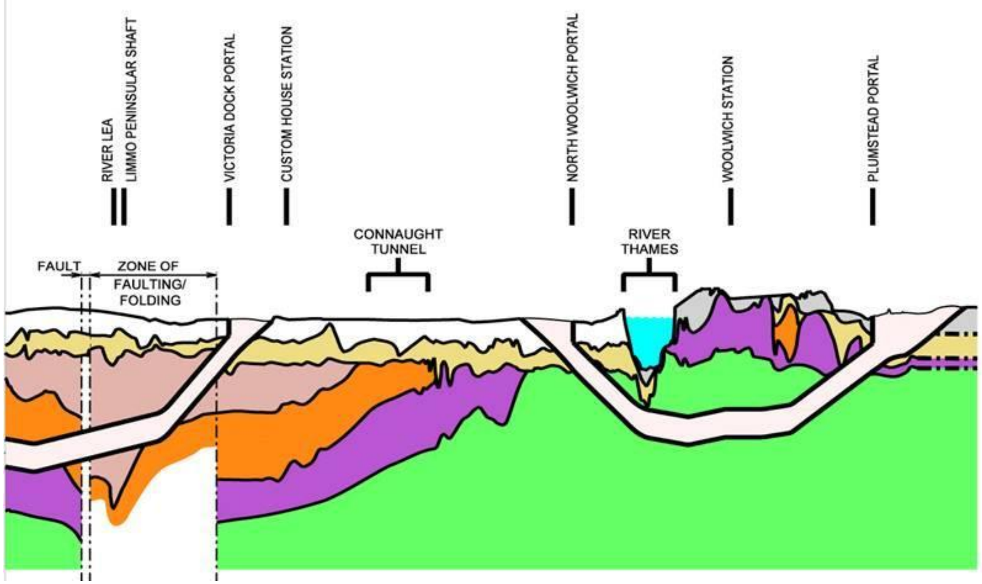
2018- Phased opening

Ground conditions

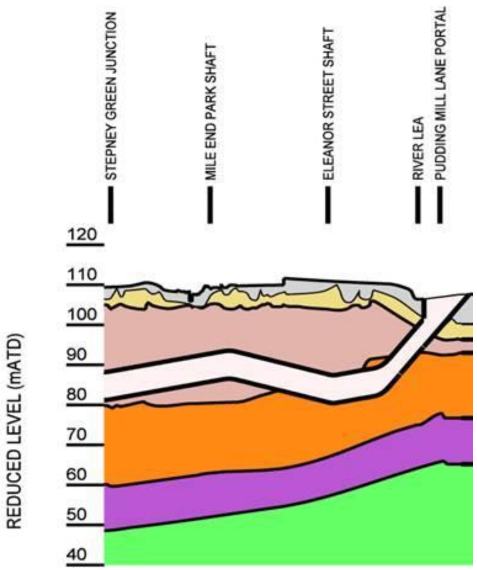


Royal Oak Portal – Isle of Dogs Station





Blackwall Way Shaft – Plumstead Portal



Stepney Green Shaft – Pudding Mill Portal

SUPERFICIAL DEPOSITS

RIVER TERRACE DEPOSITS

LONDON CLAY

LAMBETH GROUP

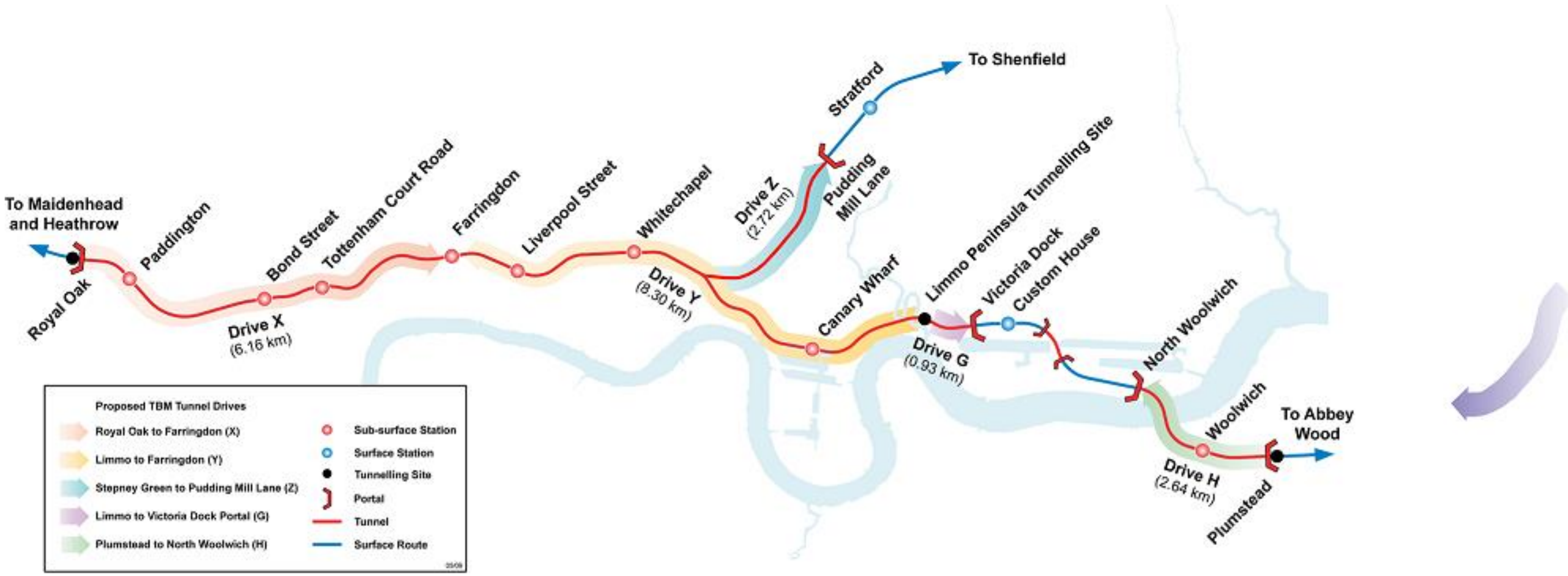
THANET SAND

CHALK

EASTBOUND TUNNEL

UNCERTAIN GEOLOGICAL BOUNDARY

Tunnelling Strategy

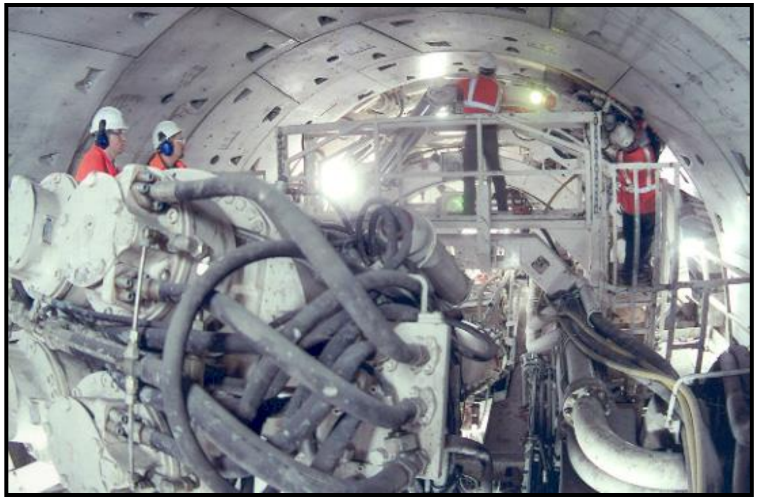


Drives X, Y, Z and G will be by EPB. Drive H will be by Slurry machine

Central Tunnels Section
Tunnel Boring Machines

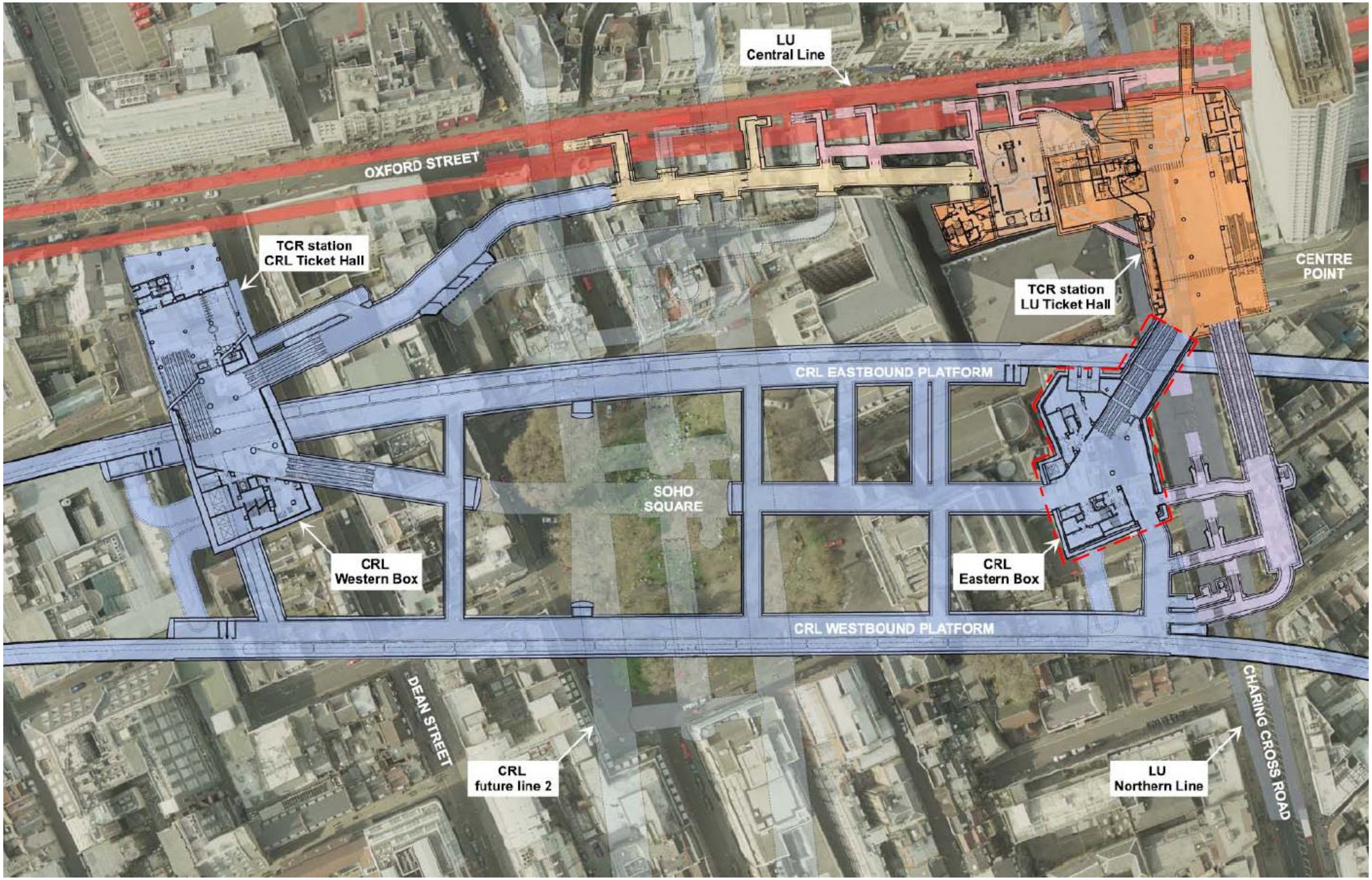
Following the success of recent tunnelling projects in London, CRL is utilising Earth Pressure Balance TBMs except for the Thames crossing where a Slurry machine will be employed

TBMs will be the primary source for controlling ground movements

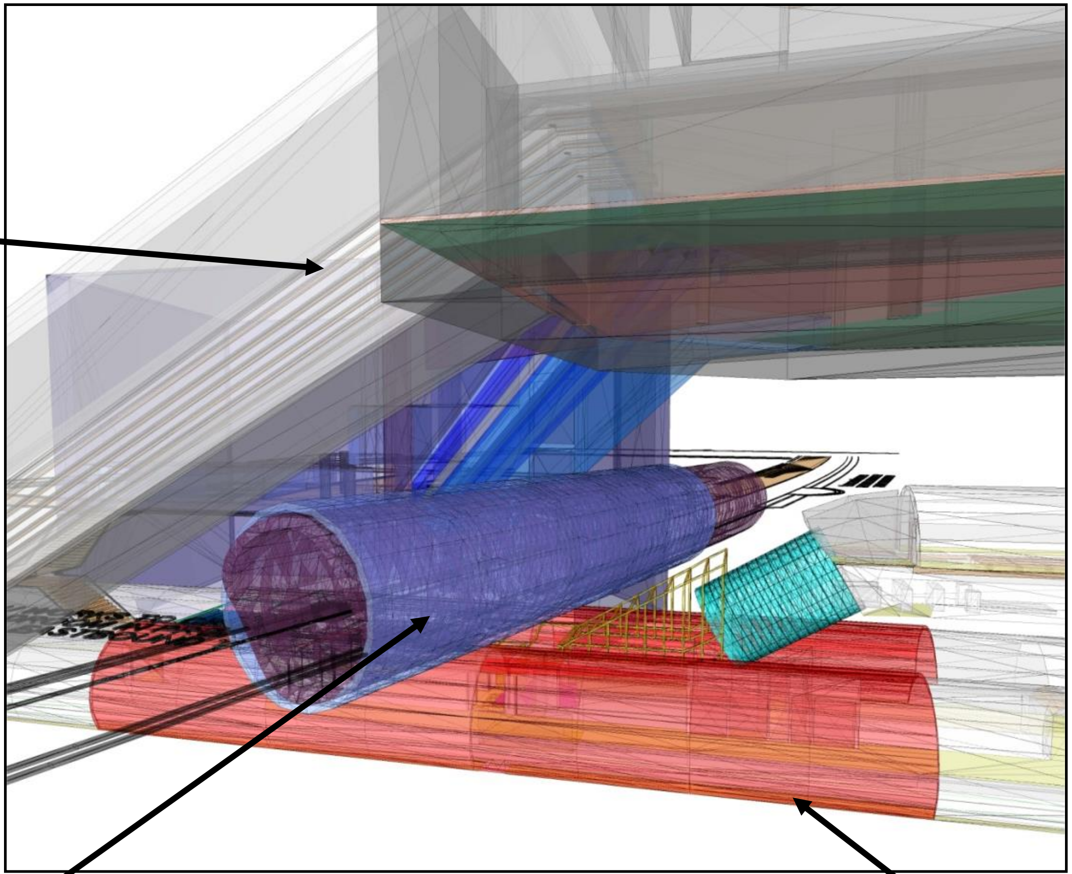


Segment erection

Tottenham Court Road – a typical mined station



Obstructions



LU station upgrade works
Escalator Box

Crossrail Eastbound Running
Tunnel

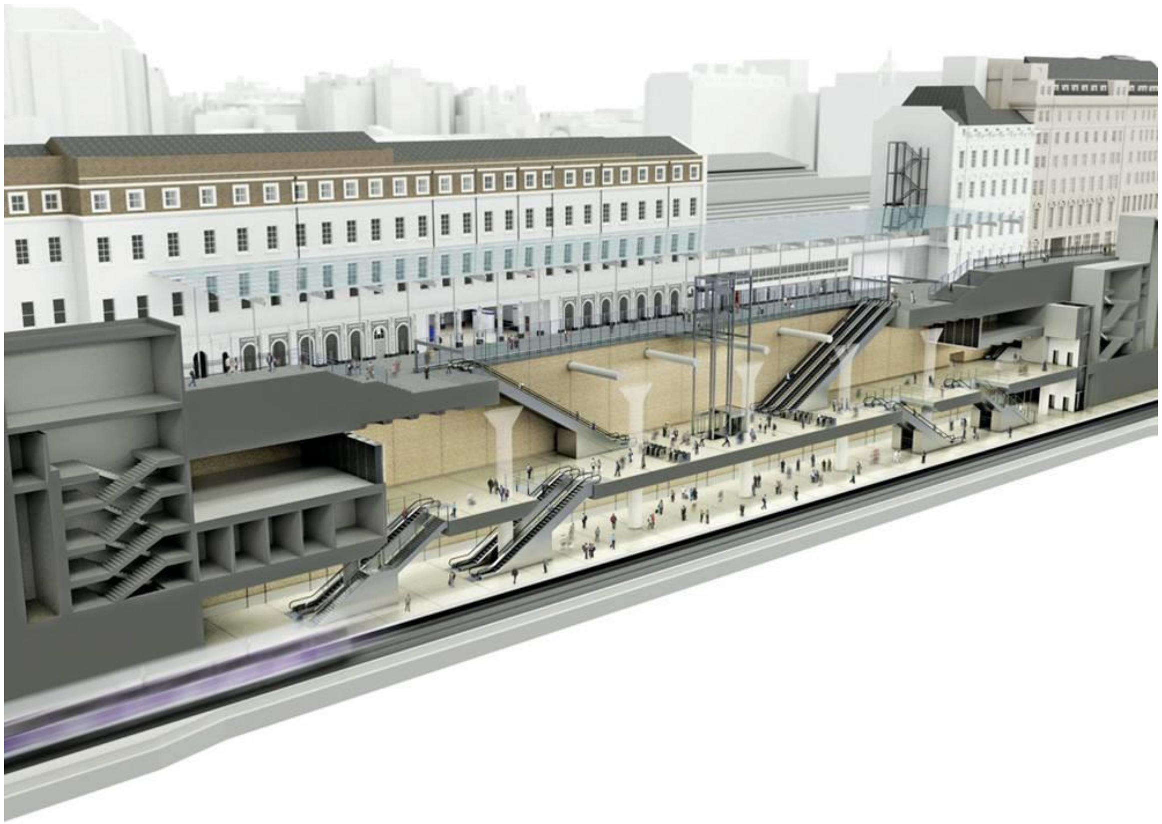
Existing Northern Line Platform
Tunnels

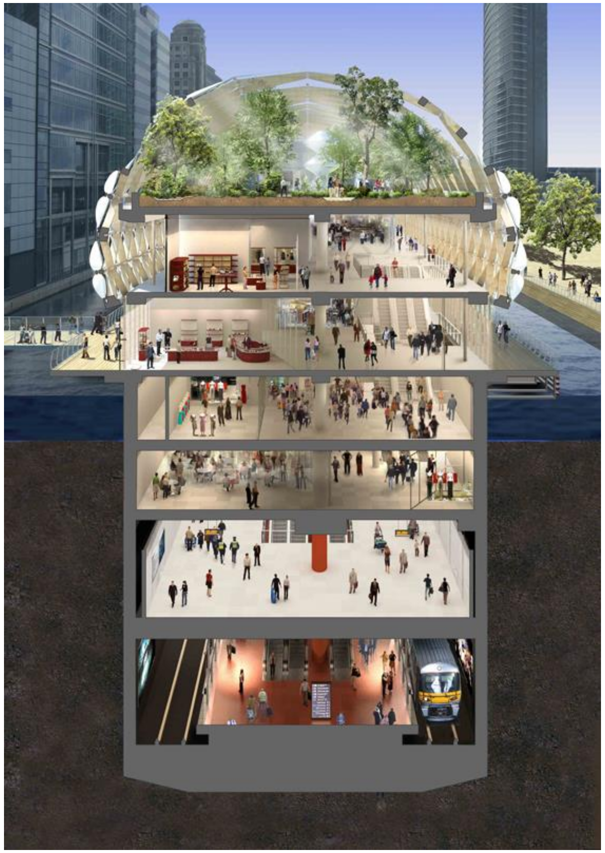
Sprayed Concrete Lining

Whitechapel Station

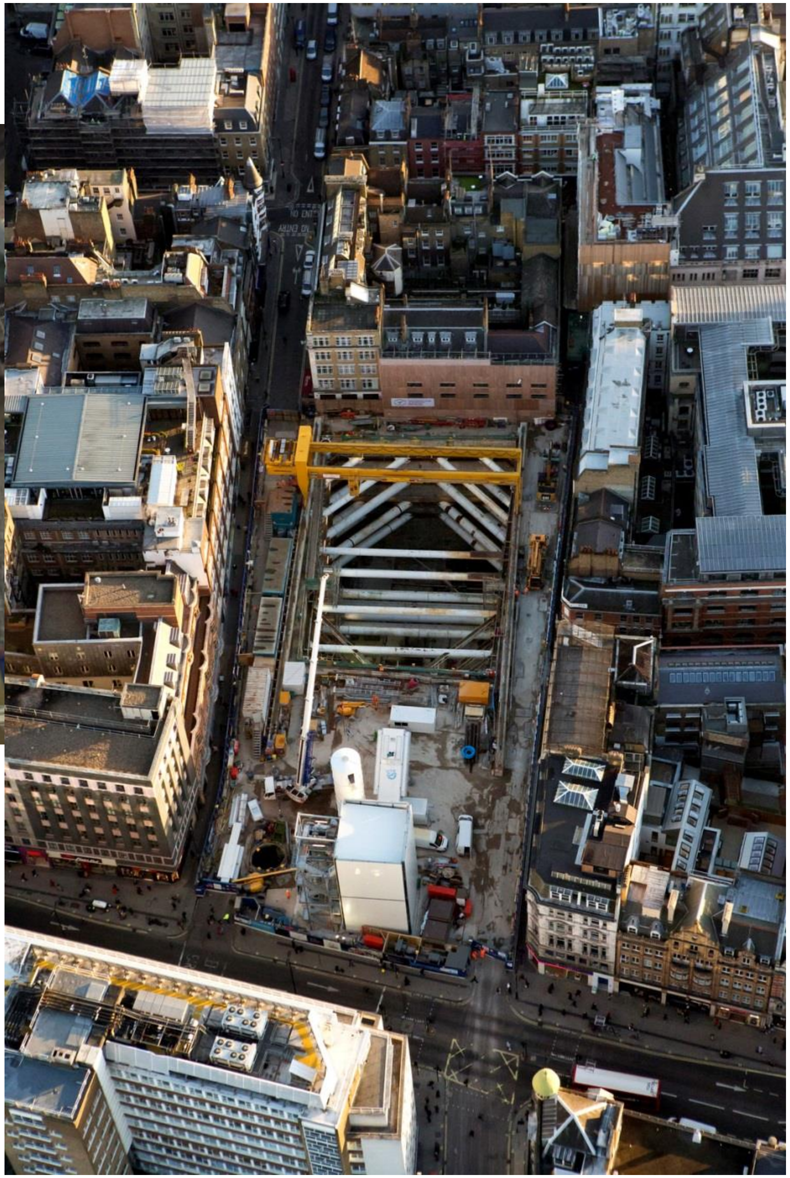
Stepney Green cavern

Box Stations





Tottenham Court Road – western ticket hall



Connaught Tunnel

Connaught Tunnel refurbishment

CG design Philosophy

Management and control of ground movement

- Maximum permitted volume loss of 1.5% for SCL tunnels
- Maximum permitted volume loss of 1.0% for bored tunnels (down to 0.5% in specified “control zones”)
- Contractor responsible for any damage to buildings or utilities if these limits are exceeded

Protective works requirements 1

- Protective measures required for numerous listed buildings and utilities
- Provision of compensation grouting was a contractual requirement
- Covers full extent of SCL tunnels, except where restricted by presence of piled buildings
- Modified during construction by VE proposals and re-developments

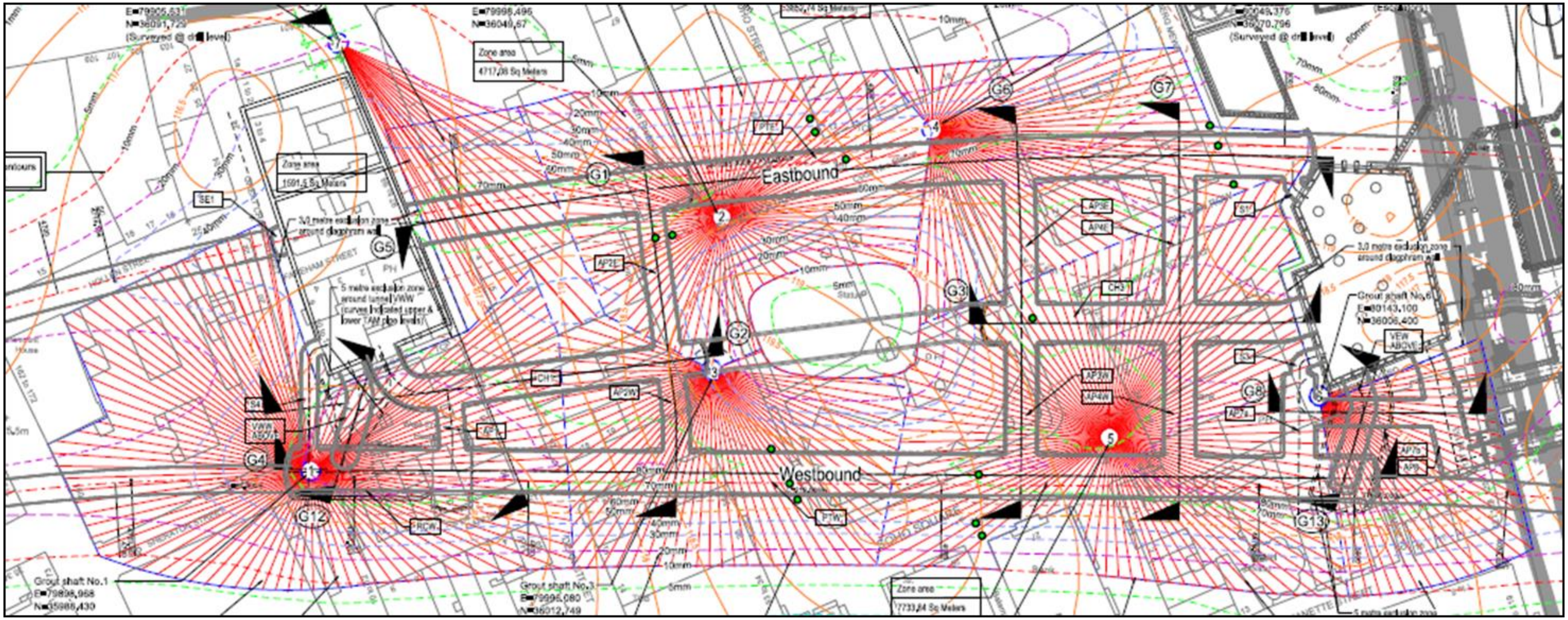
Protective works requirements 2

- For tunnels, coverage is based on 10mm surface settlement contour which is equivalent to 1mm contour at grouting level
- Allowable settlement should not result in ground slopes in excess of 1/1000 (or a deflection ratio in excess of 1/2000)
- Provision for grouting must be maintained until settlement reduces to a rate of 2mm/year or less

TaM Extent covering the predicted 10mm settlement contour from the Sprayed Concrete Lining Tunnels

Tottenham Court Road Station: Compensation Grouting extent

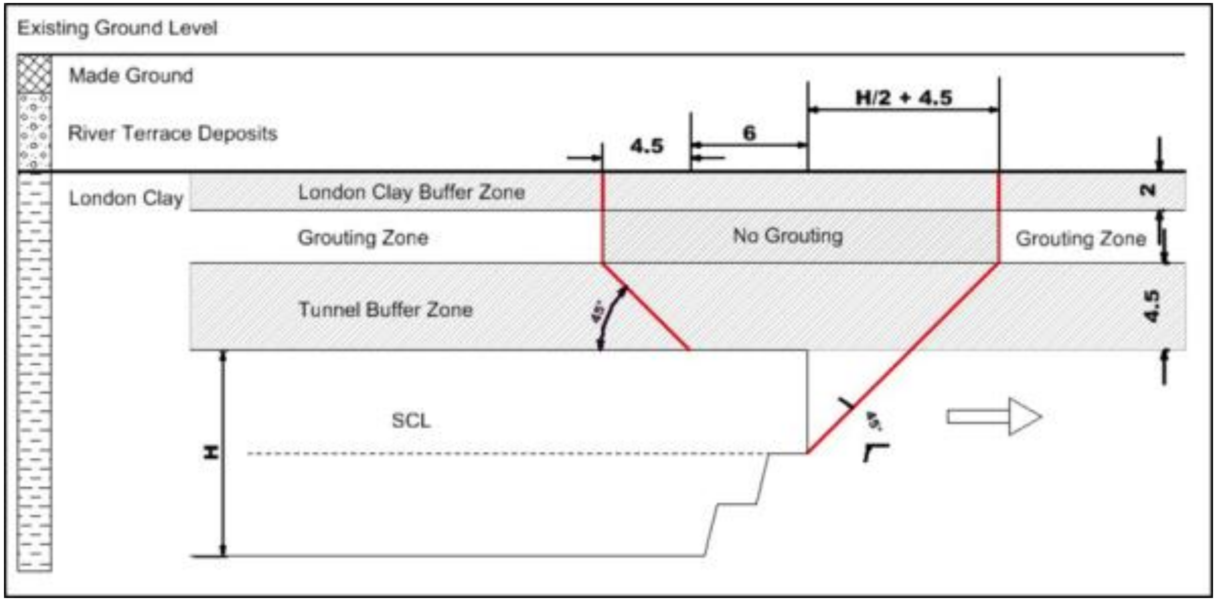
Comparison with settlement contours.

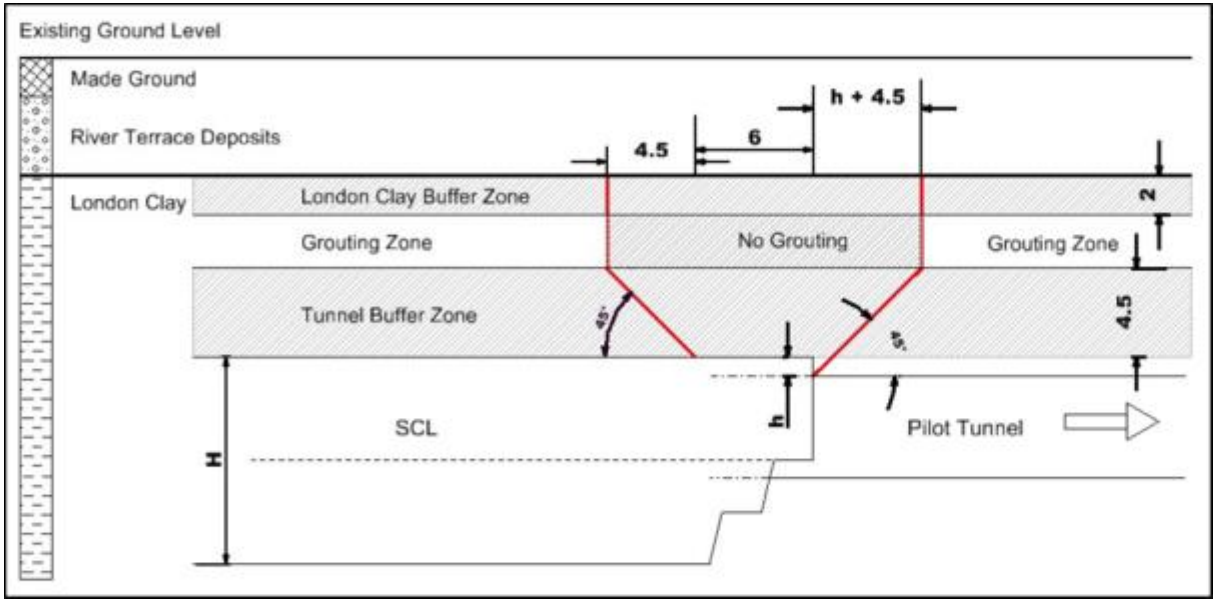


Grouting exclusion zones

- As far as practicable grout arrays are installed no closer than 4.5m above tunnel crowns (3m absolute limits)
- …and no less than 2m from the upper surface of the London Clay
- No concurrent grouting permitted in a zone immediately above the unsupported tunnel unless permitted by the Project Manager

Grouting Exclusion Zones on SCL Tunnels





Crossrail

Concurrent grouting vs grout jacking

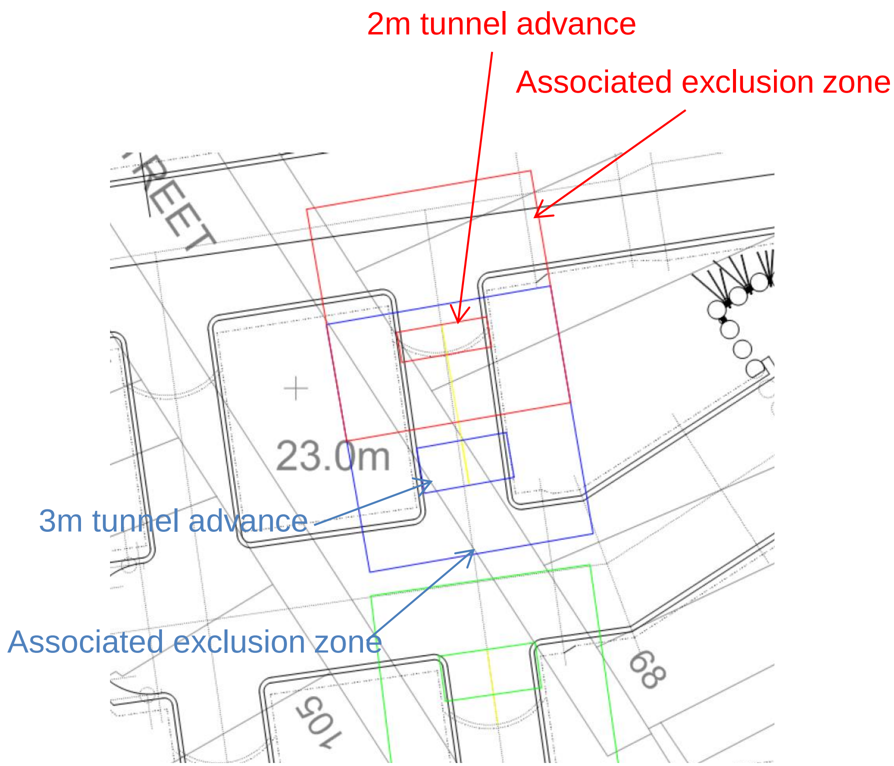
- Exclusion zone results in most compensation grouting being pre-jacking or recovery
- Maximum of 5mm heave permitted in any one grout jacking episode
- During platform enlargements, construction is suspended every 10m advance or less to allow grout jacking to take place

Shaft and box excavations

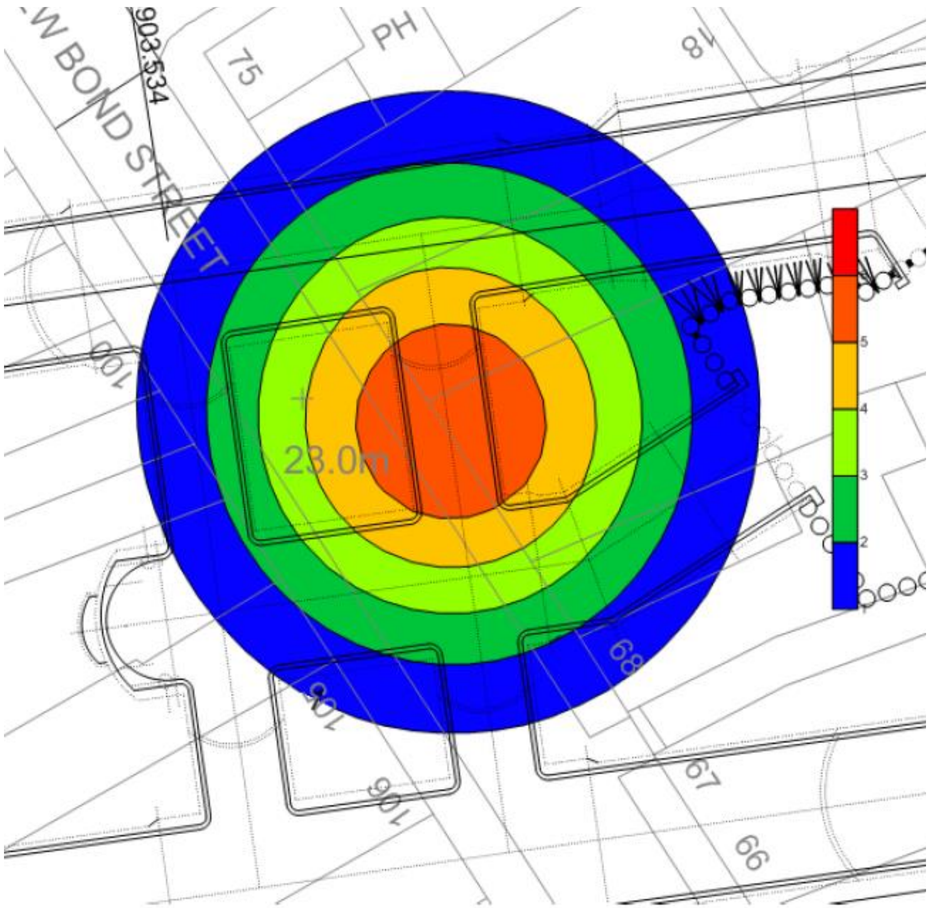
- Concurrent grouting permitted during shaft and box excavation outside a 3m exclusion zone
- TaM levels related to prop levels to avoid excessive wall loads

Compensation Grouting: approach adopted for short tunnels

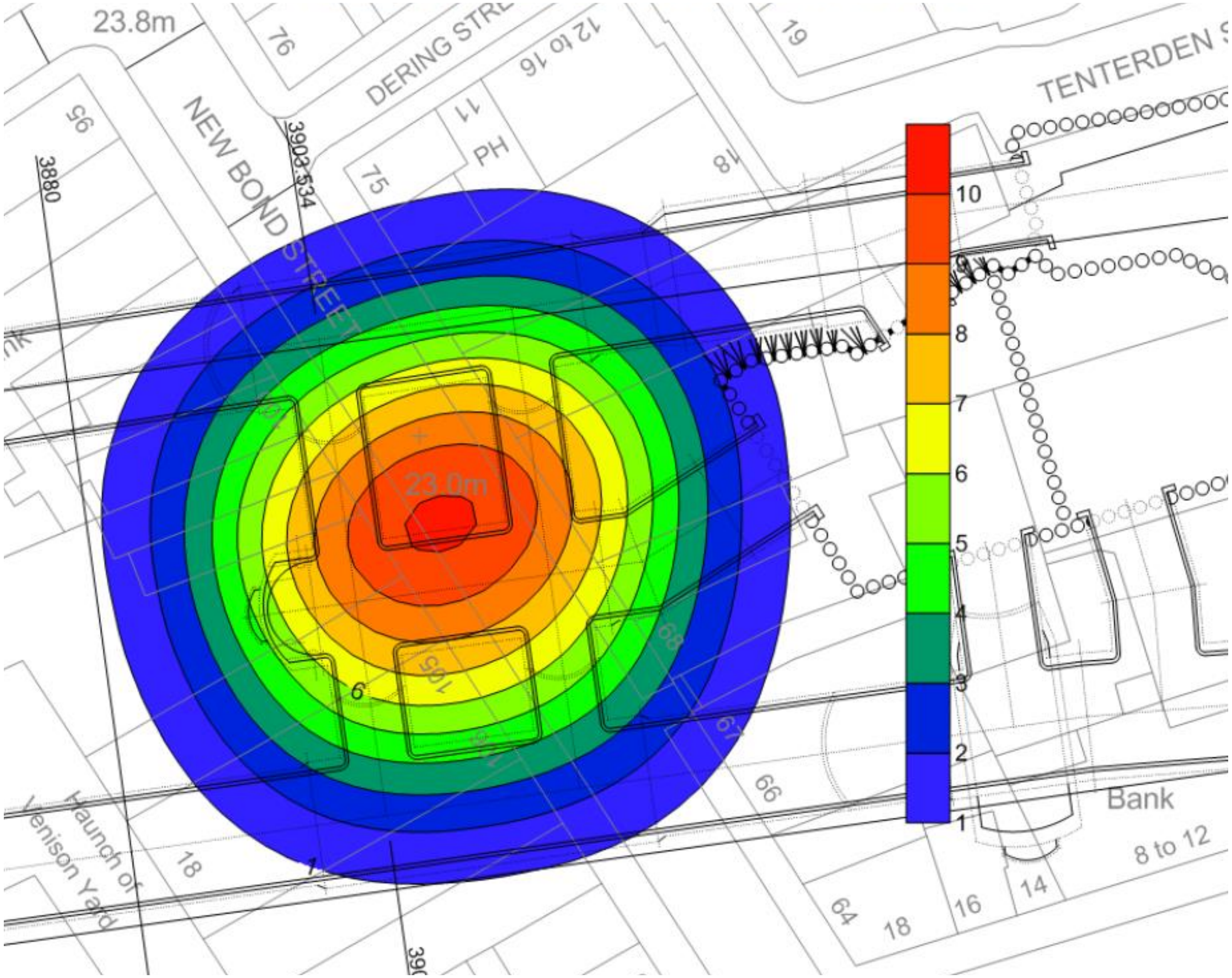
Extent of exclusion zones



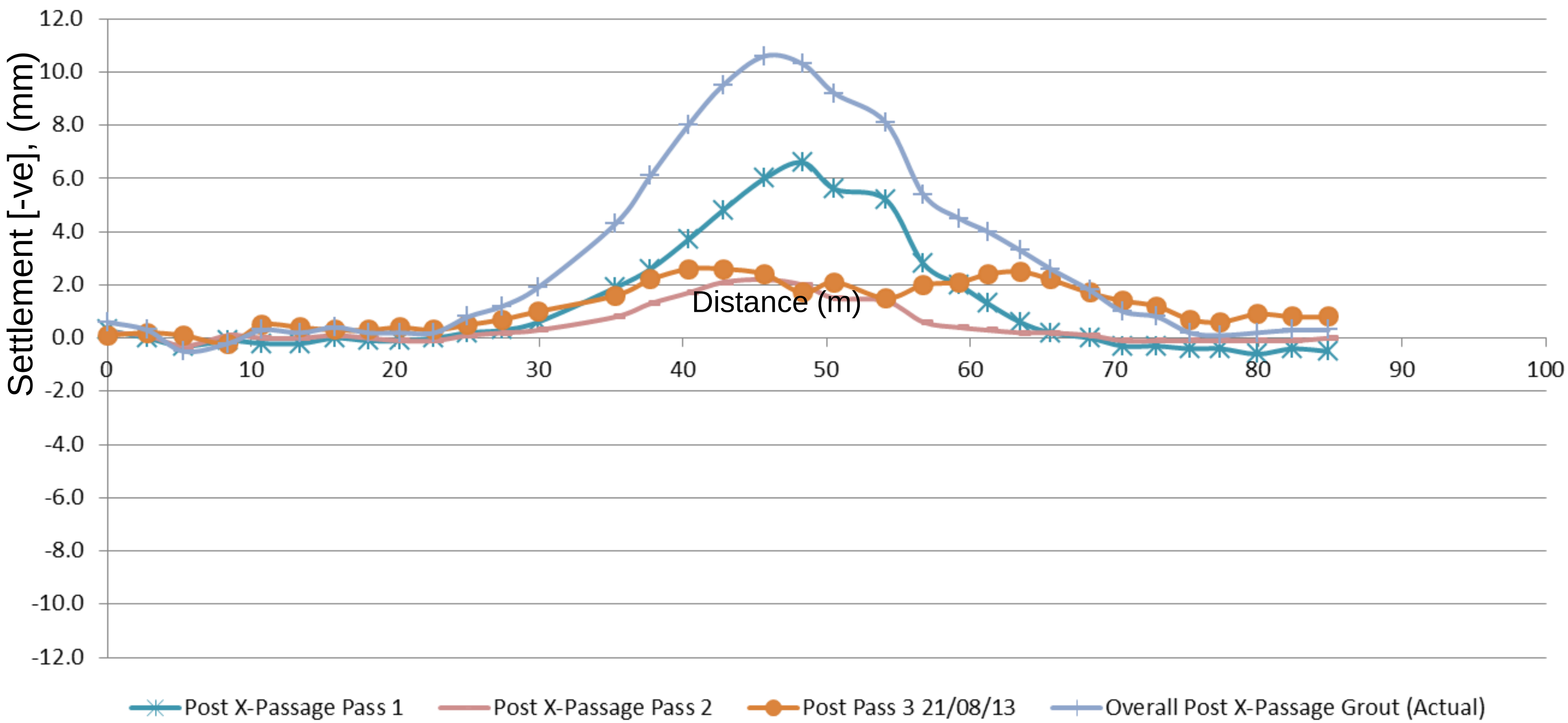
Volume loss settlement contour (1.5%)



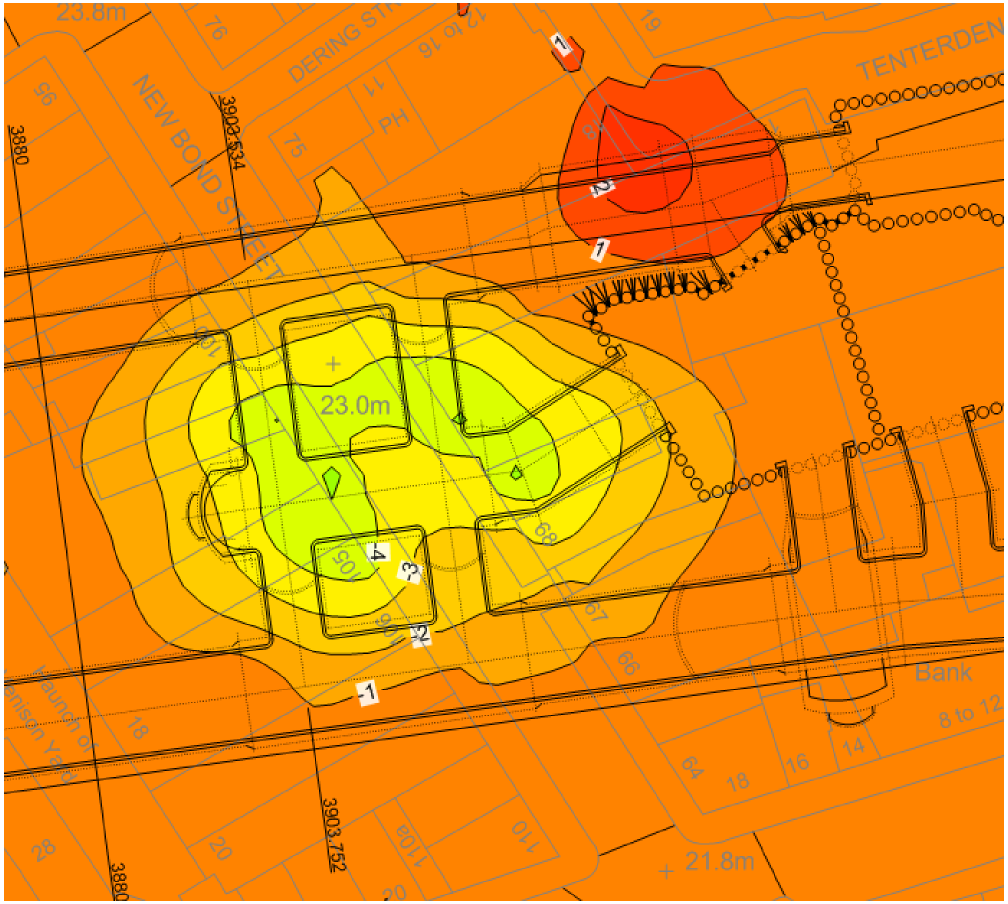
Bond Street Station: Volume loss (1.5%) settlement contour for 4 cross passages CP7 to CP10.



BOS: Observed movement from post excavation grouting episodes following construction of cross passages 7-10



BOS: Observed movement from construction of cross passages 7-10 and associated pre and post-excavation grouting episodes



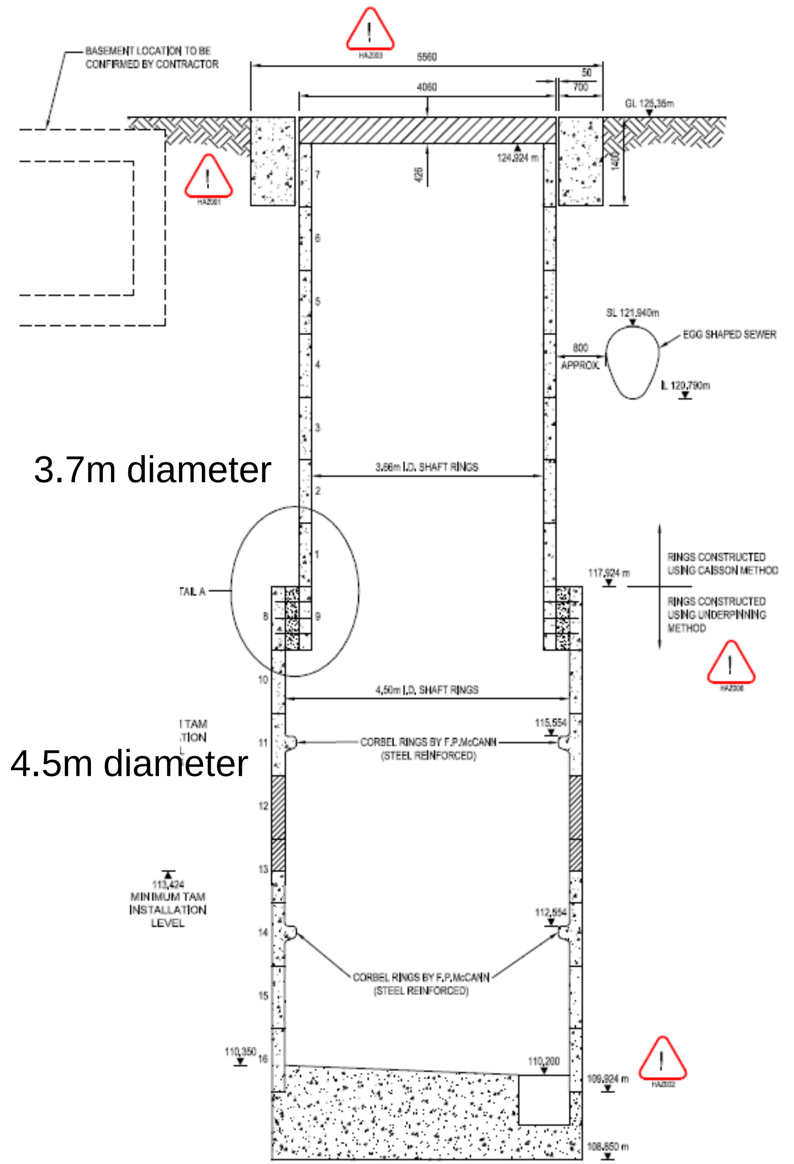
Shaft sinking and TAM drilling

Grout shafts

- In a dense urban environment worksites need to be very small
- Shaft diameters were reduced to 4.5m from an optimal 6m
- Average shaft depth is 15m

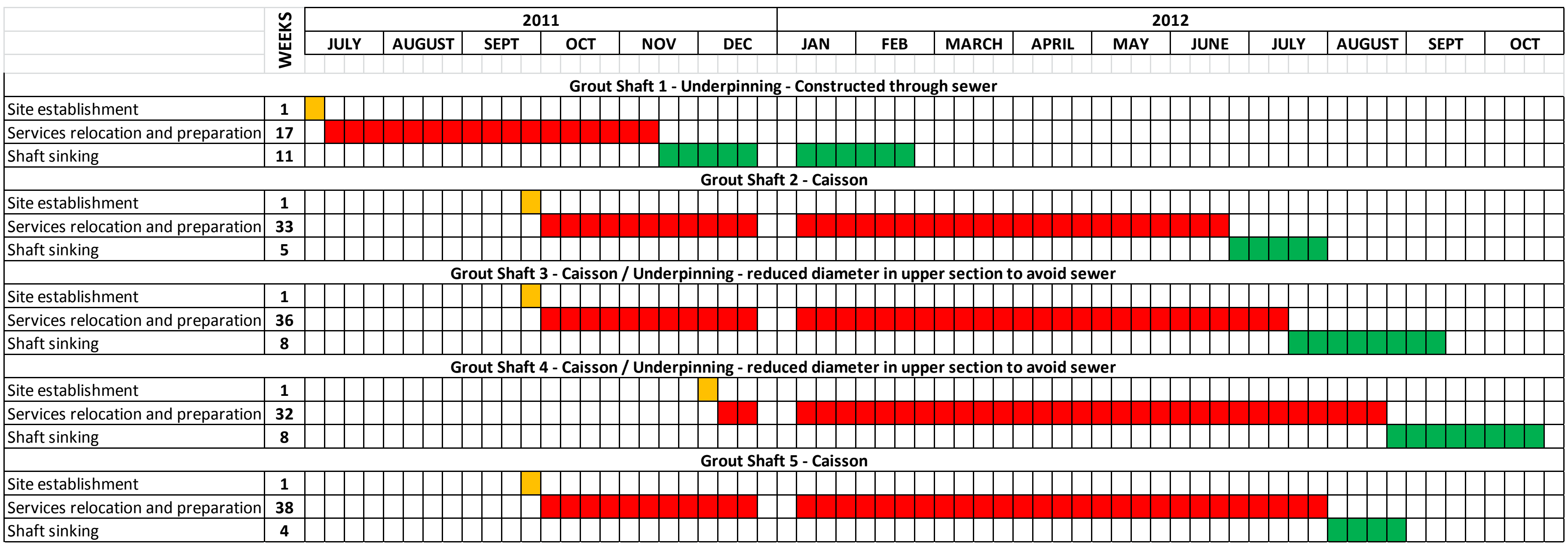
Shaft Sinking

- Example of shaft with reduced diameter in upper section to maintain minimum clearance of 0.5m to sewer.
- Upper part caisson; lower section underpinned



Shaft Sinking

- Service relocation ~35 weeks
- Caisson sink 4-5weeks
- Caisson / underpinning ~8 weeks



TaM statistics

Tottenham Court Road Station					
Shaft #	**No of Tams**	**Total Length (m)**	**Average Length (m)**	**Re-drills**	**Plan Area (m²)**
1	101	3625	35.9	3	7732
2	87	2322	26.7	10	4717
3	64	2076	32.4	12	4012
4	61	2323	38.1	11	3853
5	114	3944	34.6	8	7734
6	32	980	30.6	3	3408
7	21	983	46.8	3	1592
Total	**480**	**16255**	**35.0**	**50**	**33047**

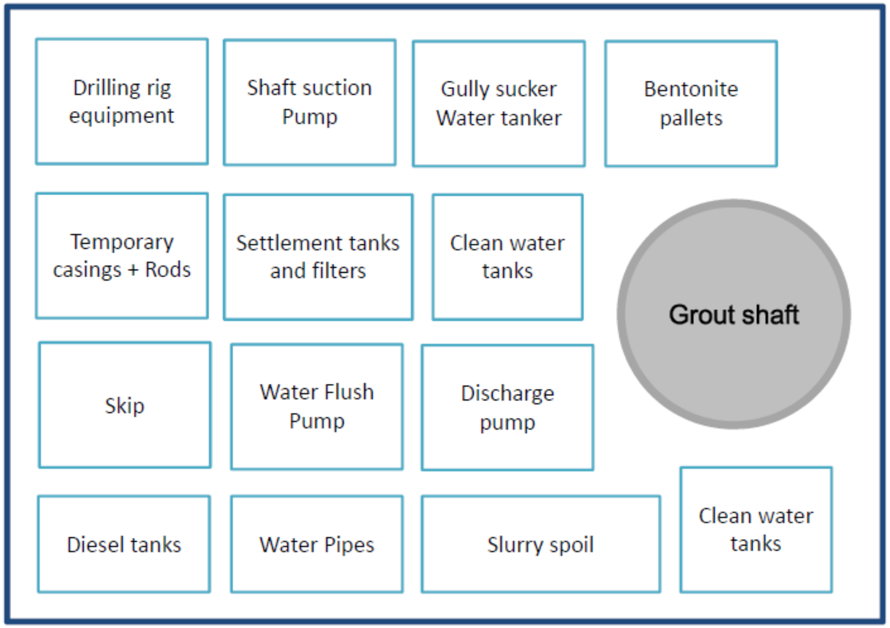
Bond Street Station					
Shaft #	**No of Tams**	**Total Length (m)**	**Average Length (m)**	**Re-Drills**	**Plan Area (m²)**
1	82	3080	37.6	7	6364
2	111	4239	38.2	8	8618
3	69	1930	28.0	10	4063
4	68	2014	29.6	10	3755
5	68	2988	43.9	8	5843
Total	**398**	**14251**	**35.5**	**43**	**28642**

TaM drilling methodology

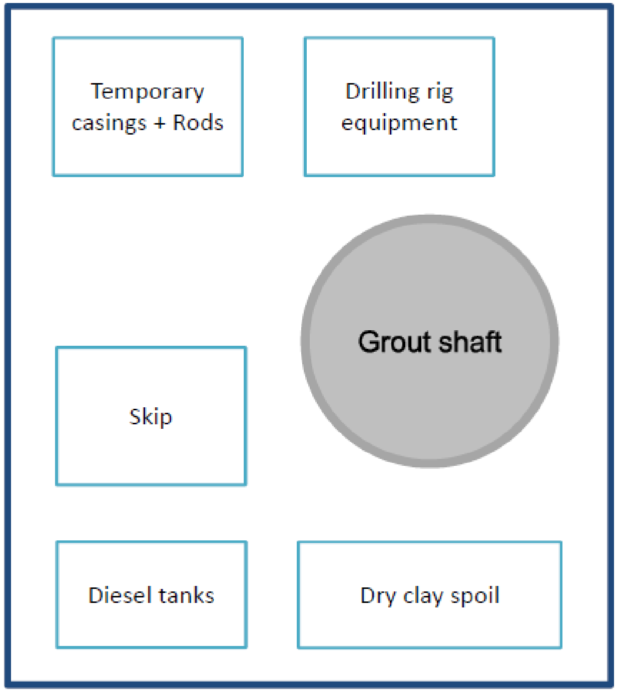
- Water flush and dry auger techniques were both used
- Factors affecting selected methods were:
  - Settlement/heave effects at ground surface
  - Site space available
  - Spoil handling and disposal
  - Access restrictions
  - Environmental impacts

Site space requirements for water flush and dry auger drilling methods

Schematic site layout for the water flush TaM drilling method



Schematic site layout for rotary auger TaM drilling

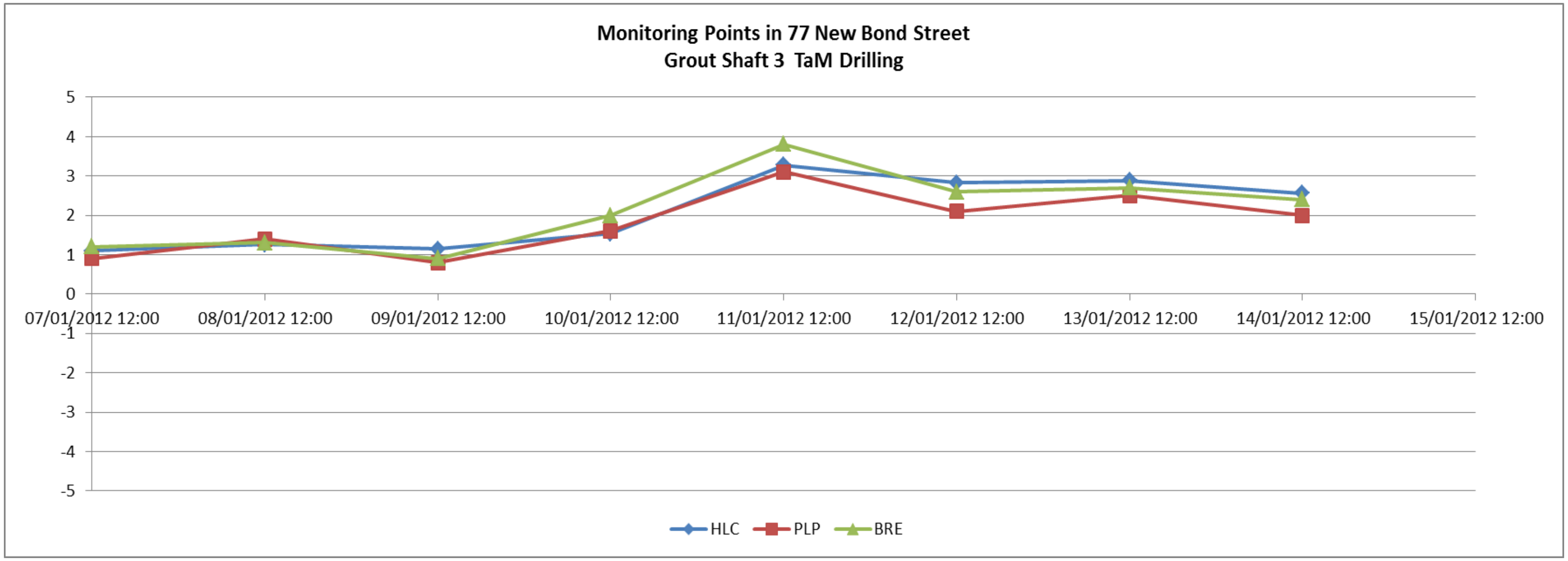


Crossrail

Water flush method

- Temporary drill casings used for 50% of holes up to 40m and all but the last 20m of longer holes
- Holes were fully cased where excessive heave was seen
- A polymer flush was initially used but abandoned due to lack of compound space
- Unacceptable heave resulted in method being abandoned

Heave generated from water flush method



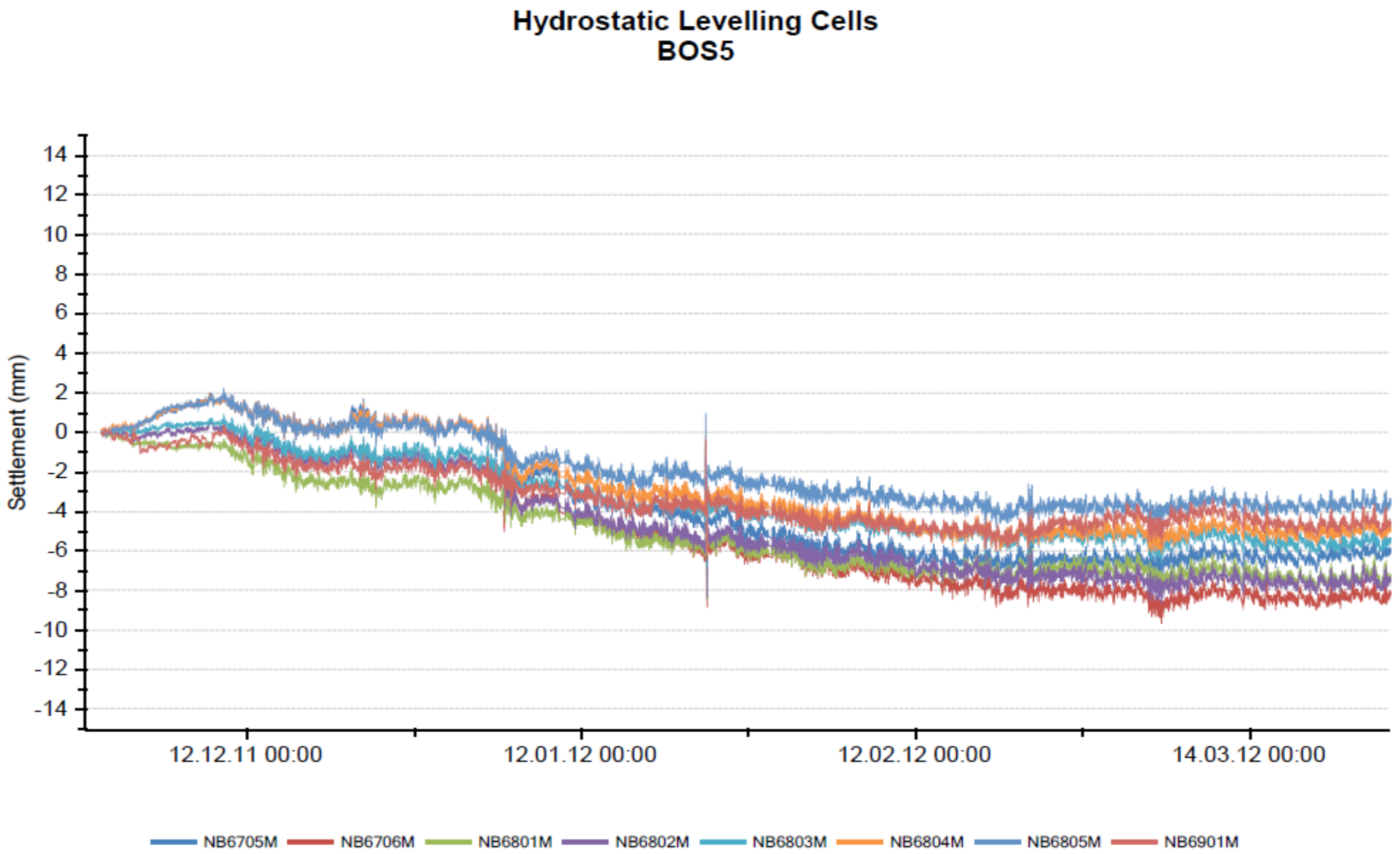
Dry rotary auger method 1

- Holes were partially cased which required air flush that was seen to generate excessive heave
- Casing use was significantly reduced
- Good alignment was still achieved

Dry rotary auger method 2

- Slow but steady settlement from dry augering
- Required periods of re-grouting during ongoing TaM drilling
- Drilling works had to be suspended during this activity thus delaying overall programme

Settlement resulting from dry auger method

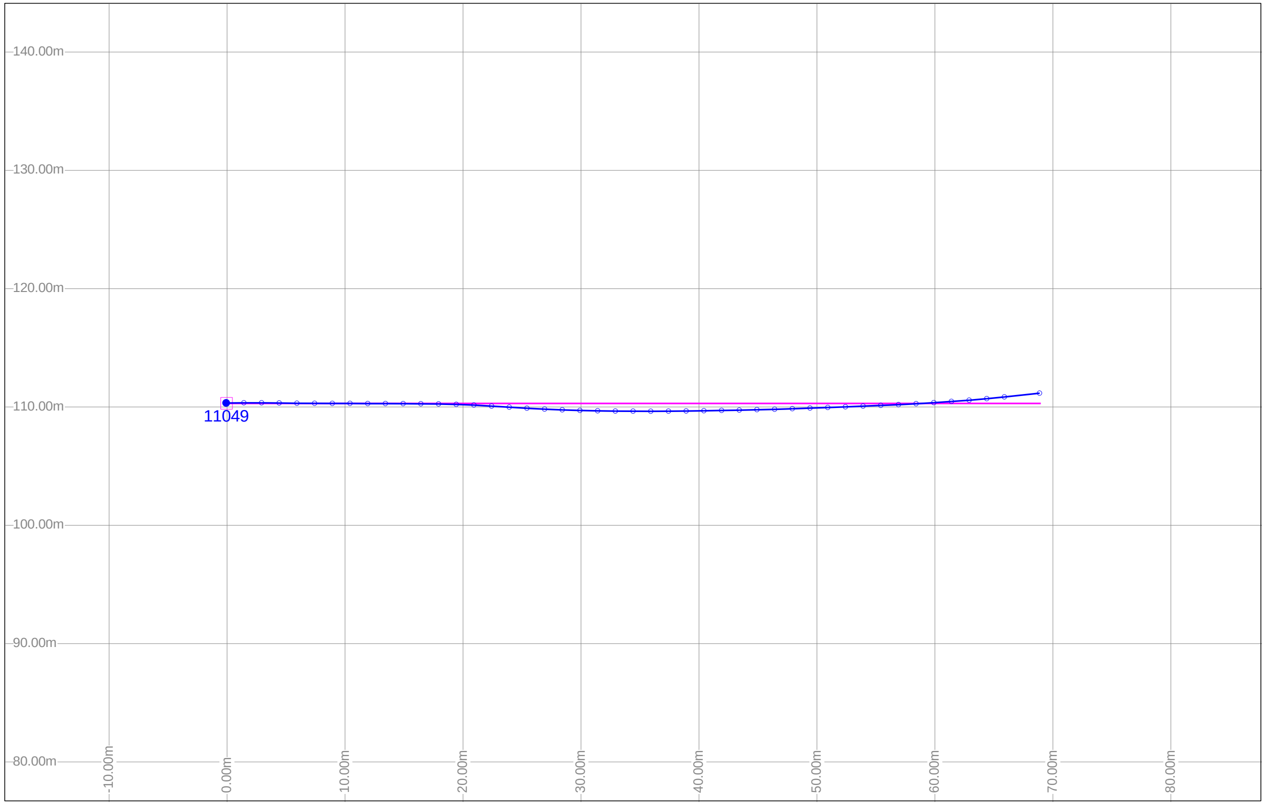


TaM drilling accuracy

Vertical tolerance of +/- 750mm at 65m

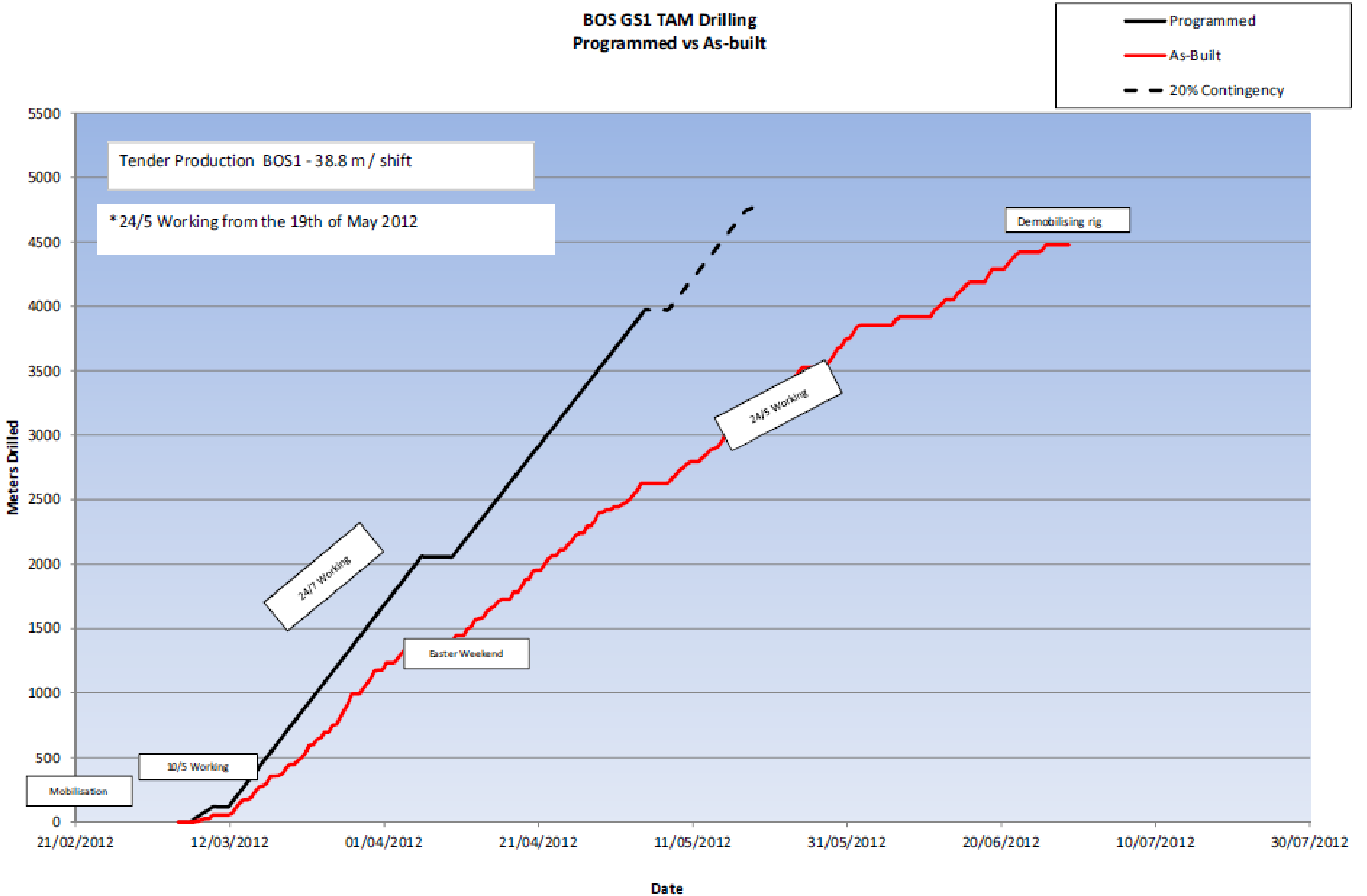
Horizontal tolerance of 500mm from theoretical location

"Line of Hole" section of survey "11049"



Scale 1:392.0

Printed on 13/09/2012 10:29:28


BOS GS1 TAM Drilling
Programmed vs As-built
Programmed
As-Built
20% Contingency
Tender Production BOS1 - 38.8 m / shift
* 24/5 Working from the 19th of May 2012
Demobilising rig
24/5 Working
24/7 Working
Easter Weekend
10/5 Working
Mobilisation
Meters Drilled
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
21/02/2012
12/03/2012
01/04/2012
21/04/2012
11/05/2012
31/05/2012
20/06/2012
10/07/2012
30/07/2012
Date

Instrumentation and Monitoring

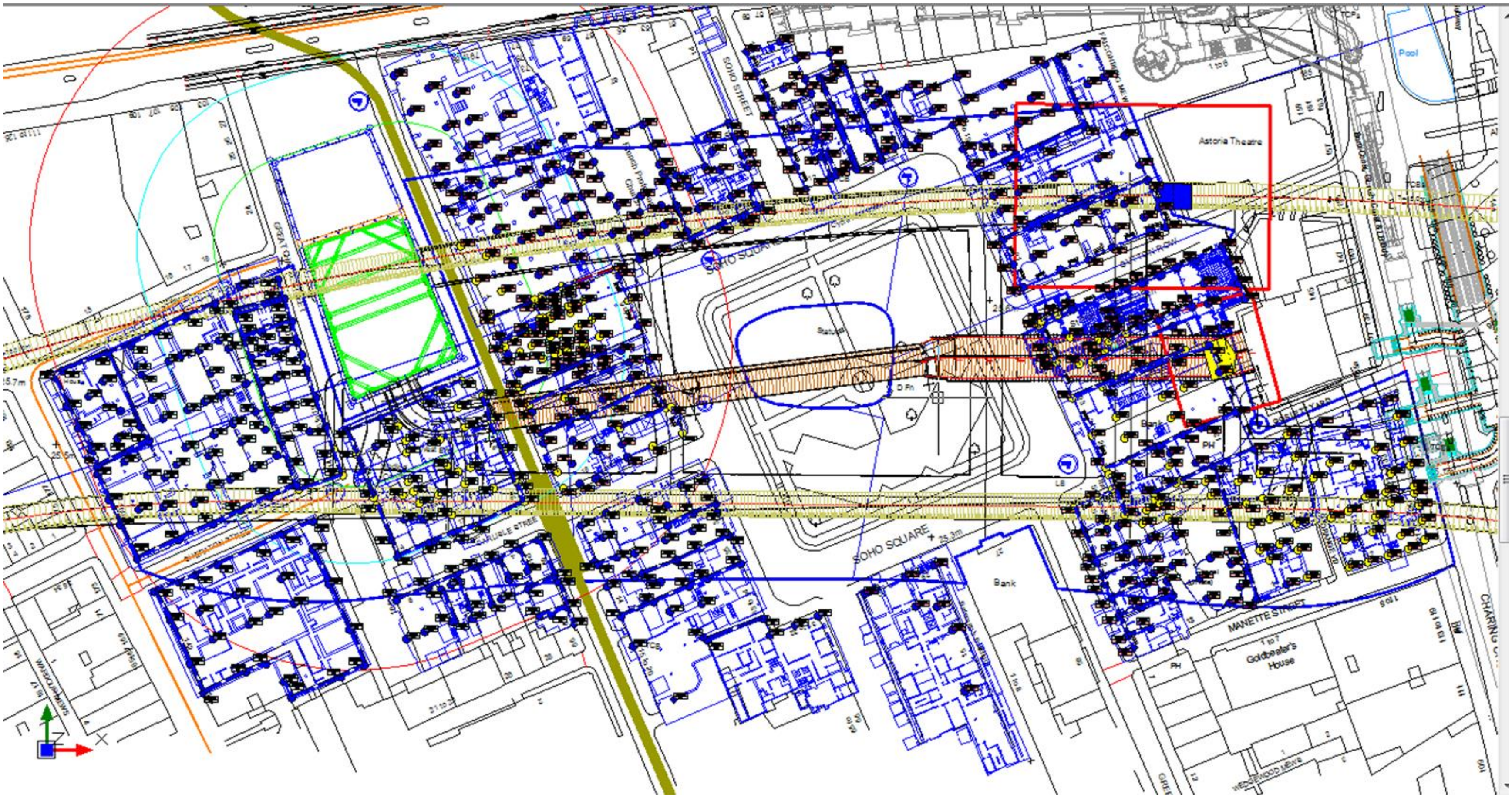
Instrumentation

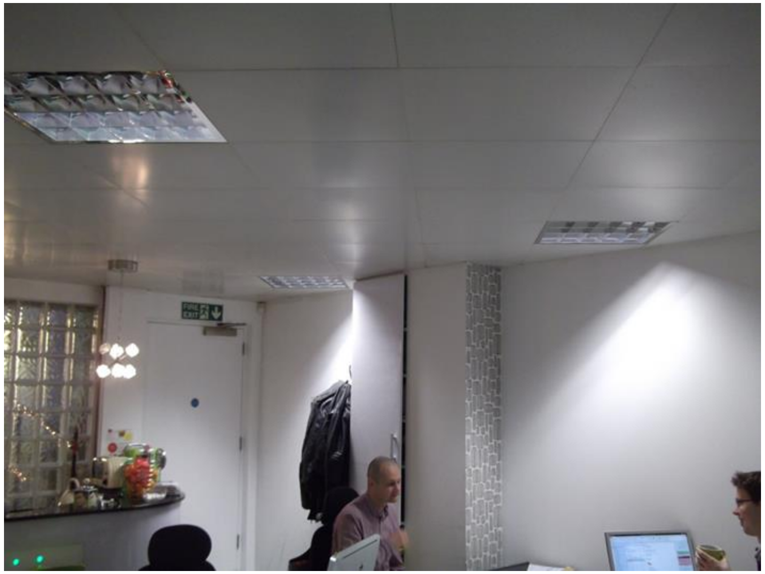
- Nos. of sensors

Location	PLP	BRE	ATS Prism	HLC
BOS	920	842		788
TCR	713	596	666	666

PLP = Precise levelling point
BRE = Demountable levelling bolt
ATS = Automatic total station
HLC = Hydrostatic levelling cell

TCR – layout of Hydrostatic Levelling Cells (HLCs)





- Example of HLC installation above false ceiling

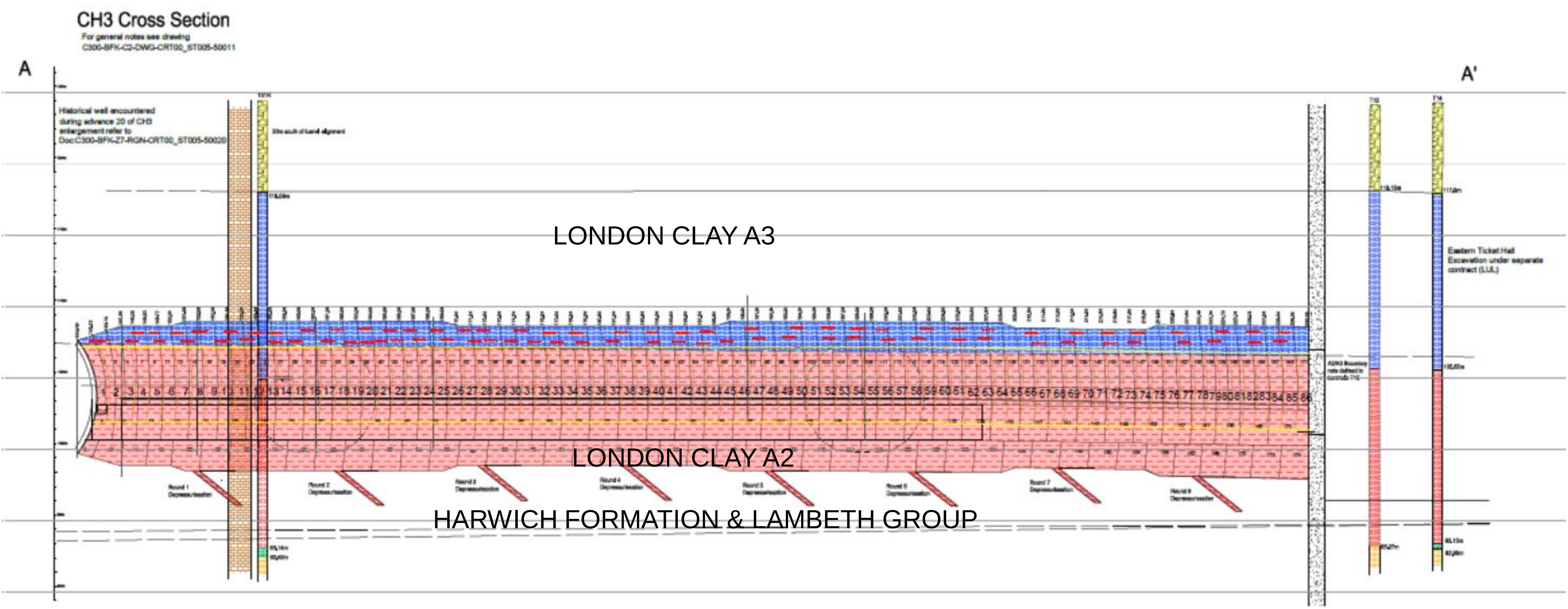
CG Implementation

Grouting Works

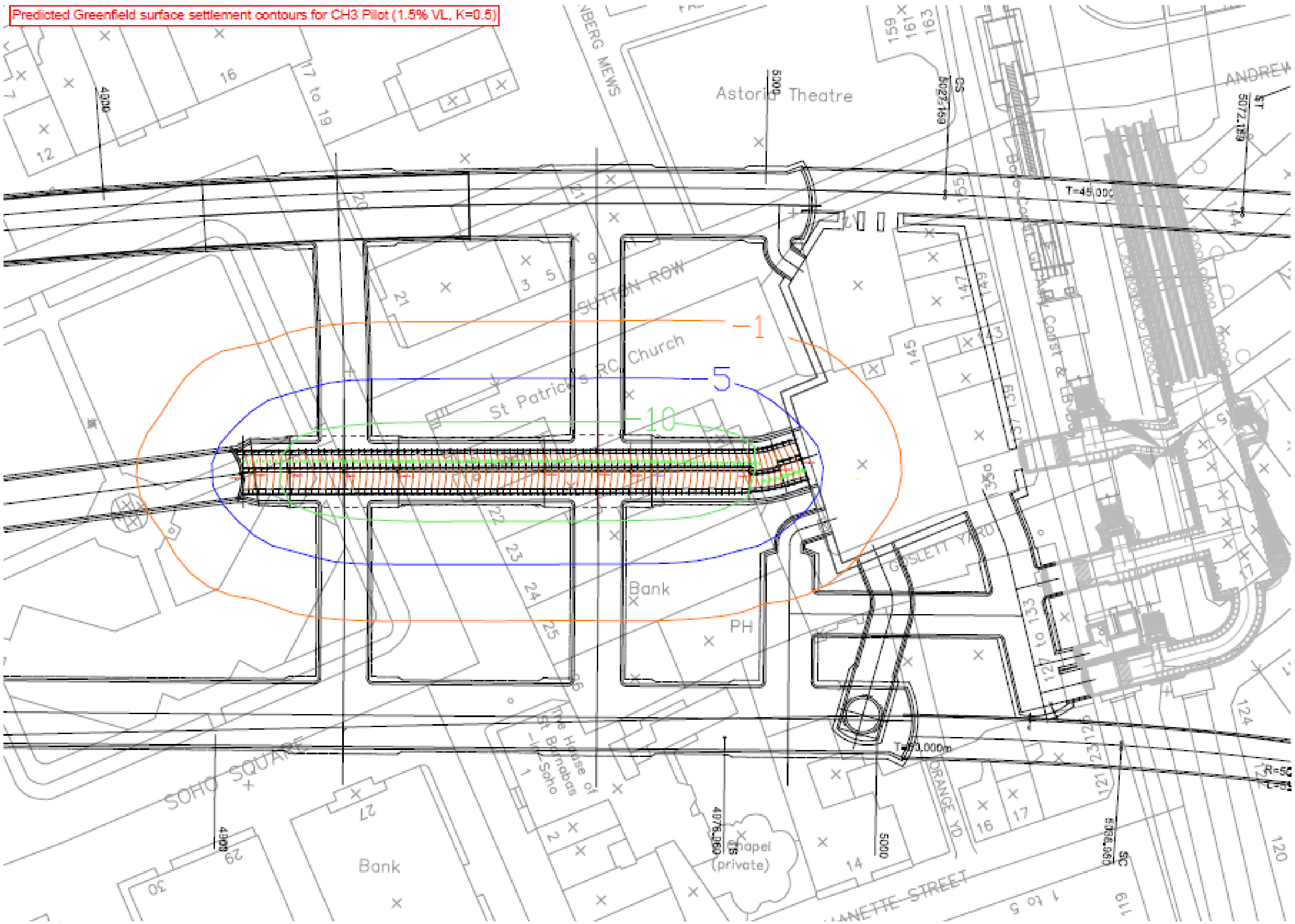
TCR

Concurrent grouting example: TCR CH3

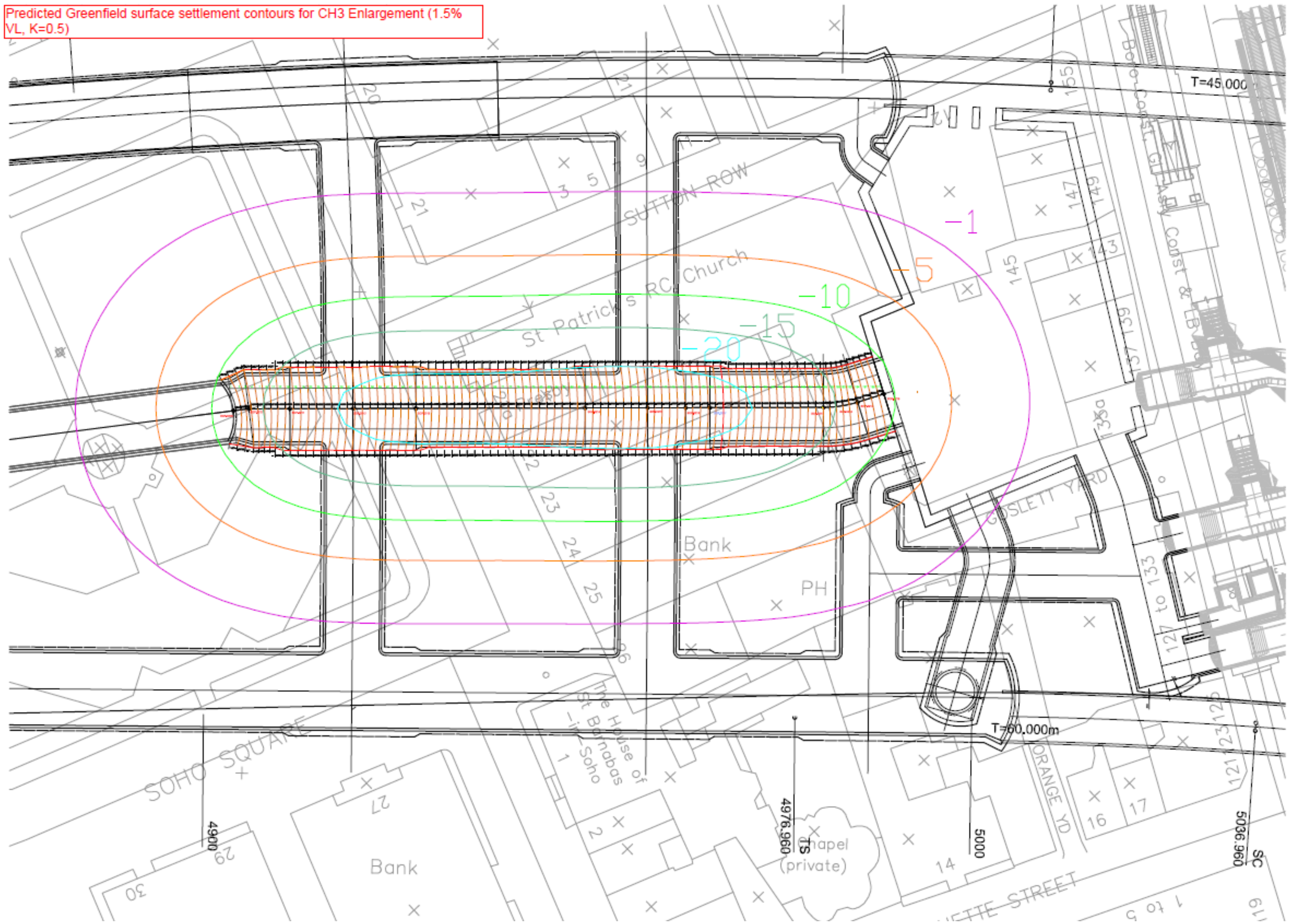
CH3 Geotechnical long section



CH3 pilot – volume loss settlement contour

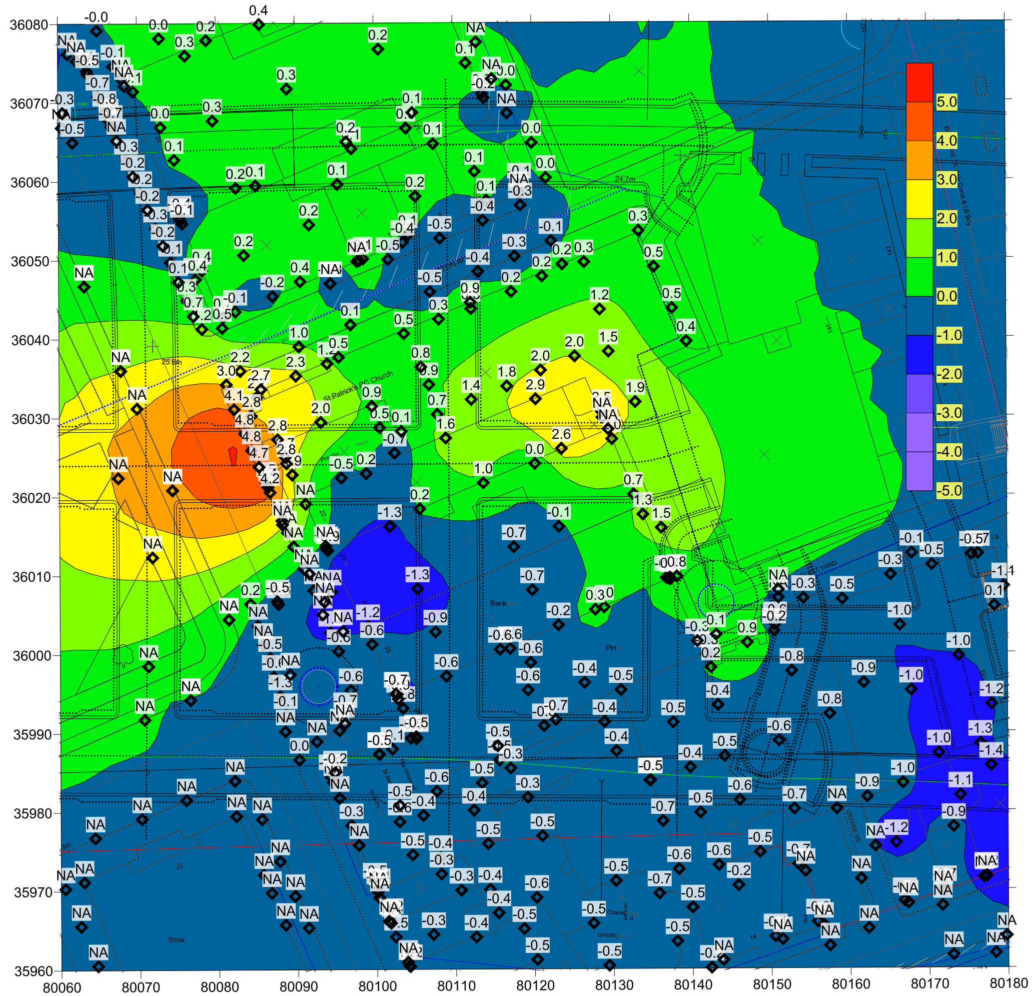


CH3 enlargement – volume loss settlement contour

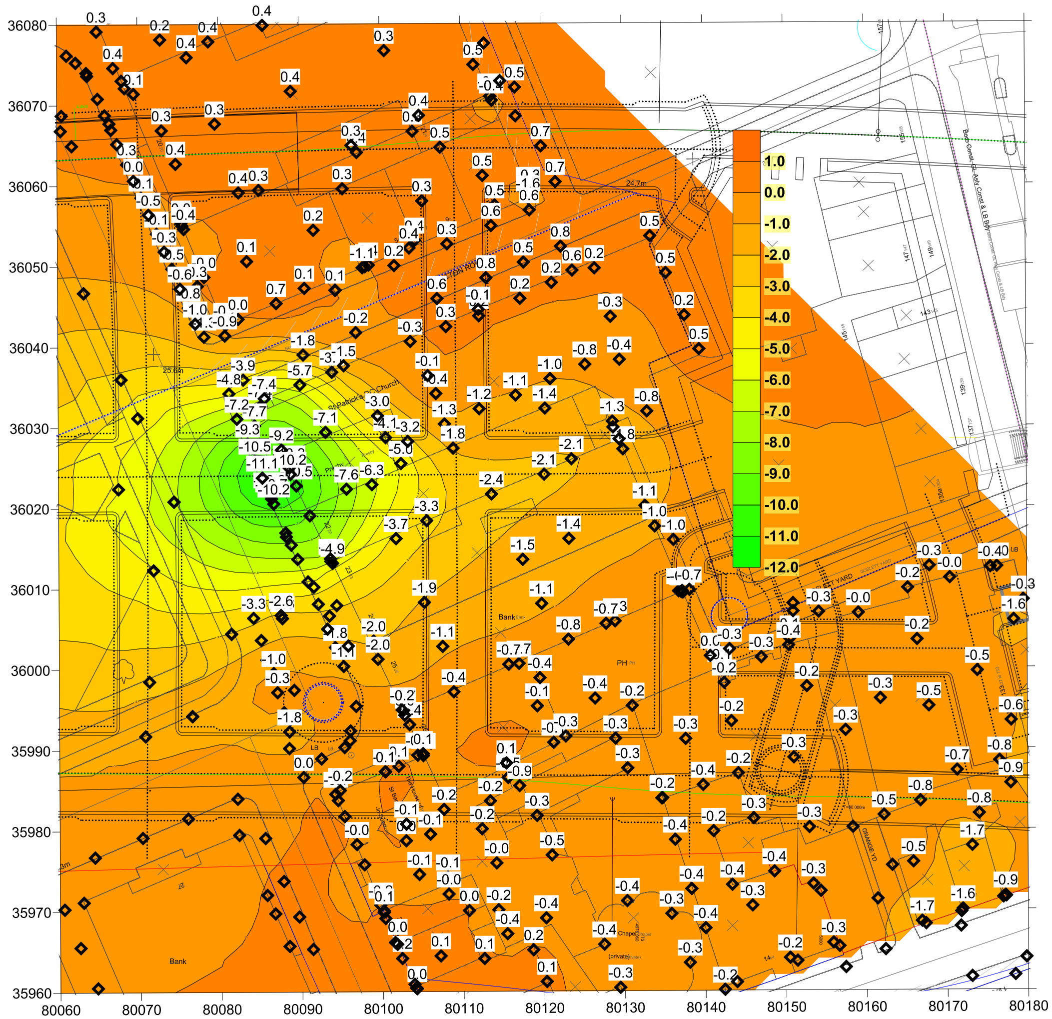


Predicted Greenfield surface settlement contours for CH3 Enlargement (1.5% VL, K=0.5)

CH3 pilot observed settlement

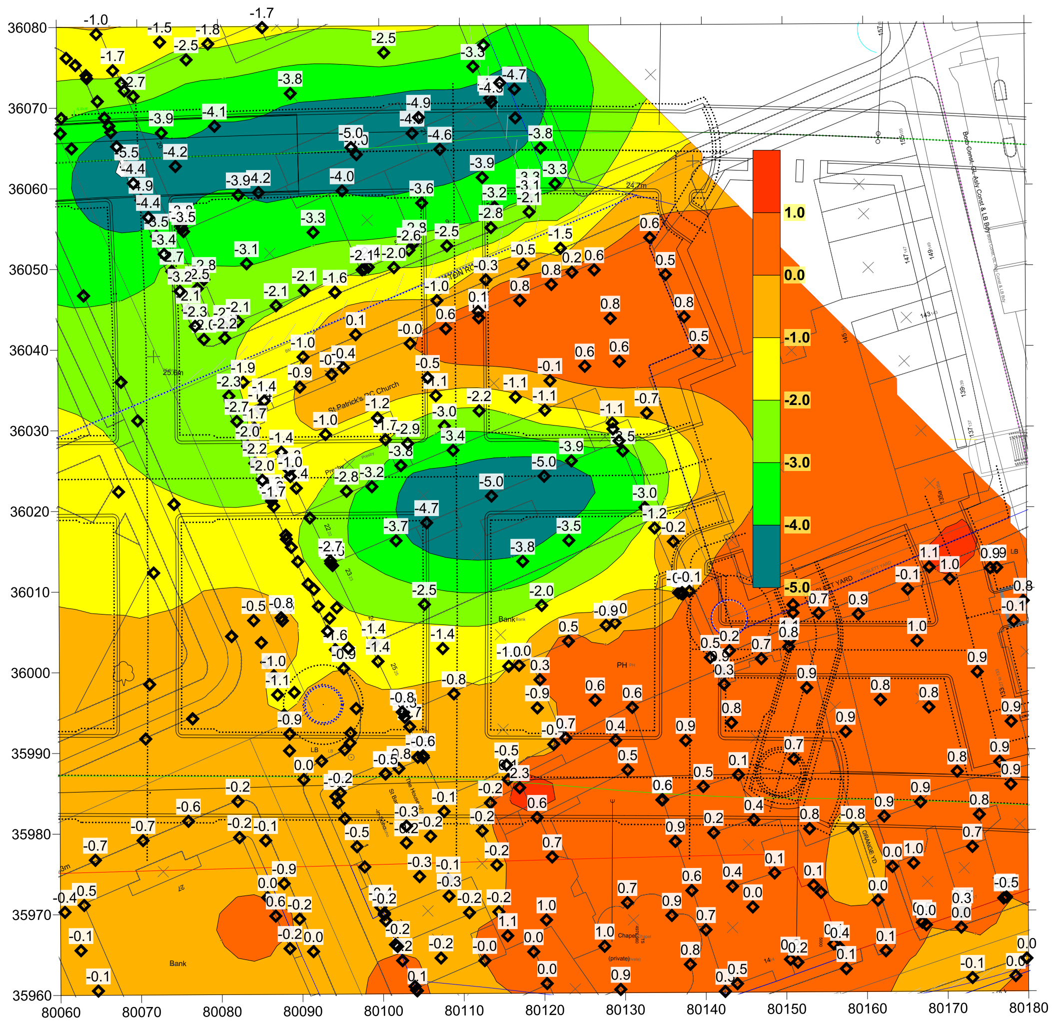


CH3 enlargement – Phase 1 observed settlement

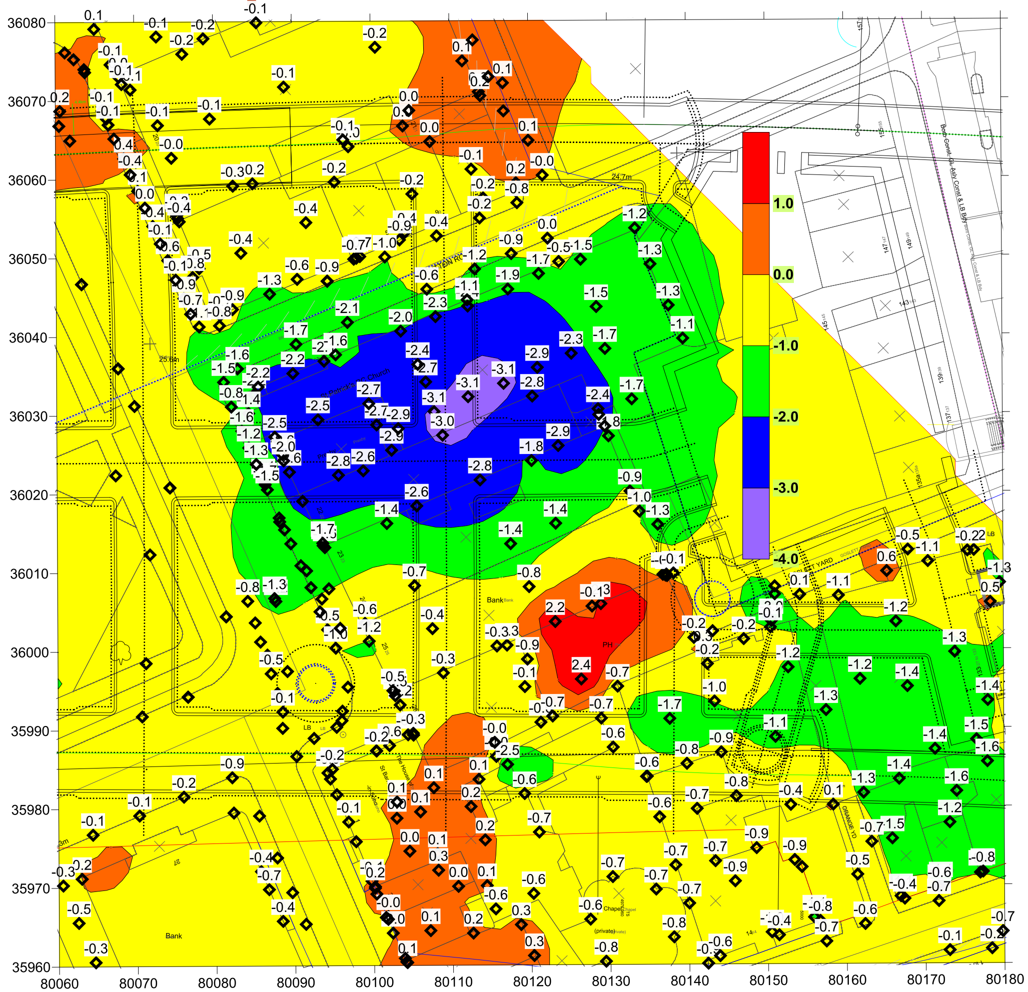


Crossrail

CH3 enlargement – Phase 2 observed settlement



CH3 enlargement – observed settlement 2 weeks after completion



MOVING LONDON FORWARD

IS-GI 2012 SHORT COURSE 4

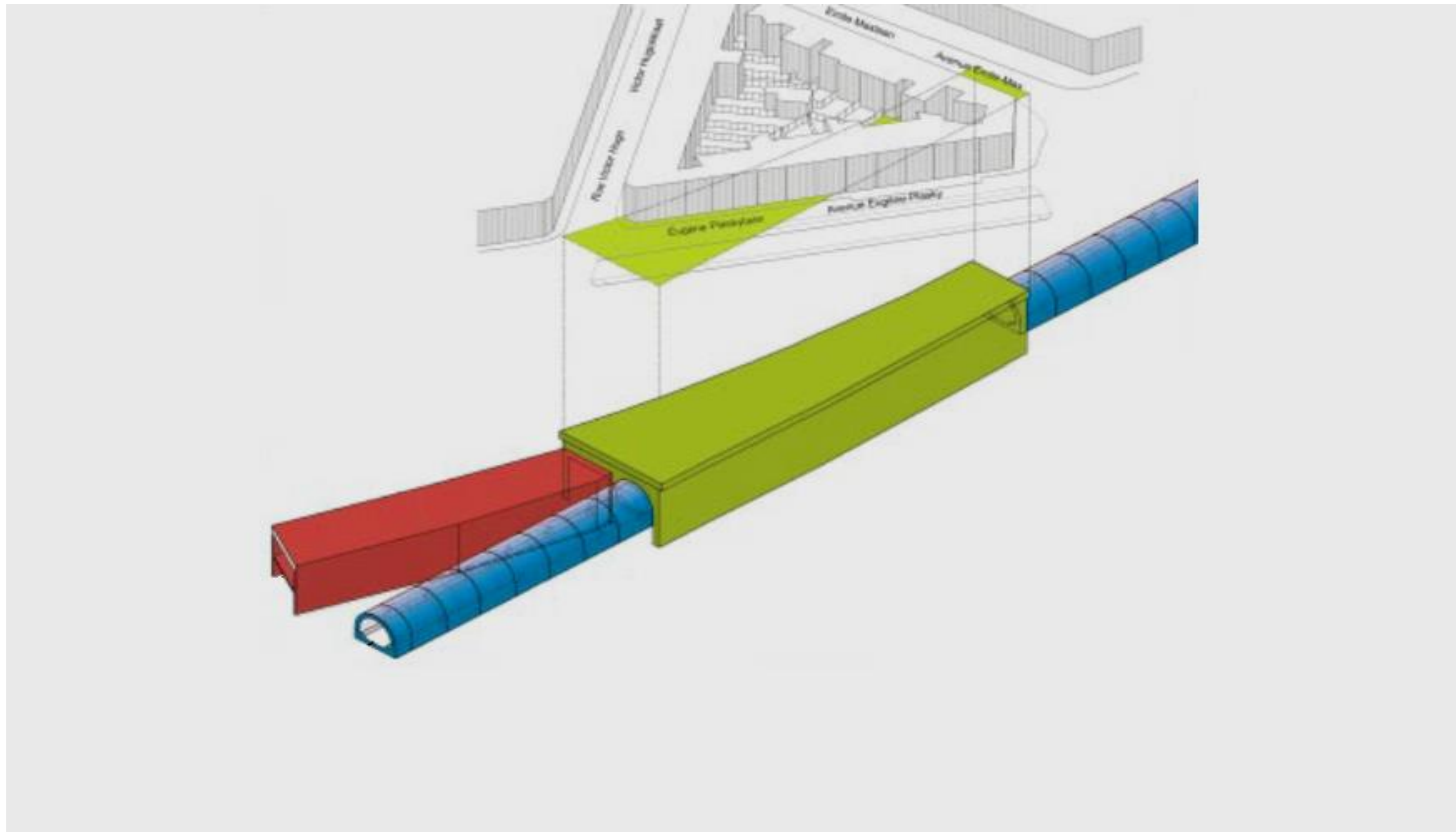
COMPENSATION GROUTING & JET GROUTING

Shumann Josaphat project in Brussels

Y. Stevens, Denys, Belgium

ISSMGE – TC 211

Short Course 4 – Compensation Grouting and Jet Grouting



Shumann Josaphat project in Brussels

Speaker: Stevens Yannick, Denys, Belgium

DENYS

Contents

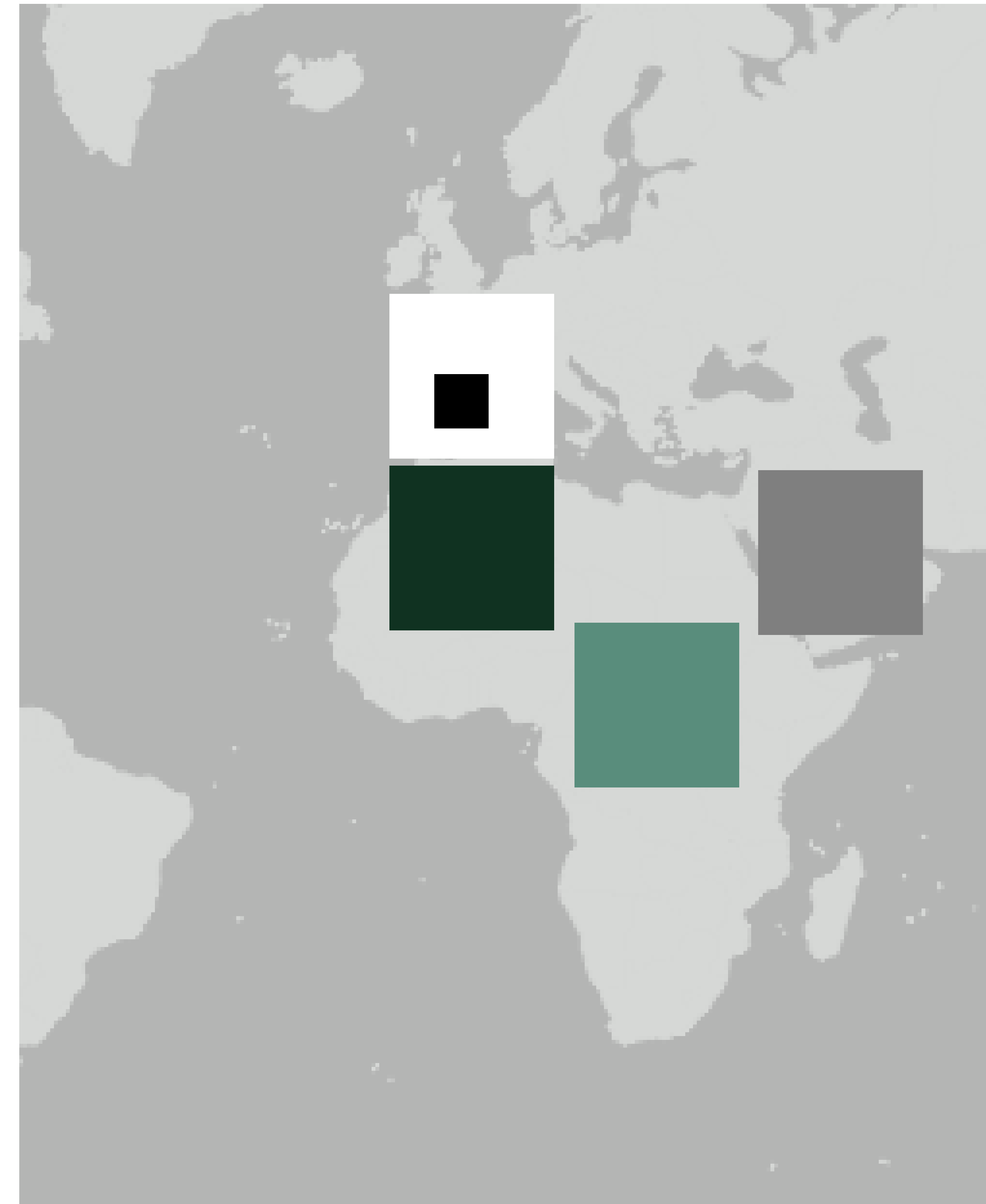
1. General project presentation;
2. Geology of the construction site;
3. Several types of grouting in Shumann-Josaphat;
4. Compensation grouting;
5. Key elements for a successful process;
6. Example measurements;

DENYS

Turnover:

- 250 mill. euro
- 1300 employees

40%	Belgium
30%	Europe (Netherlands, France, Italy, Czech Rep., Switzerland)
15%	Sub-Sahara (Cameroon, Niger, Ghana, Congo RDC, Chad)
10%	North-Africa (Algeria, Morocco)
5%	Middle-East (Yemen, …)



Our 6 Business Units...

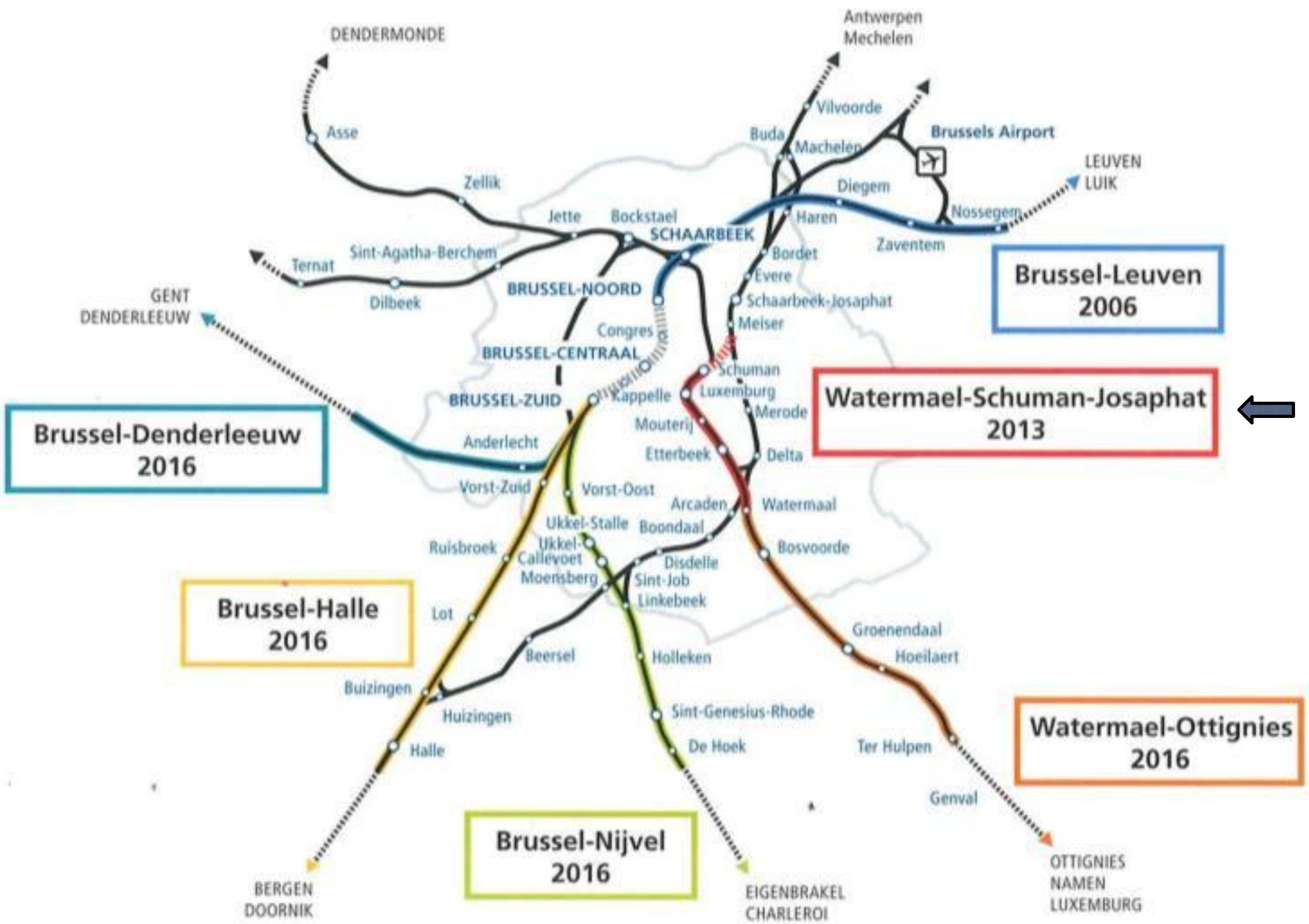
- Pipeline works
- Tunnelling works
- Water works
- Civil works
- Building works
- Restoration works

DENYS

1. General project presentation

Brussels suburban rail programme (INFRABEL):

- Improve travel around the city;
- Regional express links to the rest of the country



Underground rail improvement Schuman-Josaphat

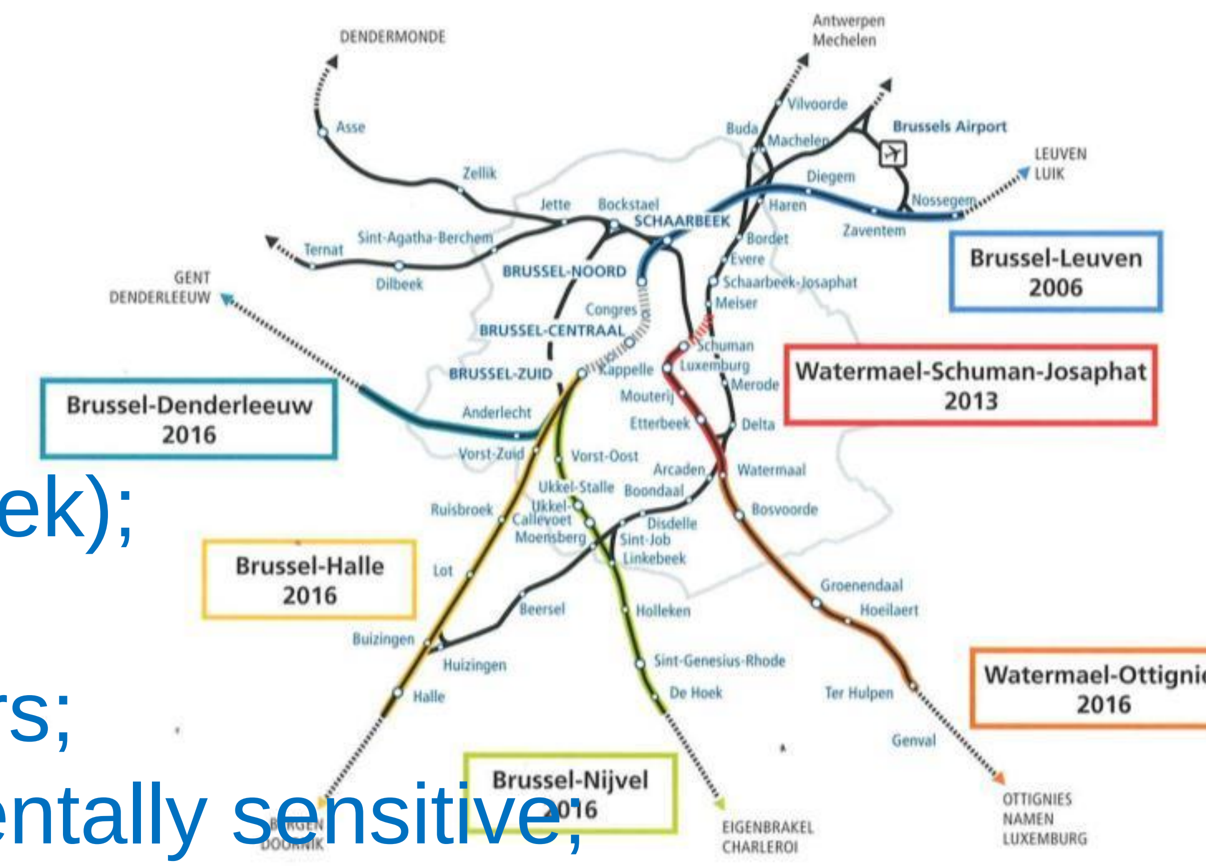
Lot 2/2 – mined tunnel and junction to operational line 26

1. General project presentation

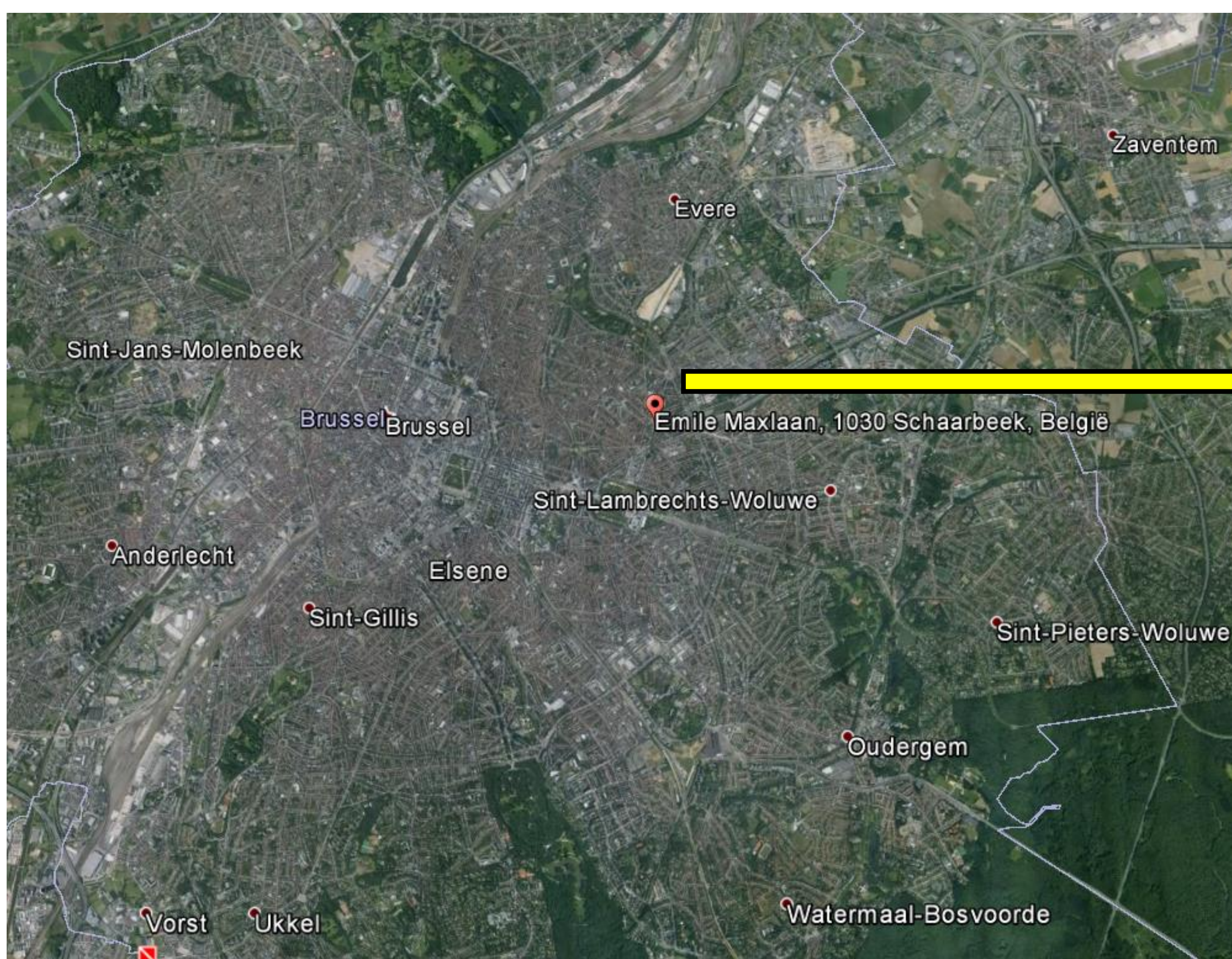
Client: Beliris/Infrabel
Structural engineering: Grontmij/Infrabel
Starting date: 04/08/2008
Construction period:48 months
Geotechnical consultant for Denys:Jan Maertens bvba

DENYS

I. General project presentation



- Construction site located in Brussels city center (Schaerbeek);
- New tunnel and tunnel junction beneath avenue Plasky;
- Five storey residential and commercial buildings with cellars;
- Triangular "Isle of houses" (dating 1890 – 1920) environmentally sensitive;
- Limited working space due to narrow streets, traffic, existing infrastructure;
- Underground construction acces starting from 2 shafts;



Tunnel de la ligne 26 existant
Bestaande tunnel van de lijn 26

Nouveau tunnel
Nieuwe tunnel

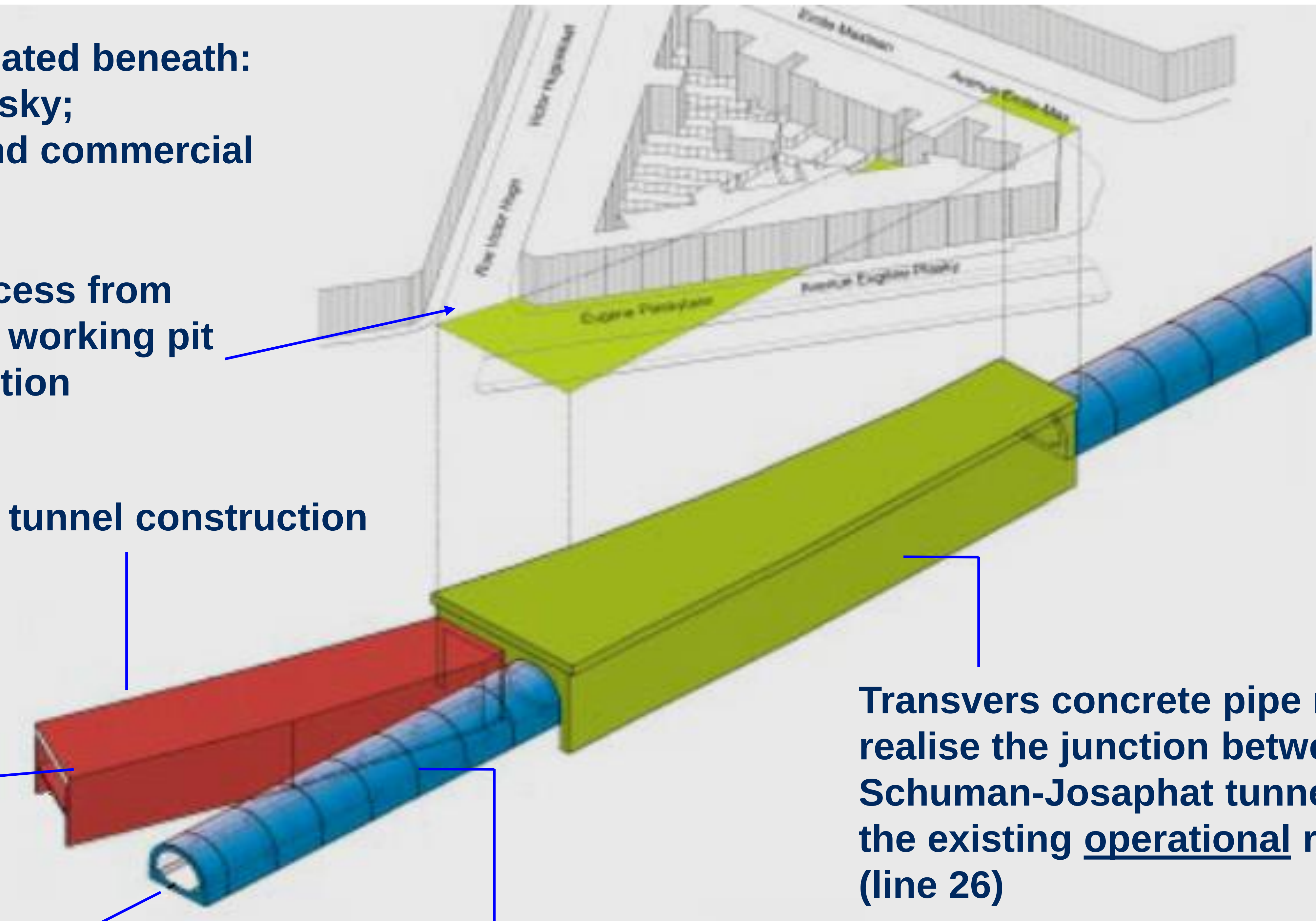
/ / / / Dispositifs anti-vibratoires
Maatregelen voor beperking trillingen

Raccordement du tunnel Schuman-Josaphat au tunnel de la ligne 26
Aansluiting van de tunnel Schuman-Josaphat op de tunnel van de lijn 26

1. General project presentation

Mined tunnel located beneath:
- **Avenue E. Plasky;**
- **Residential and commercial buildings;**

Underground access from shafts and pits – working pit Victor Hugo junction



To Meiser

New tunnel construction

To Brussels-Schuman

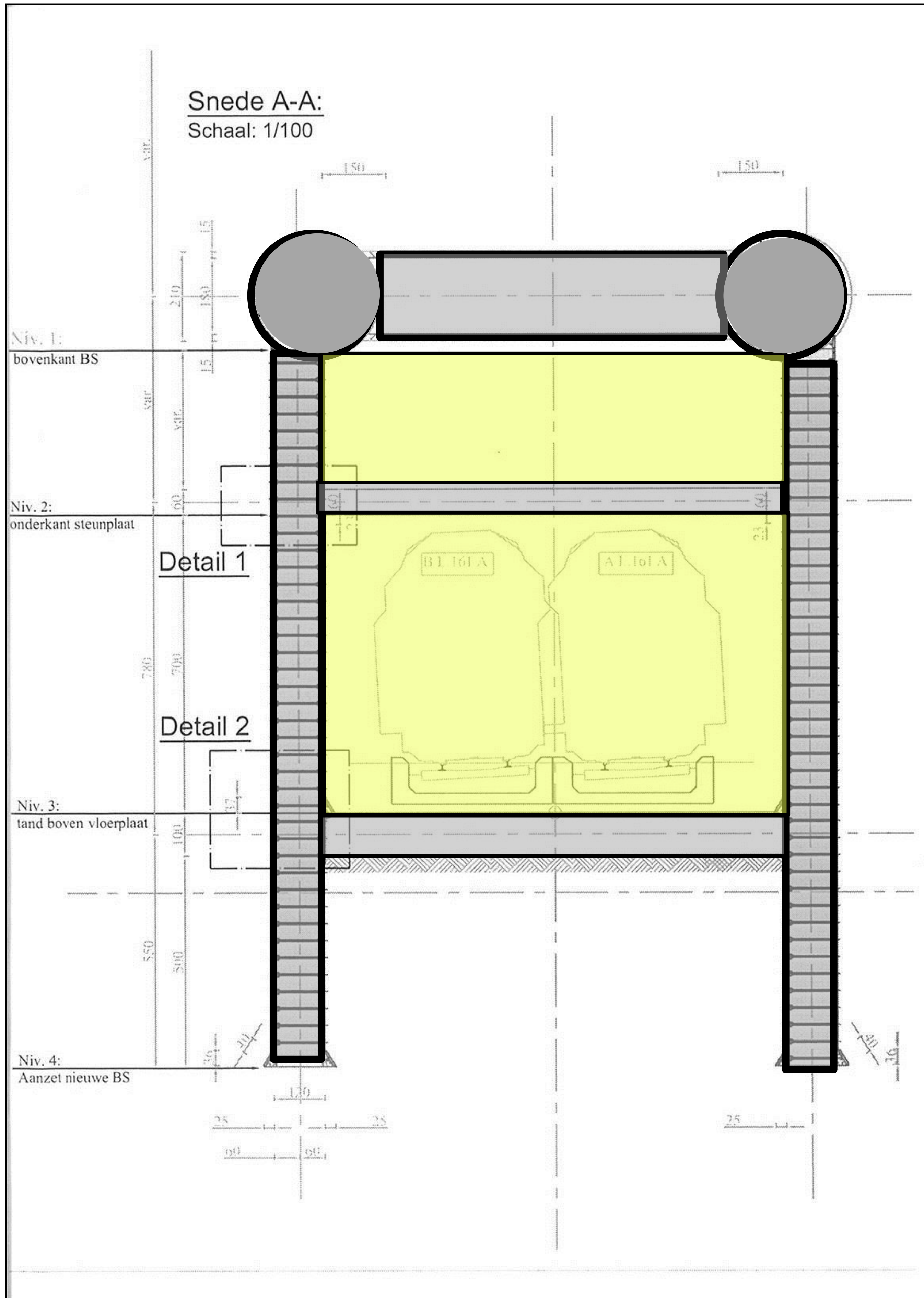
Transvers concrete pipe roof stucture to realise the junction between the new Schuman-Josaphat tunnel (line 161) and the existing <u>operational</u> railway tunnel (line 26)

To Delta

Existing tunnel line 26

1. General project presentation

1. Construction stages



STAGE 1: Longitudinal steel pipe drives – DN3000 by mechanised pipe jacking

STAGE 2: Manually dug slot walls

STAGE 3: Transverse concrete pipe jacking DN2100

STAGE 4: Concrete filled pipe-roof and reinforced concrete walls

STAGE 5: First excavation phase in canopy (stross)

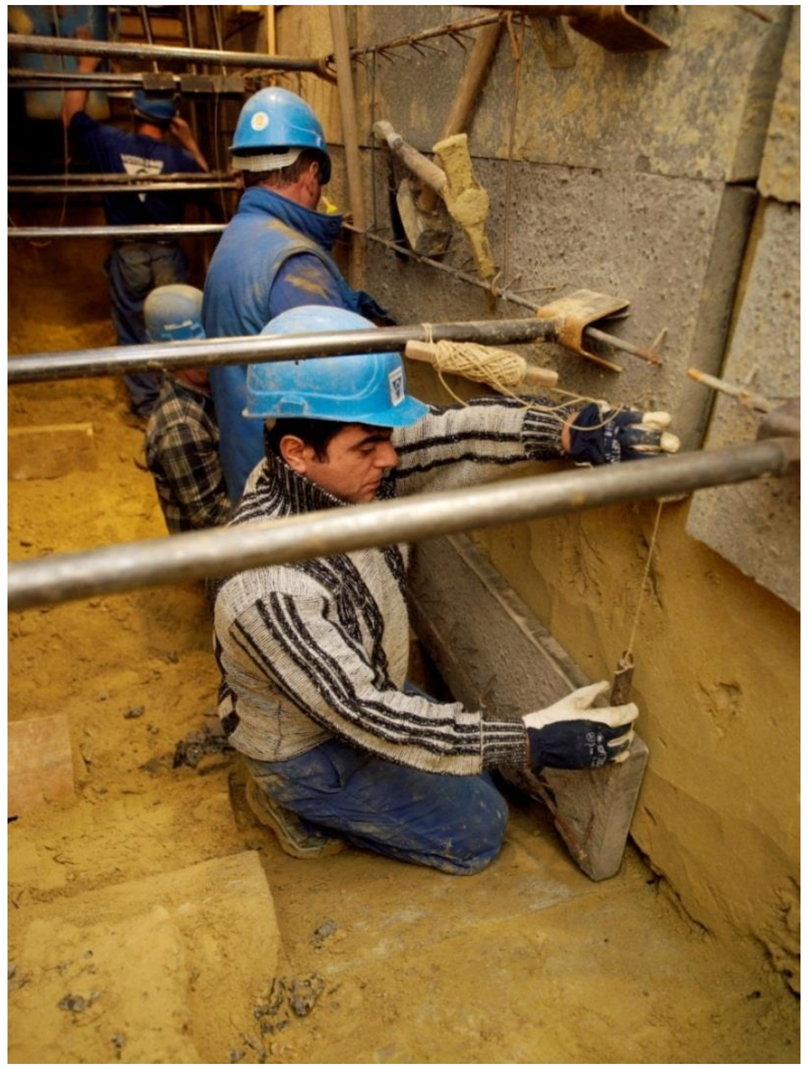
STAGE 6: Construction of struts in between slot walls

STAGE 7: Second excavation phase beneath strut and pipe roof

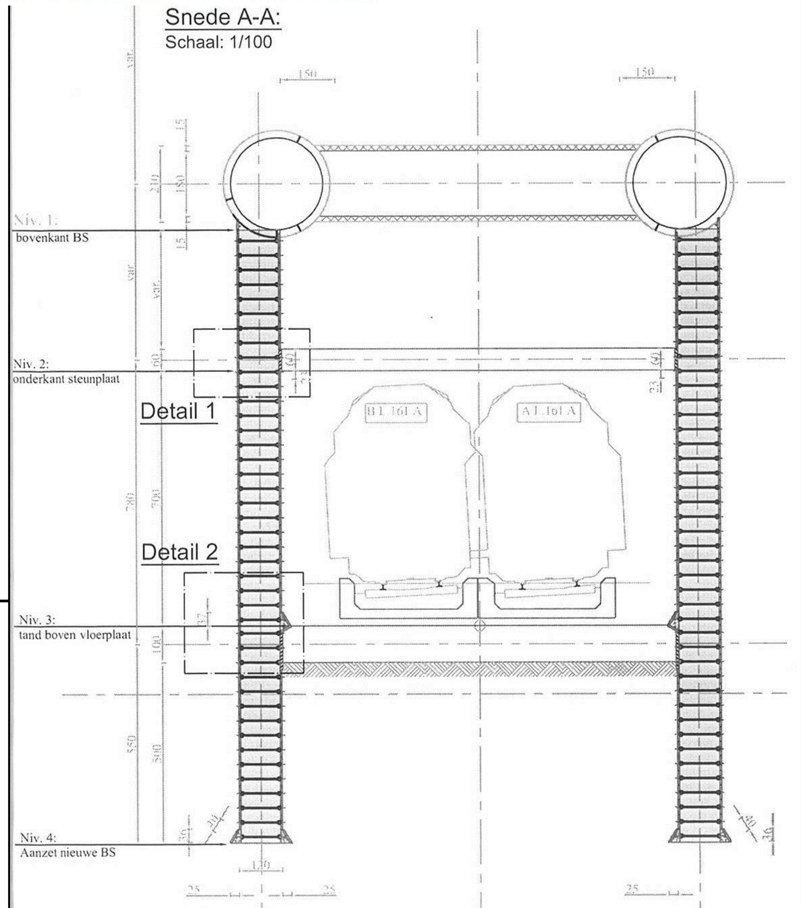
STAGE 8: Concrete floor slab/strut

1. Construction stages

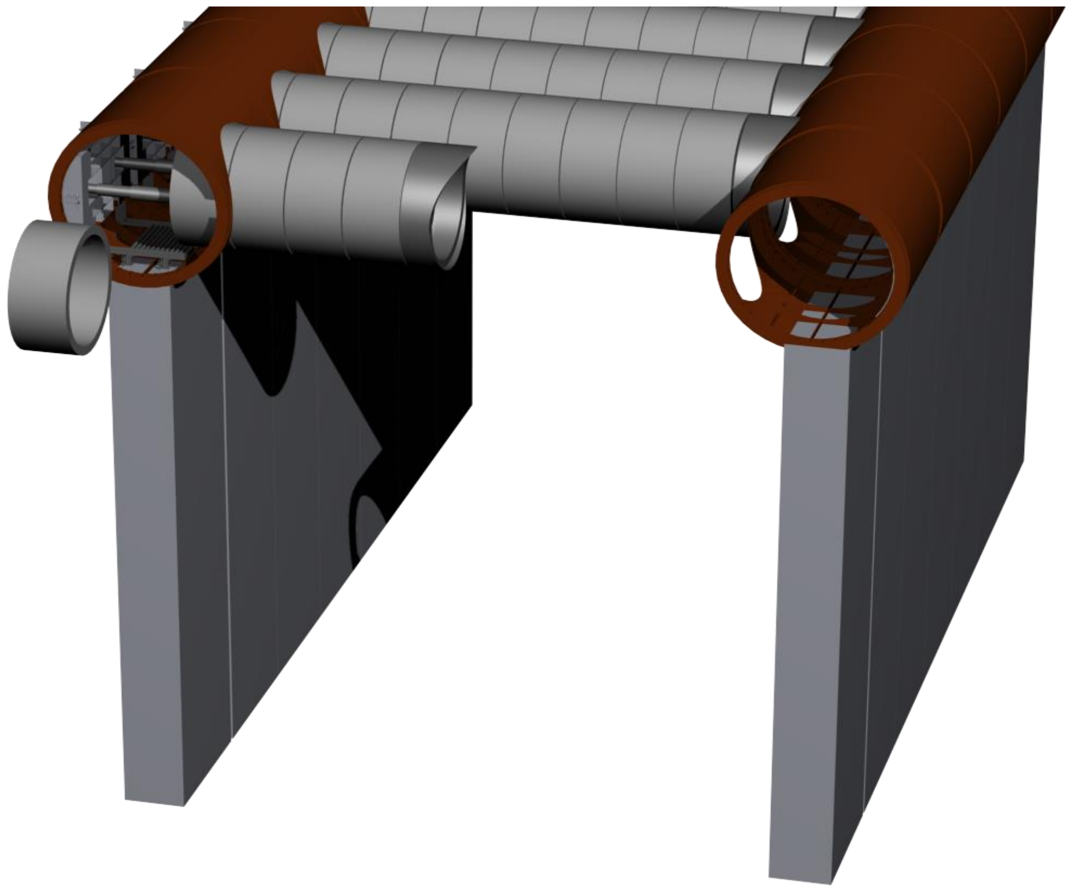
Longitudinal steel pipes – DN 3000



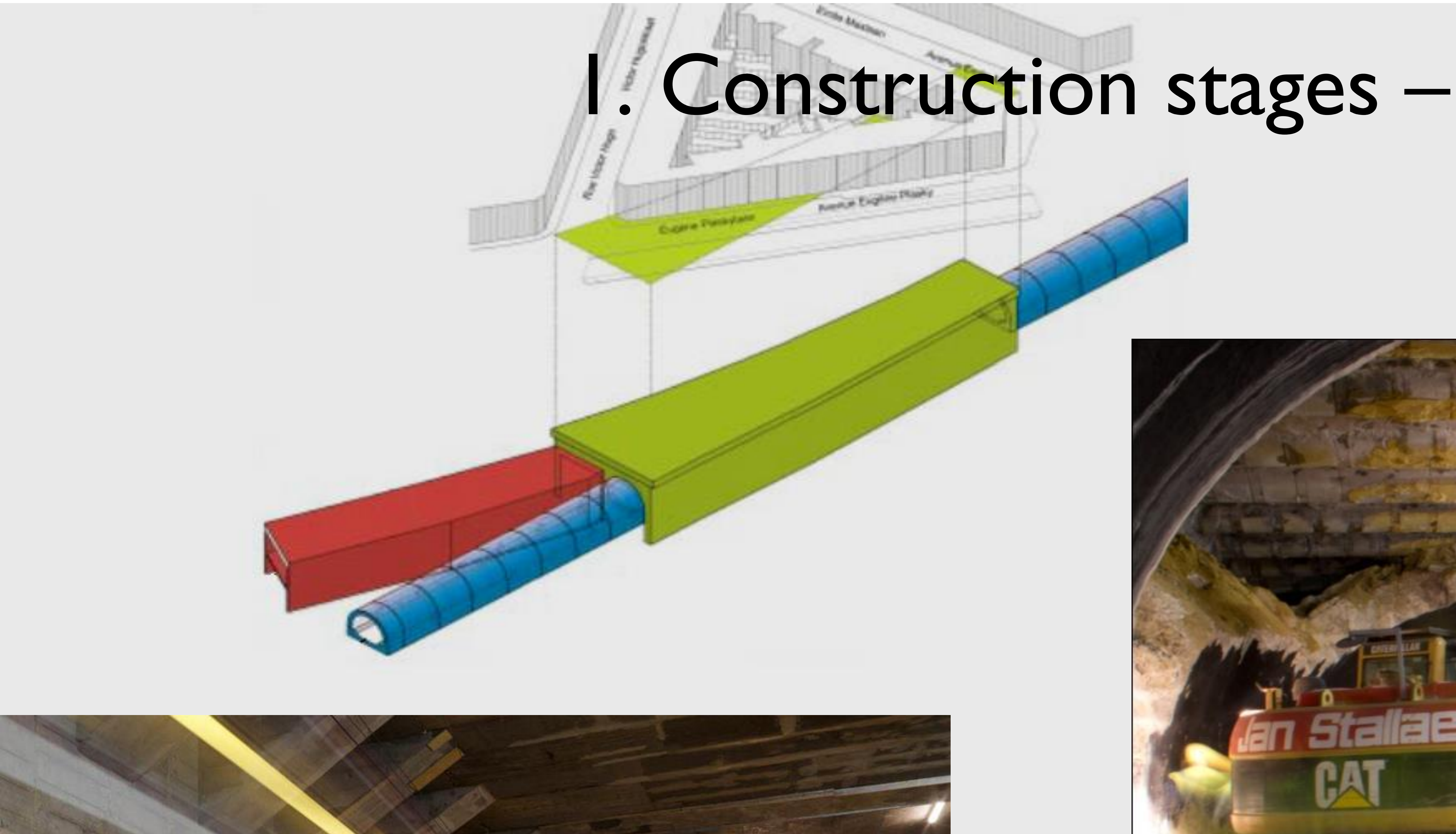
Manually dug slot walls



1. Construction stages – transverse pipe roof



I. Construction stages – excavation




Picture: tucrail.be

Excavation in narrow spaces: train traffic continues
Demolition of old tunnel in 1 week: train connections suspended

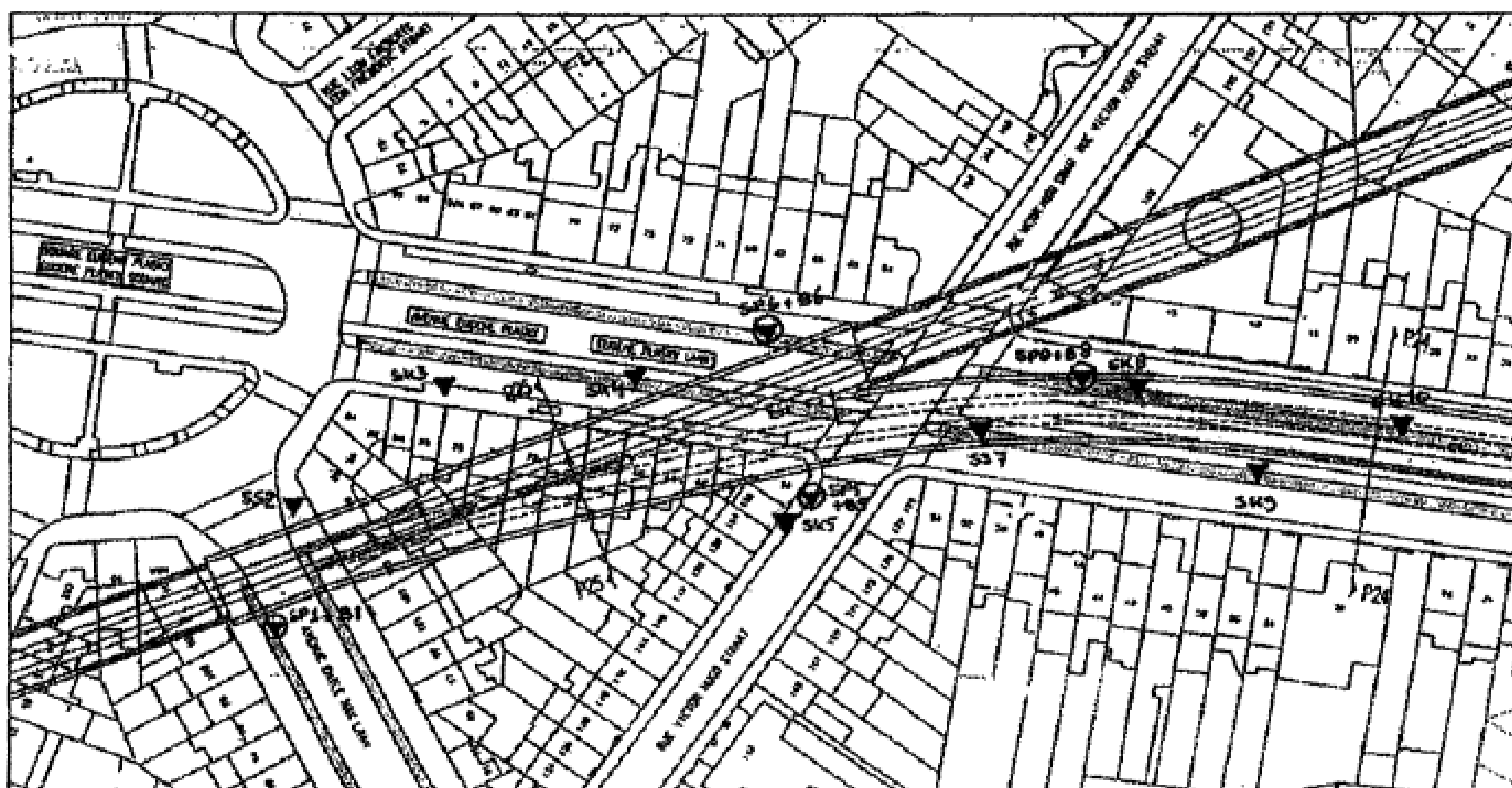
2. Geology of the construction site

Different sources for soil investigation data:

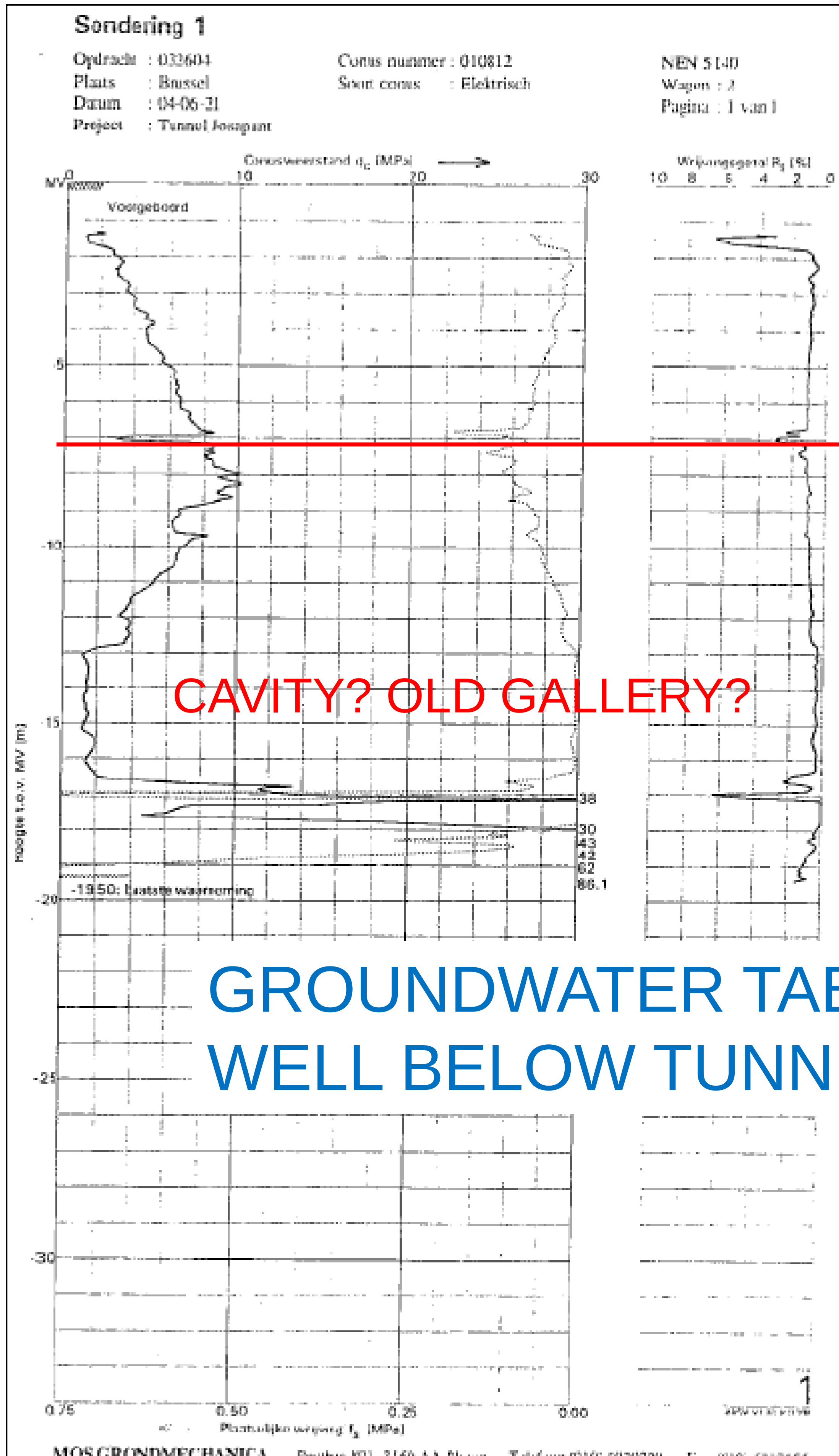
1. Cone penetration tests (CPT) made by client;

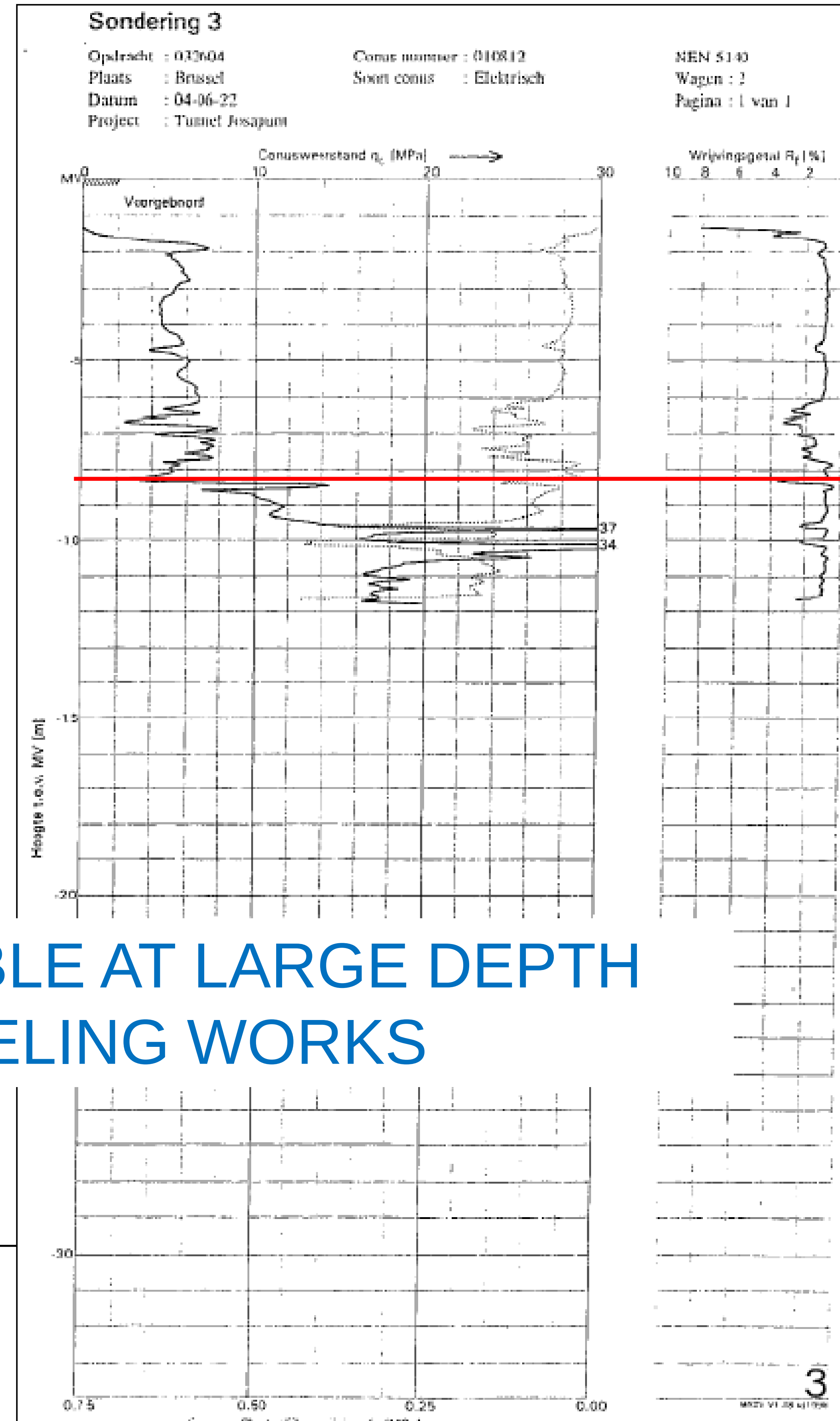
2. Pressuremeter tests (PMT) made by client;

3. CPT's and boreholes from Databank Ondergrond Vlaanderen, free online database for geotechnical data in Flanders and Brussels;



2. Geology of the construction site





GROUNDWATER TABLE AT LARGE DEPTH
WELL BELOW TUNNELING WORKS

Difficult to distinguish layers
Variable CPT-data
Extra soil investigation necessary

- **Man made material**
  - Top layer;
  - Variable characteristics;
- **Quaternary LOAM**
  - Typical for Brussels;
  - Variable characteristics;
  - Locally alluvial loam/silt;
  - Difficult to distinct;
- **Tertiary Ledian SAND**
  - Sandstone banks;
  - Historical information on mining;
  - Possible galleries, cavities;
  - Decalcification sandstones;
  - Evidence found in CPT;

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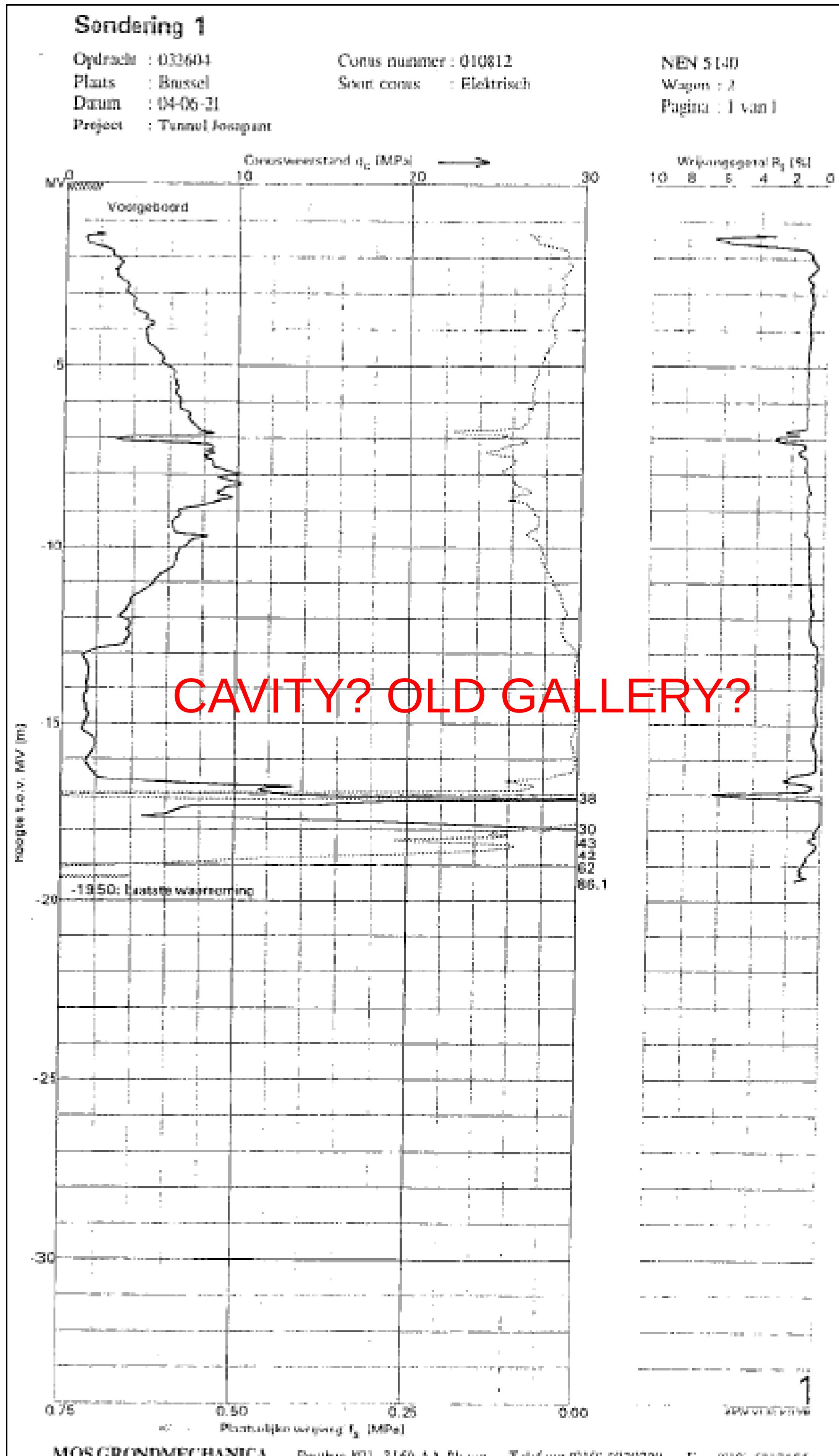
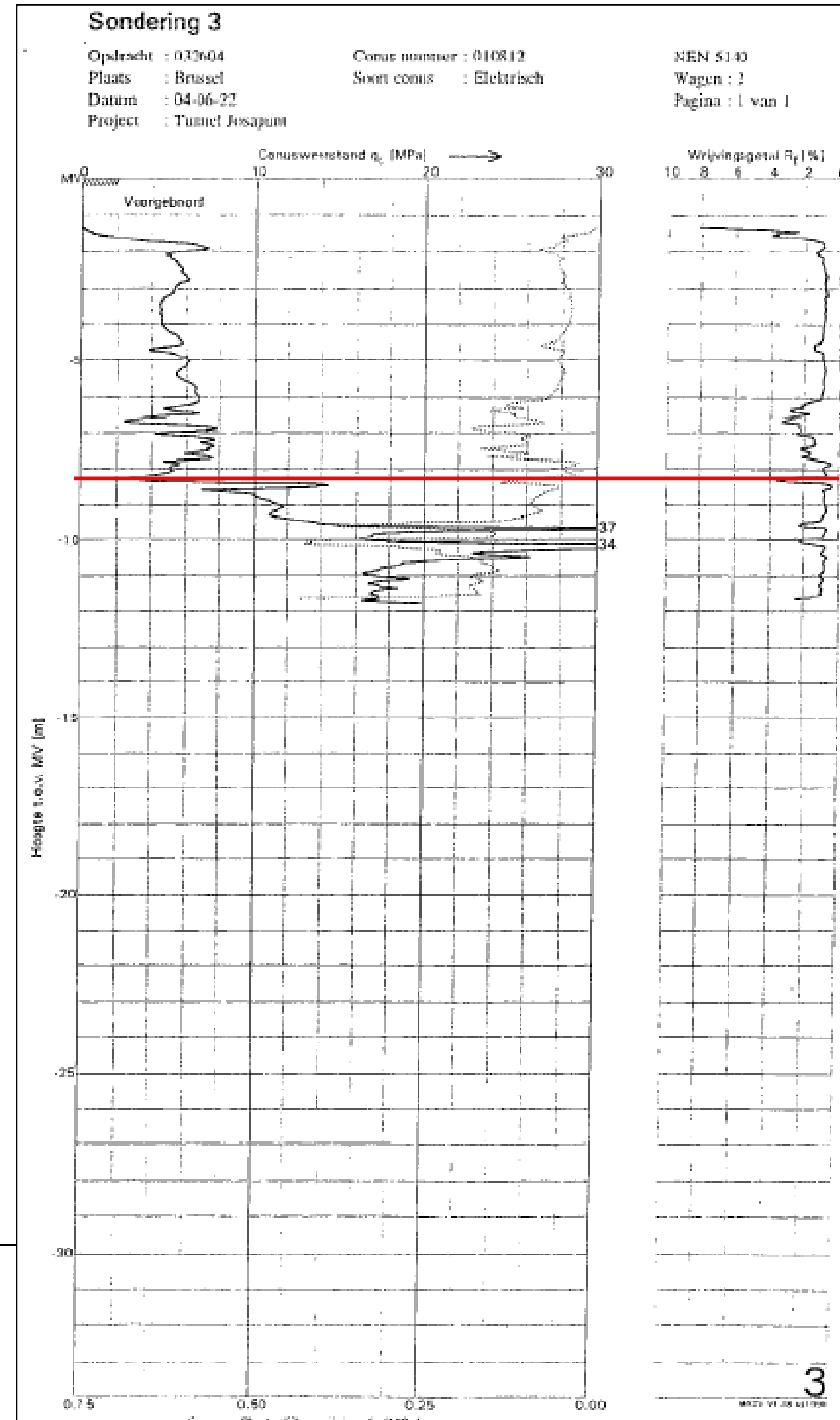
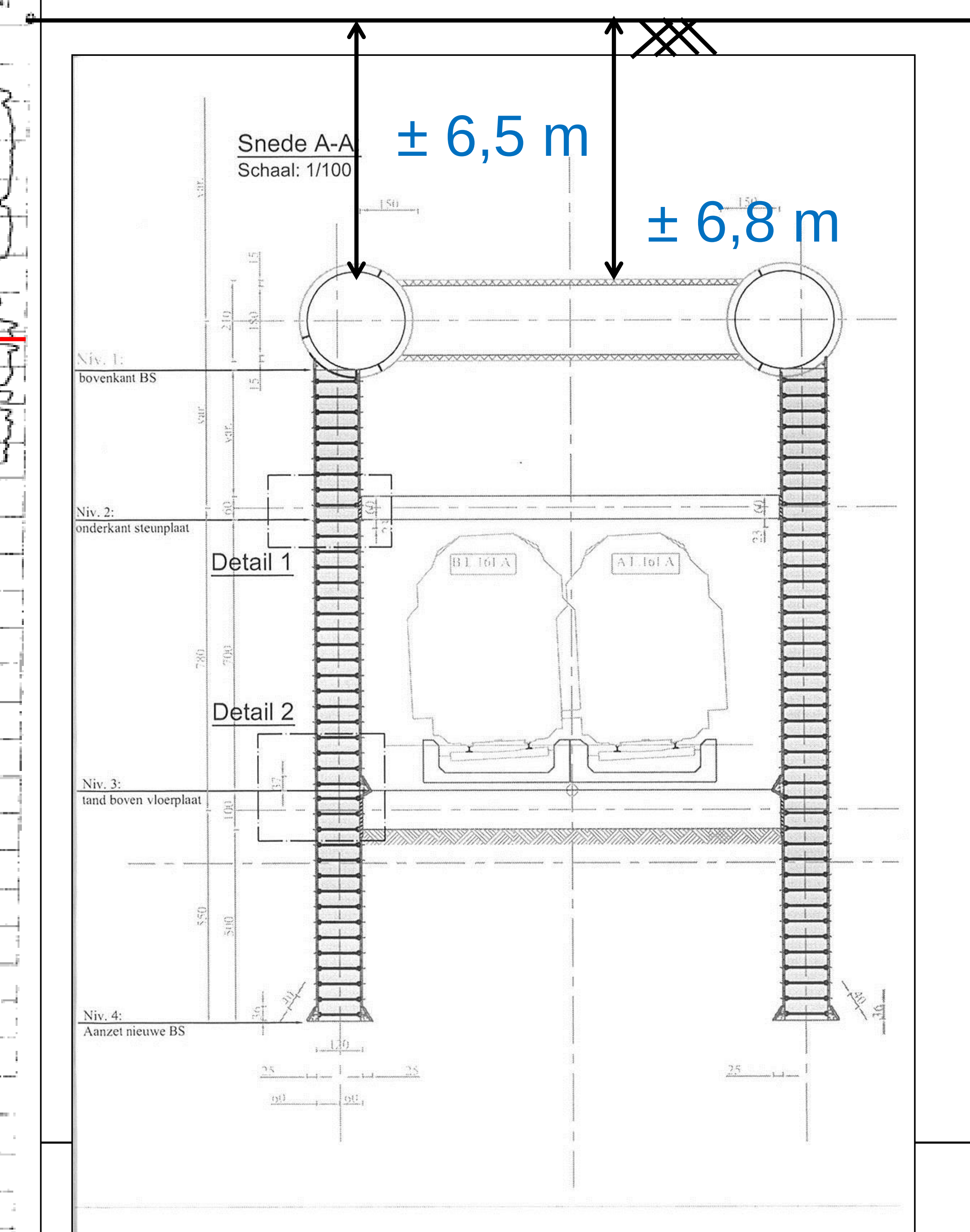
2. Geology of the construction site







2. Geology of the construction site

Three important issues:

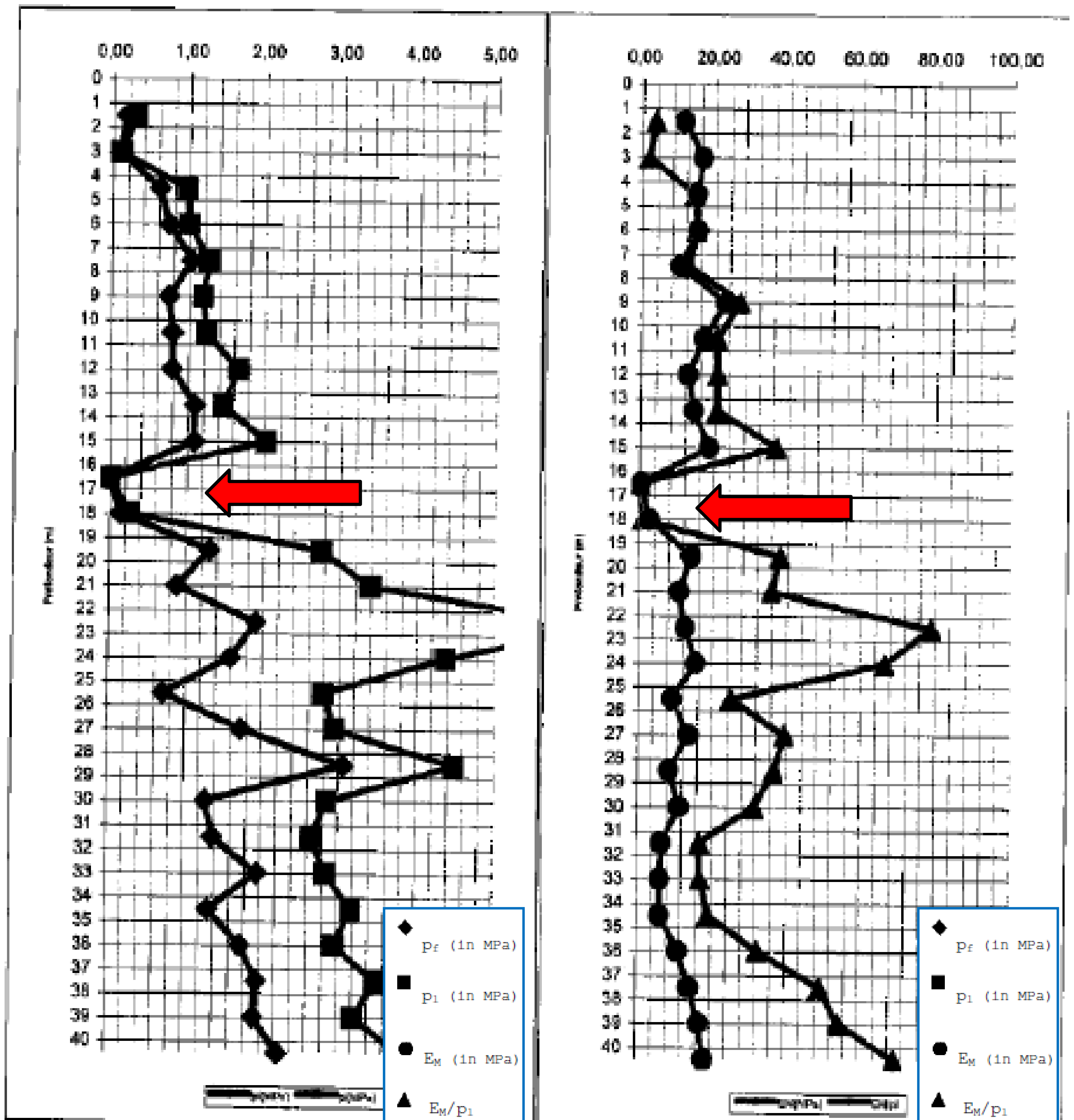
1. Construction of tunnel is **quite close to basement structures** of housing blocks – vertical distance from 3,5 m to 6m;

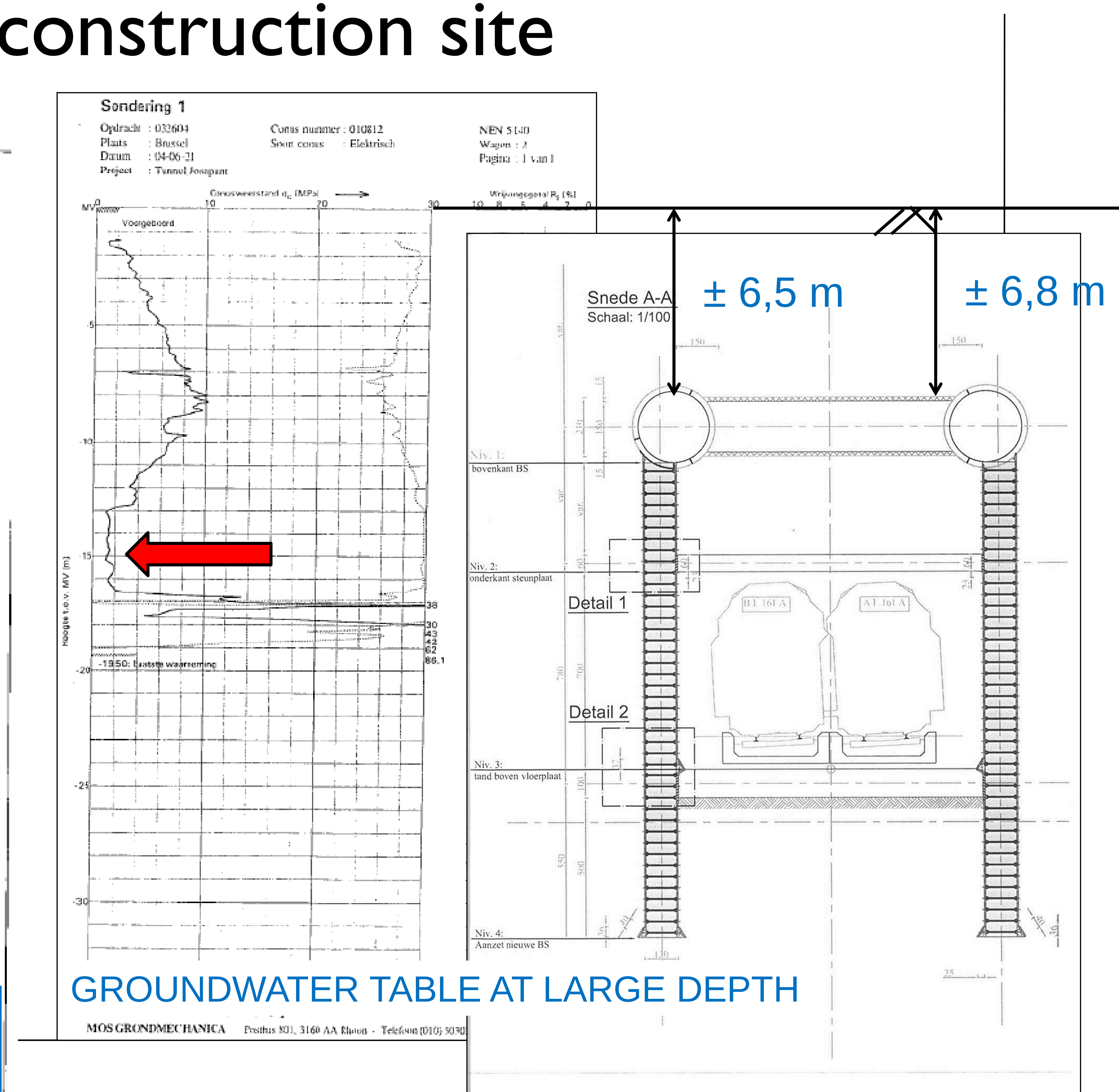
2. Tunnel construction mainly located in Tertiary sand layers where **old galleries, cavities and porous areas** might be encountered;

3. Compensation grouting for settlements induced by tunnel works will mainly be necessary in **Quaternary loam layers**;

2. Geology of the construction site

Pressuremeter test SP21





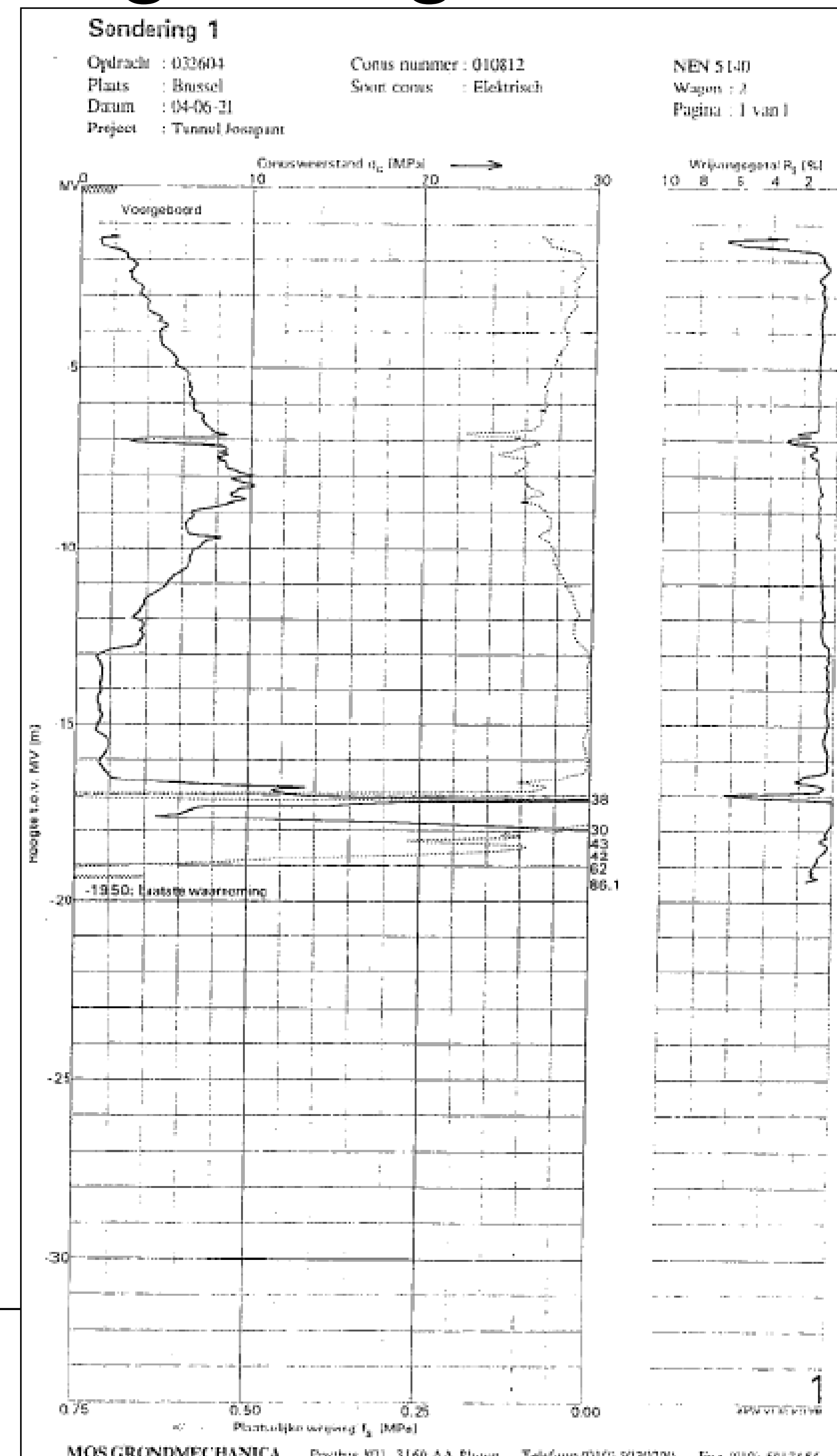
3. Several types of grouting in Shumann Josaphat

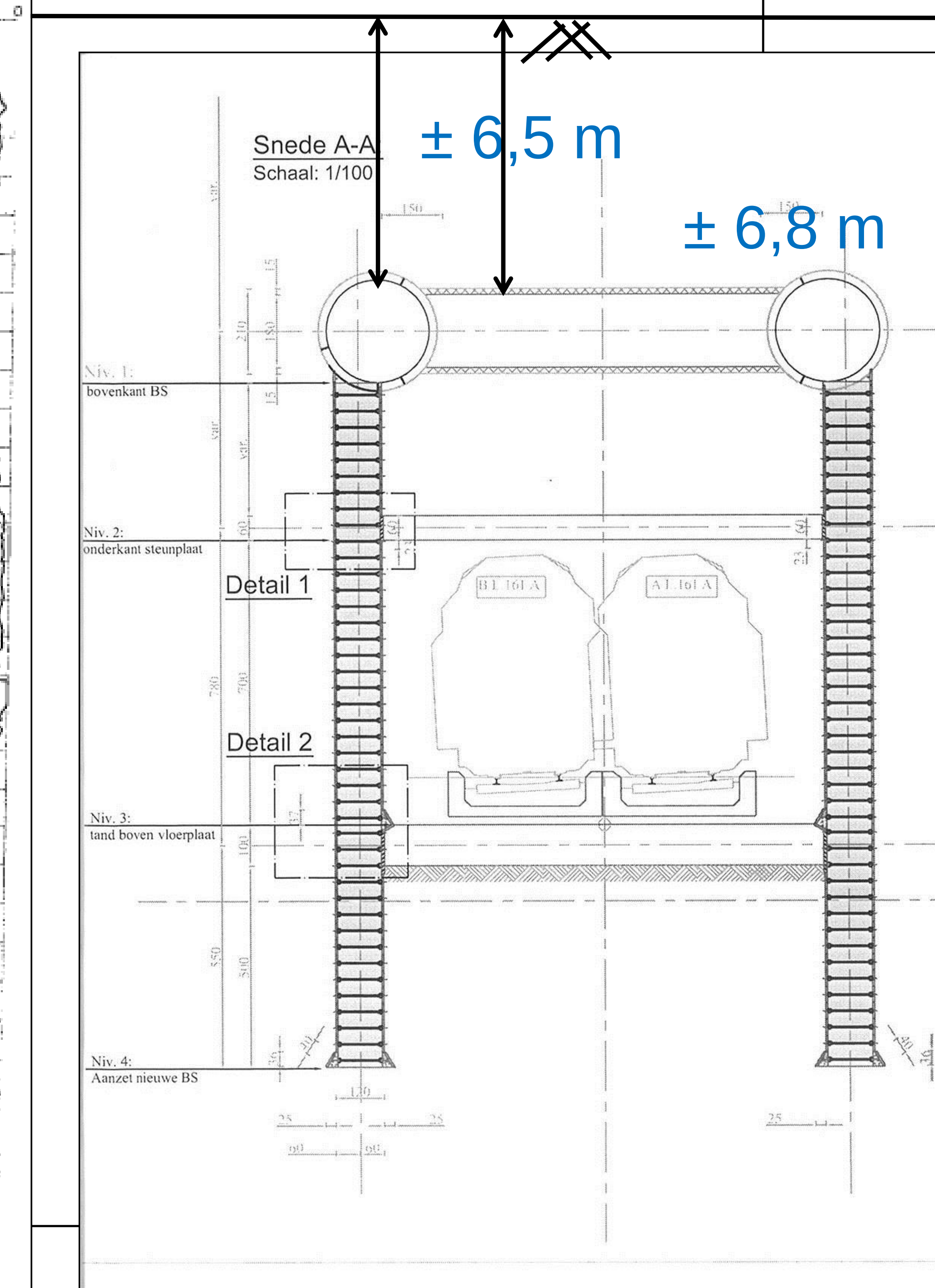
1. Exploratory boreholes to find possible cavities, galleries during jacking, mining => **bulk filling**;

2. Exploratory boreholes + injections + grouting underneath, around slot wall trenches
   a) Possible cavities below trench bottom
   b) Grouting behind prefab concrete plates of the slot walls

   Bulk filling and fissure/contact grouting

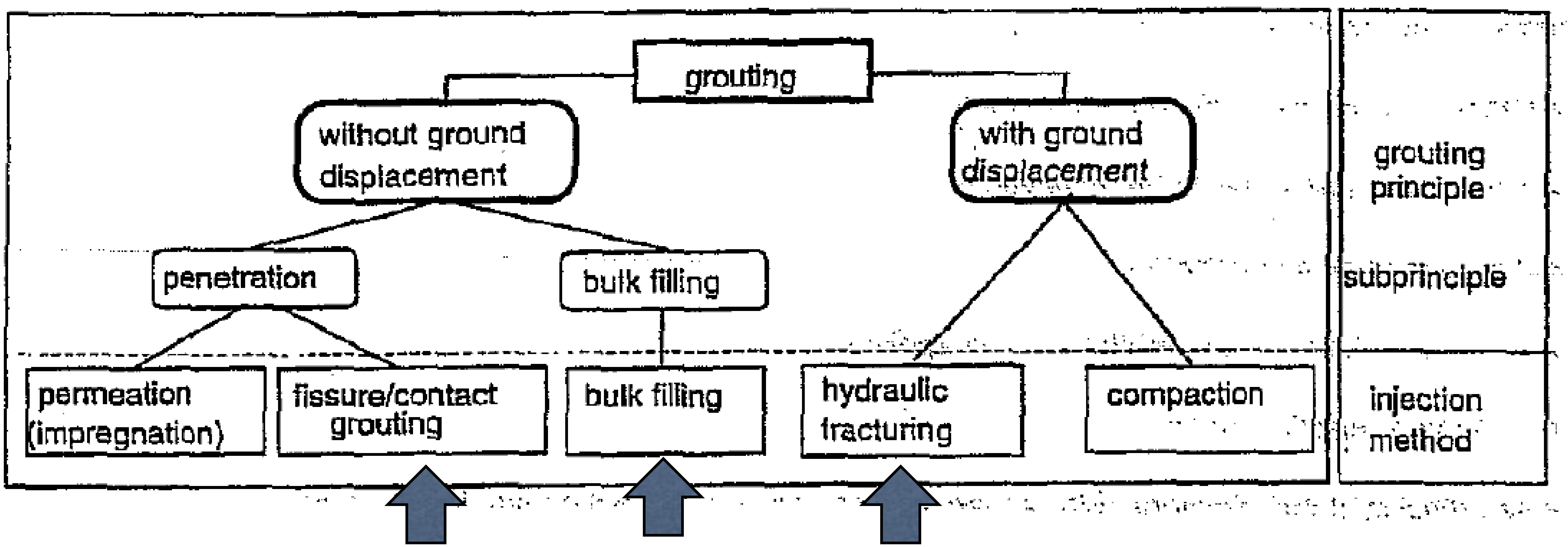
3. Compensation grouting, **fracture grouting** to compensate settlements of building due to tunneling works





3. Several types of grouting in Schumann Josaphat

EN 12715:Execution of special geotechnical work - Grouting



4. Compensation grouting

Geotechnical consultant:

Choice for fracture grouting **based on soil investigation data** (loam layer) + **experiences** in similar tunnel projects.

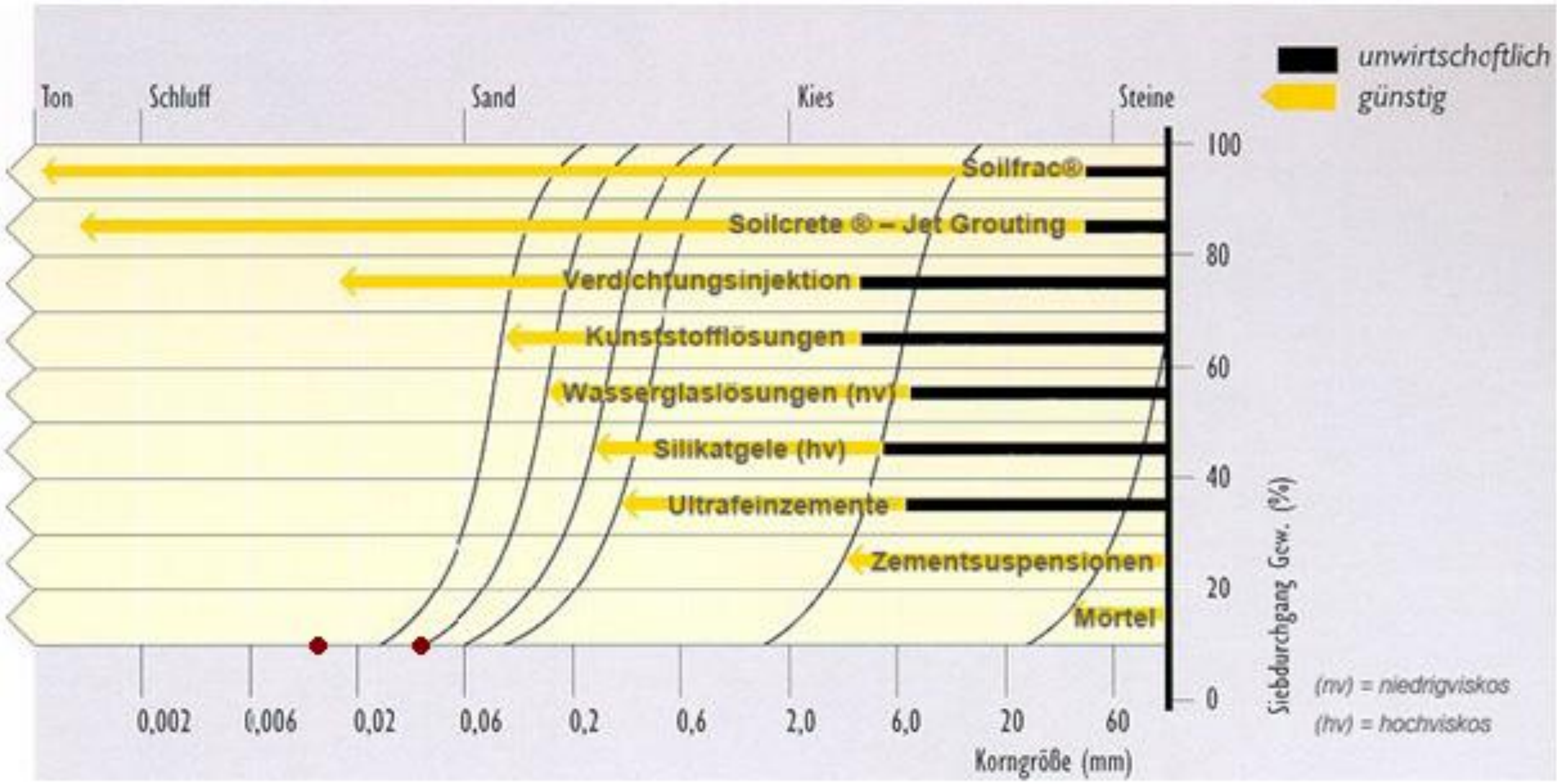
Possible applications fracture grouting (EN 12715):

- Stabilize or reinforce soil;
- Controlled lifting of a building;
- Create a hydraulic barrier;

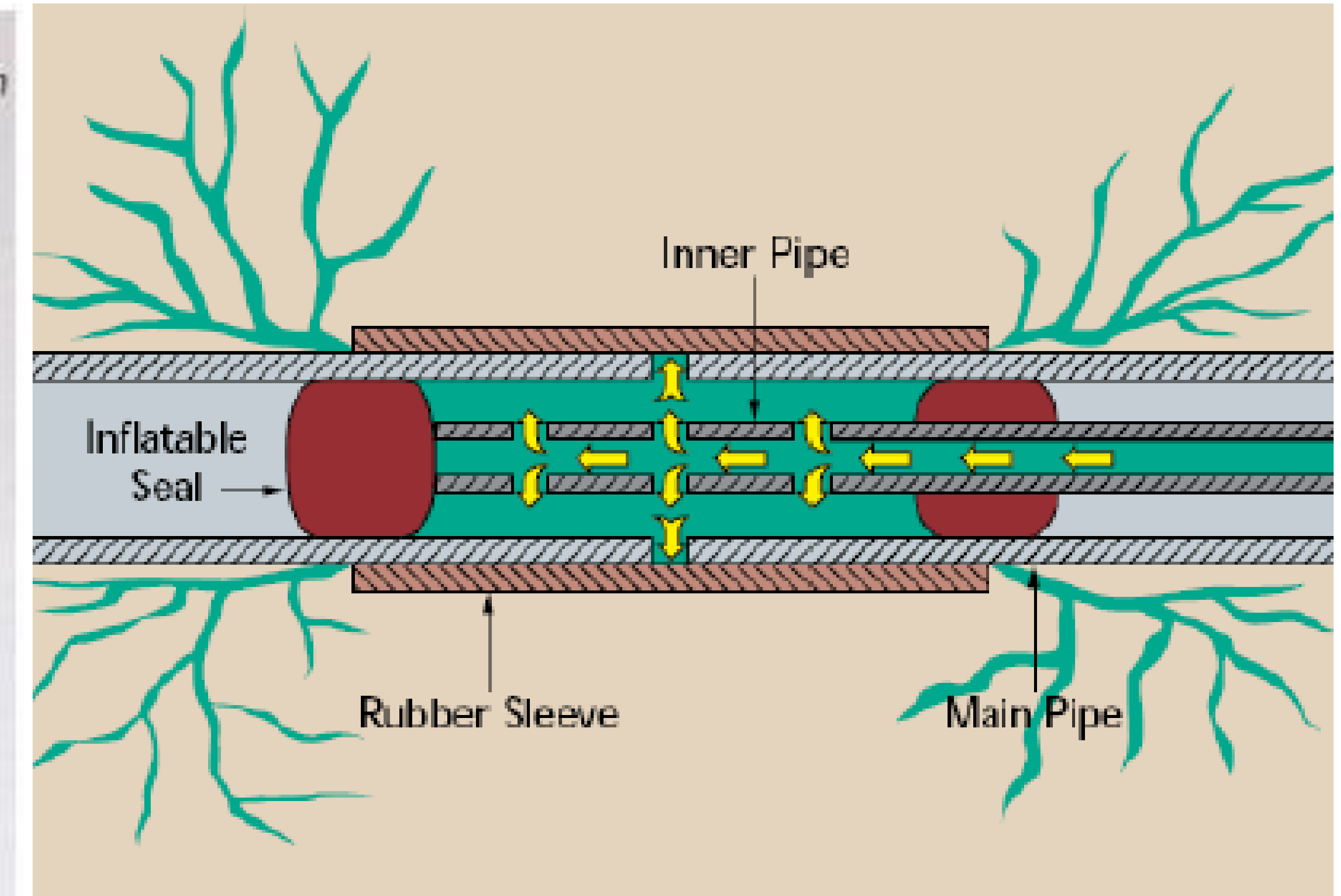
Typical characteristics for compensation or fracture grouting with horizontal TAM’s:

- Fluid grout, low viscosity;
- (High) pressures 4 - 5 MPa, going up to 10 – 30 MPa in certain cases;
- Diameter of TAM’s: 1 to 4 inches;
- Distance between TAM’s: 300 – 1000 mm;
- Total lengths of the horizontal drillings mostly < 50 m, lengths up to 70-75 m have been executed successfully;
- Spacing between drillholes (depth < 25 m): 0,8 – 2,0 m in sandy soils;

4. Compensation grouting – fracture grouting



Fracture grouting is applicable in wide range of soils
© Keller Grundbau



Principle TAM's
© Keller Grundbau

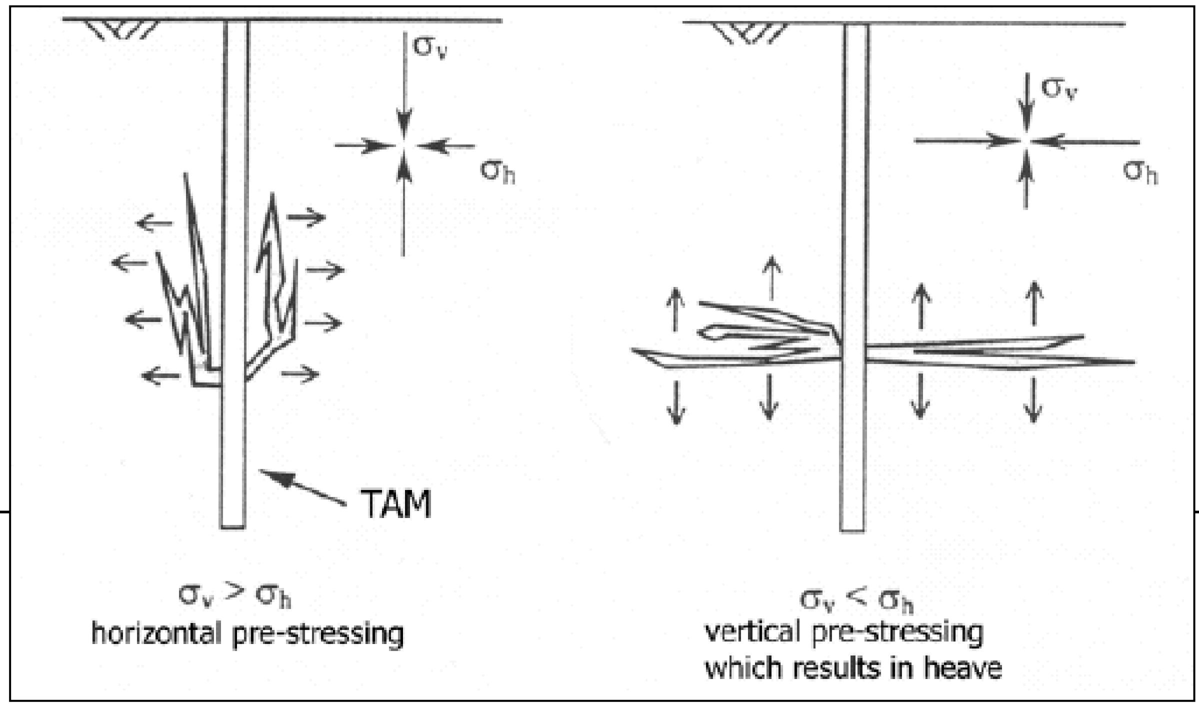
4. Fracture grouting – working principle

- Pre treatment of the soil: contact and stabilization injection;
  a) In general $\sigma'_v > \sigma'_h$: creation vertical fissures → **compaction** but no heave;
  b) Secondly creation of horizontal fissures → **heave** of soil and buildings;
  c) Typically heaving of 1 -2 mm of buildings during pre treatment;

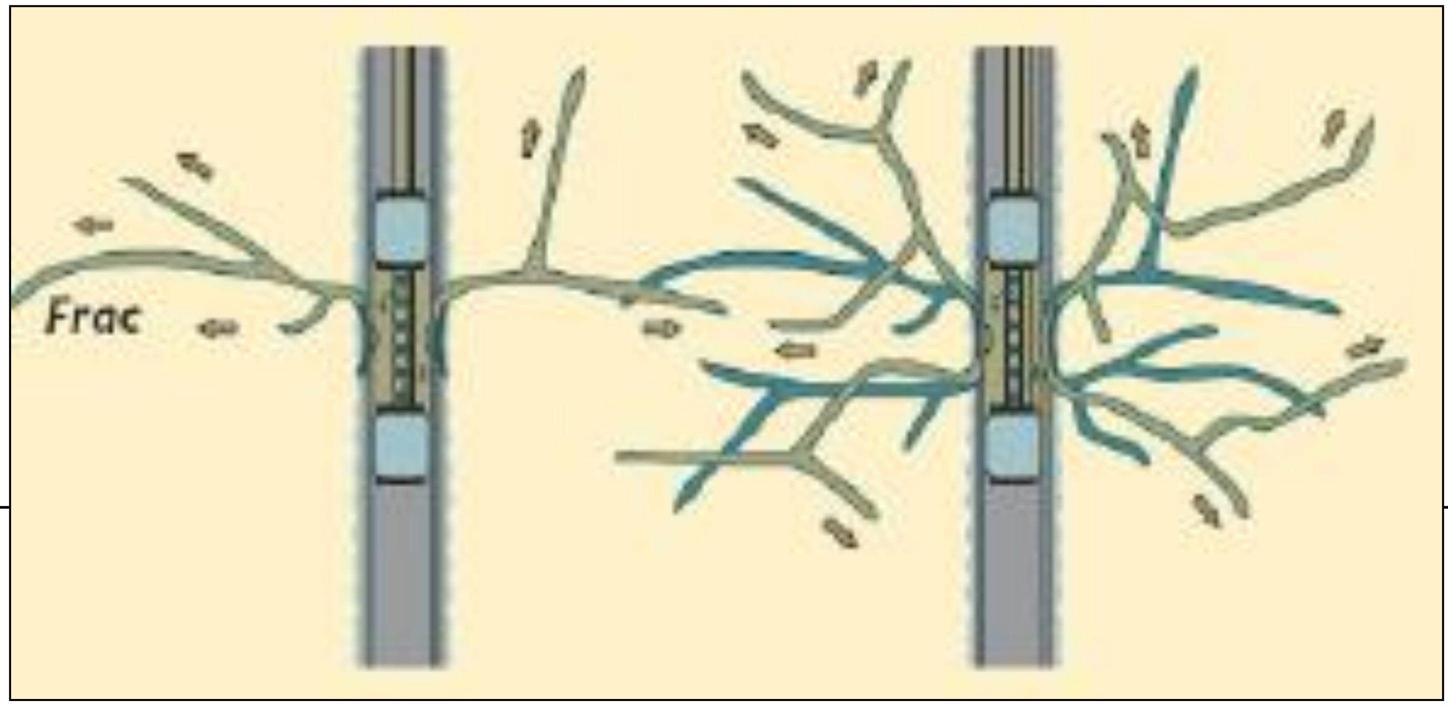
- Tunneling works can start after pre treatment phase – **relaxation** in soil will cause extra pore volume and settlements;

- Injection of grout through double packer based on settlement measurements;

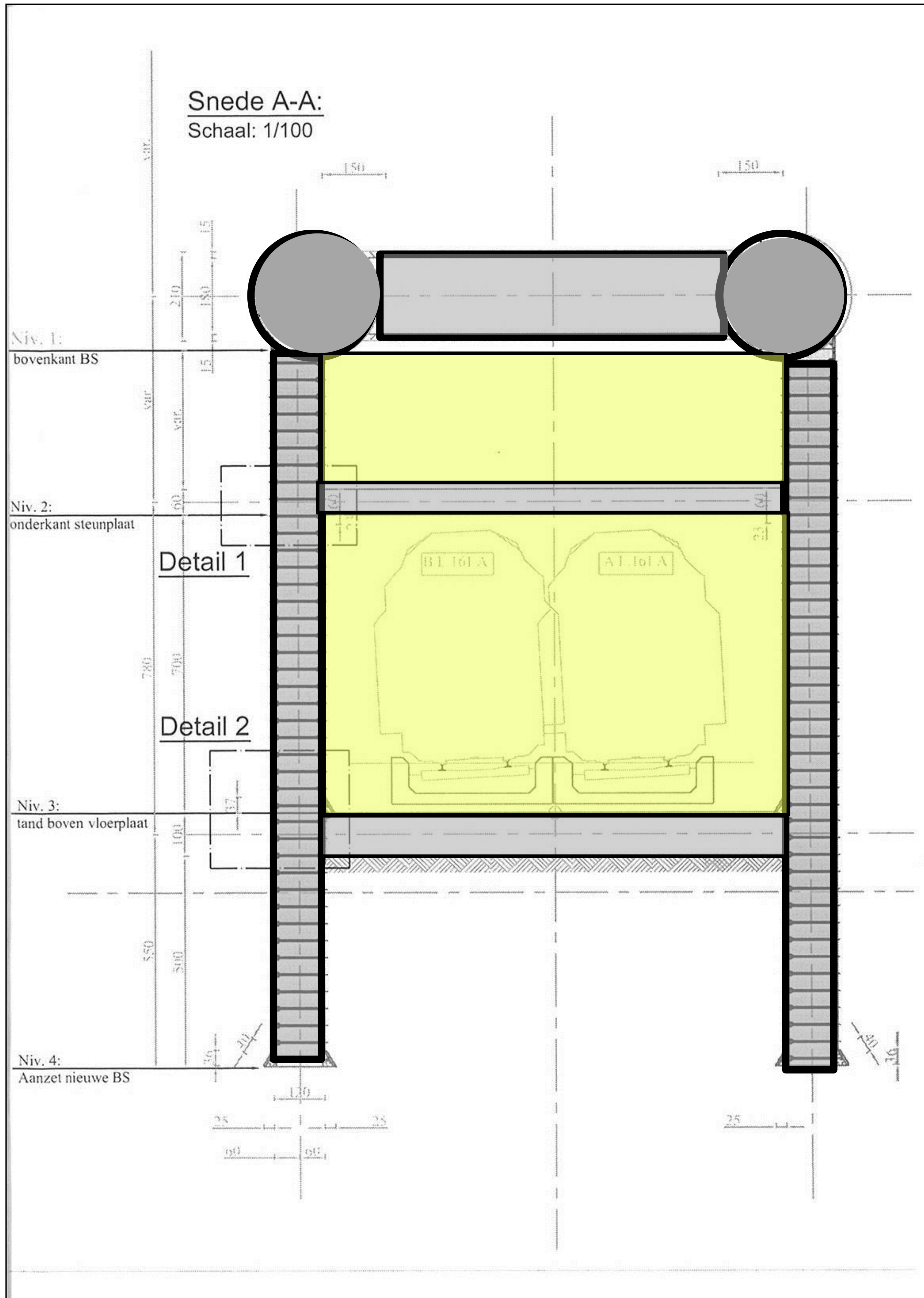
- Post grouting if necessary;



[Hockx, 2001]



4. Calculated construction settlements



STAGE 1: Longitudinal steel pipe drives – DN300 by mechanised pipe jacking

Δs_1 = 4,2 cm

STAGE 2: Manually dug slot walls

Δs_2 = 1,0 cm expected for good execution works

STAGE 3: Transverse concrete pipe jacking DN2100

Δs_3 = 2,3 cm

STAGE 4 - 8: Long term deformation of pipe roof under overburden (130 kPa) + construction settlements

Δs_4 = 0,8 - 2 cm

Δs_{tot} = 6 - 8 cm maximum to be expected

=> Within the range of what can be compensated with fracture grouting

5. Key elements for a successful process

1. **Monitoring system** to follow movements of the foundations;
2. Vertical shafts from where **horizontal drillings** will start for TAM;
3. **Working limits** – restrictions: orange light (intervention) – red light (alert);
4. **Follow up** the monitoring data;

5. Monitoring system

- FIRST: Water level system to monitor the tilting of each building

  a) System installed in basements;
  b) 4-6 stations in each property;
  c) Over 170 monitoring stations were installed + reference stations;
  d) Precision = 0,1 – 0,3 mm;

- SECOND: Reflector stations installed on all buildings in survey area

  a) Automatically sighted by tow motorised Leica theodolites at stable position;
  b) Sensitivity = 1,0 mm

- Data collection, acquisition, processing in a centrally measurement container on Plaskylaan

  a) Data processing to produce trends;
  b) Calculate differential settlements and check alarm values
  c) System is linked to the compensation grouting system;

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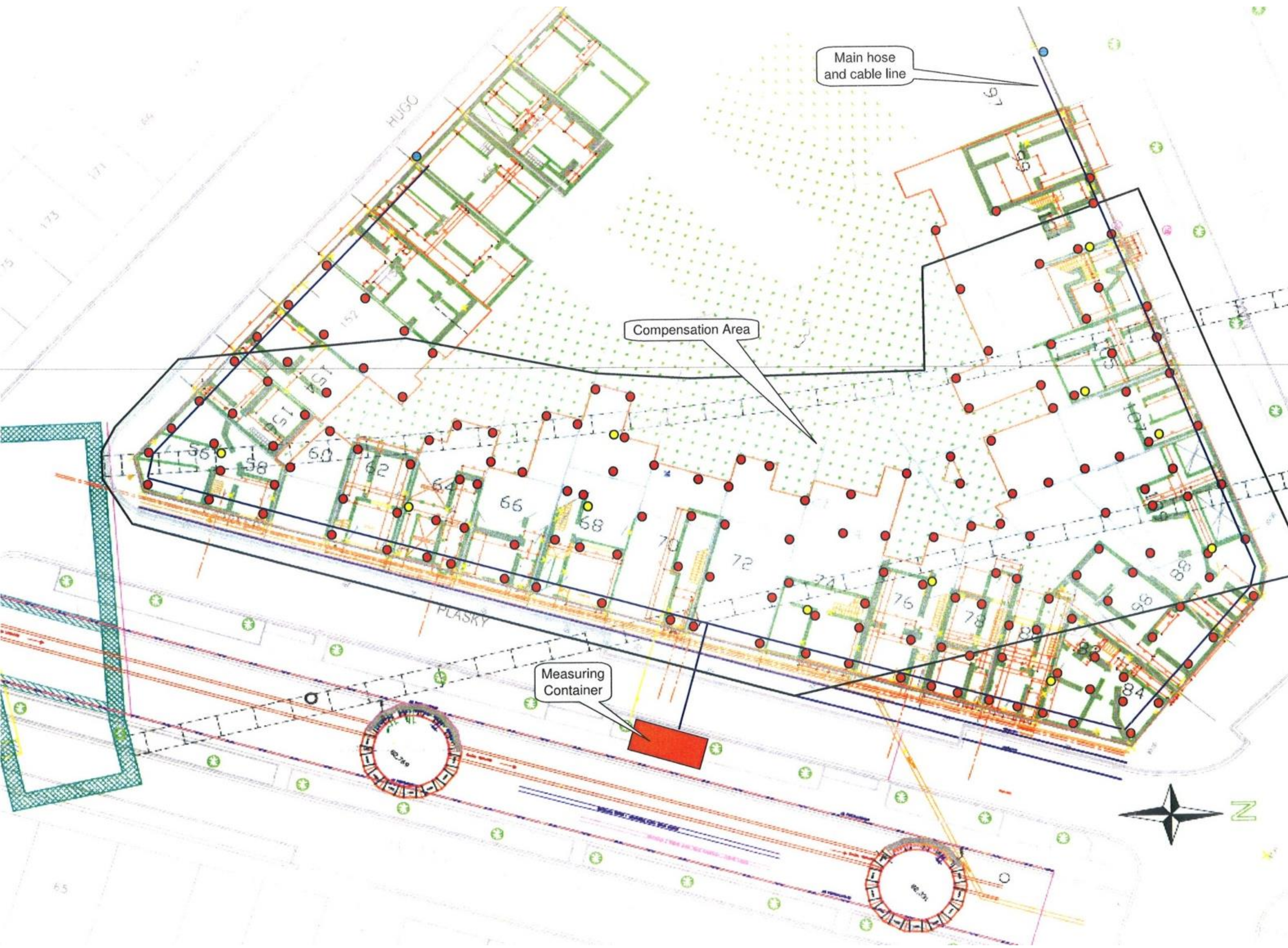
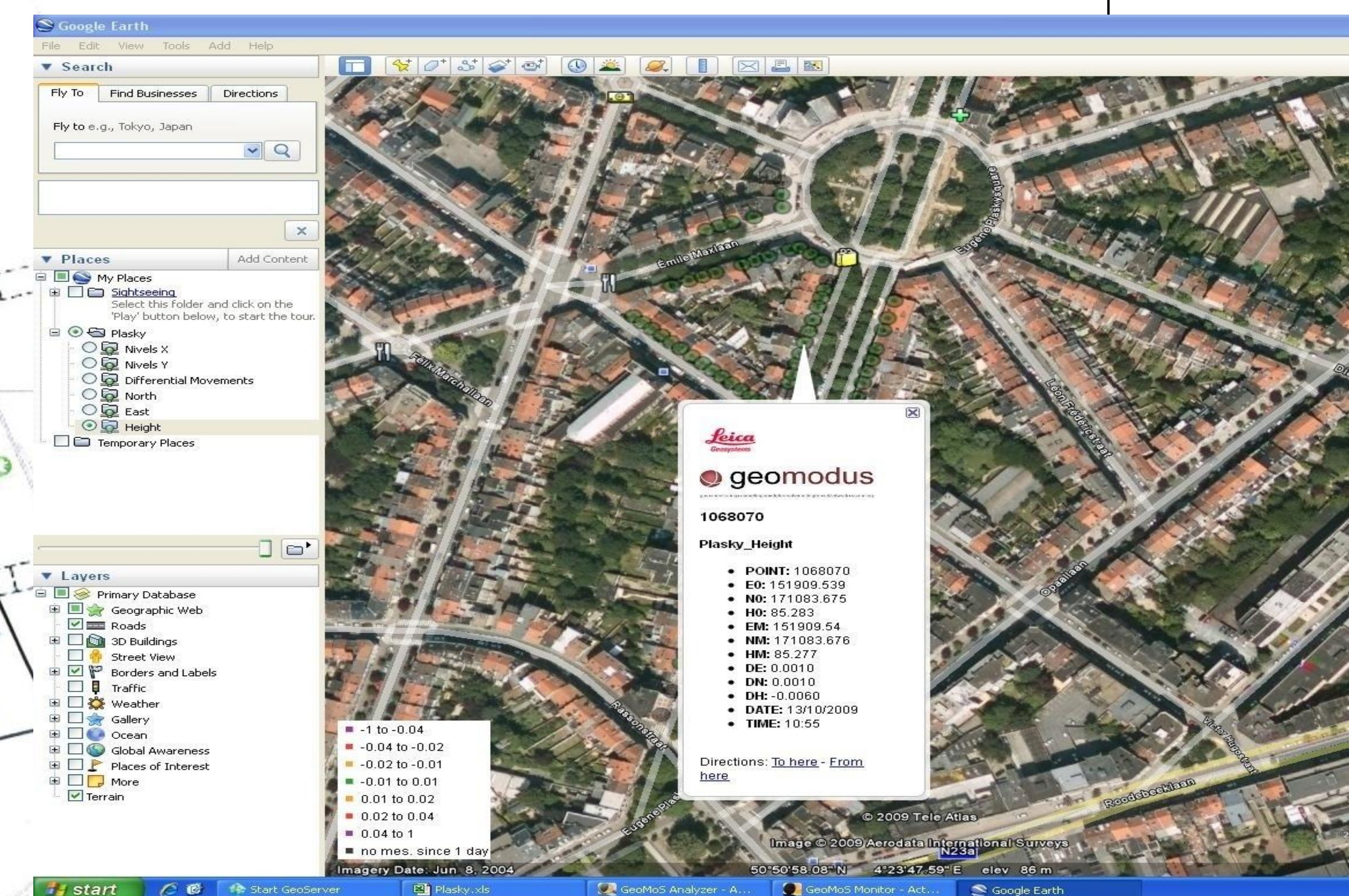
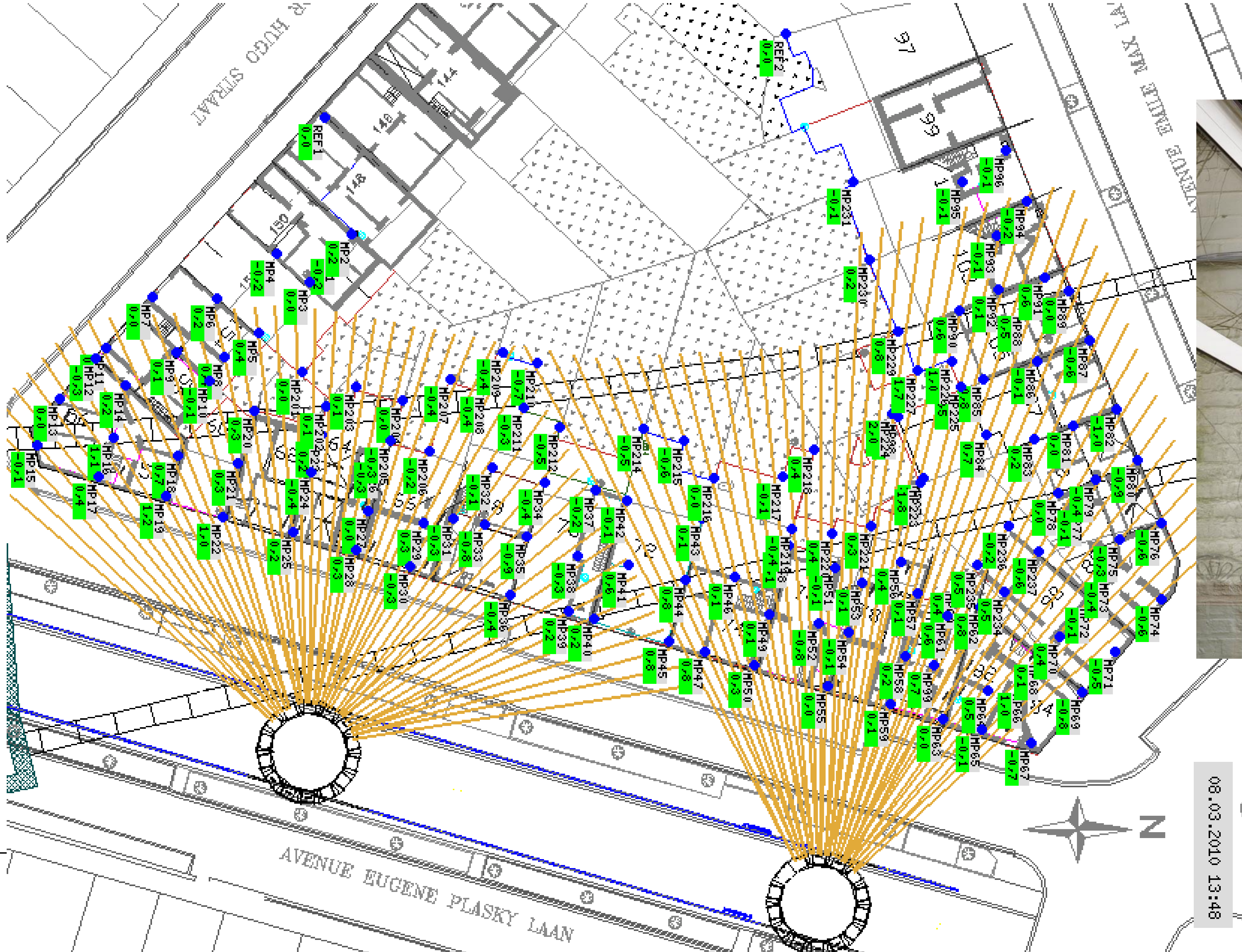
5. Monitoring system – measuring points

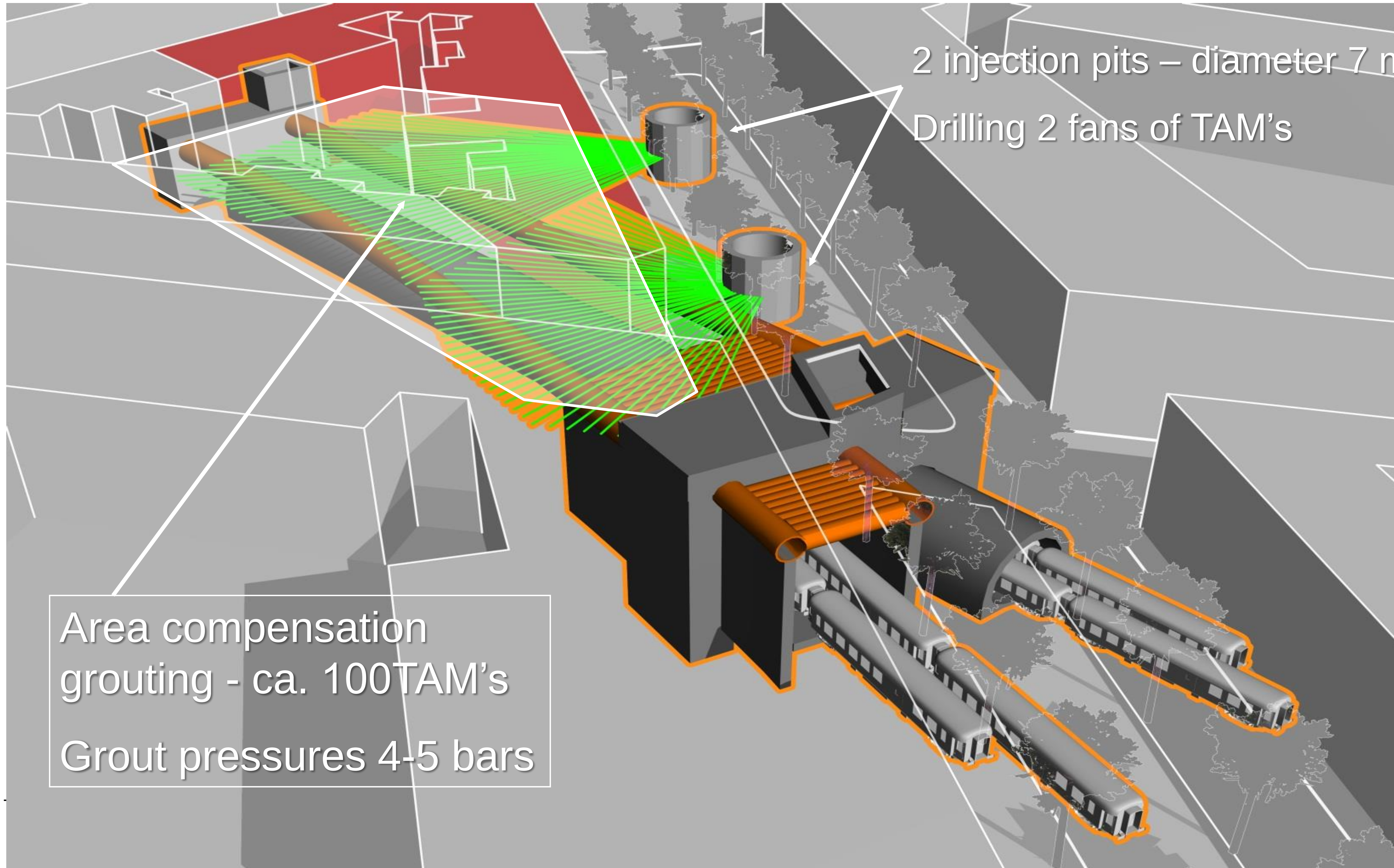


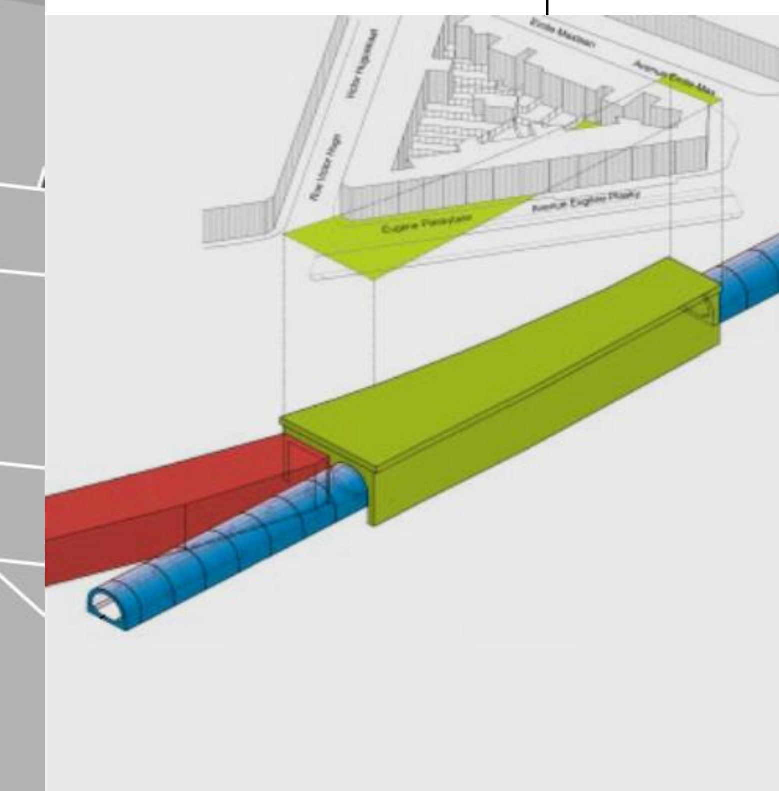


5. Monitoring system



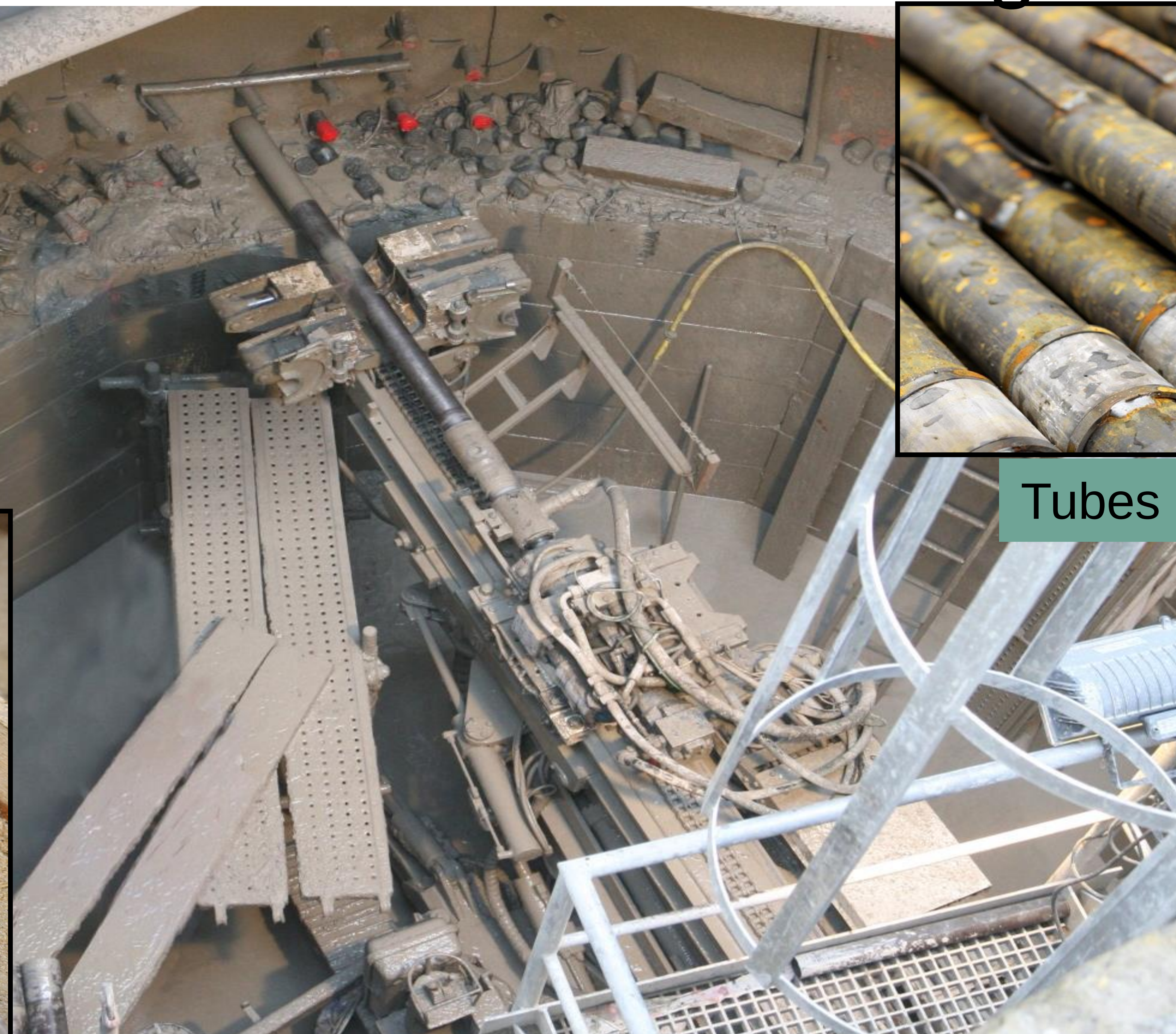
DENYS 5. Vertical shaft + horizontal drillings





5. Site installation

5. Vertical shaft + horizontal drillings



Tubes à manchettes

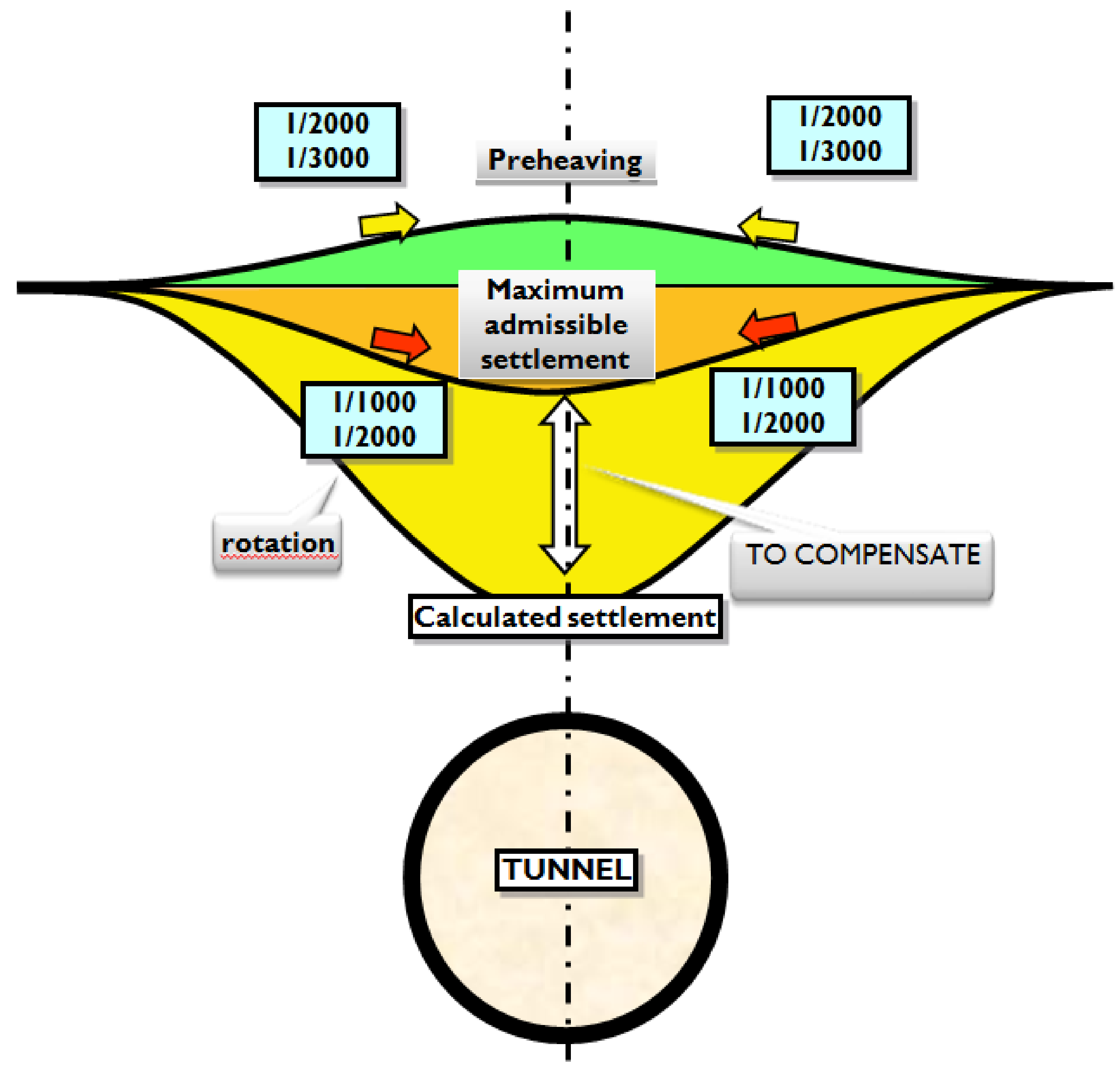
Packers

5. Working limits – restrictions on settlements

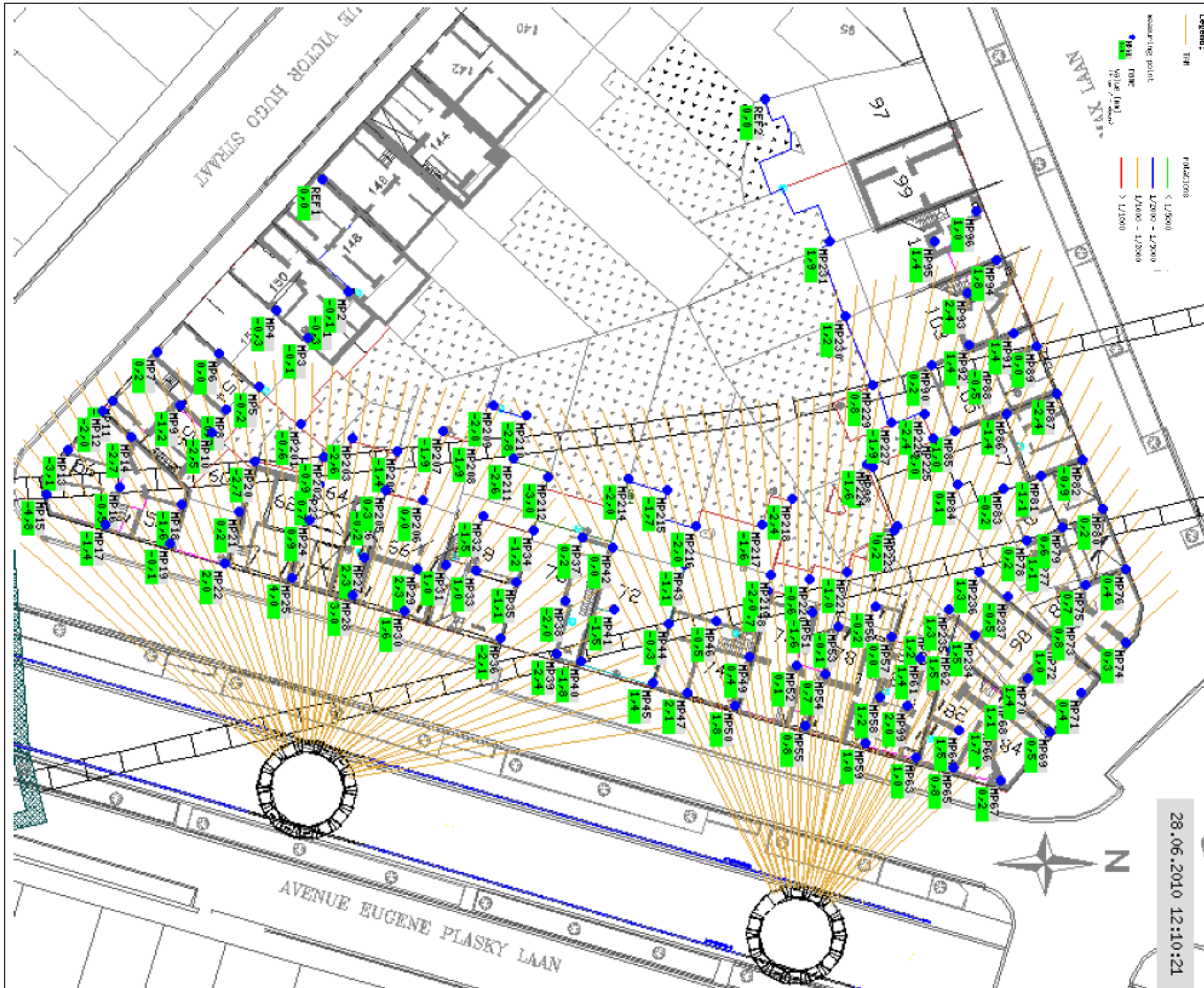
BUILDINGS	Absolute settlements [mm]
Intervention value	20
Alert value	40

ROAD AND GARDENS	Absolute settlements [mm]
Intervention value	40
Alert value	50

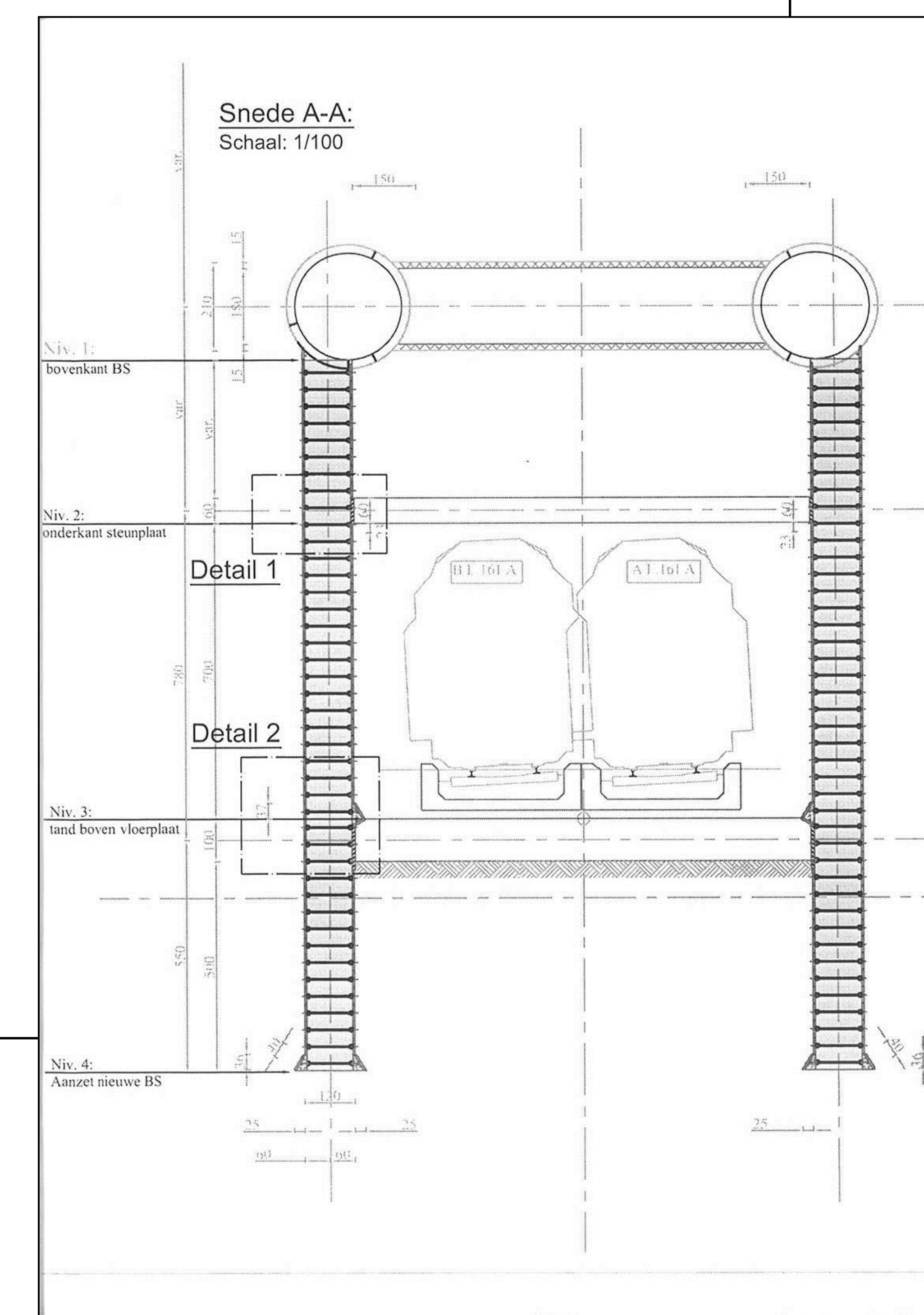
Δs_{tot} = 60 - 80 mm maximum to be expected



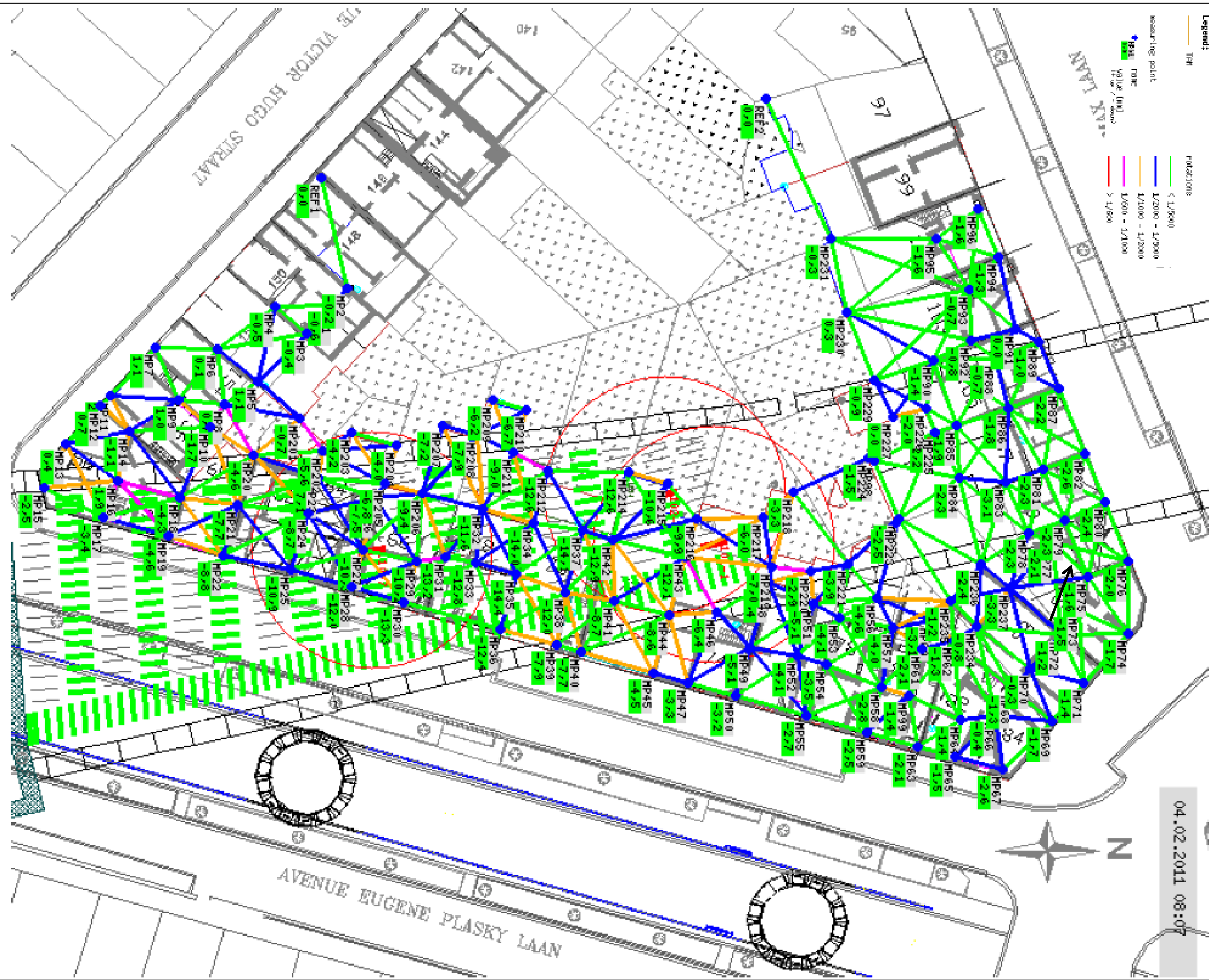
6. Absolute settlements – 28/06/2010



Example: construction of longitudinal DN3000:
- Settlements: 7mm
- Rotations: <1/1000

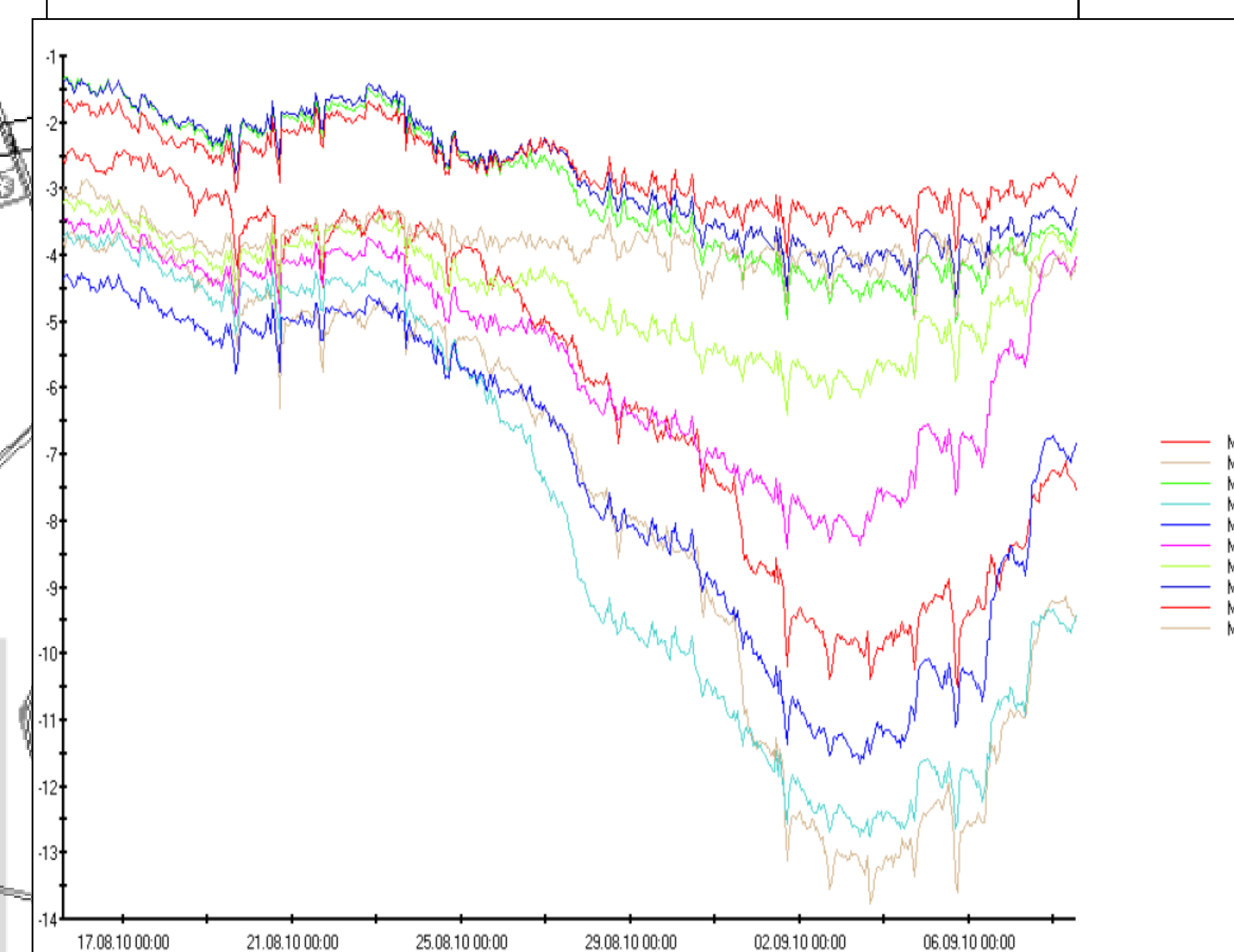


6. Rotations – 4/02/2011

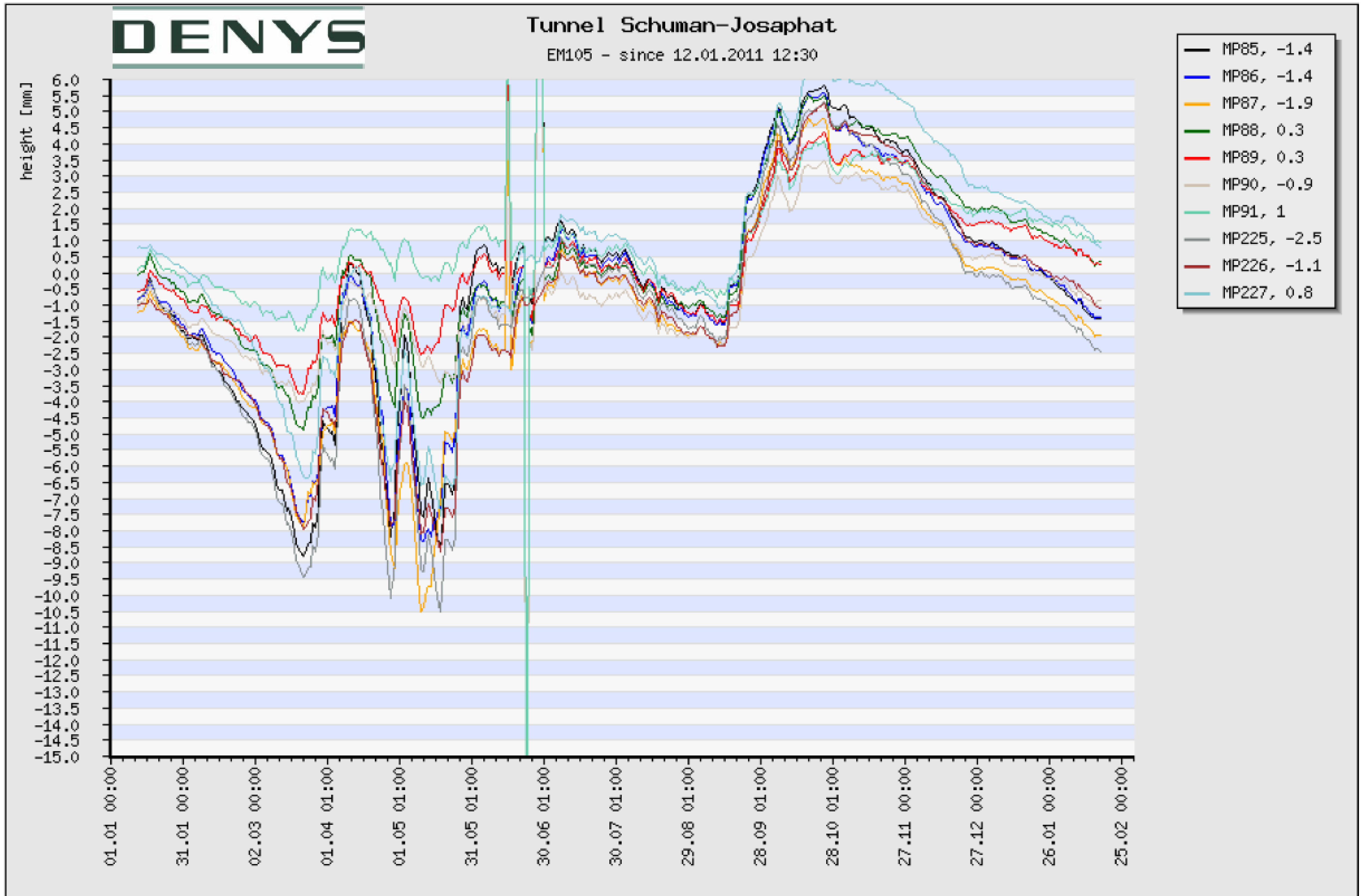


Example: construction of pipe-roof:

-settlements of max. 15mm
-rotations: < 1/600



6. Example house Emile Max n°105



1. Preheaving
2. Longitudinal DN3000 -> compensation
3. Transverse pipe roof DN2100 (graph) ->compensation
4. Before excavation (graph) -> compensation
5. After excavation -> compensation

DENYS

ir. Yannick Stevens, project manager

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ir. Kristof Van Royen, geotechnical engineer

Kristof.vanroyen@denys.com

www.denys.com

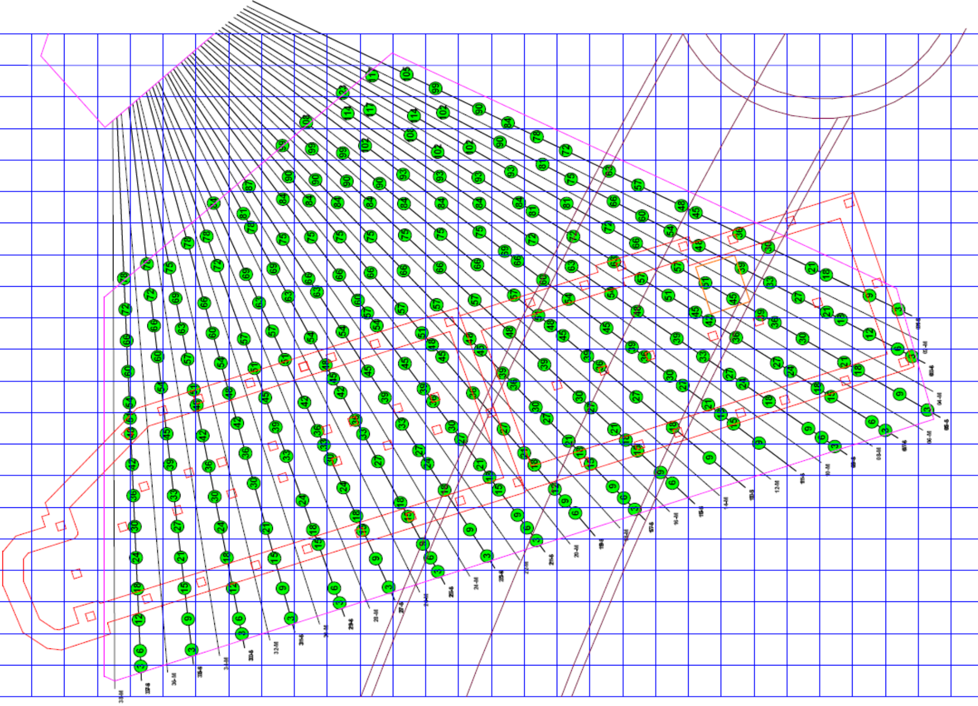
Questions?

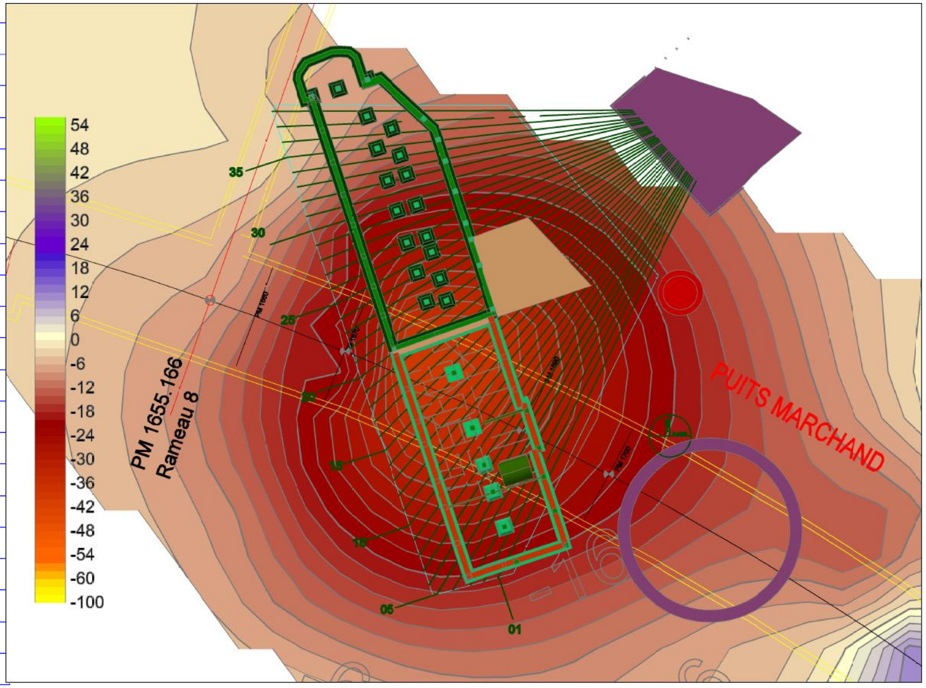
IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Monitoring during compensation grouting

J.G. La Fonta, Sol-Data, France



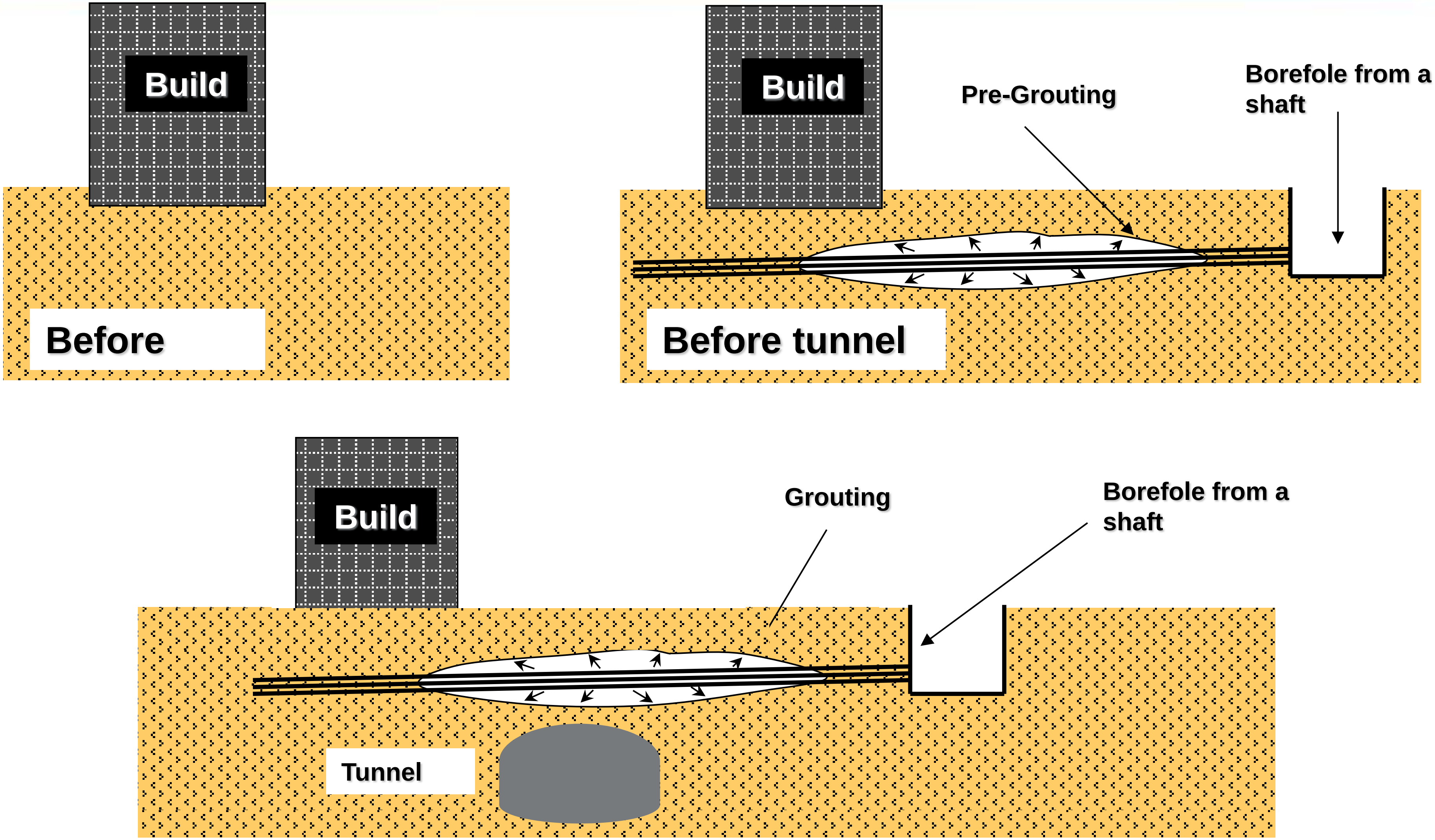


Monitoring during Compensation Grouting

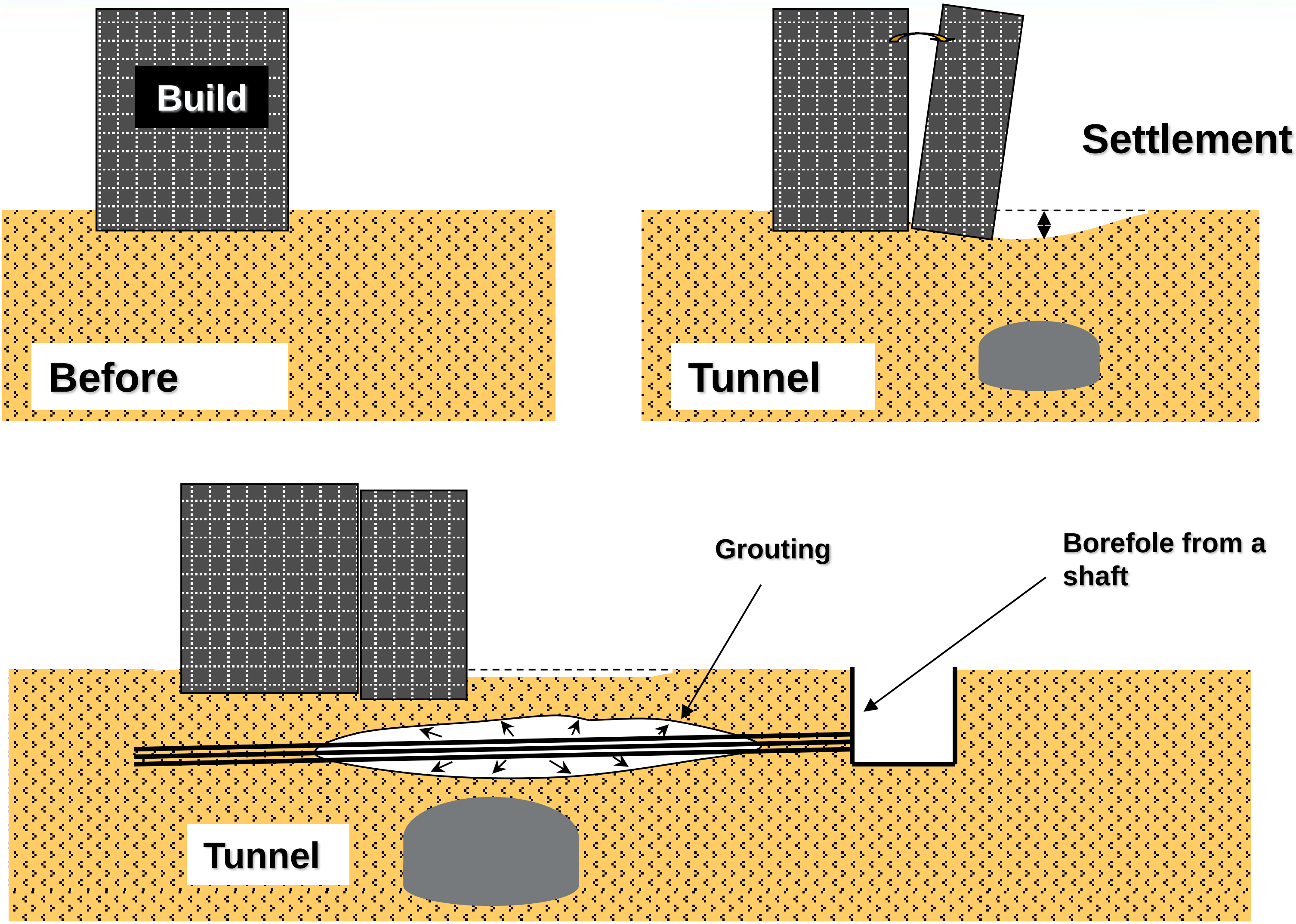
ISSMGE - TC 211
SHORT COURSE

Jean G. La Fonta – SOLDATA
September 1st 2013 - Paris

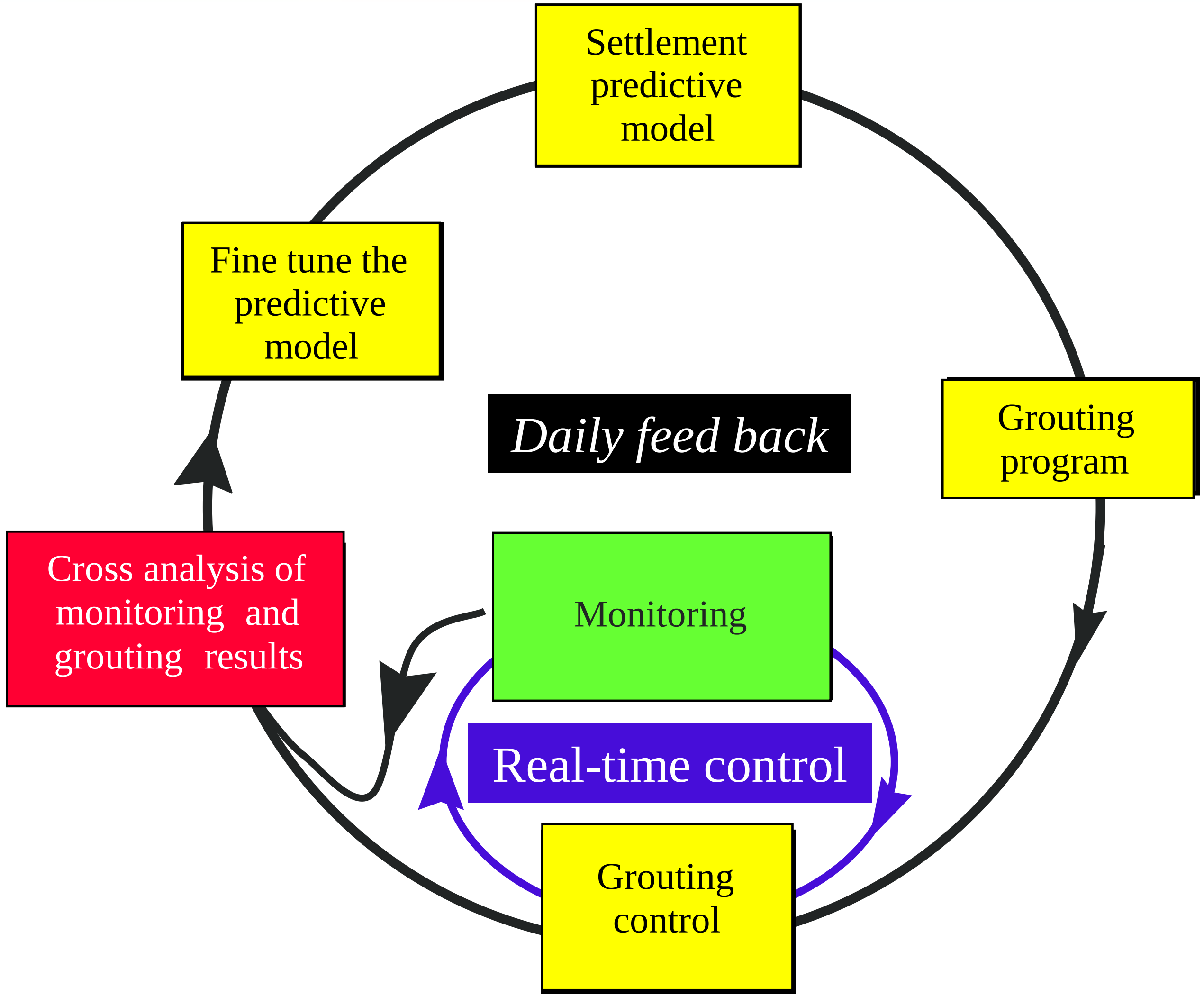
Principle of Preventive Compensation Grouting



Principle of Corrective Compensation Grouting

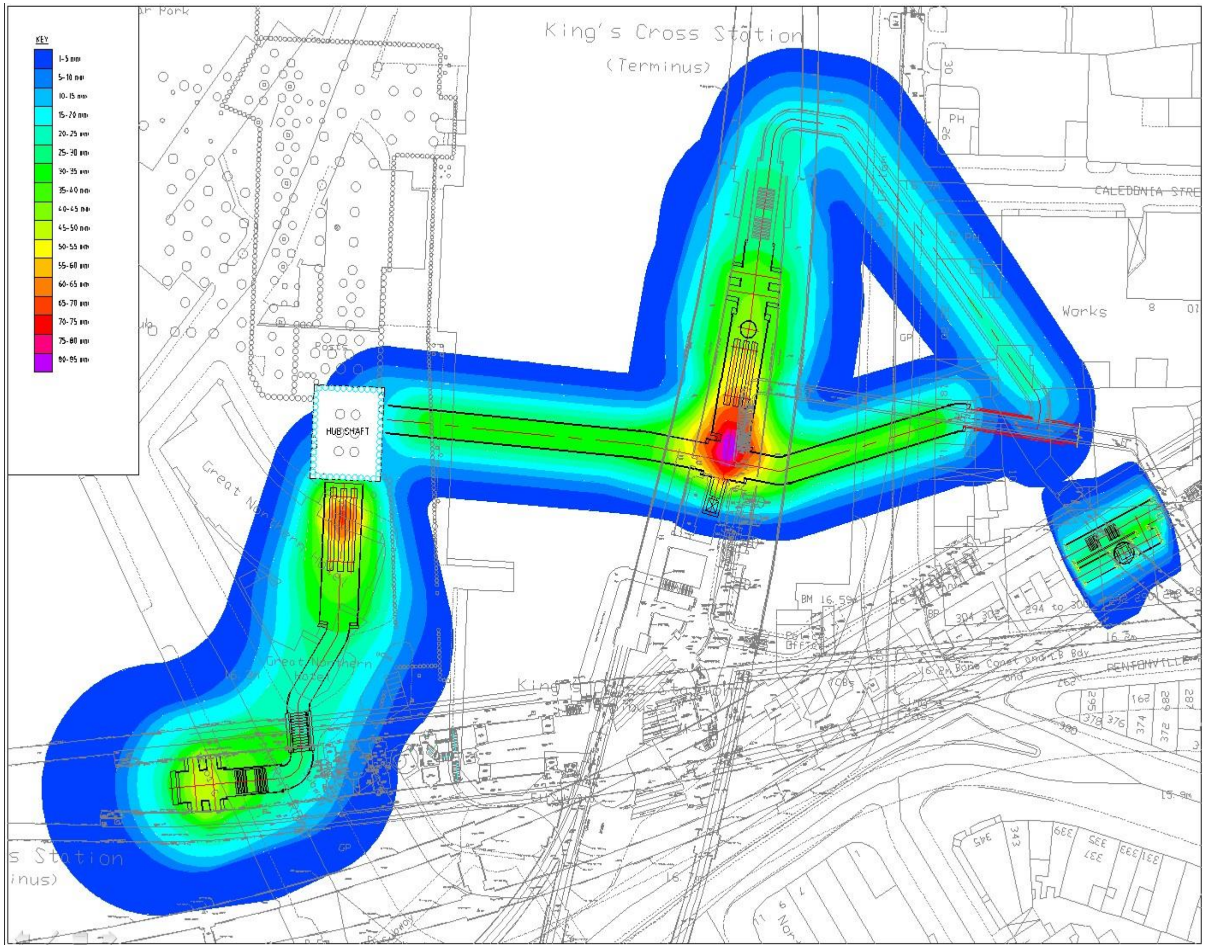


The Compensation Grouting LoopS



Predictive Model &Dynamic Adjustment

COGNAC (COmpensation GroutiNg Aided by Computer)



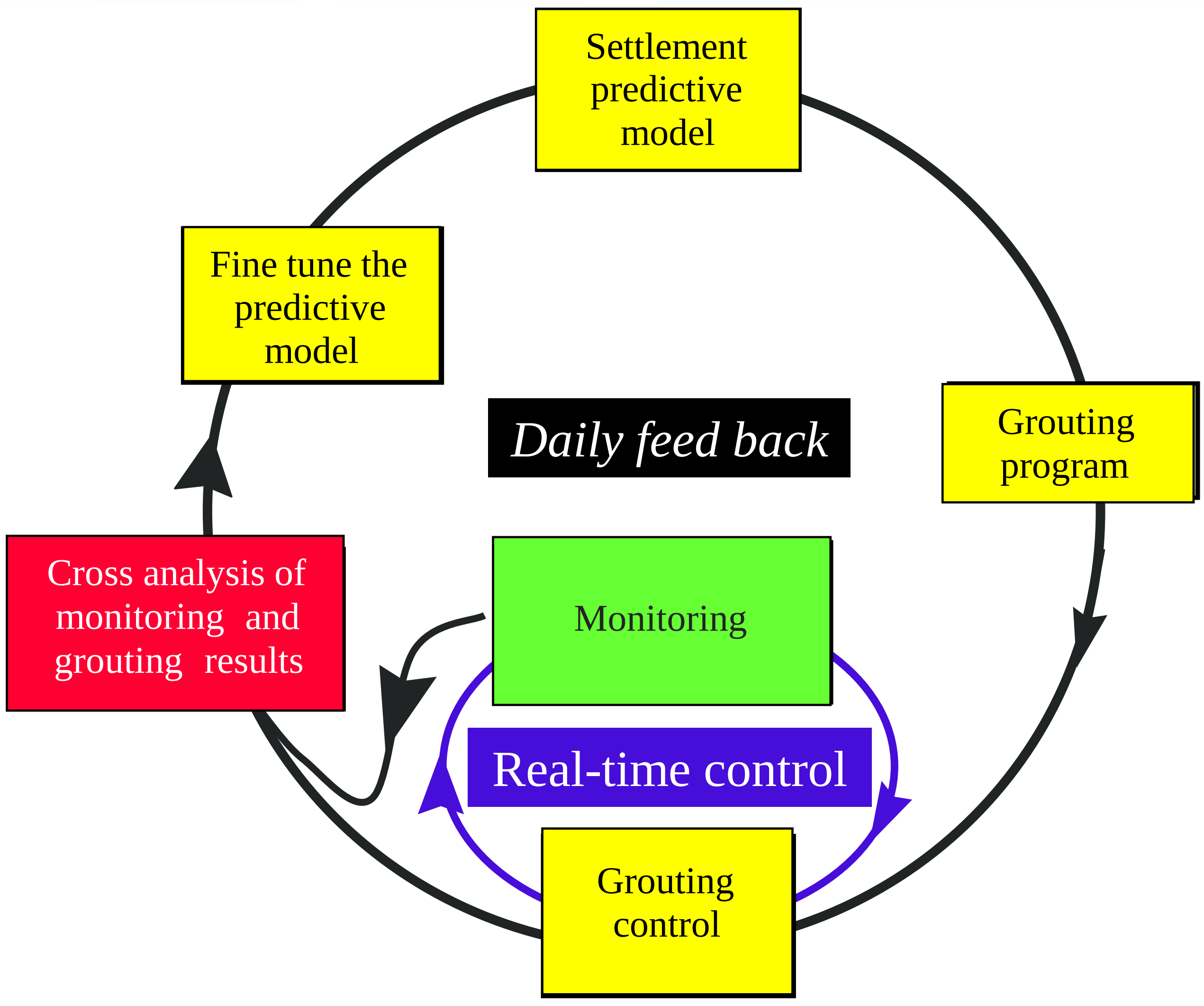
Before the Project

- Static
- Predictive settlement at termination
- Finite Element

During the Project

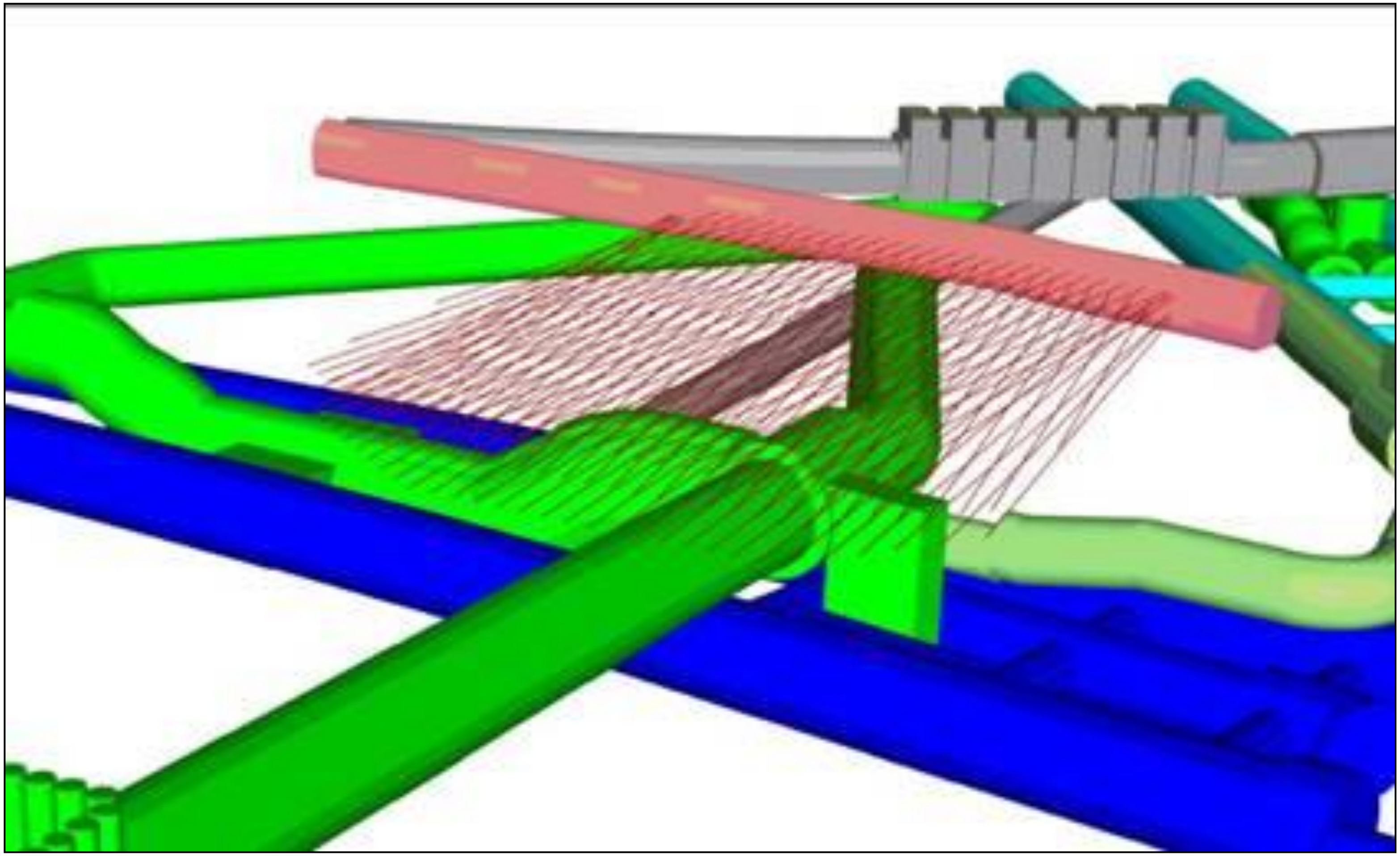
- Dynamic
- Fine Tune the Predictive model

The Compensation Grouting LoopS



Grouting Program

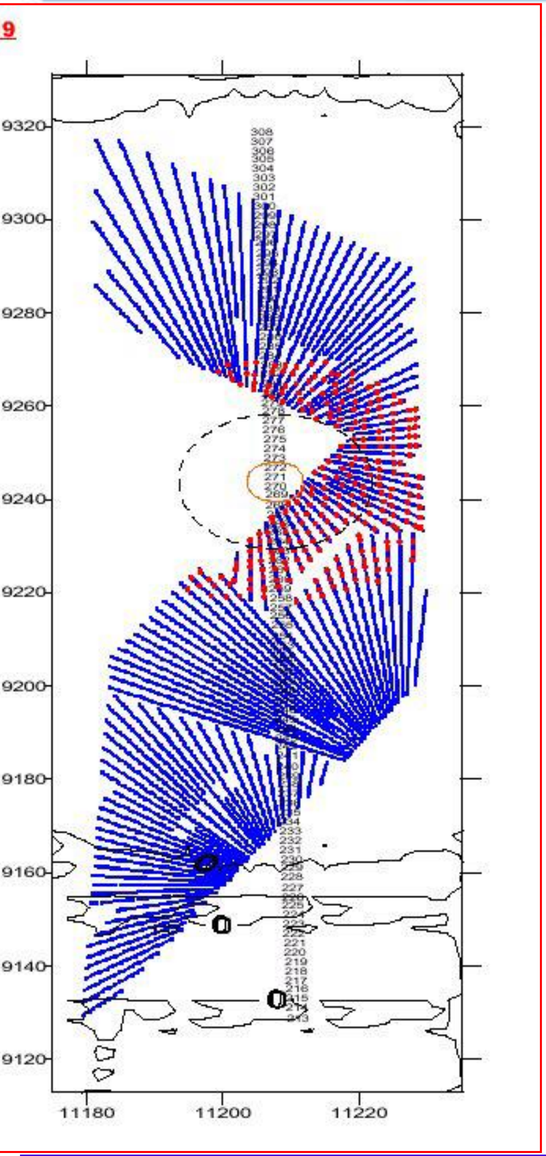
CASTAUR (Conception Assistée des Auréoles d'injection)



Boreholes

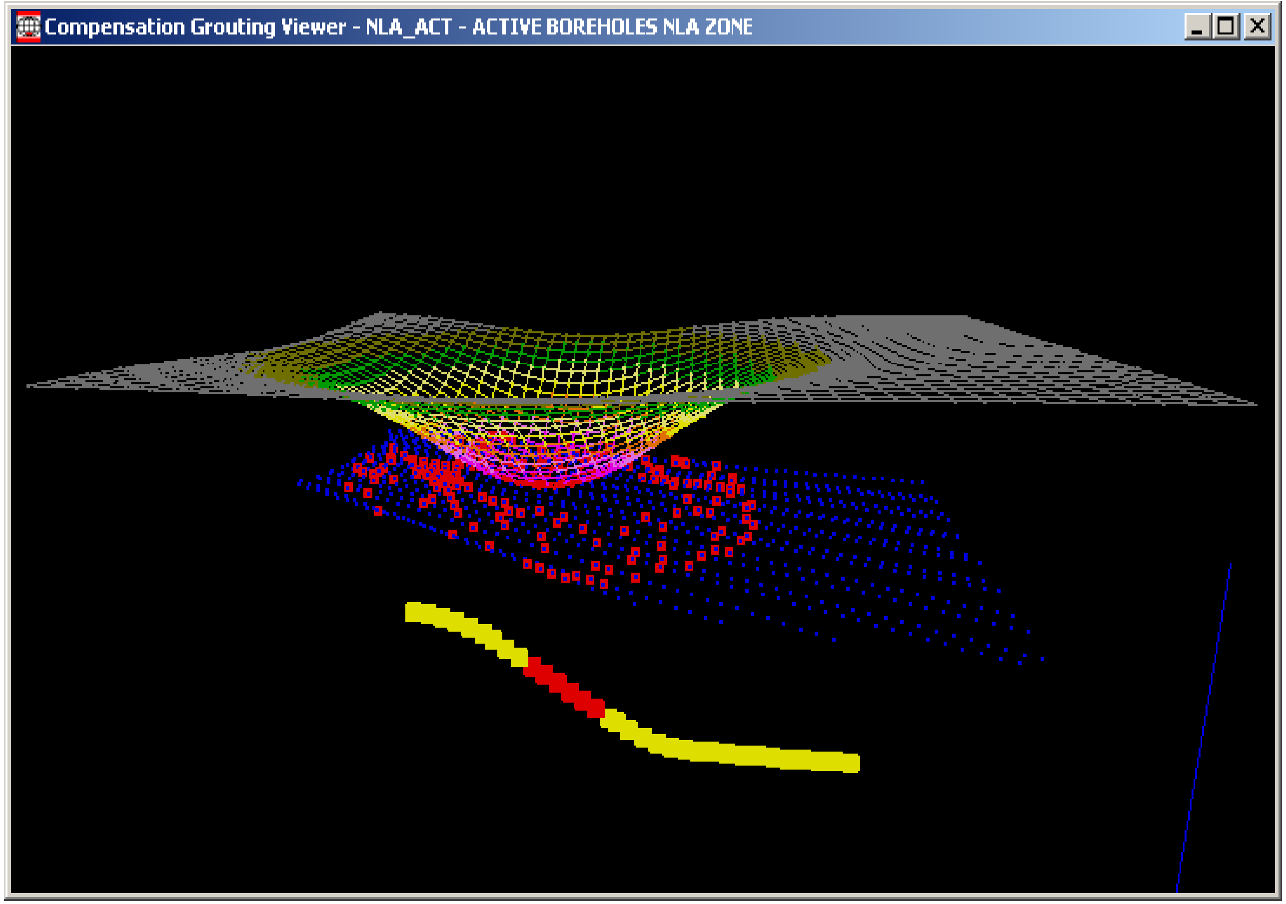
- **Position**
- **Angle**
- **Length**

Grouting Program

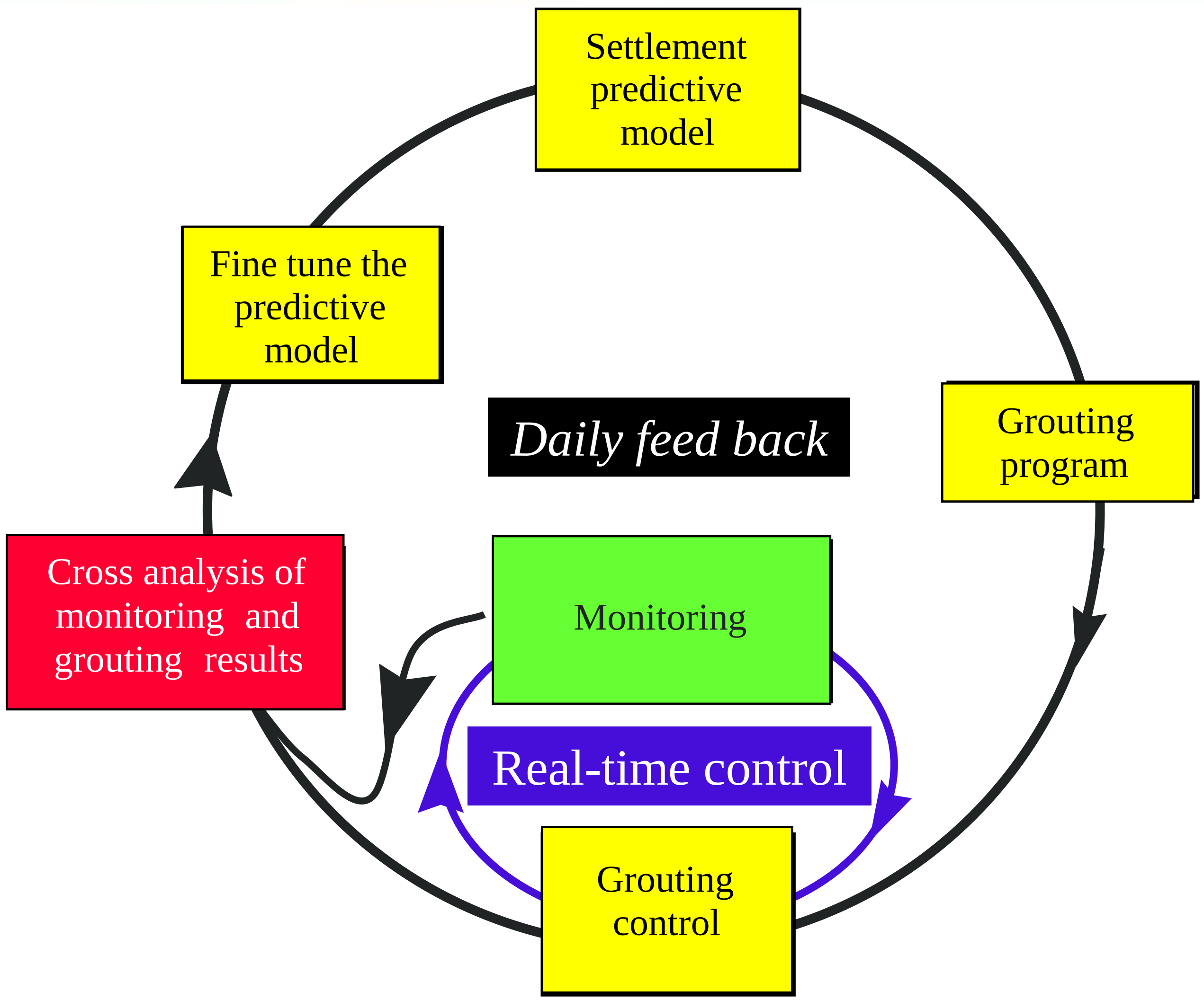


COGNAC
(COmpensation GroutiNg
Aided by Computer)

Grout :
-Volume
- Pressure



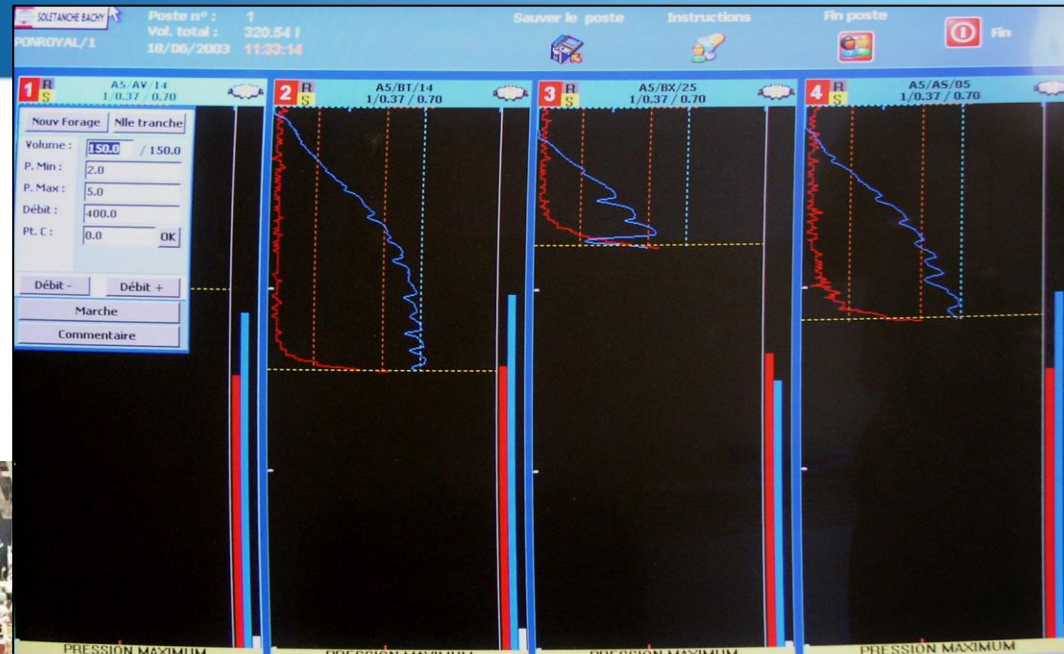
The Compensation Grouting LoopS

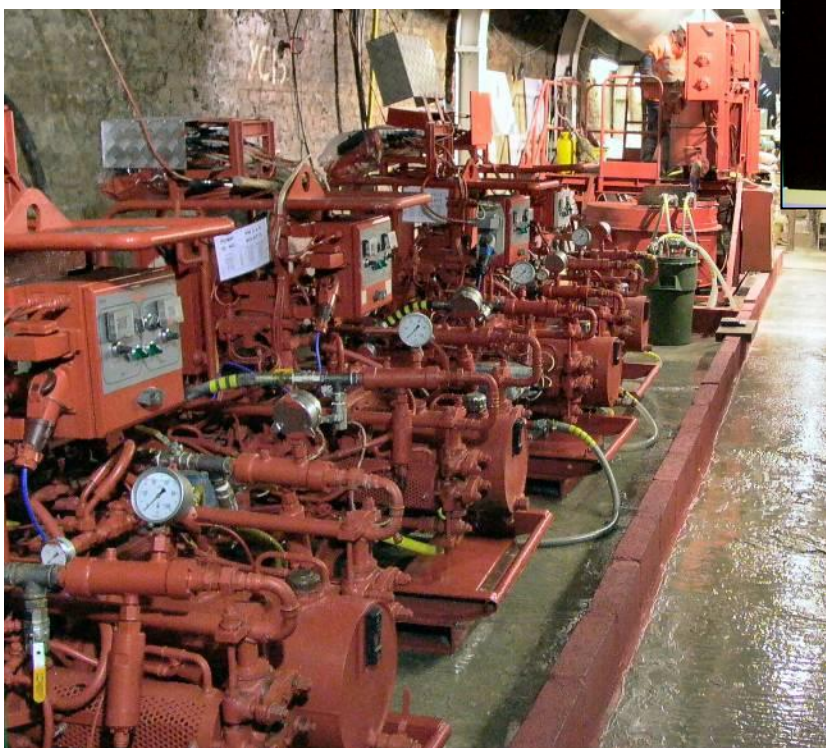


Grouting Control

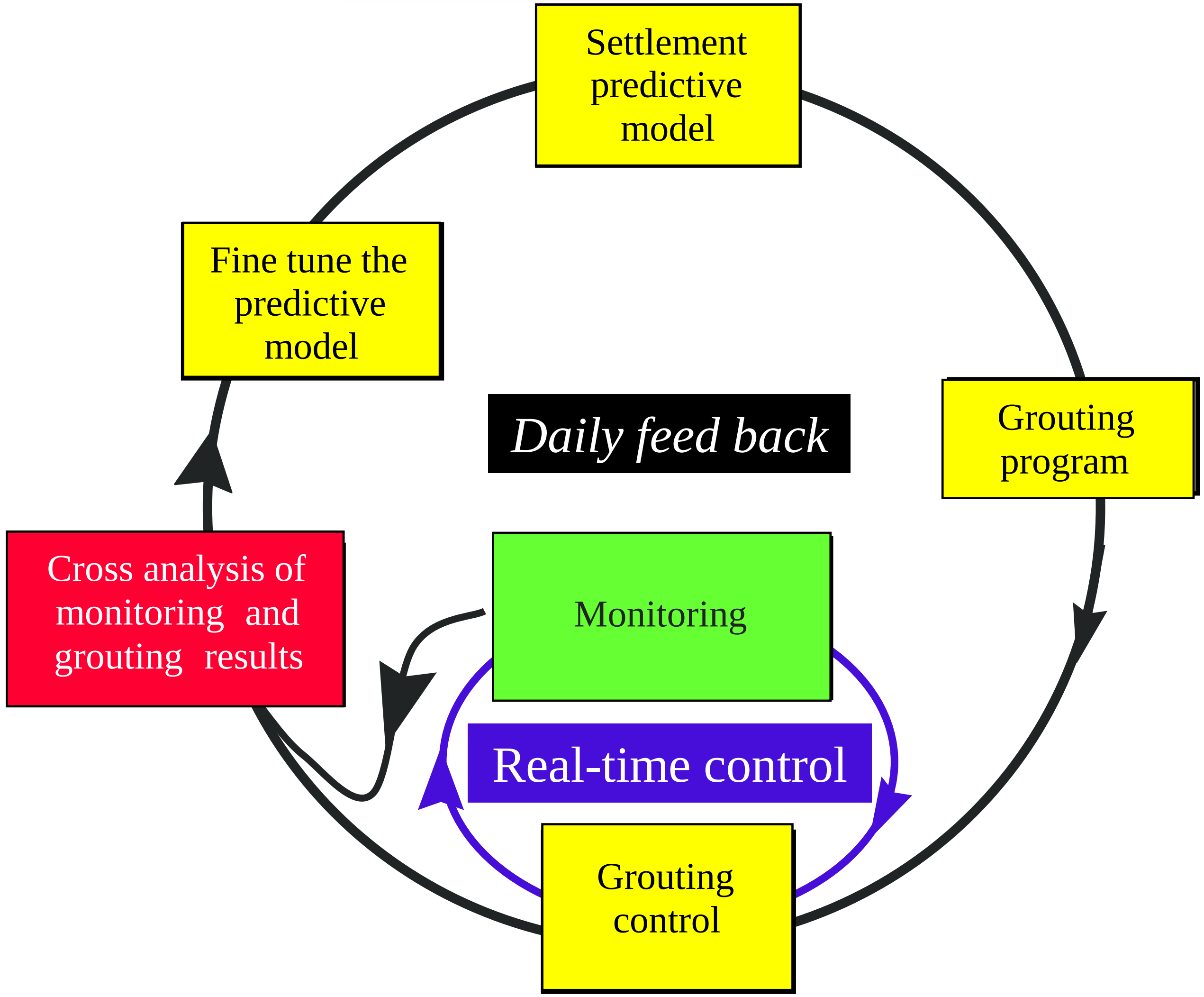
Compensation Grouting
=> Very close control of grouting works :

- pressure
- volume
- grout flowrate

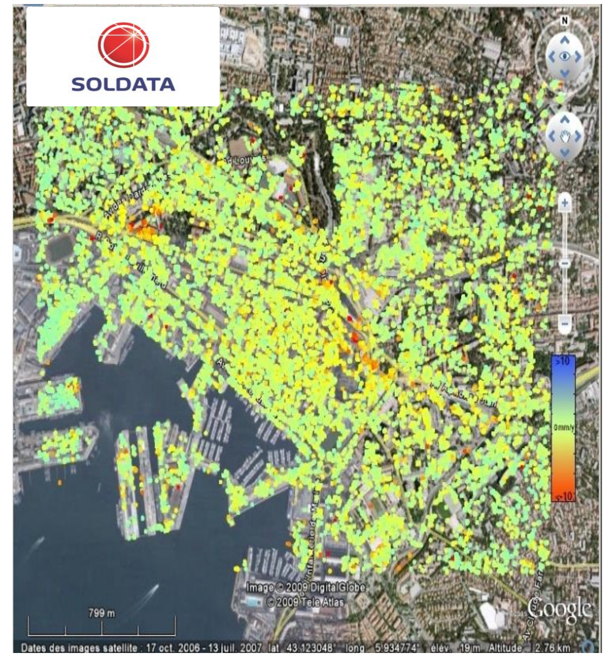




The Compensation Grouting LoopS



Monitoring

Manual	Automated	Satellite
		
Base line Back-up Specific area	Real time Grouting Control Risk mitigation, alarms	Large Scale Not real-time Impact analysis

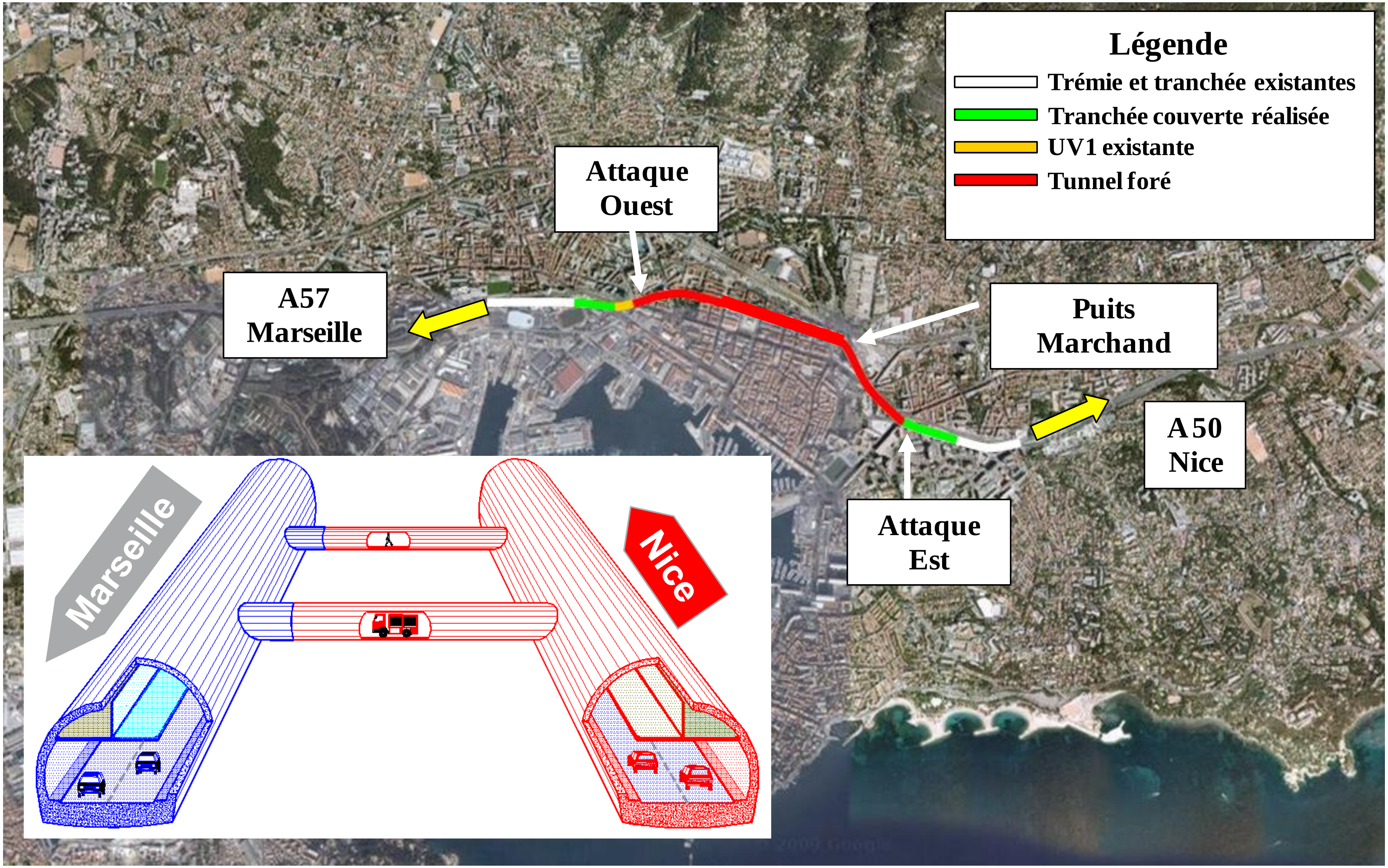
Subsurface & Surface

Space

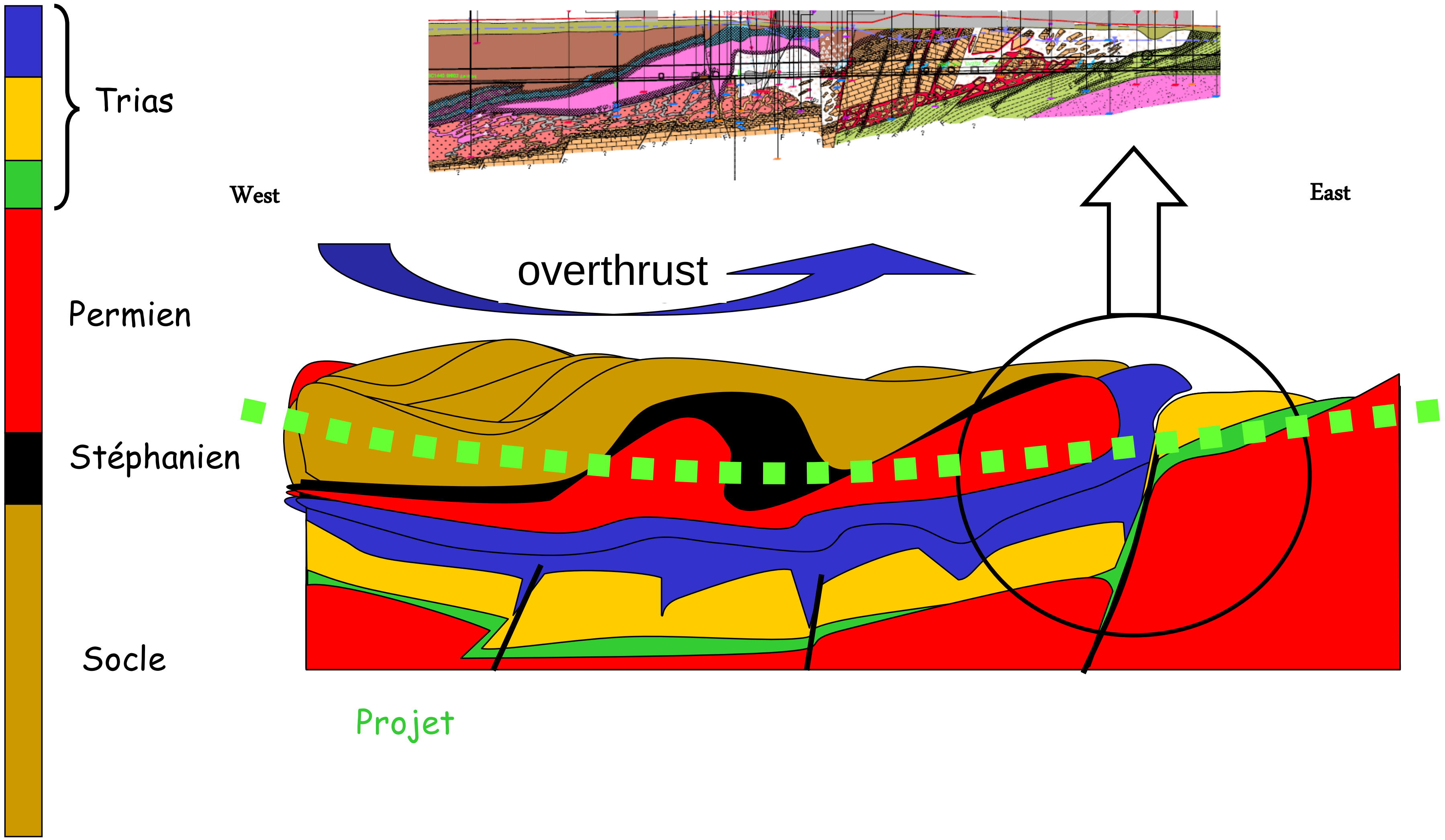
Toulon – South Route

Compensation Grouting for saving the tunnel project

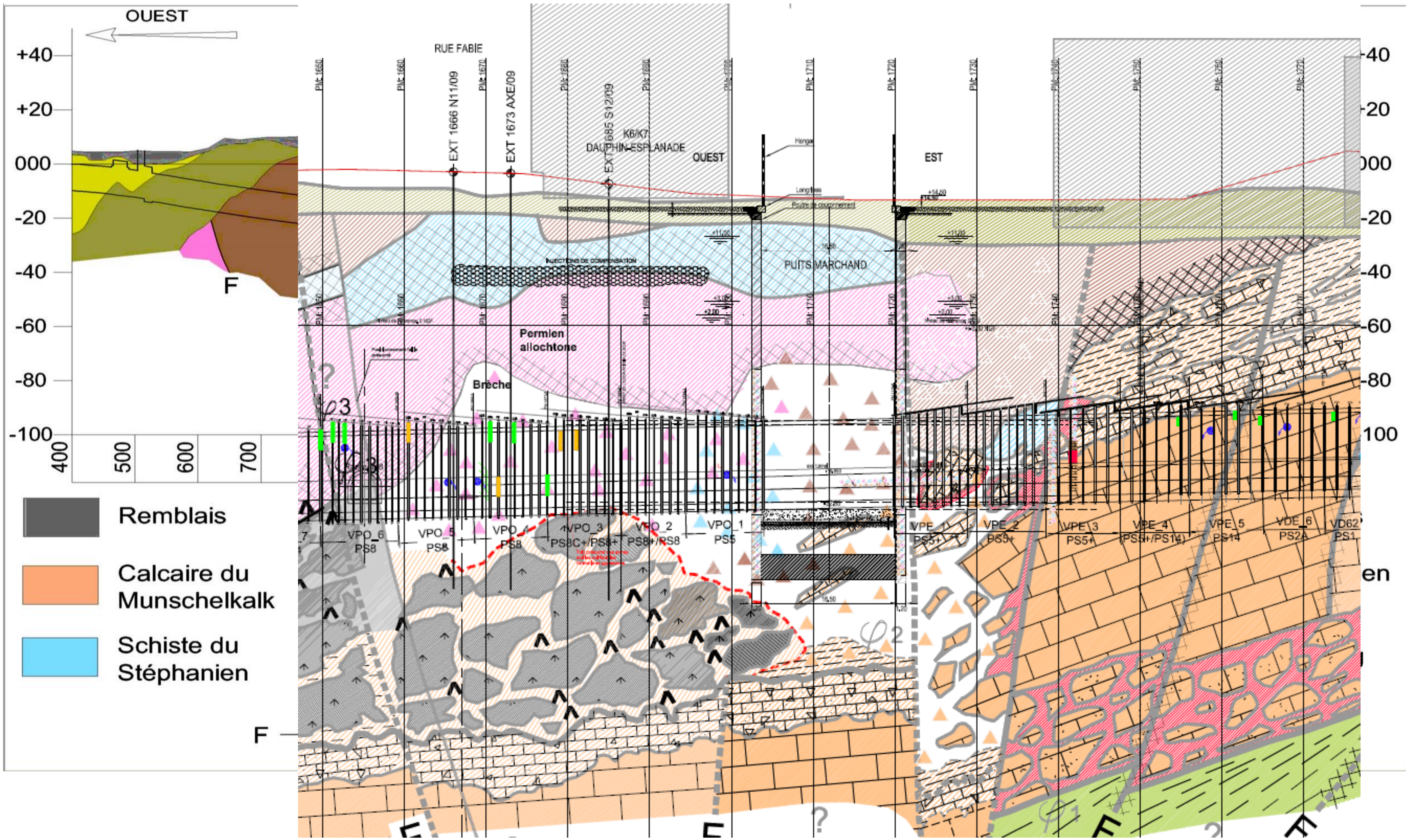
A CASE STUDY : Toulon (France) South Tunnel



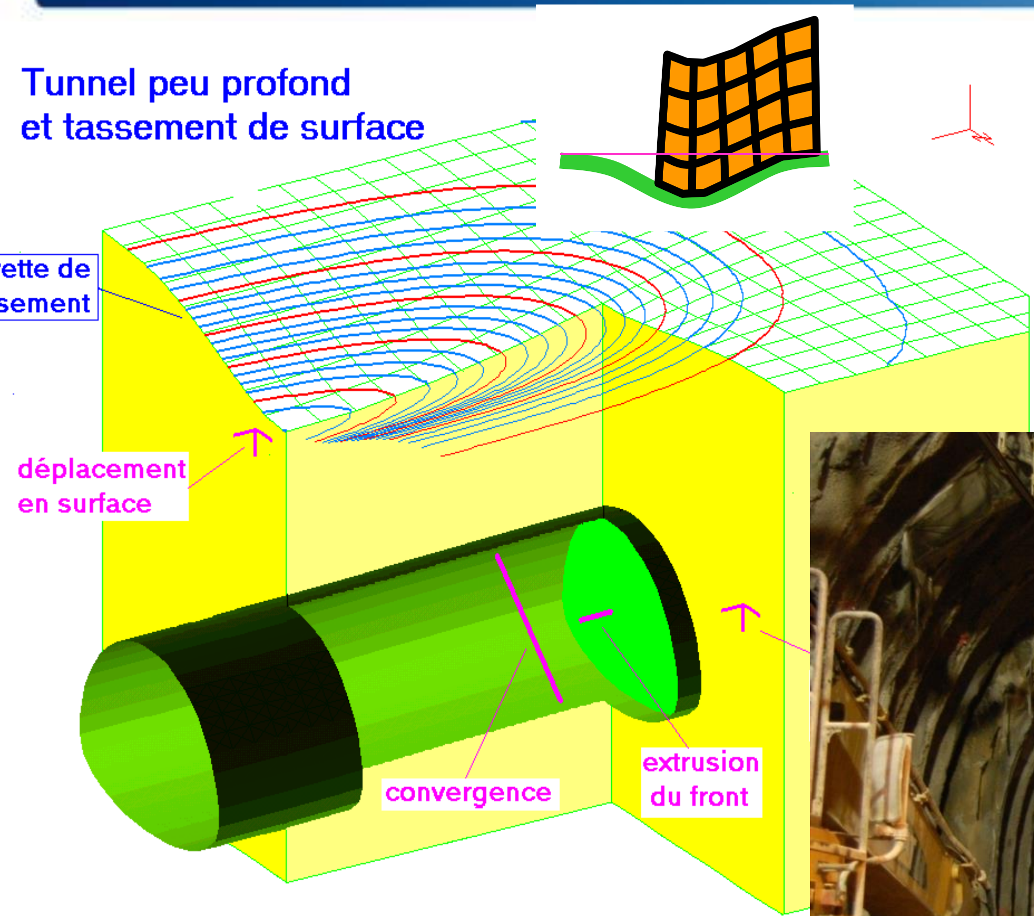
Toulon (France) South Tunnel, 2007 - 2011



Toulon (France) South Tunnel, 2007 - 2011



Toulon (France) South Tunnel, 2007 - 2011

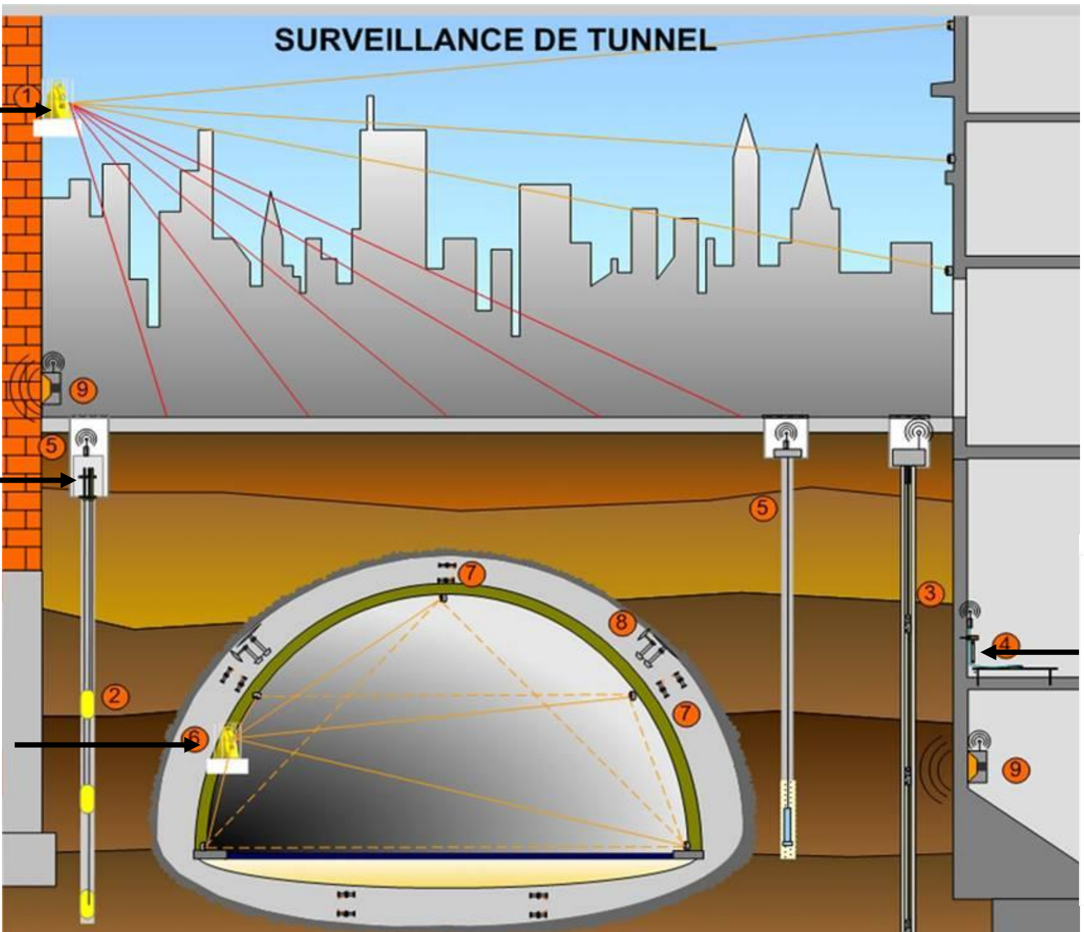


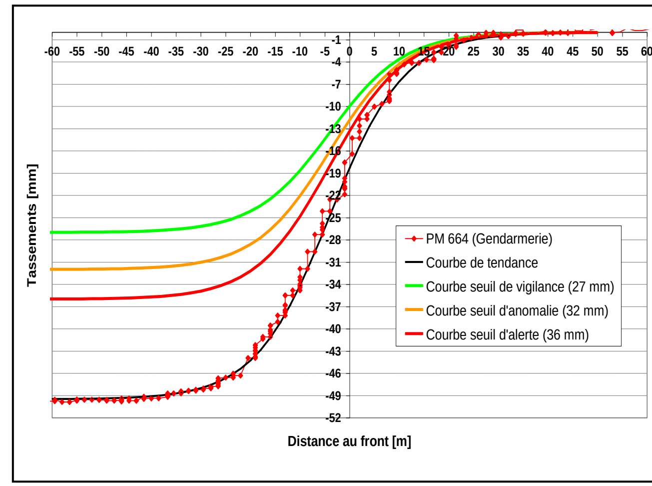
- Heterogenous Geology
- Short coverage (15 m - 40 m)
- High Urban density
- Previous sinkhole accident during the excavation of North tunnel
- Below water level
- Large section (120 m²)

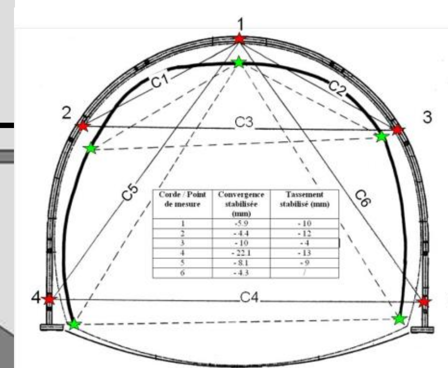
Toulon (France) South Tunnel, 2007 - 2011

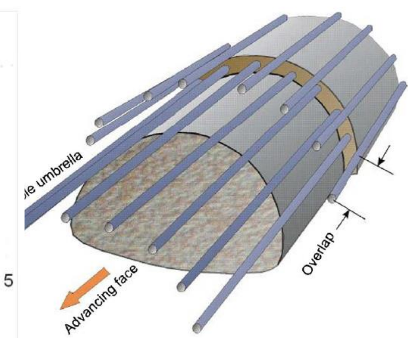
AUTOMATIC & REAL TIME MONITORING TO DRIVE THE WORKS

- **Observational method used to design the temporary support**
- **180 Buildings (36 Cyclops position + 2 700 targets + 1 800 Centaur points)**

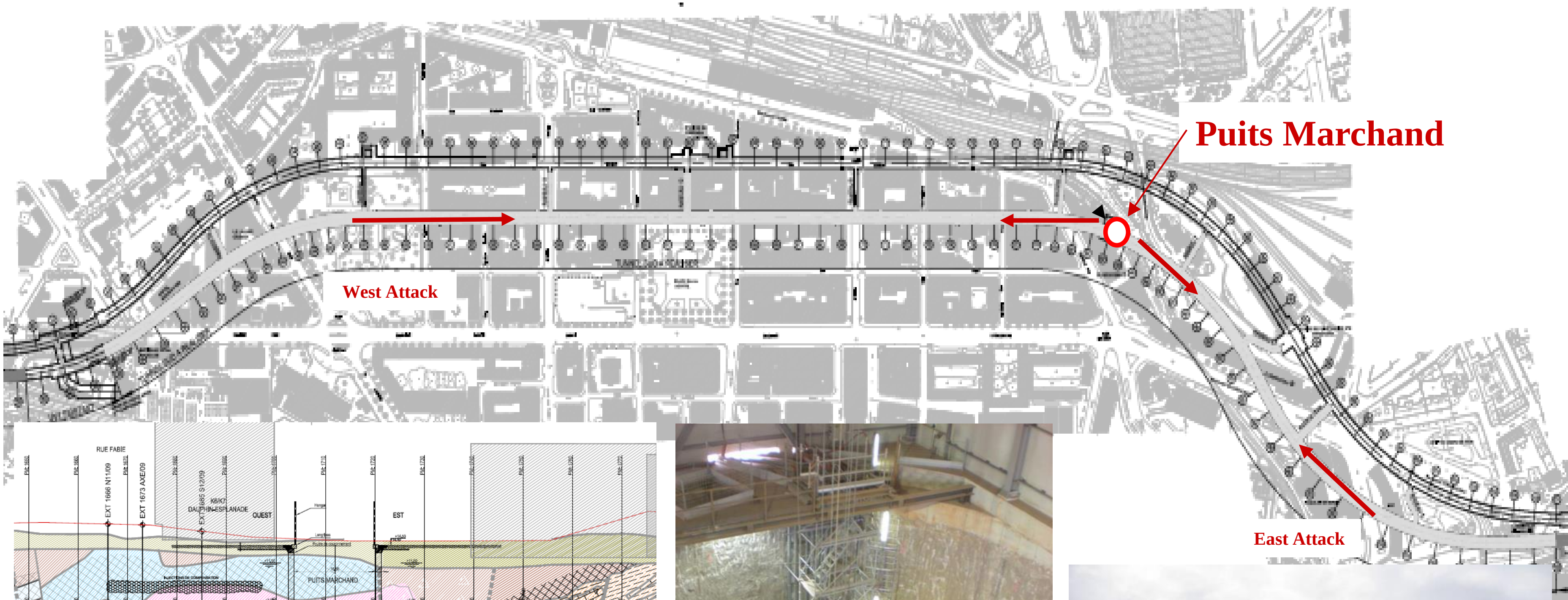


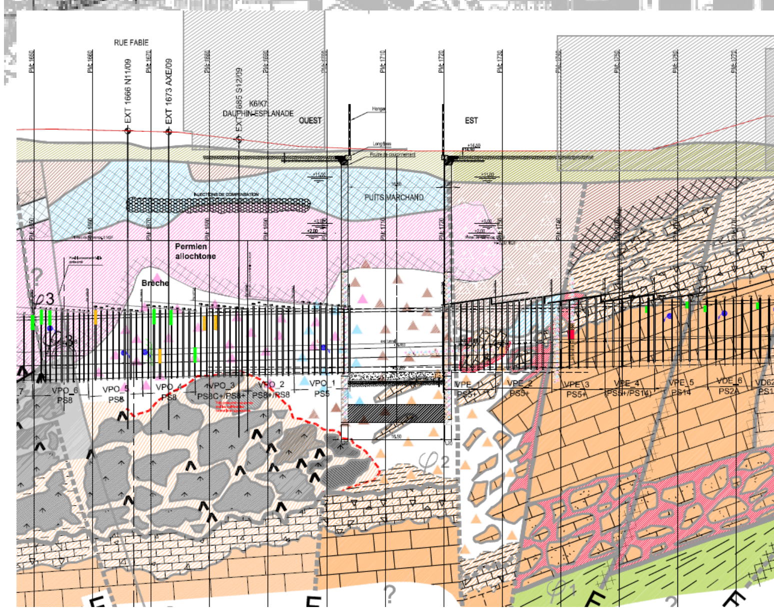






Toulon : Focus on « puits Marchand » & Buildings K6-K7





Toulon : Focus on « puits Marchand » & Buildings K6-K7

Monitoring already operating on the project

Settlement of K6-K7 reached 40mm due to cumulated works

-D. Wall

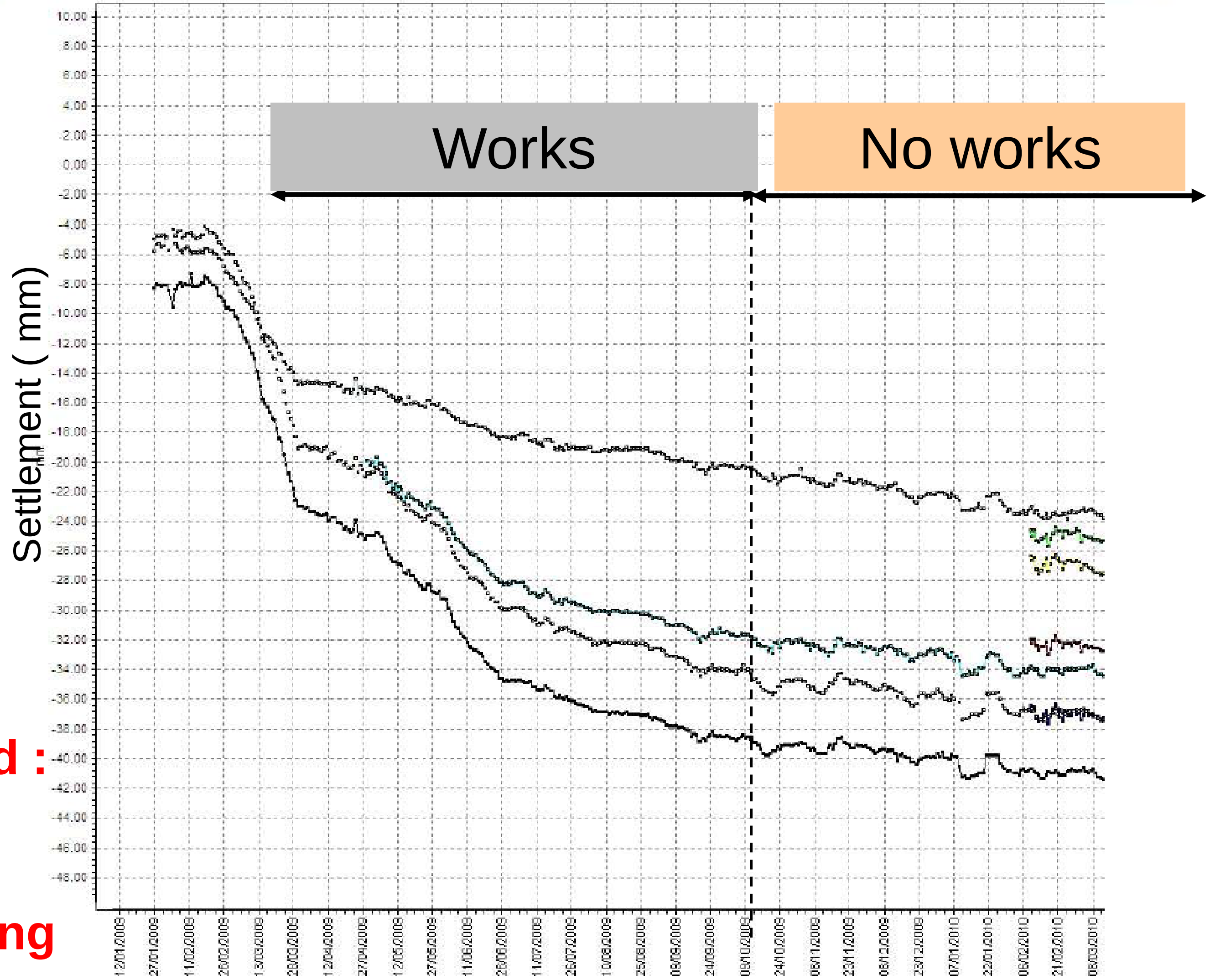
-Shaft excavation

- Start of tunnel

Trigger levels exceeded :

⇒Stop of tunnel

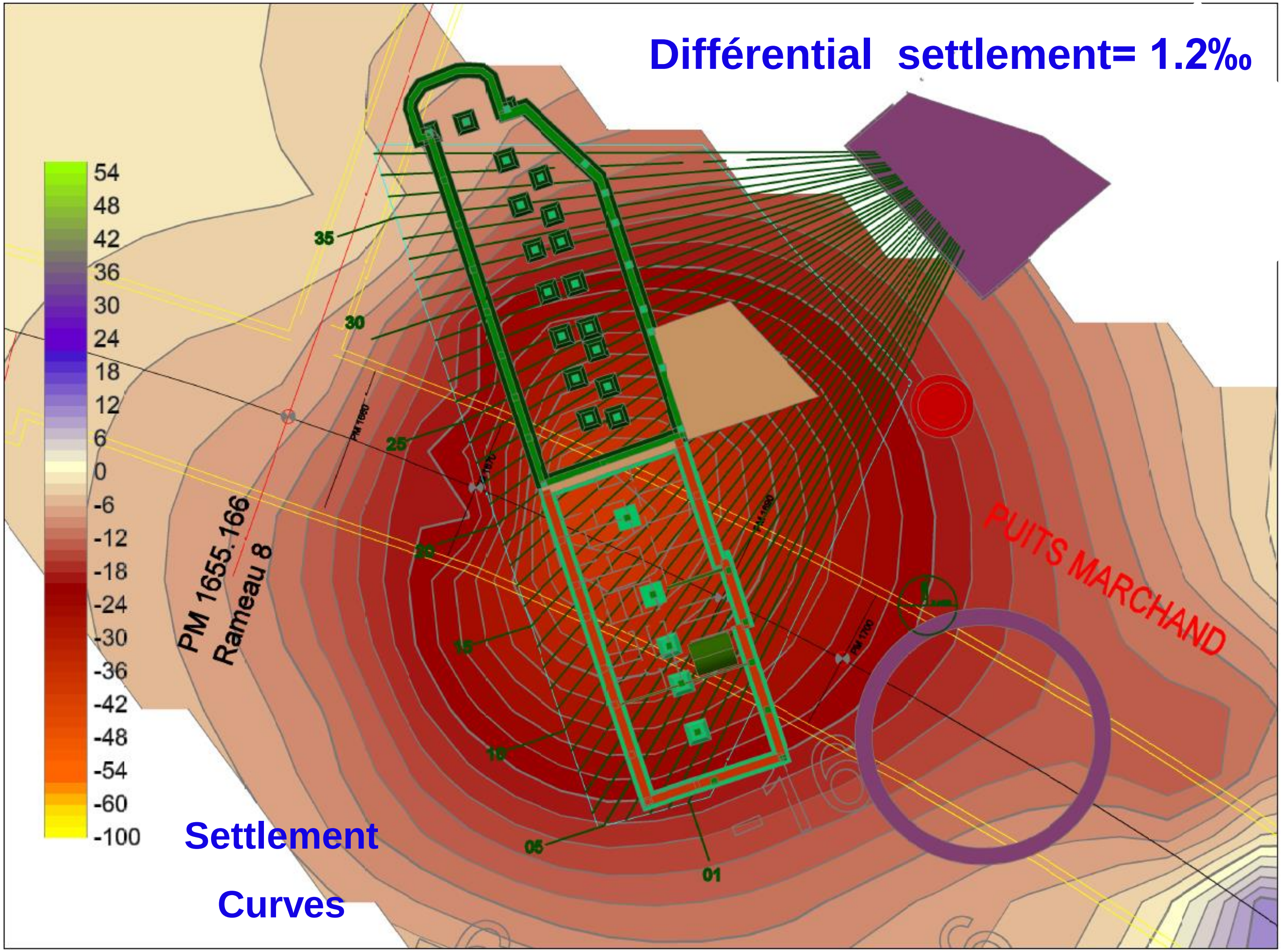
⇒ Evacuation of Building



Toulon : Focus on « puits Marchand » & Buildings K6-K7

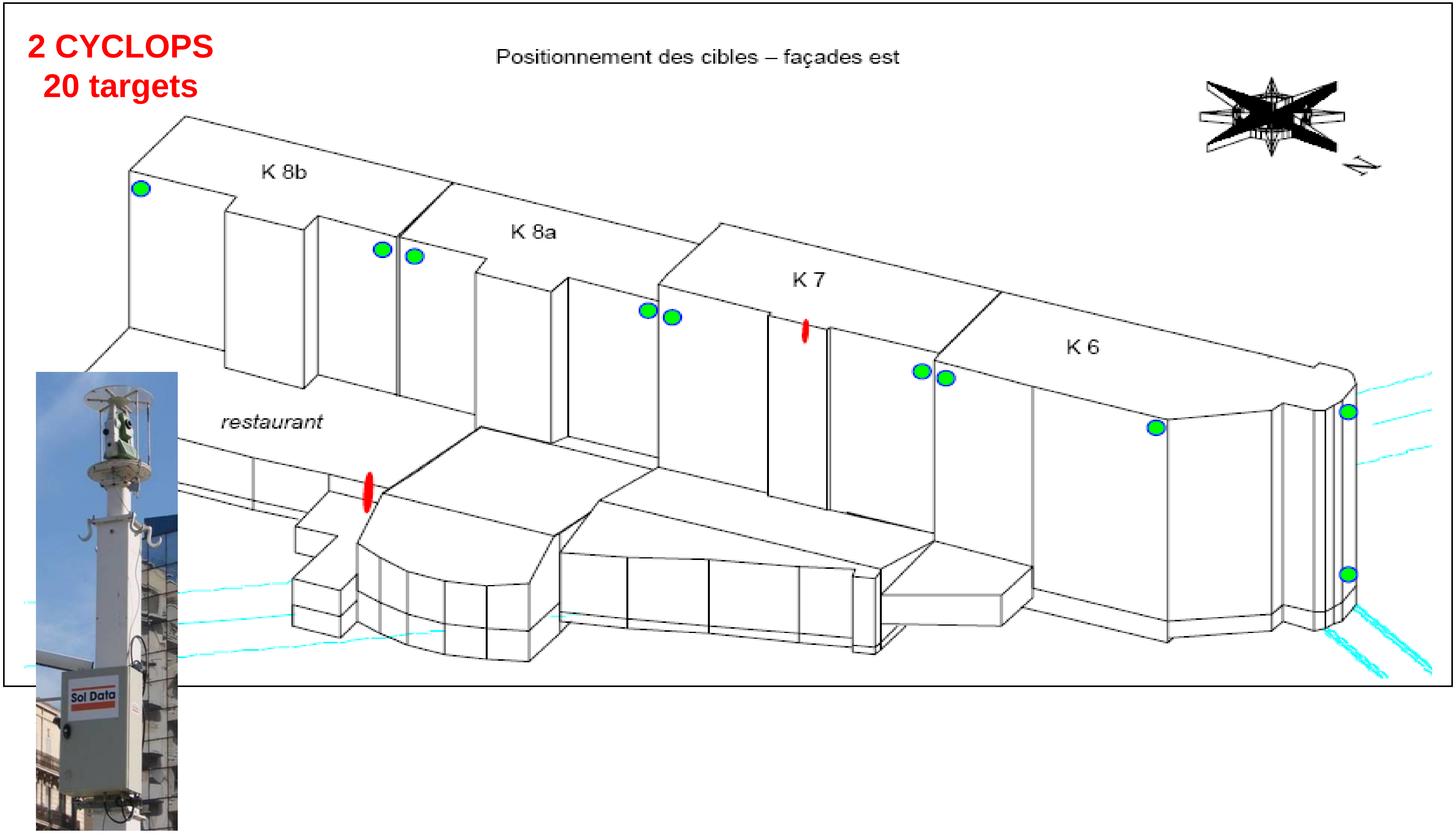
Absolute settlement = 42 mm

Différential settlement= 1.2‰



Toulon , CG Puits Marchand –Initial Monitoring System

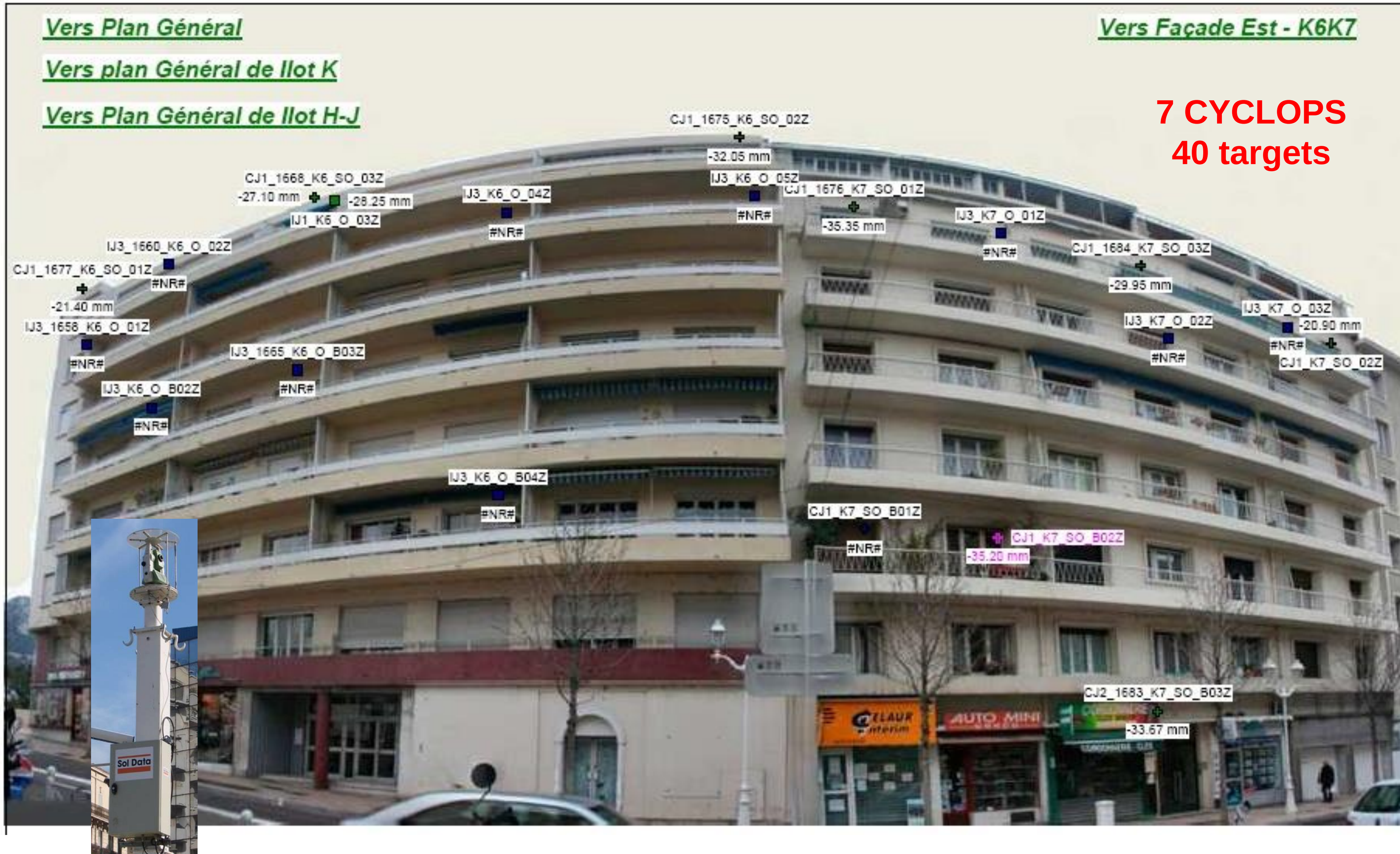
2 CYCLOPS
20 targets



Toulon , CG Puits Marchand – Extensive Monitoring System

7 CYCLOPS
40 targets

Toulon , CG Puits Marchand – Extensive Monitoring System



Toulon , CG Puits Marchand – Extensive Monitoring System

OUTSIDE

CYCLOPS (X,Y,Z on building)
CENTAUR (Z on surface)

Frequency: up to 8 min
Accuracy: 0,5 mm
Absolute movements

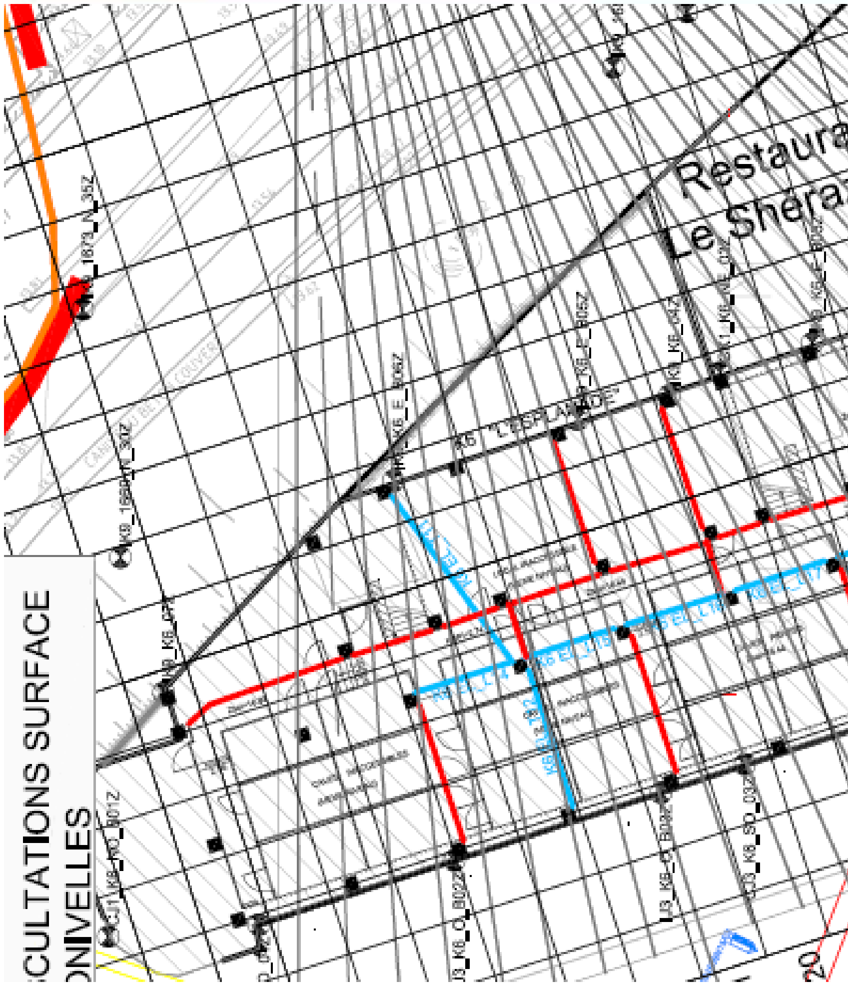
INSIDE (basement)

ELECTROLEVELS

Frequency: up to 1 s
Accuracy: 0,01 mm / m
Relative movements

+ Convergence in the Tunnel

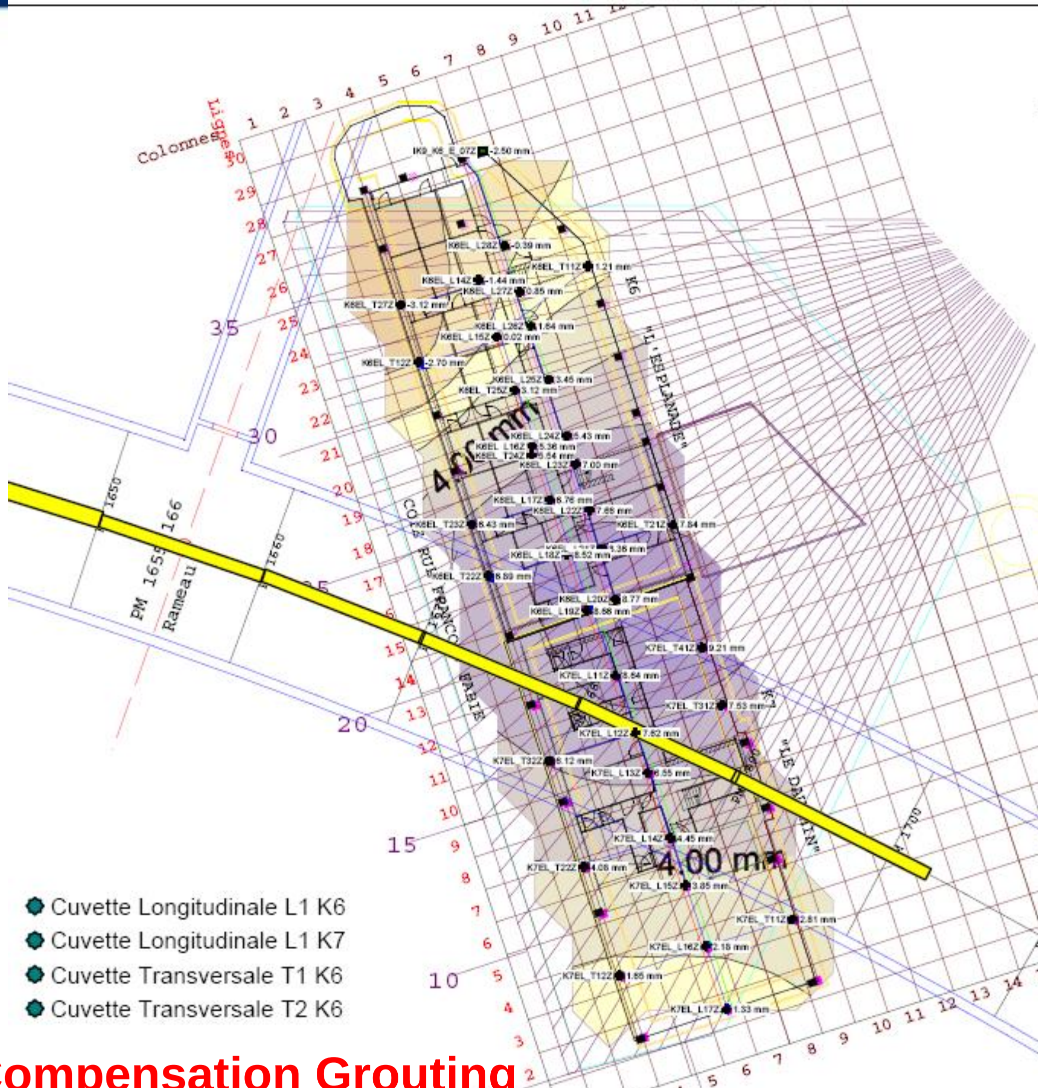
Toulon , CG Puits Marchand – Extensive Monitoring System

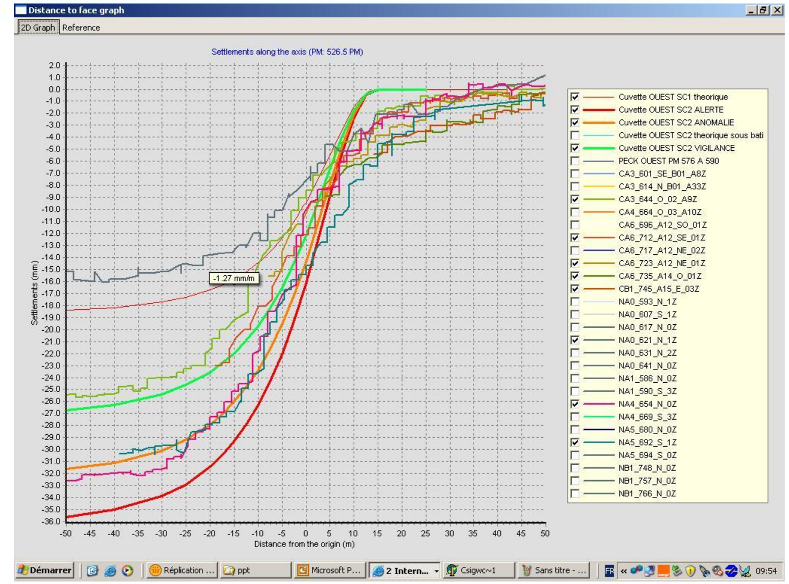


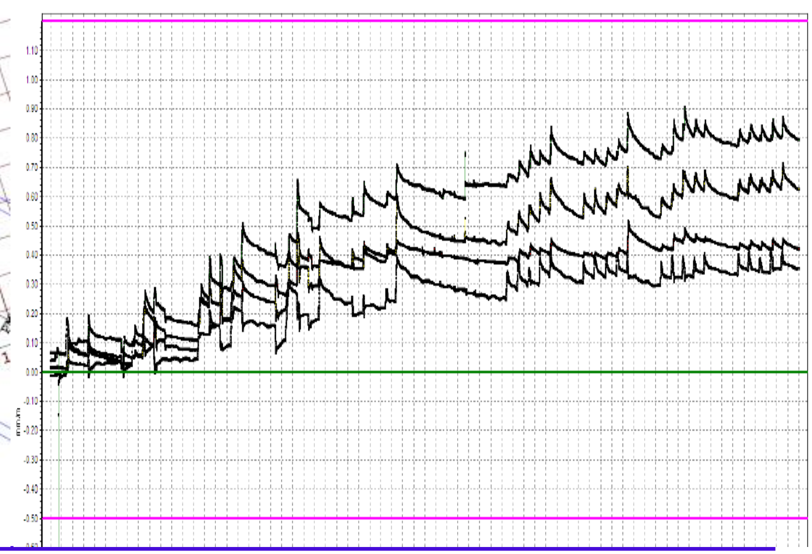
36 electrolevels, between facades and cc

Accuracy = 0,01 mm / m

Toulon , CG Puits Marchand – Monitoring by GEOSCOPE



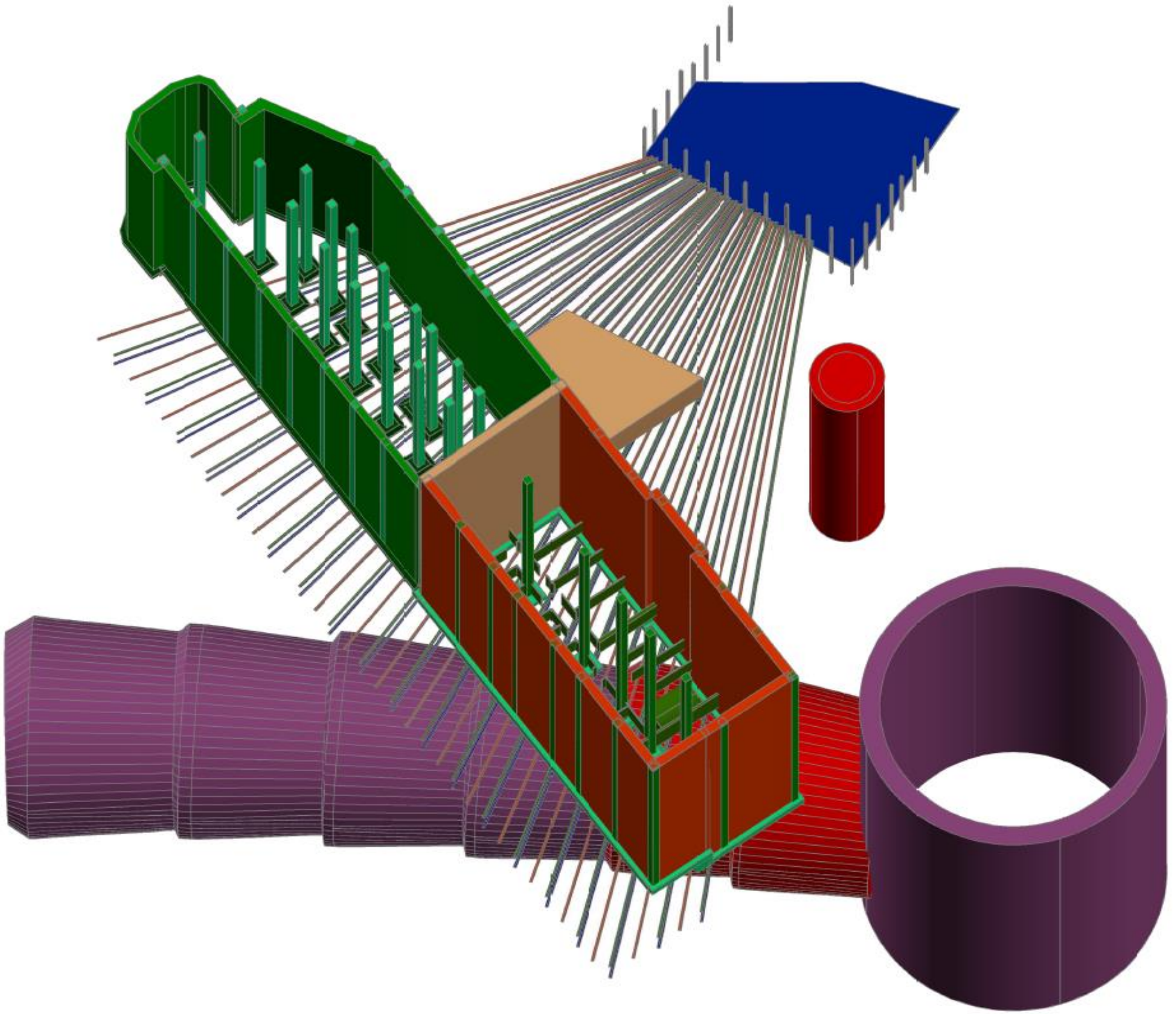




Compensation Grouting

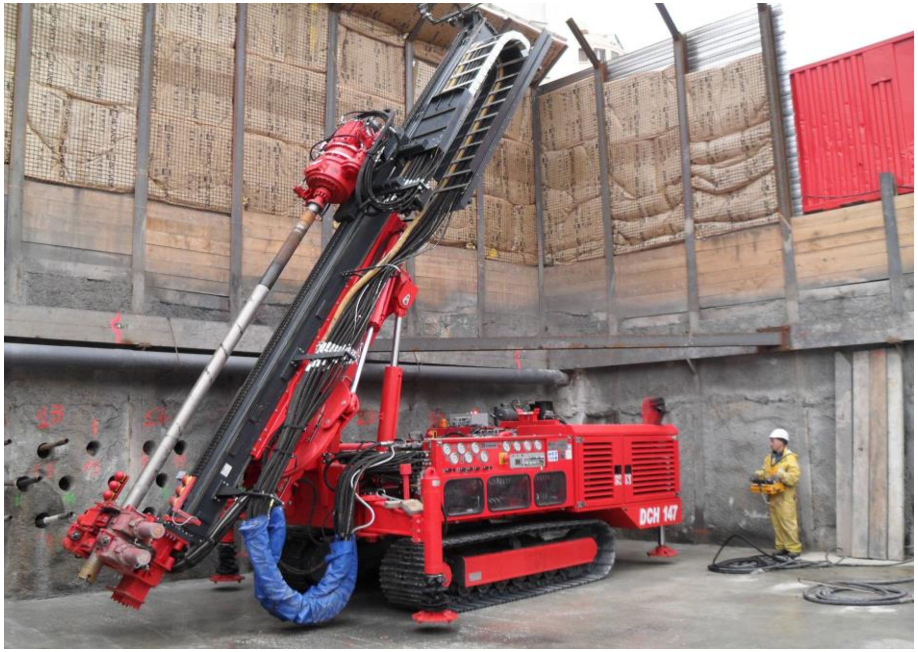
=> High acquisition rates (> 2 Hz)

Toulon , CG Puits Marchand – Drilling Scheme



Toulon , CG Puits Marchand – Drilling Phase

Toulon , CG Puits Marchand – Drilling Phase



Limited water use

2 345 meters under the buldings K6-K7 from a trench (drilling = 9.5m/h)

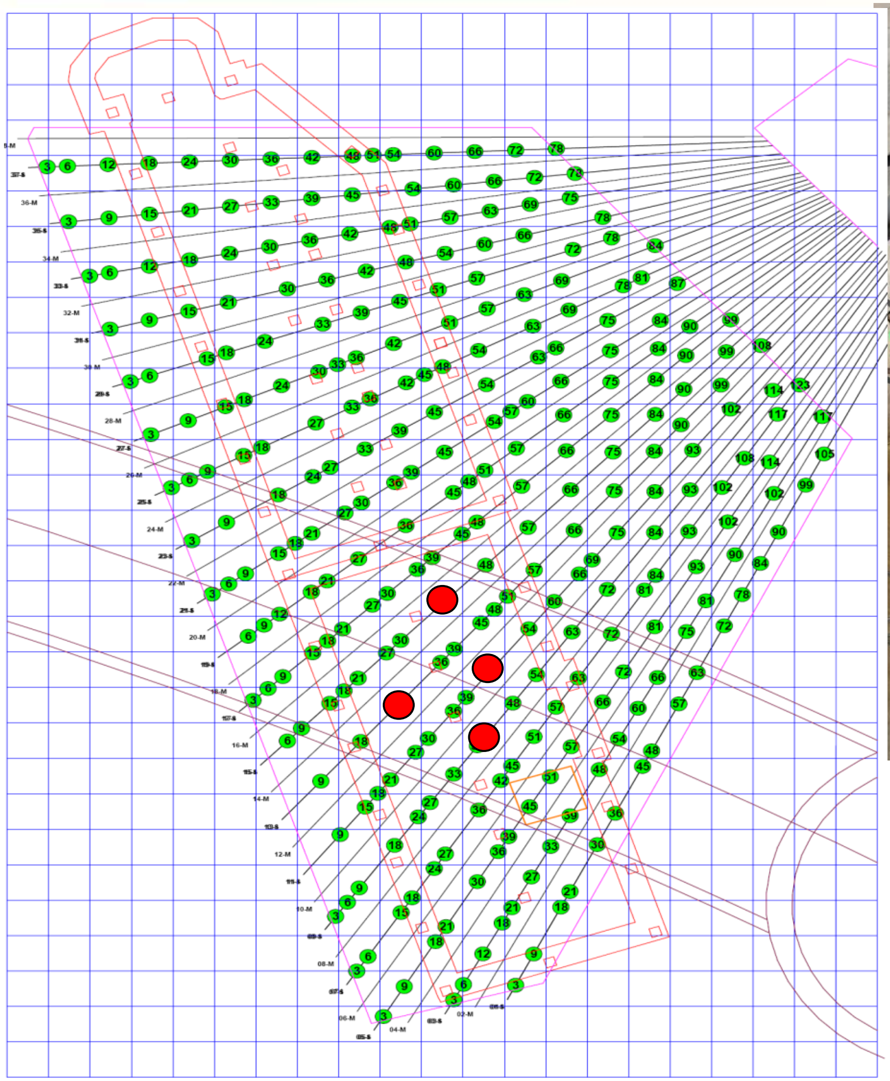
57 boreholes (average length = 41 m)

3 levels of boreholes with angle between 8° to 10° from horizontal

Metallic TAM, 2''

Toulon , CG Puits Marchand – Drilling Phase

Toulon , CG Puits Marchand – Grouting Phase



Toulon , CG Puits Marchand, pre-conditionning phase

- **Low volume of grout (30 liters by TAM)**

  Opened soils = Grout layer

  Closed soils = Compression

  => Will allow an homogeneous and fast reaction when CG

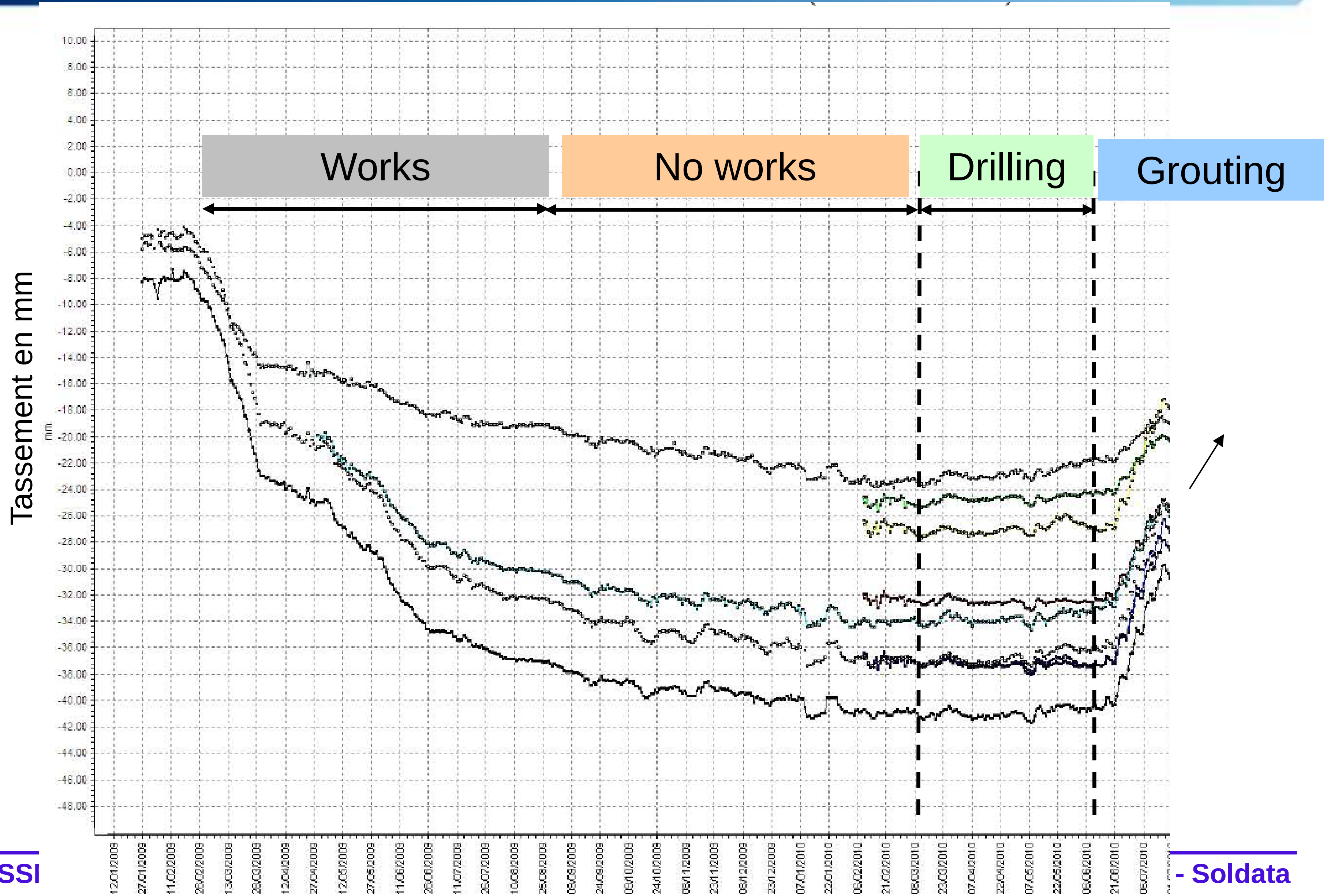
  => Test & calibration (efficience)

  => Settlement reduction

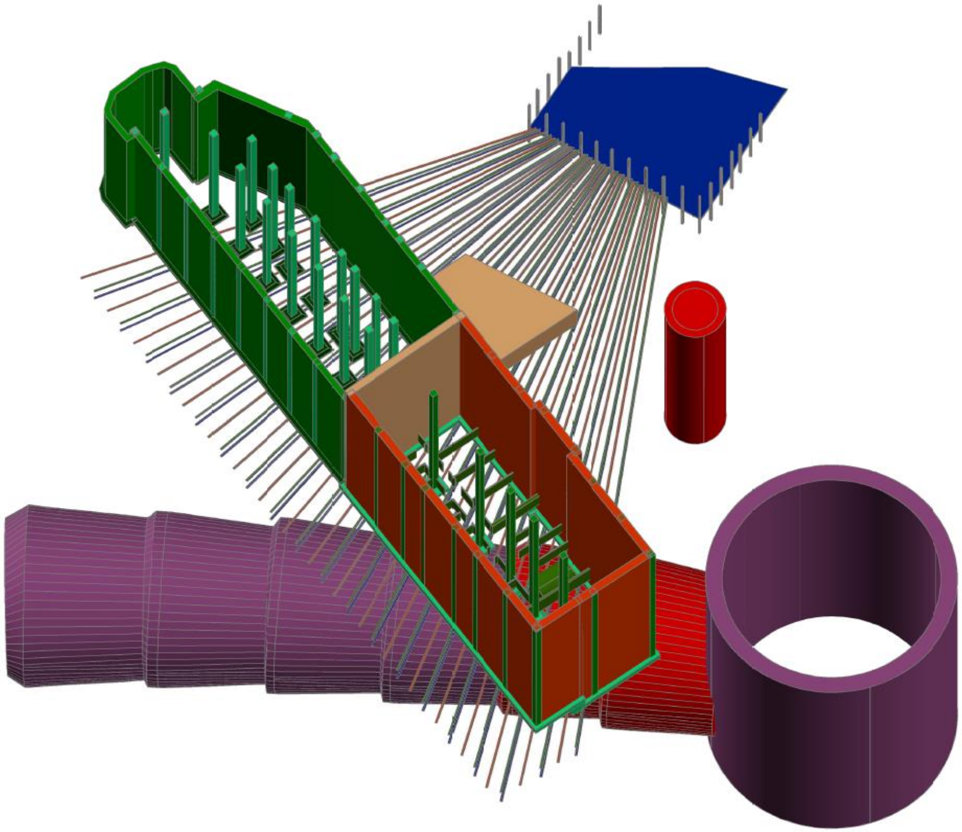
  => Decrease of differential movement

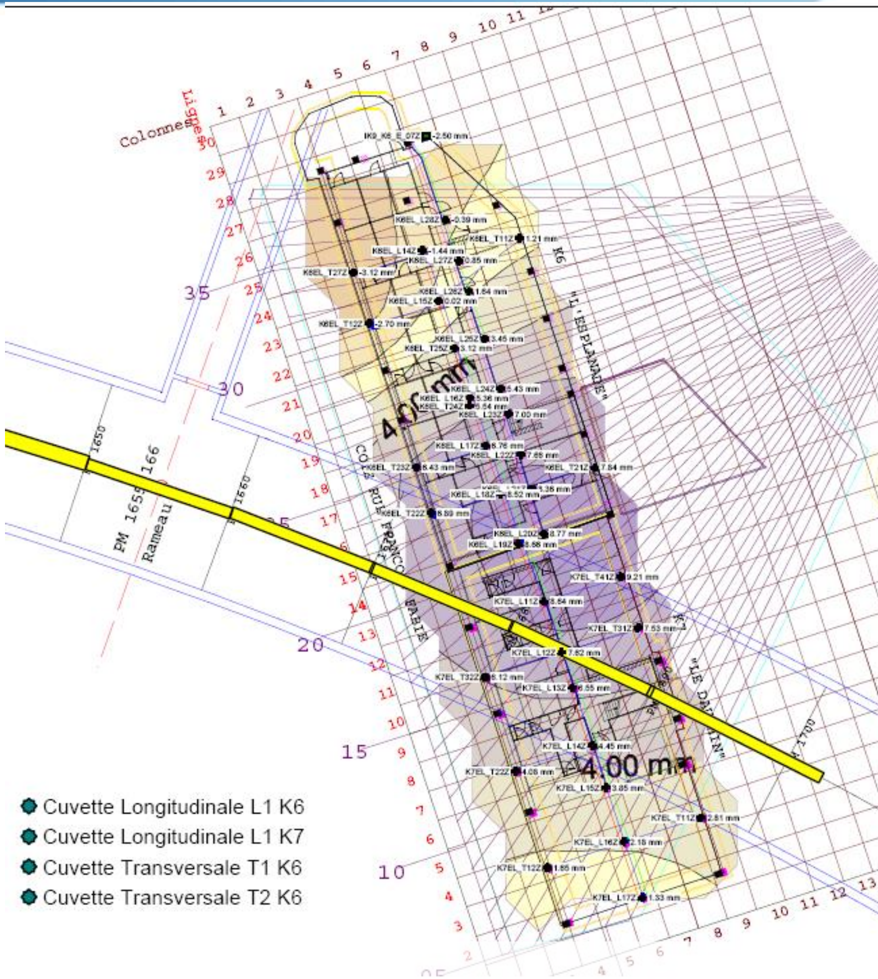
➔No movement inside the tunnel

Toulon , CG Puits Marchand, pre-conditionning phase



Toulon , CG During Tunnel works

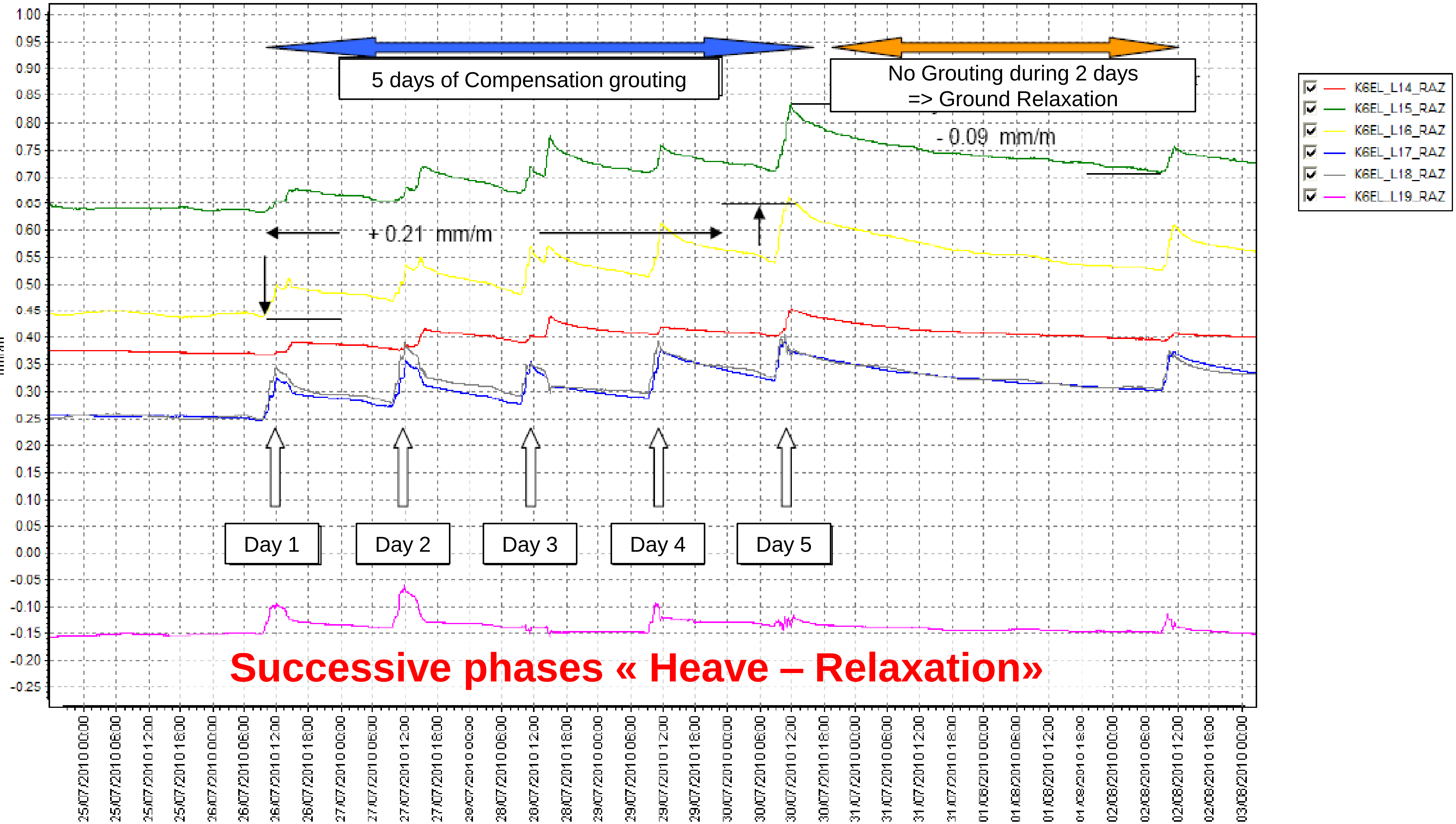




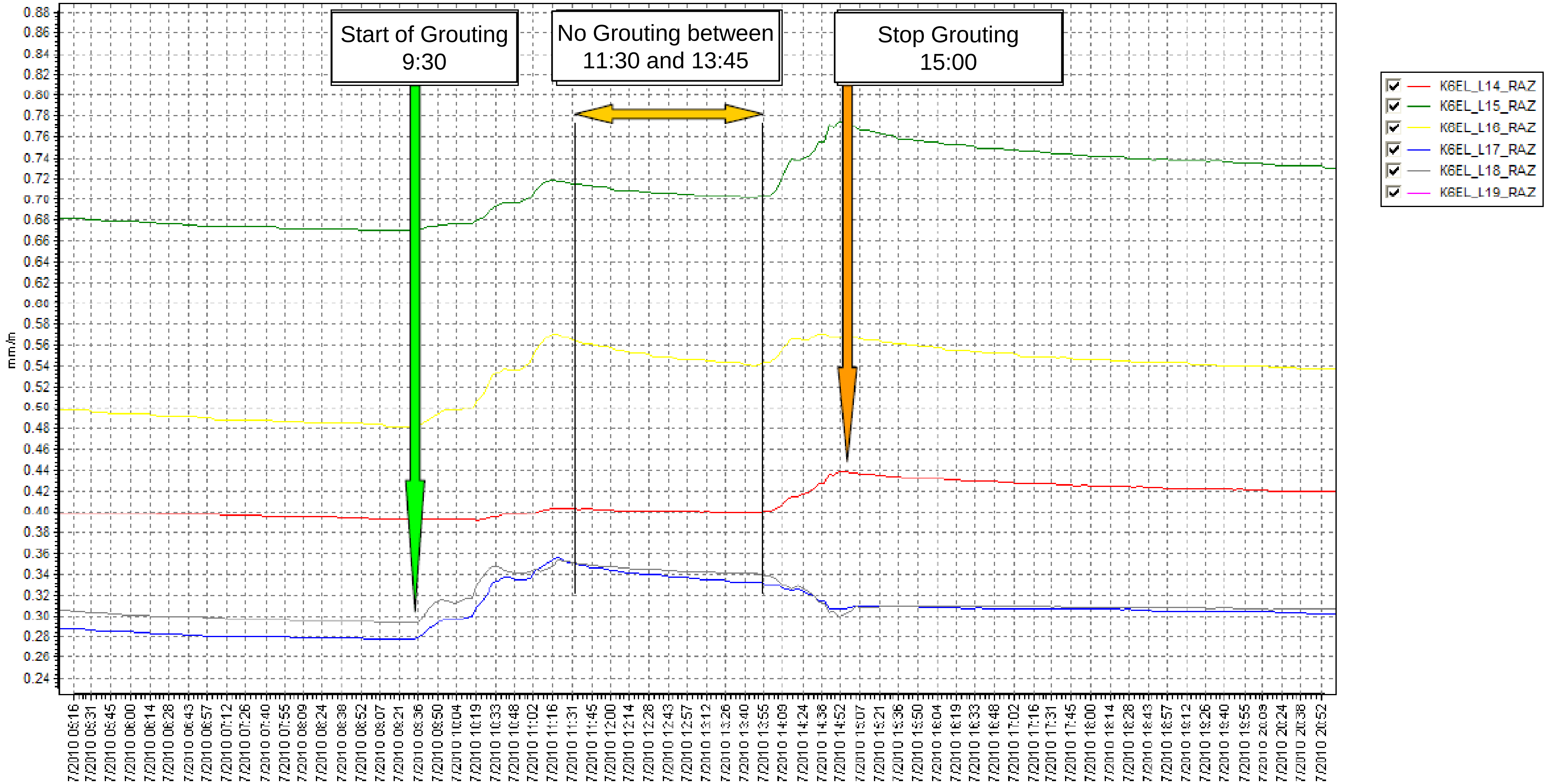
Tunnel :1 m / day

Compensation Grouting : Average Heave = 1,2 mm, Relaxation : 0,5 mm

Accurate Monitoring of Compensation Grouting

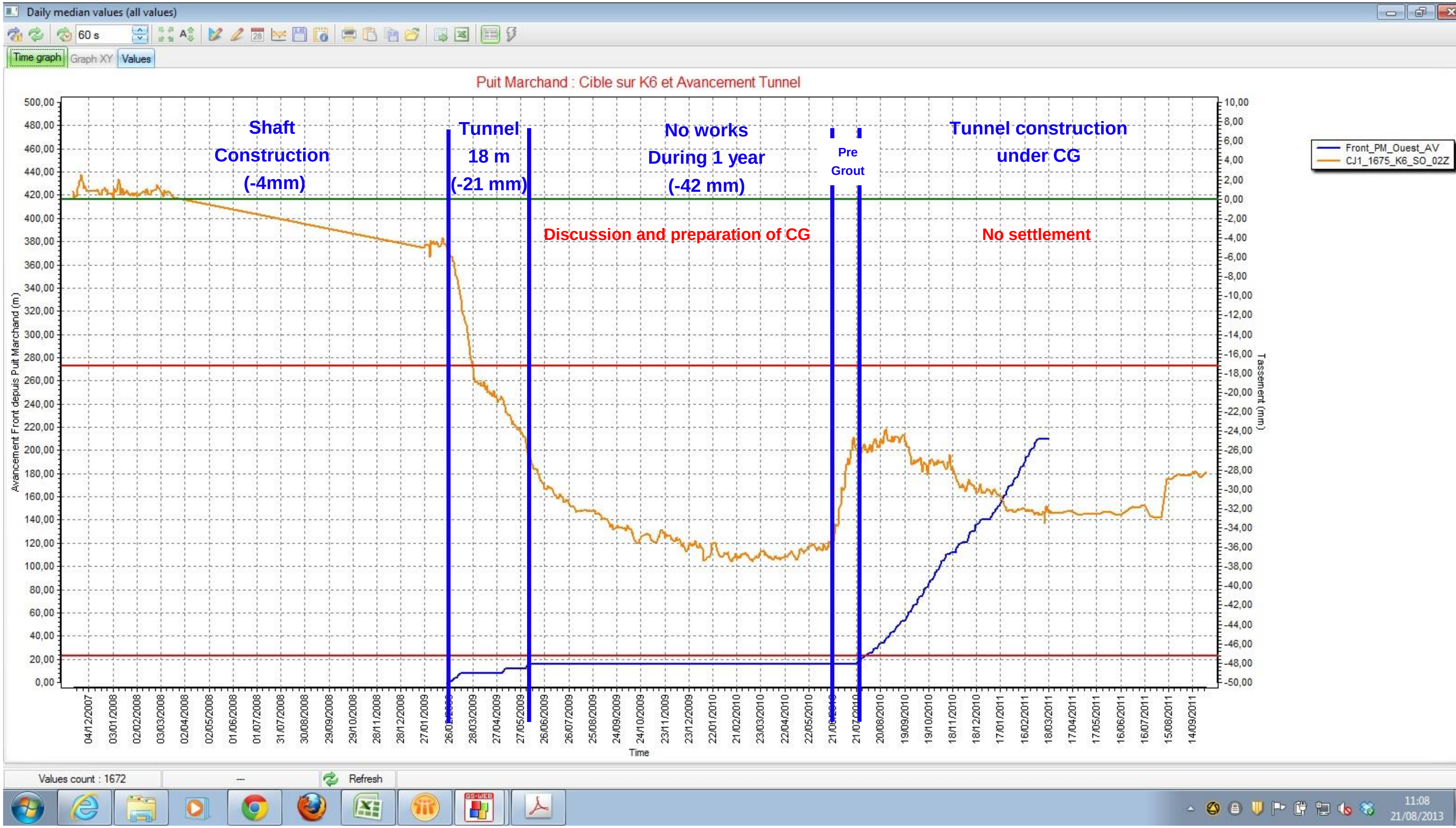


Accurate Monitoring of Compensation Grouting

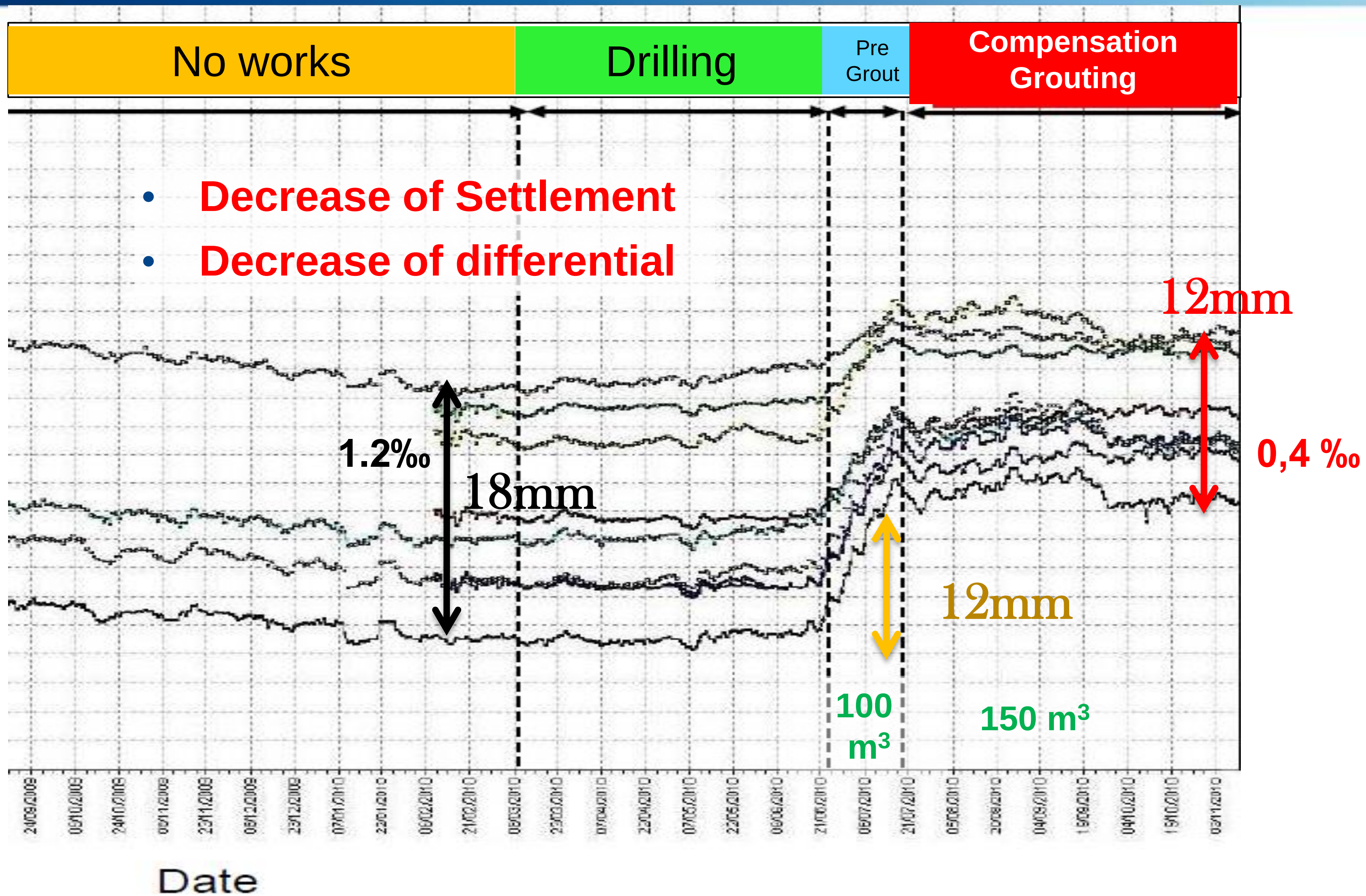


- **Immediate reaction of the structure from Grouting**
- **Electrolevels well fitted for this monitoring (high frequency)**
- **Compensation adjusted thanks to the high density of TAM**

Accurate Monitoring of Compensation Grouting



Accurate Monitoring of Compensation Grouting



Compensation Grouting in Toulon = A success !

TRAVAUX SOUTERRAINS

Le tunnel de Toulon sauvé par des injections

Alors que le percement du tunnel avait été stoppé par crainte d'une forte déstabilisation du bâti en surface, des injections de compensation ont permis de traverser la zone avec succès. Une première en France.

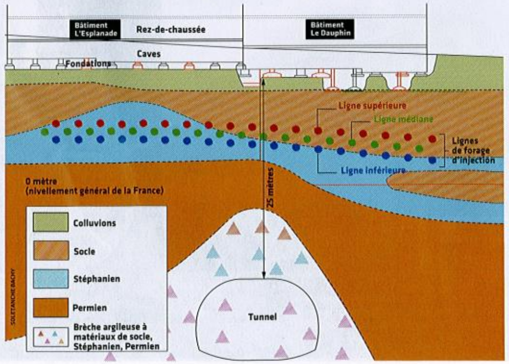
A l'été 2009, des fissures apparaissent sur les cloisons d'un immeuble situé en plein centre-ville de Toulon. La cause? L'arrivée imminente du front d'attaque du tunnel routier en construction 25 mètres plus bas. Bien que les désordres n'atteignent pas la partie structurelle du bâtiment, et que les tassements observés restent en deçà du seuil admissible fixé dans le cahier des charges (42 mm de tassement pour une limite à 80 mm, le tassement différentiel atteignant 1,2 mm/m), le maître d'ouvrage, la Dreal Paca, décide en août 2009 d'arrêter le chantier. Pour les Toulonnais, cet aléa rappelle l'épisode le plus sombre du percement du premier tube de ce tunnel: en mars 1996, dans la même zone, dite zone «Marchand», le tunnel s'était effondré, créant un fontis en surface. Par chance, aucune victime n'était à déplorer, mais le percement ne reprit qu'en 1998.
Treize ans plus tard, pour ne pas risquer l'aléa majeur, le maître d'ouvrage décide d'agir avec grande précaution. L'immeuble (l'Esplanade) est vidé de ses occupants et est lourdement instrumenté, tout comme l'immeuble voisin (le Dauphin), afin de suivre l'évolution de leurs mouvements dans le temps *(voir texte Instrumentation p. 34)*. Techniquement, la problématique est la suivante: comment arriver à poursuivre le percement du tunnel sans toucher à l'intégrité des immeubles? En lien avec la maîtrise d'œuvre (groupement Setec TPI/Terrasol), la réponse viendra de Solétanche-Bachy, cotraitant du groupement d'entreprises piloté par Bouygues TP pour le percement du tunnel. L'entreprise maîtrise en effet une technique inédite en France, mais qu'elle a déjà mise en œuvre sur des chantiers à l'international, notamment sur le métro de Londres: les (•••)

6 millions d'euros HT
(Coût des travaux d'injection de compensation)

- **Maître d'ouvrage: Dreal Paca.**
- **Maître d'œuvre: groupement Setec TPI/Terrasol.**
- **Entreprise injections: Solétanche-Bachy.**

INJECTIONS Bétonner des matelas souterrains pour compresser le sous-sol

A une dizaine de mètres sous les fondations des immeubles, les 57 forages nécessaires à l'injection sont répartis en trois nappes superposées. Le coulis, faiblement dosé en ciment, est injecté dans le sous-sol par l'intermédiaire de trous percés tous les 33 cm dans les tubes à manchettes introduits dans les forages. La compensation est précédée d'une phase de conditionnement. Lors de cette étape préalable, le coulis est injecté depuis les lits de forages supérieurs et inférieurs. Progressivement, deux «matelas» se forment sous la surface des immeubles: ils mettent le sol en compression, et ce faisant, le rigidifient. Une fois ces deux matelas bétonnés, la préparation du sous-sol est terminée, et le percement du tunnel peut reprendre. Pour compenser en temps réel les tassements induits par celui-ci, du coulis de ciment est injecté mais cette fois à partir du lit intermédiaire. Le sol, rendu réactif par les matelas, répond ainsi instantanément aux sollicitations du coulis: l'effet des injections est parfaitement contrôlé.



La plate-forme d'injection
Les injections de compensation sont effectuées depuis une plate-forme spécialement créée pour l'opération. Afin de minimiser les vibrations transmises au sol, c'est une technique sonique qui a été utilisée pour créer les 57 forages tubés d'injection, répartis en trois lits (supérieur, médian, et inférieur).

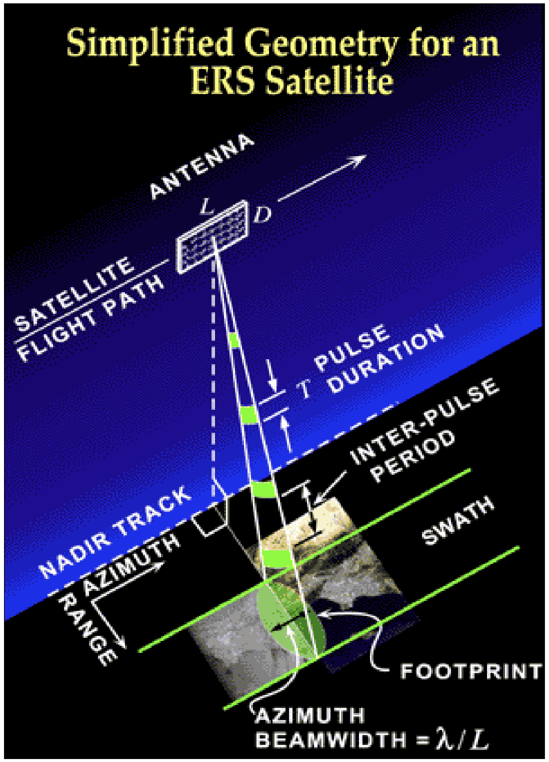
Une injection de haute précision
Chaque forage est équipé d'un tube à manchettes percé tous les 33 cm. L'injection est effectuée via un flexible introduit dans le tube, et terminé par un organe appelé «obturateur double», positionné au droit d'un trou. Quand le coulis arrive, les parties en caoutchouc (photo) se gonflent pour canaliser le flux libéré dans le sous-sol.

Les immeubles impactés
«L'Esplanade» et «Le Dauphin» (au fond sur la photo) subissent l'influence de la cuvette de tassement générée par l'arrivée du front d'attaque du tunnel. L'Esplanade a subi un tassement absolu de 42 mm et un tassement différentiel de 1,2 mm/m. Les injections ont permis de contrôler les tassements tout en menant l'excavation à son terme.

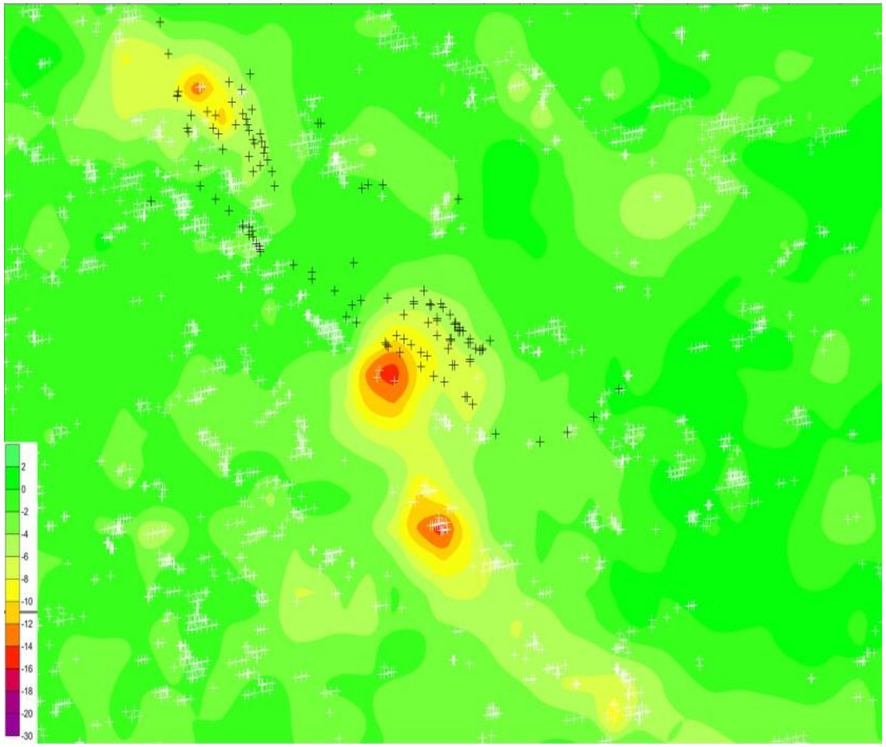
Le percement du tunnel
Le tunnel, long de 1818 mètres, est situé sous le centre-ville. Son percement a nécessité l'utilisation de lourds moyens de confortement, dont le préconfinement du front par boulons de fibre de verre (photo ci-contre). Pour contrôler les tassements en surface, le percement a été ralenti durant les injections de compensation.

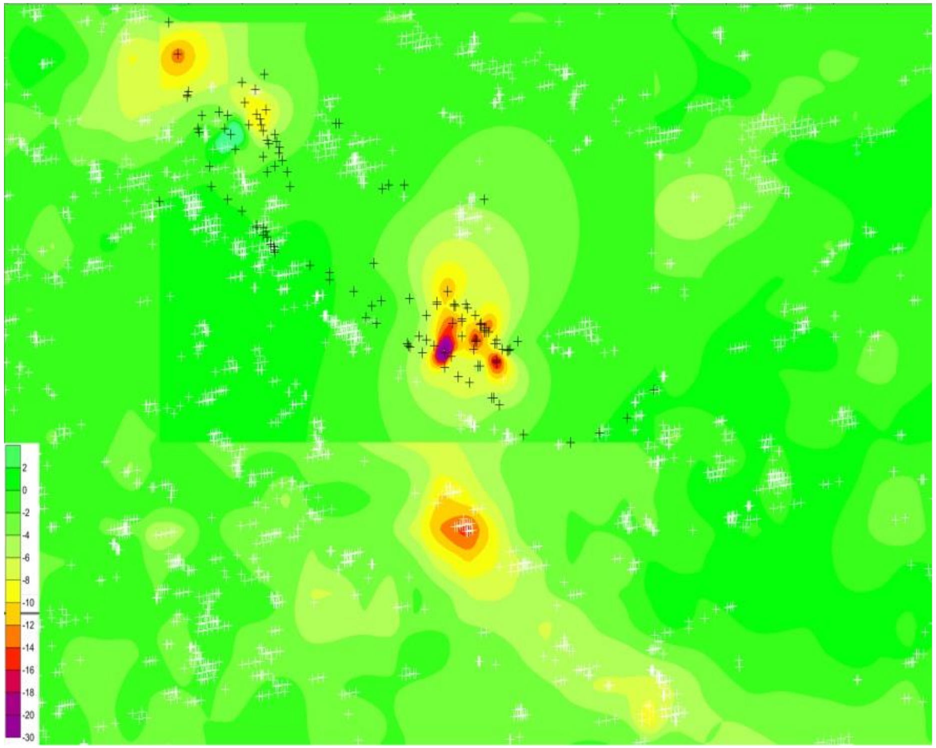
Le puits Marchand
Situé à proximité des immeubles, dans le secteur géologique le plus critique, le puits Marchand a servi d'accès à l'un des trois points d'attaque du tunnel de Toulon. Réalisé en parois moulées, il est profond de 36 mètres et large de 16 mètres.

ATLAS on Toulon



ATLAS on Toulon

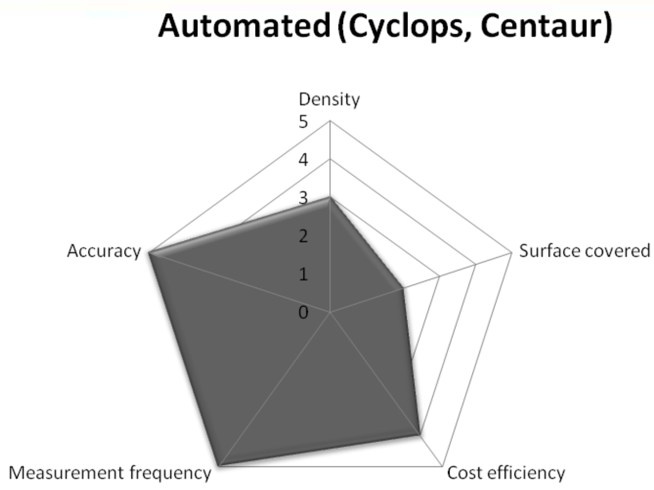


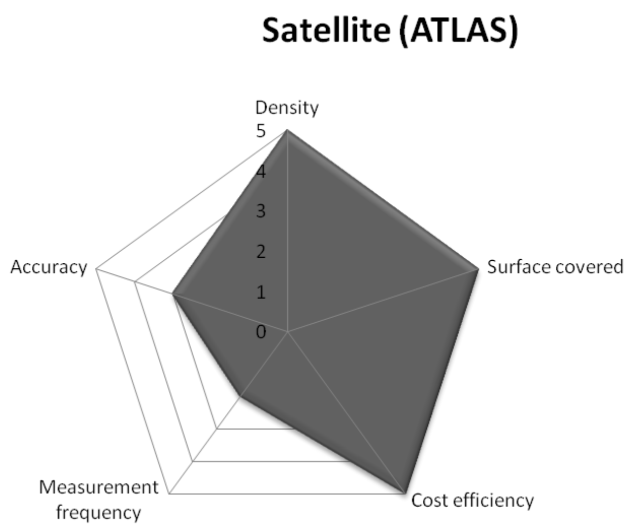


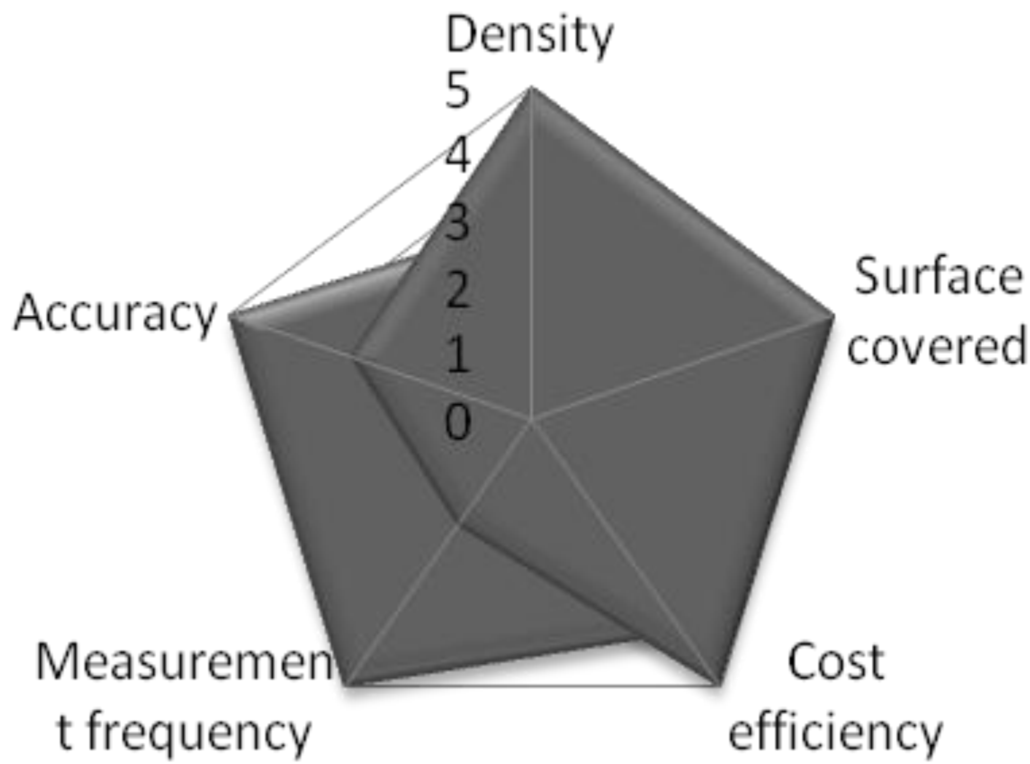
Correlation

between Atlas (Space) & Cyclops (Surface)

A complete Monitoring Scheme







Compensation Grouting

- Generally preventive but can also be corrective
- Specific tools & Expertise
- Observational method =
cooperation between Owner / Engineer / Contractor

Monitoring

- Automatic & Real Time
- need high frequency
- Several measurement technics
- Sofware adapted => fast and clear analysis

Thank you

IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Probability analysis to determine jet grout cut off design

R. Essler, RG Geotech Ltd, United Kingdom

Probability Analysis To Determine Jet Grout Cut Off Design

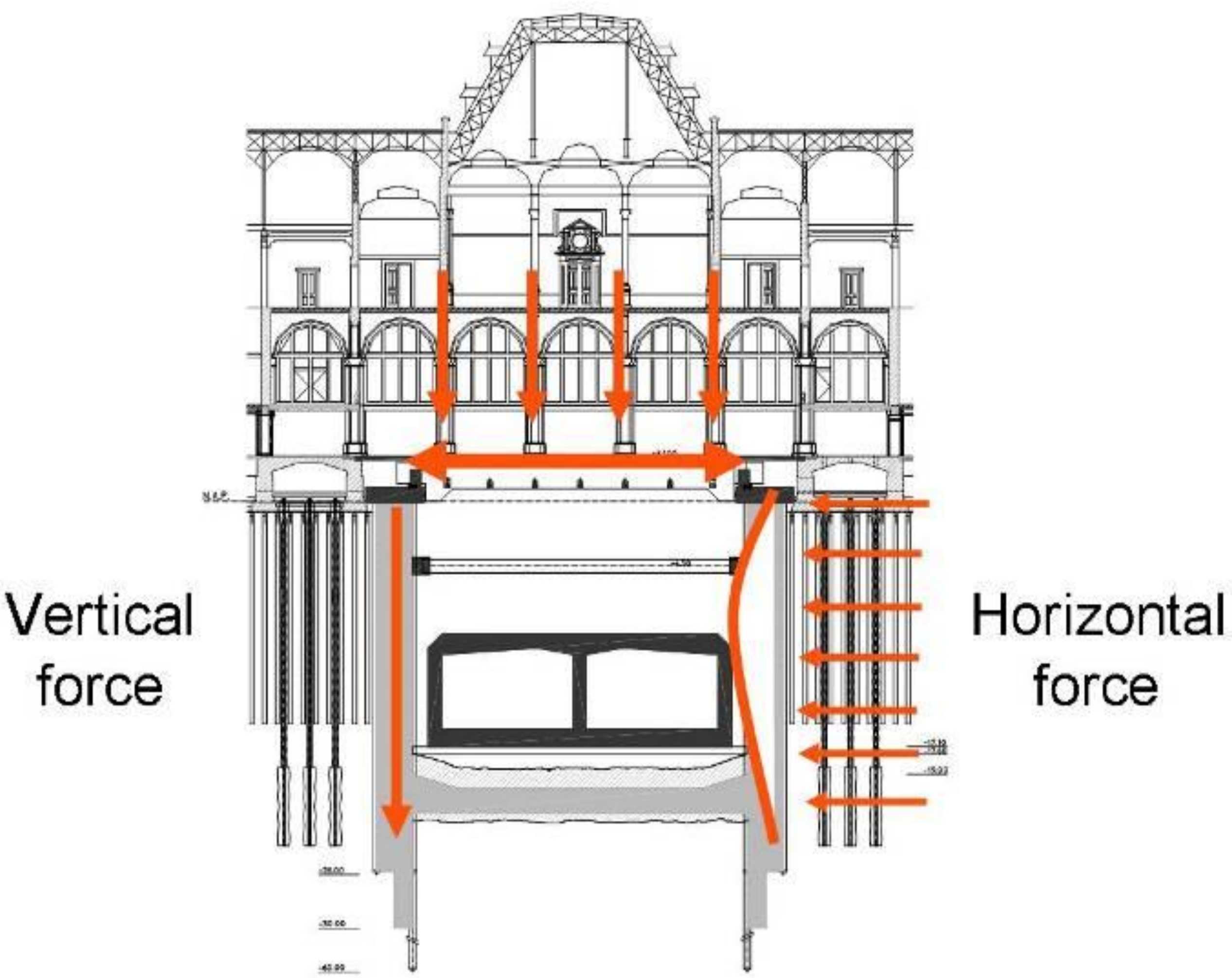
RD Essler
RD Geotech Ltd
1st September

RD GEOTECH LTD

The Progression from Concept to Execution

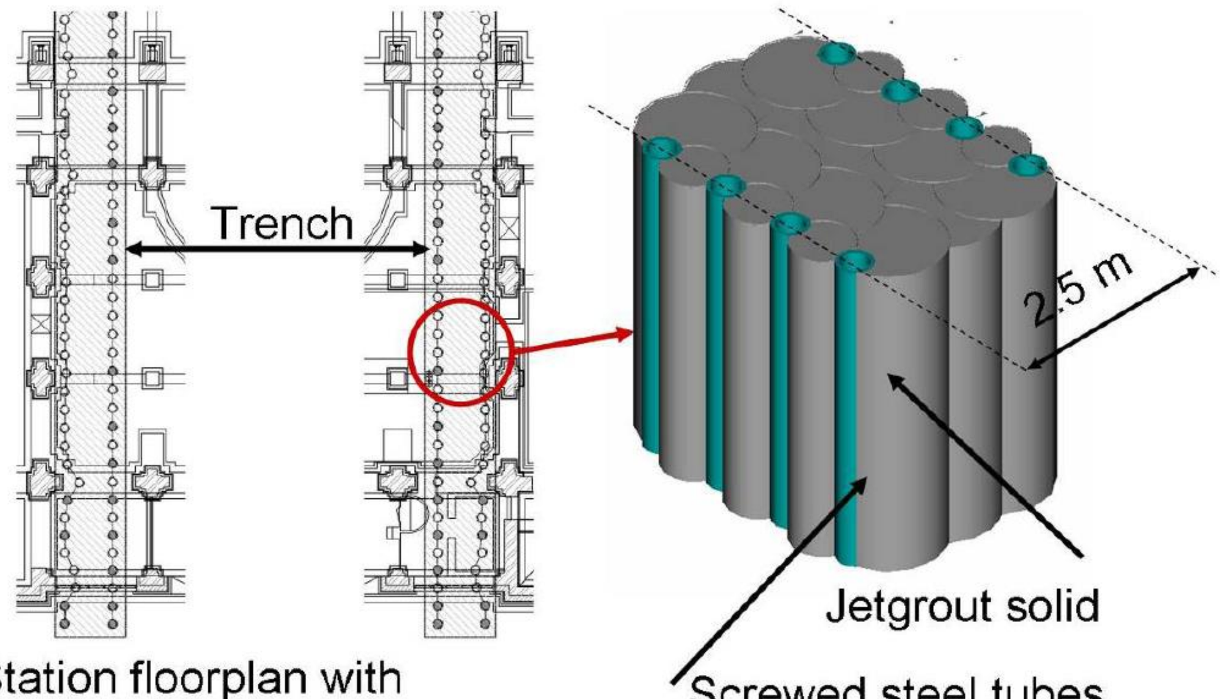
- Concept Design
- Detailed Design
- Execution Design

Example of Concept Design



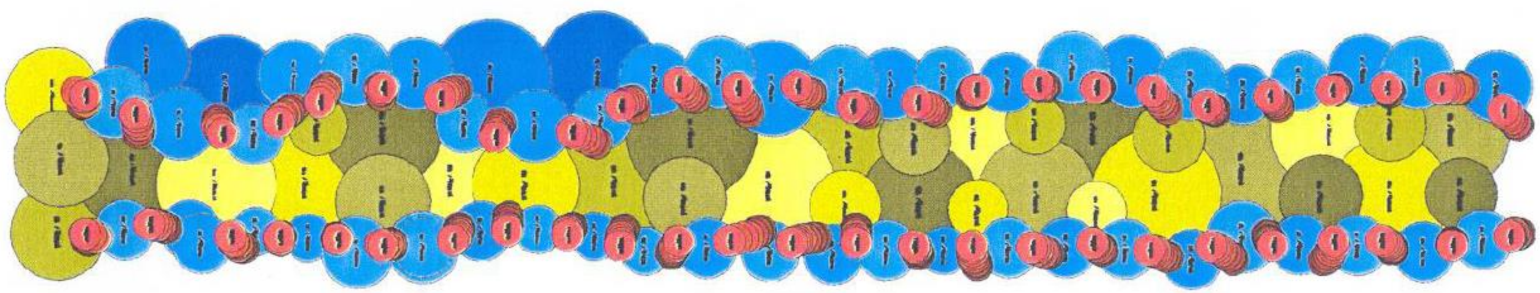
Central Station Amsterdam

Detailed Design

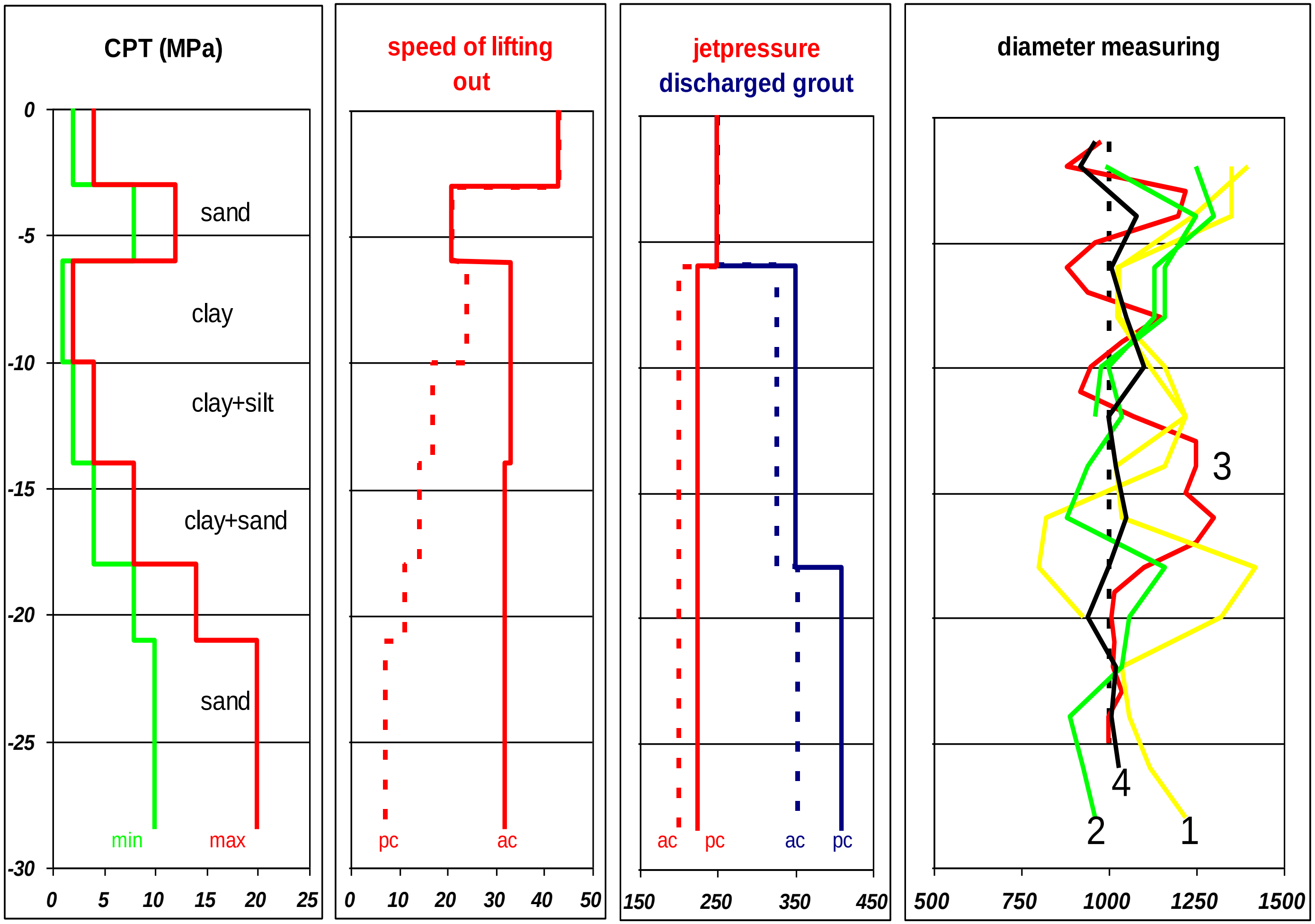


Station floorplan with trenchwalls

Isometric view



Execution Design

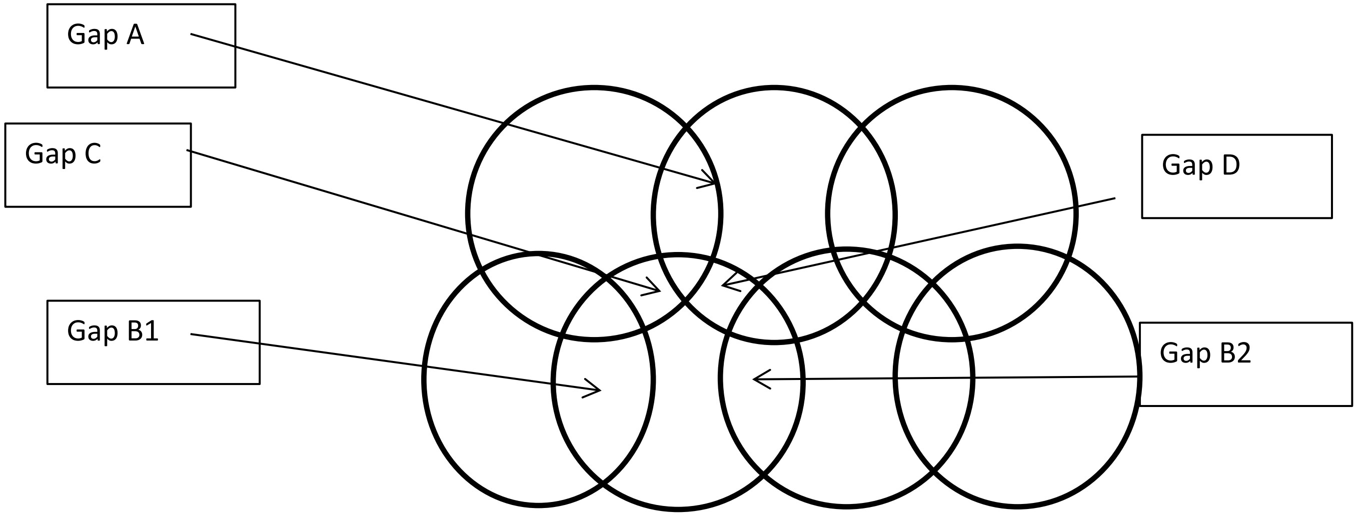


Each column requires 7 sets of jetting parameters constructed in three phases

Detailed Design stage should specify the following:

- Cut Off Geometry (thickness and position, top and bottom levels etc)
- Permeability (minimum, maximum etc)
- Strength (minimum, maximum etc)
- Construction methodology (jet grouting, permeation grouting etc)
- Other aspects associated with construction, for example a minimum two or three row cut off

Terminology for Gap Analysis



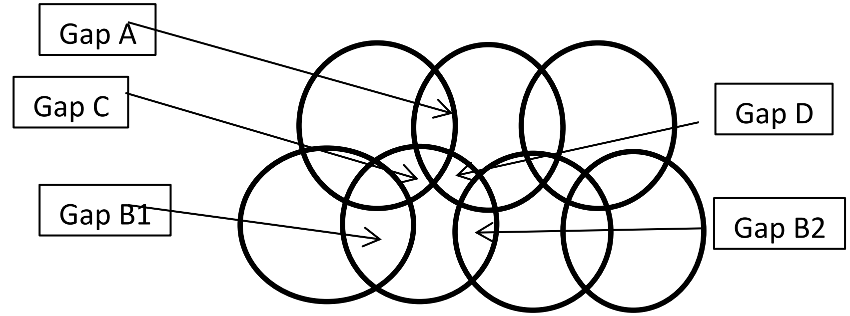
Statistical Evaluation of Jet Grouting

COLUMN DEVIATION ESTIMATION

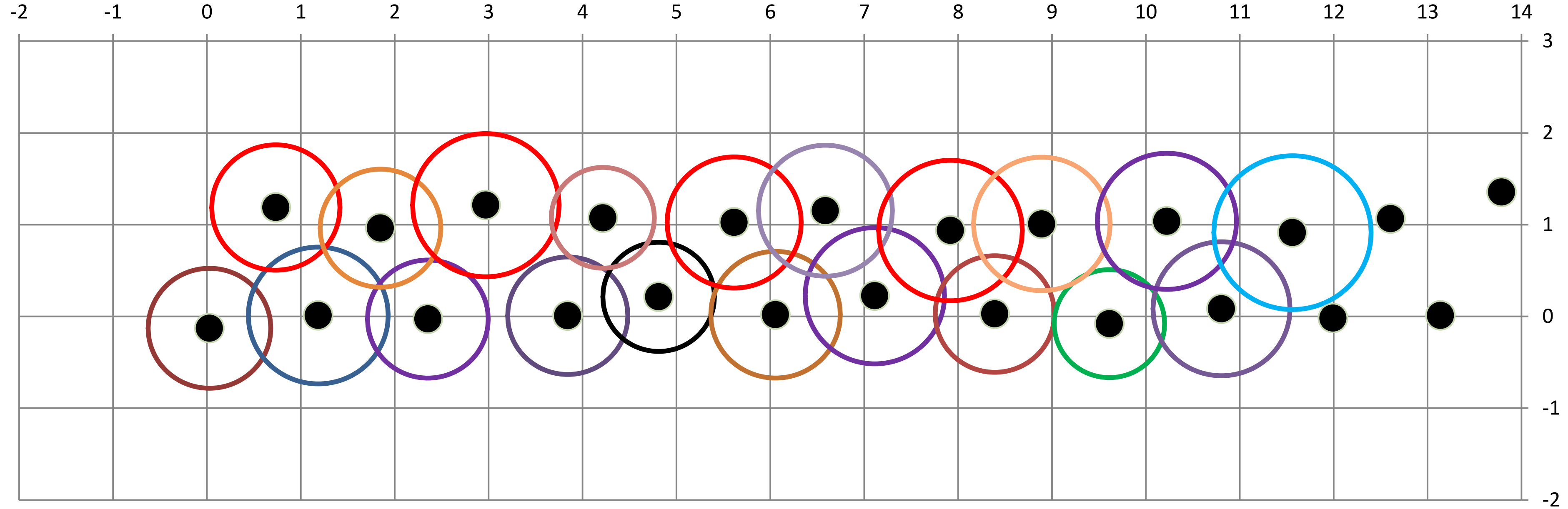
Maximum Drilling Deviation (95%)	2.0%	
Depth	12	m
Primary Column Radius	0.7	m
Secondary Column Radius	0.7	m
Variation in Radius	20%	
Column Spacing (X)	1.20	m
Column Spacing (Y)	1.10	m

				Setting Out Error		Mast Inclination Error		Drilling Deviation Error								
Column No	Diameter (m)	Column Y Coord	Column X Coord	Error (m)	Direction (degrees)	Error (%)	Direction	Deviation %	Direction (degrees)	Deviation Y (m)	Deviation X (m)	Revised Y Coord (m)	Revised X Coord (m)	Actual Overlap (m)	No with Negative overlap	No with Overlap <0.1m
1	1.67	0	0	-0.006	105	0.8%	227	-0.9%	257	-0.039	0.028	-0.039	0.028	0.127	0	0
2	1.21	0	1.2	0.021	335	-0.6%	280	-0.4%	225	0.040	0.101	0.040	1.301	0.218	0	0
3	1.35	0	2.4	-0.061	277	0.0%	149	0.3%	127	-0.022	0.083	-0.022	2.483	0.271	0	0
4	1.33	0	3.6	-0.038	126	-0.5%	32	-2.2%	344	-0.278	0.012	-0.278	3.612	0.091	0	1
5	1.58	0	4.8	-0.078	244	0.7%	172	-0.3%	250	-0.038	0.121	-0.038	4.921	0.248	0	0
6	1.49	0	6	-0.004	262	-0.3%	333	-0.5%	237	0.000	0.073	0.000	6.073	0.252	0	0
7	1.39	0	7.2	-0.035	213	0.2%	247	-0.4%	326	-0.020	0.020	-0.020	7.220	0.167	0	0
8	1.52	0	8.4	-0.064	272	0.4%	63	2.2%	192	-0.241	0.053	-0.241	8.453	0.186	0	0
9	1.34	0	9.6	-0.043	62	-0.9%	188	-0.9%	304	0.032	0.068	0.032	9.668	0.148	0	0
10	1.14	0	10.8	0.016	183	0.9%	111	-0.4%	329	-0.094	0.120	-0.094	10.920	0.278	0	0

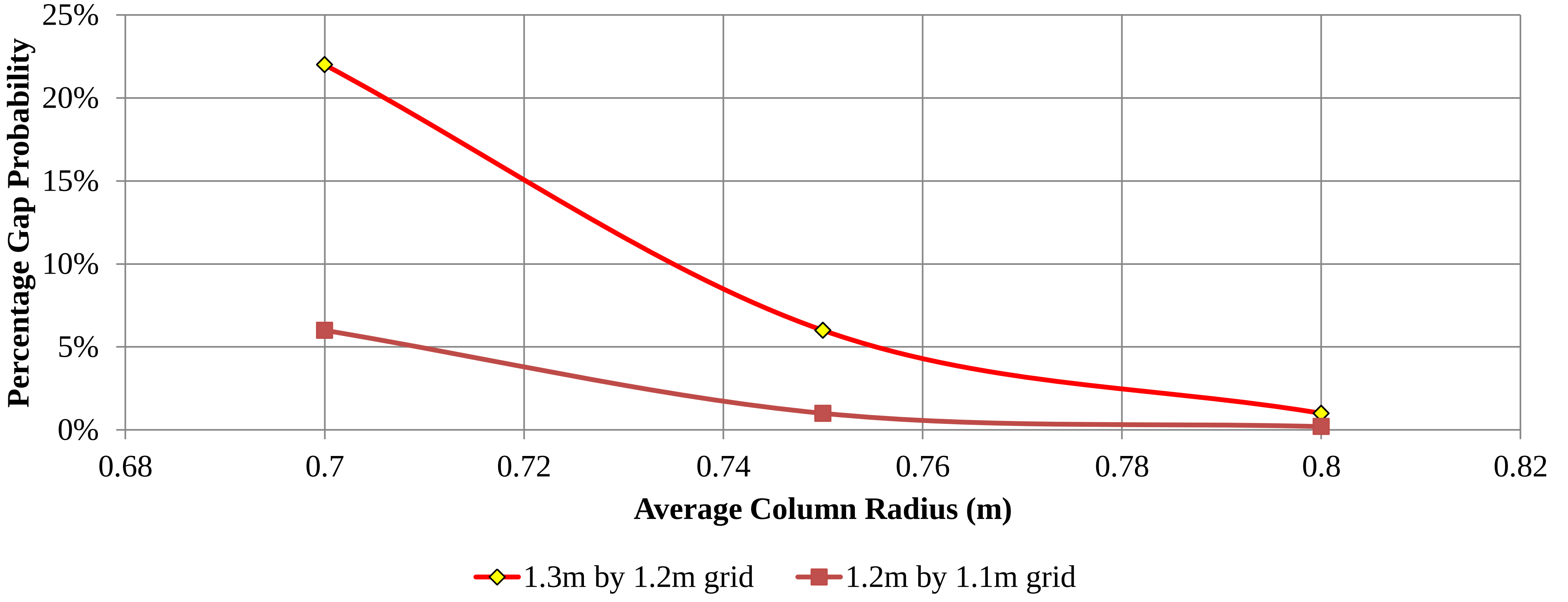
Min Overlap	0.1m	
Minimum Distance to next column	0.0m	
Maximum Deviation (95% prob)	2.0%	Assumed to be 95% confidence (twice stdev)
Setting out Error	100mm	Assumed to be 95% confidence (twice stdev)
Mast Inclination error	1.0%	Assumed to be 95% confidence (twice stdev)
Depth	12m	
Primary Column Radius	0.7m	
Secondary Column Radius	0.7m	
Variation in Radius	20%	Assumed to be 95% confidence (twice stdev)
Column Spacing (X)	1.20m	
Column Spacing (Y)	1.10m	



										Column Gap	A	C	B1	Path (2 gaps)	Path (3 gaps)	A	D	B2	Path (2 gaps)	Path (3 gaps)	Drilling into Columns	
										%	**28.7%**	**41.0%**	**28.5 %**	**22.5%**	**5.8%**	**28.7%**	**39.4%**	**28.5%**	**22.1%**	**5.8%**	0.3%	
										Count	498	498	498	498	498	498	498	498	498	498	996	995
Dia	Revised Y	Revised X					Revised Y	Revised X	Dia	Hits	143	204	142	112	29	143	196	142	110	29	2	1
						1	0.076	-0.114	1.882													
1.453	0.897	0.334	501	0.732																	0	0
					0.042	2	0.081	1.470	1.430		1	0	1	1	0	1	1	0	1	0	0	0
1.448	1.019	1.655	502	0.483																	0	0
					0.249	3	-0.047	2.378	1.625		0	0	0	0	0	0	0	1	0	0	0	0
1.298	1.012	3.065	503	0.200																	0	0
					0.193	4	-0.012	3.642	1.437		0	0	1	0	0	0	0	0	0	0	0	0
1.438	1.194	4.217	504	0.102																	0	0
					0.147	5	0.016	4.770	1.459		0	0	0	0	0	0	0	0	0	0	0	0
1.247	1.261	5.415	505	-0.049																	0	0
					0.057	6	0.001	6.039	1.680		0	1	0	0	0	0	1	0	0	0	0	0
1.551	1.109	6.574	506	0.385																	0	0
					0.125	7	-0.211	7.160	1.588		0	0	0	0	0	0	0	0	0	0	0	0
1.792	1.289	7.909	507	0.013																	0	0

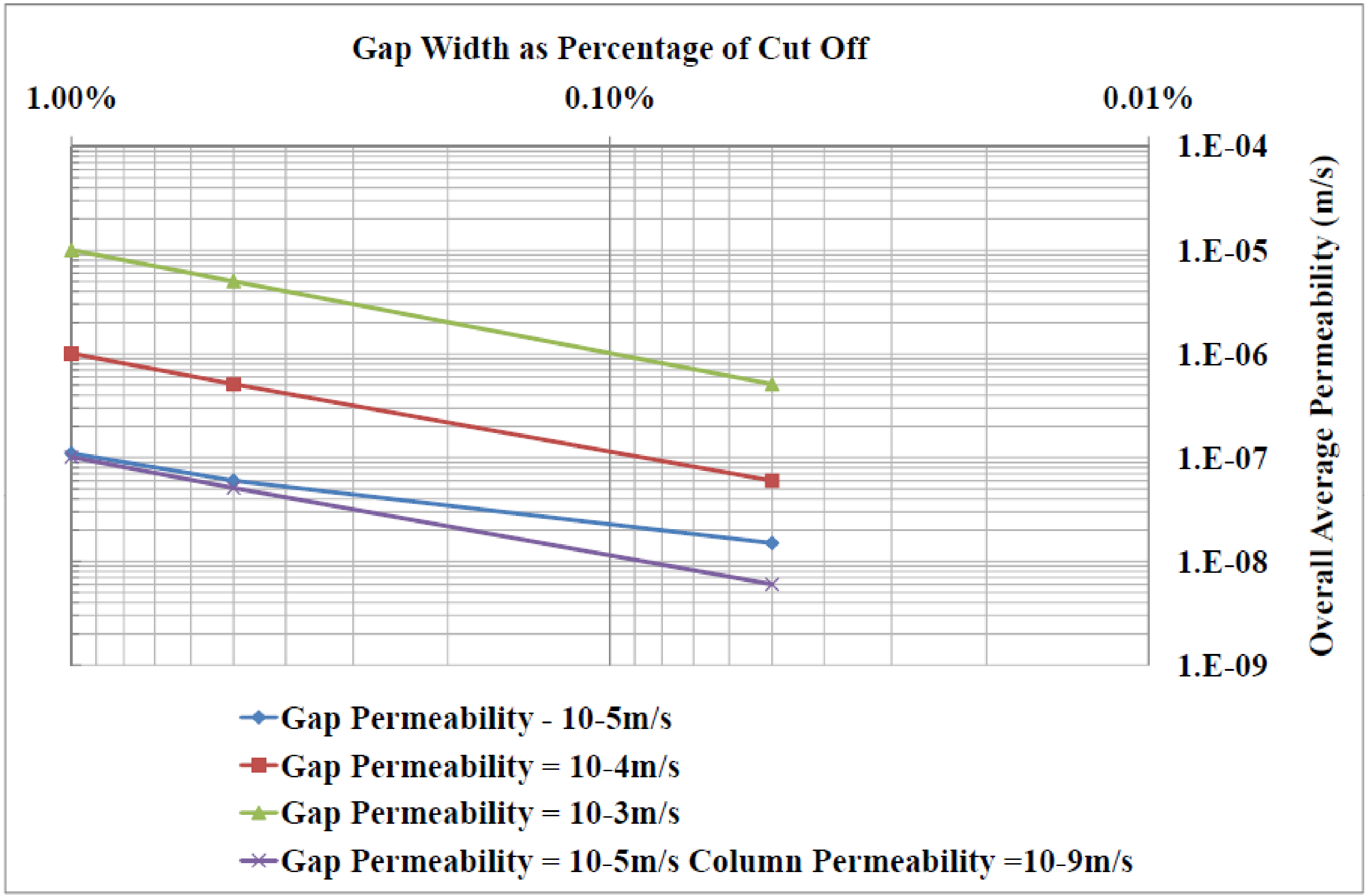


-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
3
2
1
0
-1
-2



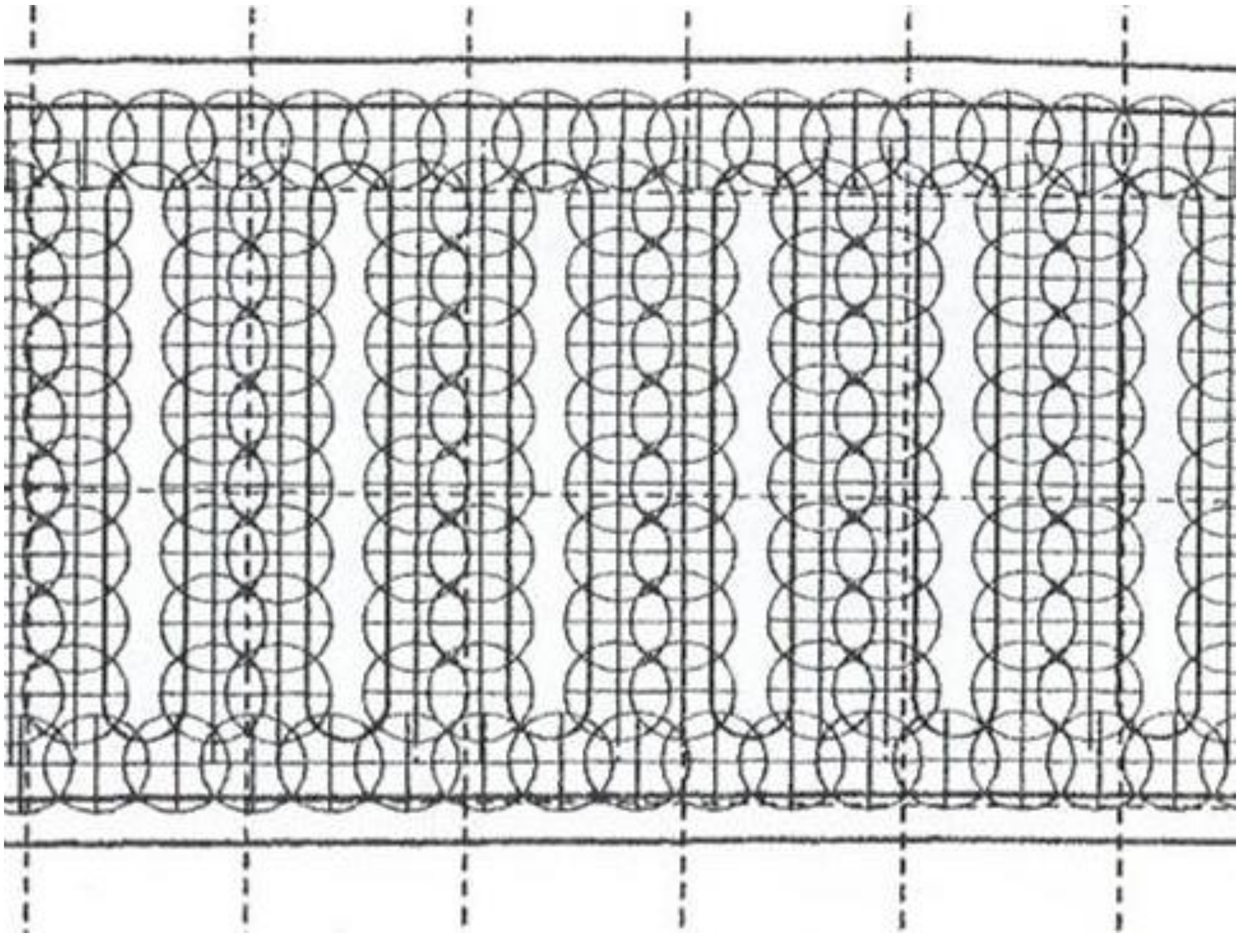
Percentage Gap Probability
25%
20%
15%
10%
5%
0%
0.68
0.7
0.72
0.74
0.76
0.78
0.8
0.82
Average Column Radius (m)
1.3m by 1.2m grid
1.2m by 1.1m grid

Effect Of Gap Percentage And Column Permeability On Mass Permeability



Column permeability does not affect mass permeability drastically

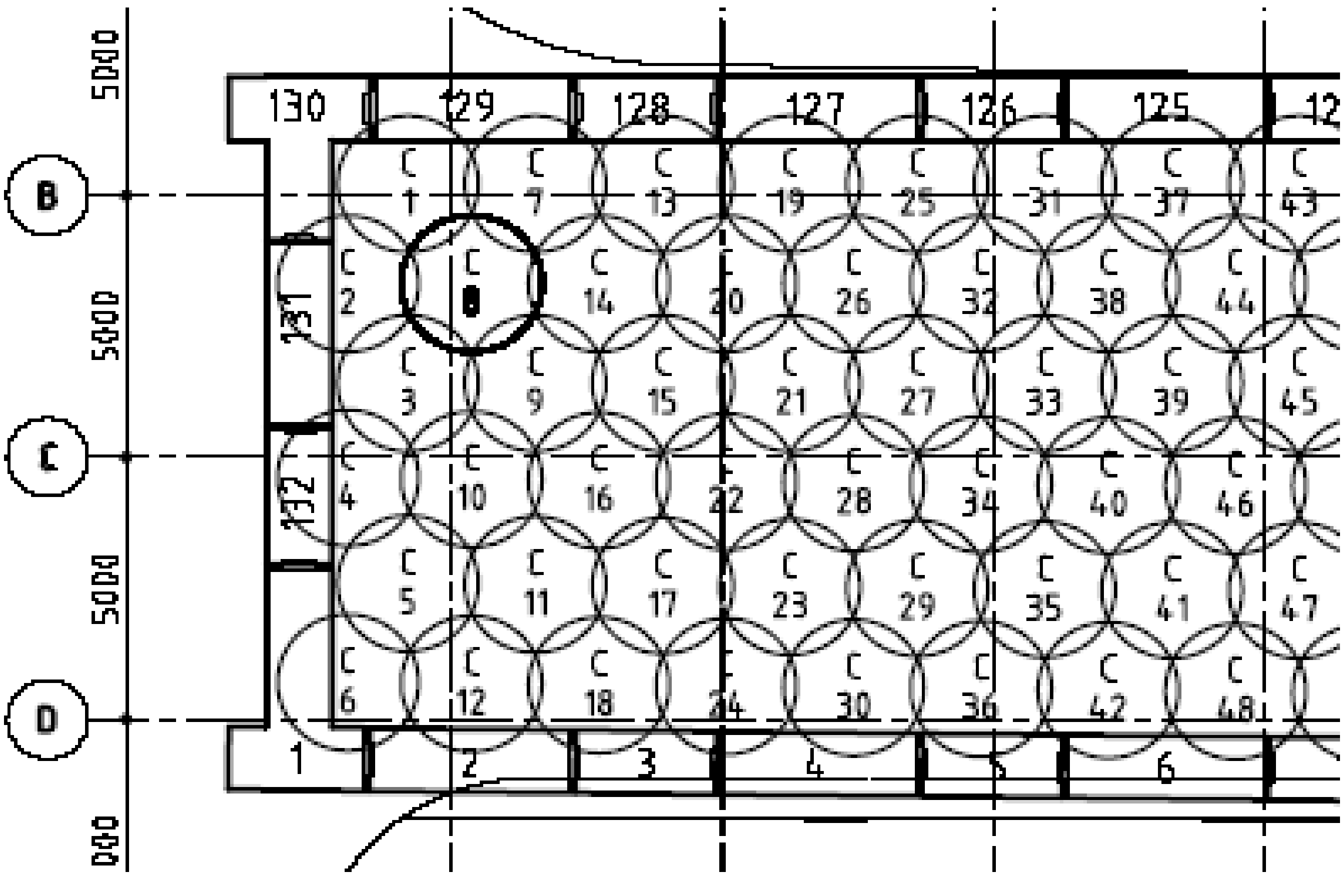
Detailed Design Amsterdam Station Boxes



Design did not take account of hole deviation

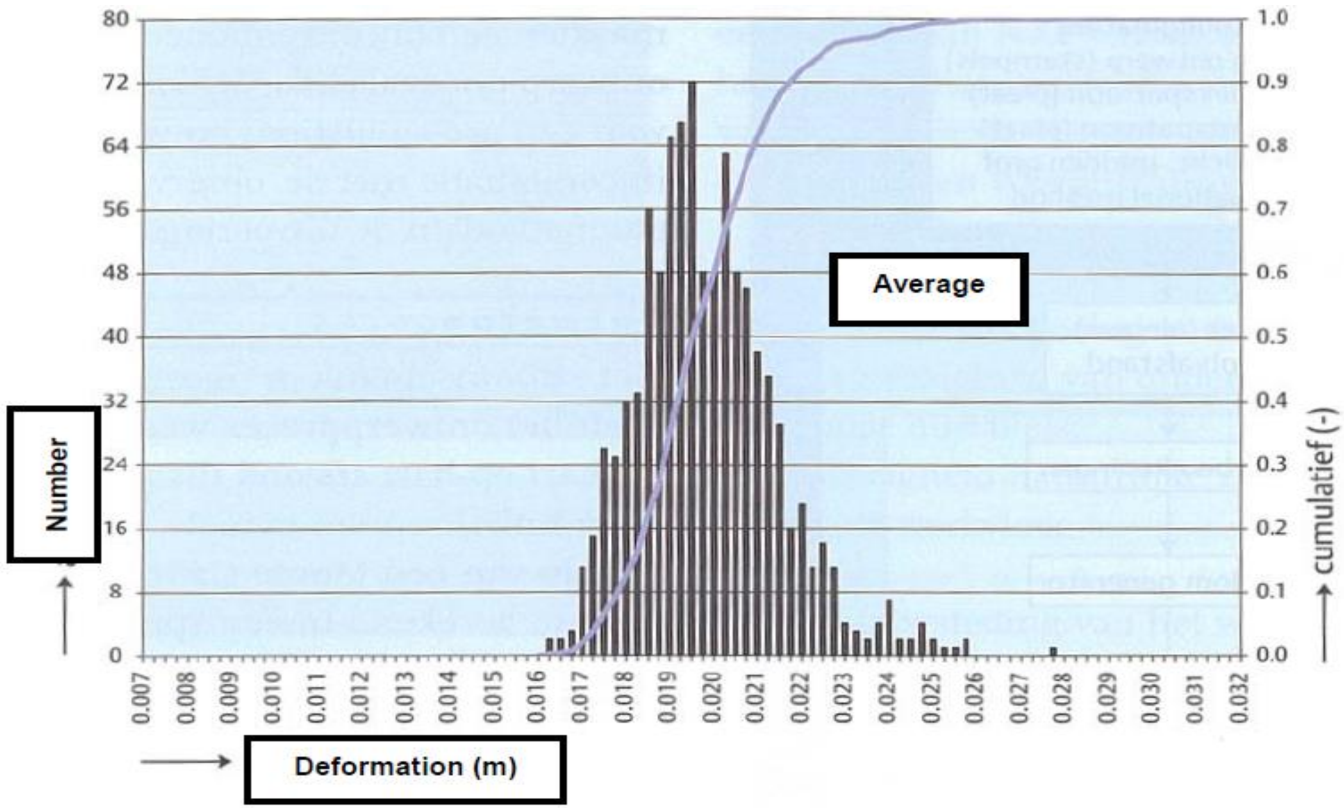
Difficult to construct in practice

Detailed Design Amsterdam Station Boxes

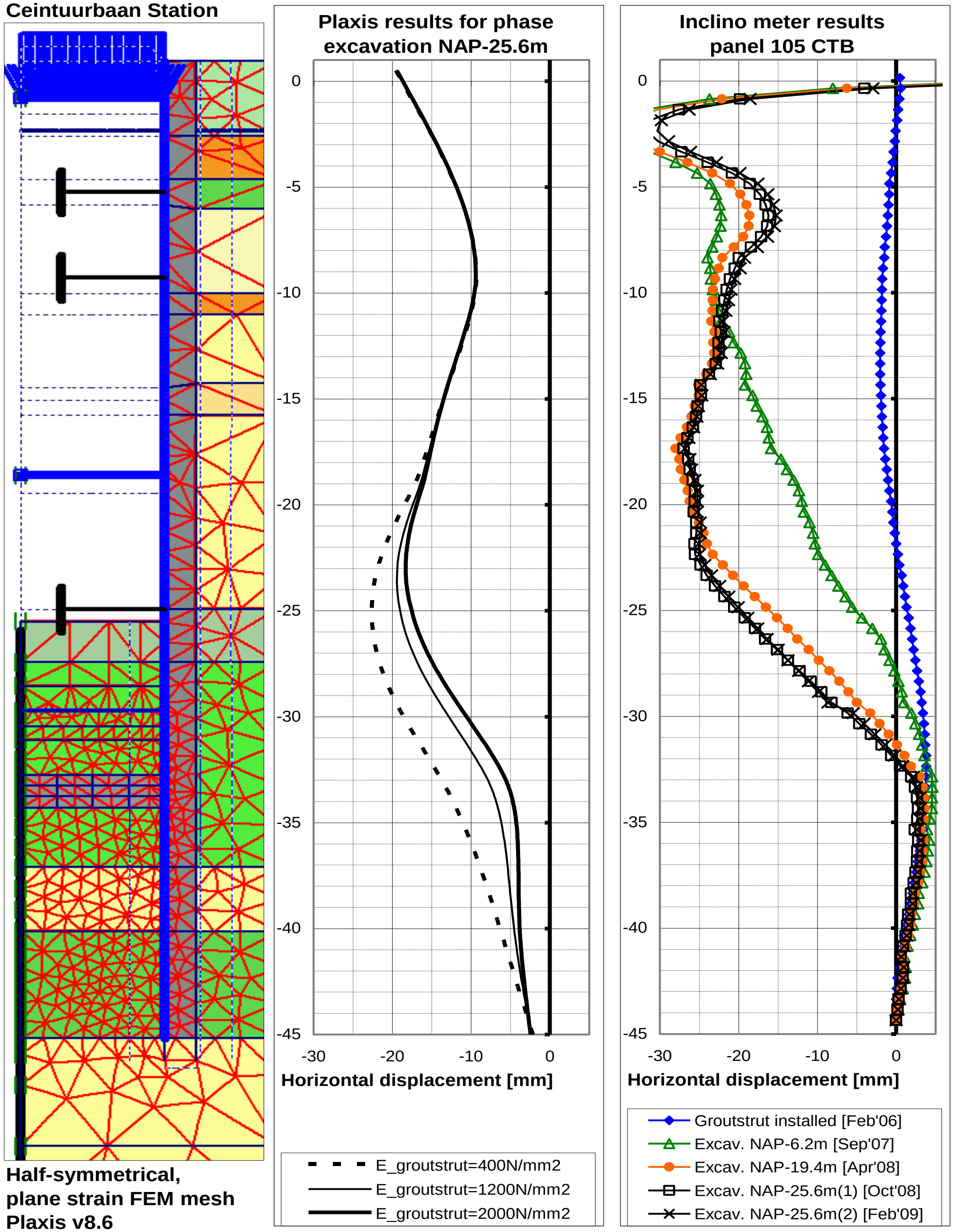


Revised Design considered hole deviation and diameter variation

Detailed Design Amsterdam Station Boxes



Statistical distribution of wall deviation. 1000 column layouts generated automatically and input into Plaxis Analysis



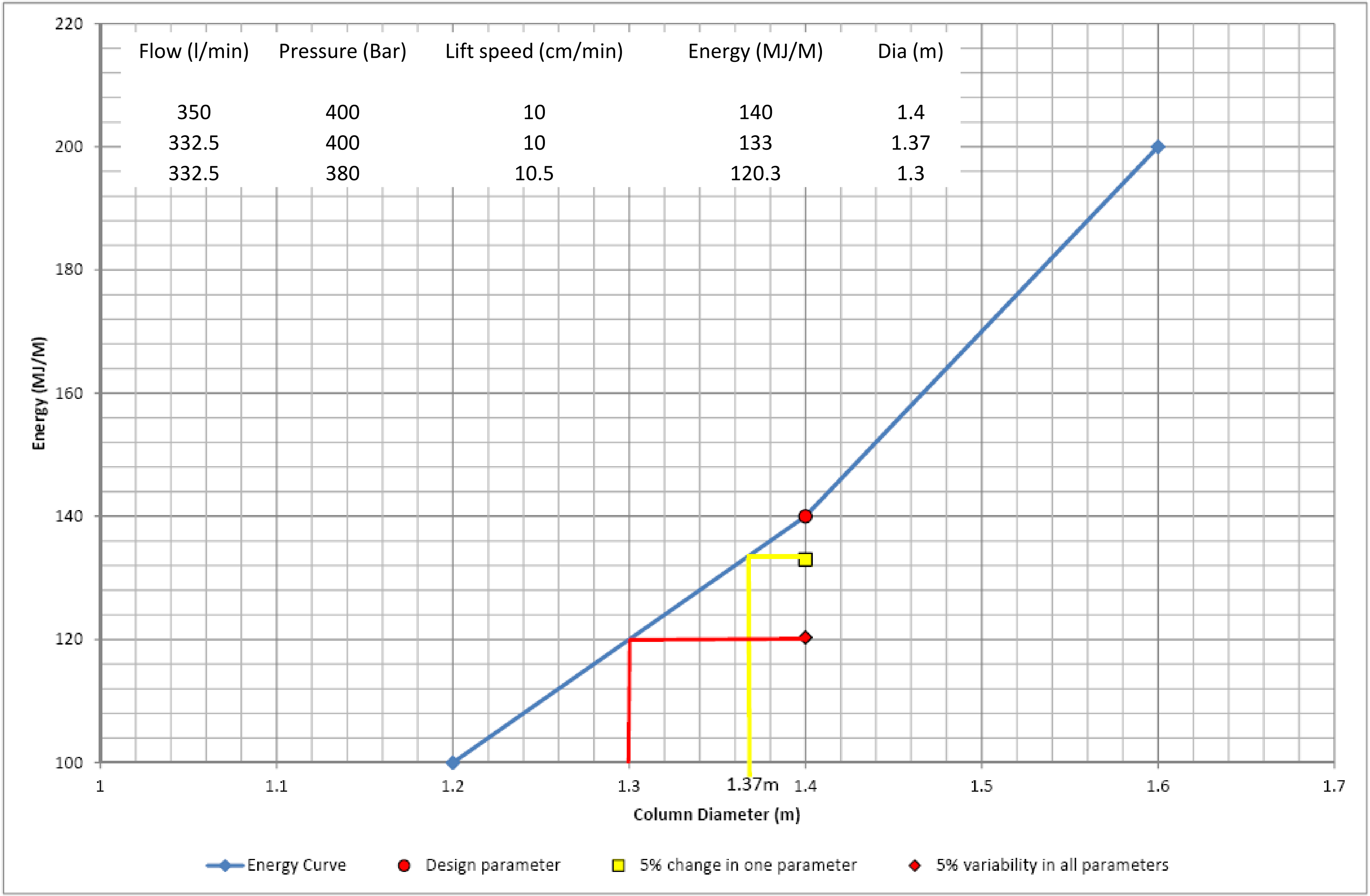
Actual results from inclinometers backed up design

Predicting Jet Grout Column Strength

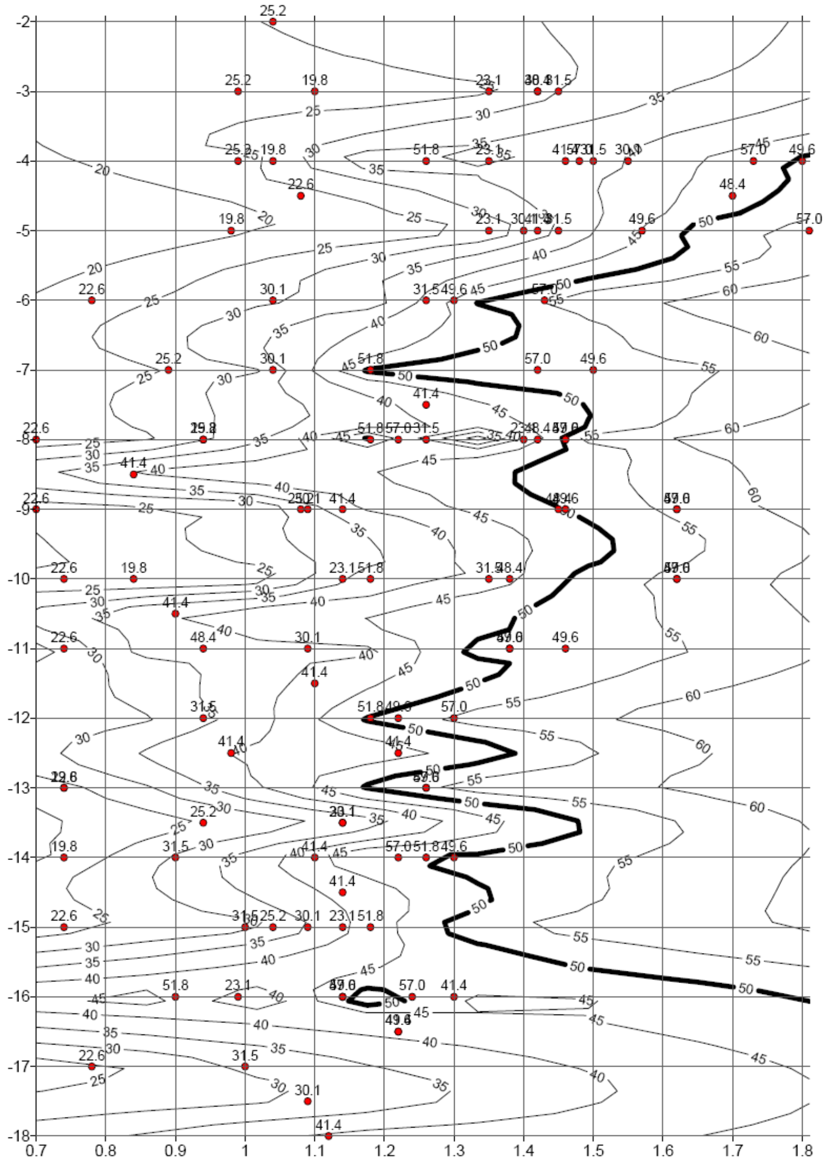
	JETGROUT PAAMETERS						Ground				Spoil after Jetgrout			
Depth	Diameter	Pressure	Flow	Lift speed	Energy (MJ/m)	Grout W/C Ratio	Grout Density	Density	SG	Mc	Density	Cement Content (kg/m3)	Computed Strength (Mpa)	W/C ratio
-4.4	1.20	400	300	20	60	1	1.500	1.6	2.7	67.9%	1.542	468	4.7	1.5
	1.35	400	300	20	60	1	1.500	1.6	2.7	67.9%	1.548	403	2.8	1.7
Strata 1	1.50	400	300	20	60	1	1.500	1.6	2.7	67.9%	1.554	344	1.4	2.0
Alluvium	1.65	400	300	20	60	1	1.500	1.6	2.7	67.9%	1.558	292	0.6	2.4
-7.4	1.80	400	300	20	60	1	1.500	1.6	2.7	67.9%	1.563	247	0.2	2.8
-7.4	1.20	400	300	20	60	1	1.500	2.1	2.7	20.2%	1.753	468	8.3	1.3
	1.35	400	300	20	60	1	1.500	2.1	2.7	20.2%	1.789	403	6.2	1.4
Strata 2	1.50	400	300	20	60	1	1.500	2.1	2.7	20.2%	1.822	344	4.3	1.6
Gravels	1.65	400	300	20	60	1	1.500	2.1	2.7	20.2%	1.850	292	2.8	1.7
-11.4	1.80	400	300	20	60	1	1.500	2.1	2.7	20.2%	1.876	247	1.6	2.0
-11.4	1.20	400	300	10	120	1	1.500	1.8	2.7	5.0%	1.580	576	15.1	1.0
Strata 3	1.35	400	300	10	120	1	1.500	1.8	2.7	5.0%	1.595	525	14.6	1.0
Gravels	1.50	400	300	10	120	1	1.500	1.8	2.7	5.0%	1.610	472	14.0	1.1
Unsaturated	1.65	400	300	10	120	1	1.500	1.8	2.7	5.0%	1.624	420	13.3	1.1
-11.9	1.80	400	300	10	120	1	1.500	1.8	2.7	5.0%	1.637	372	12.4	1.1

Abram’s Law can be used to predict Column strength based on lab data on materials tested at varying water binder ratios. Approximate and needs calibration on site especially with the double system in gravels as the air pressure tends to remove the groundwater around the immediate column

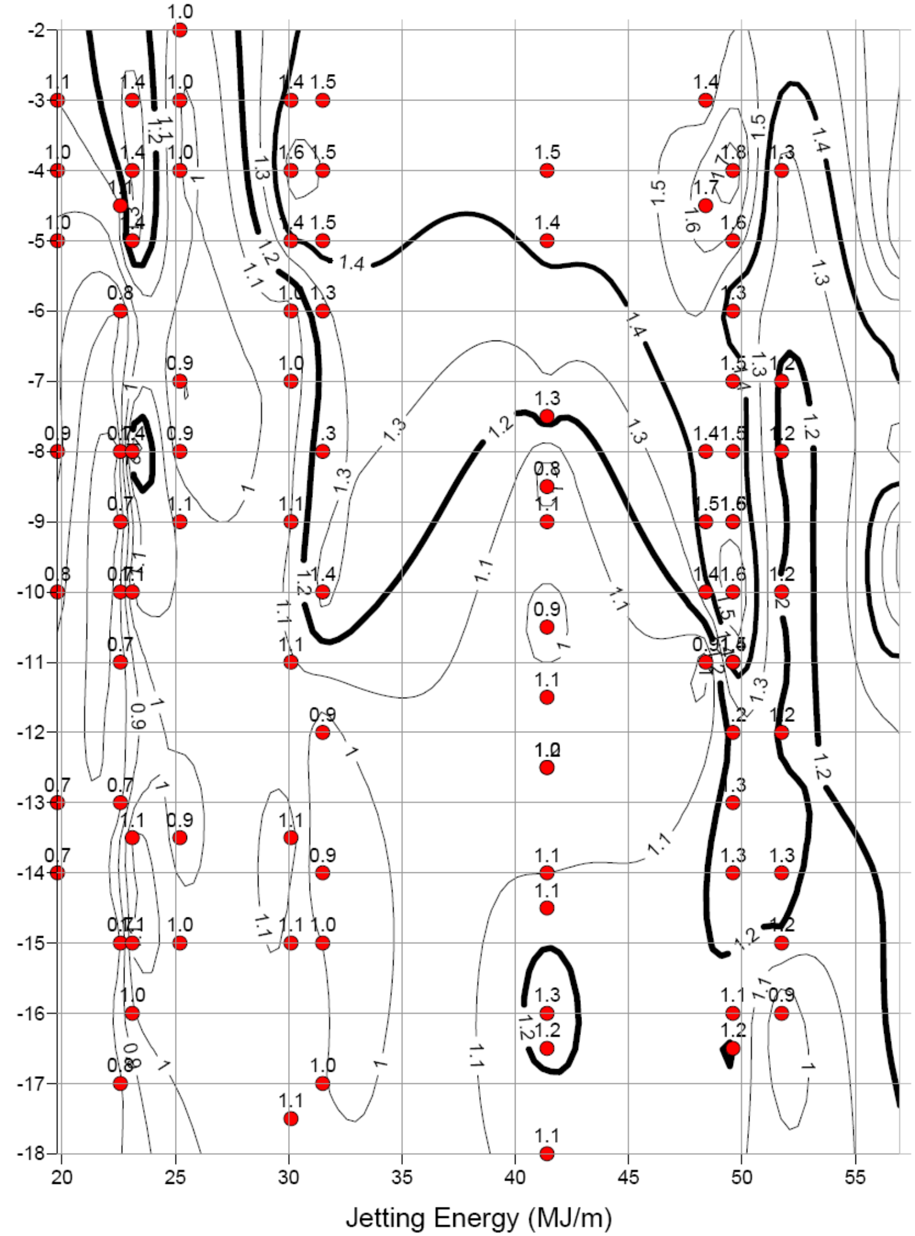
Parameter Variability Can affect Diameter



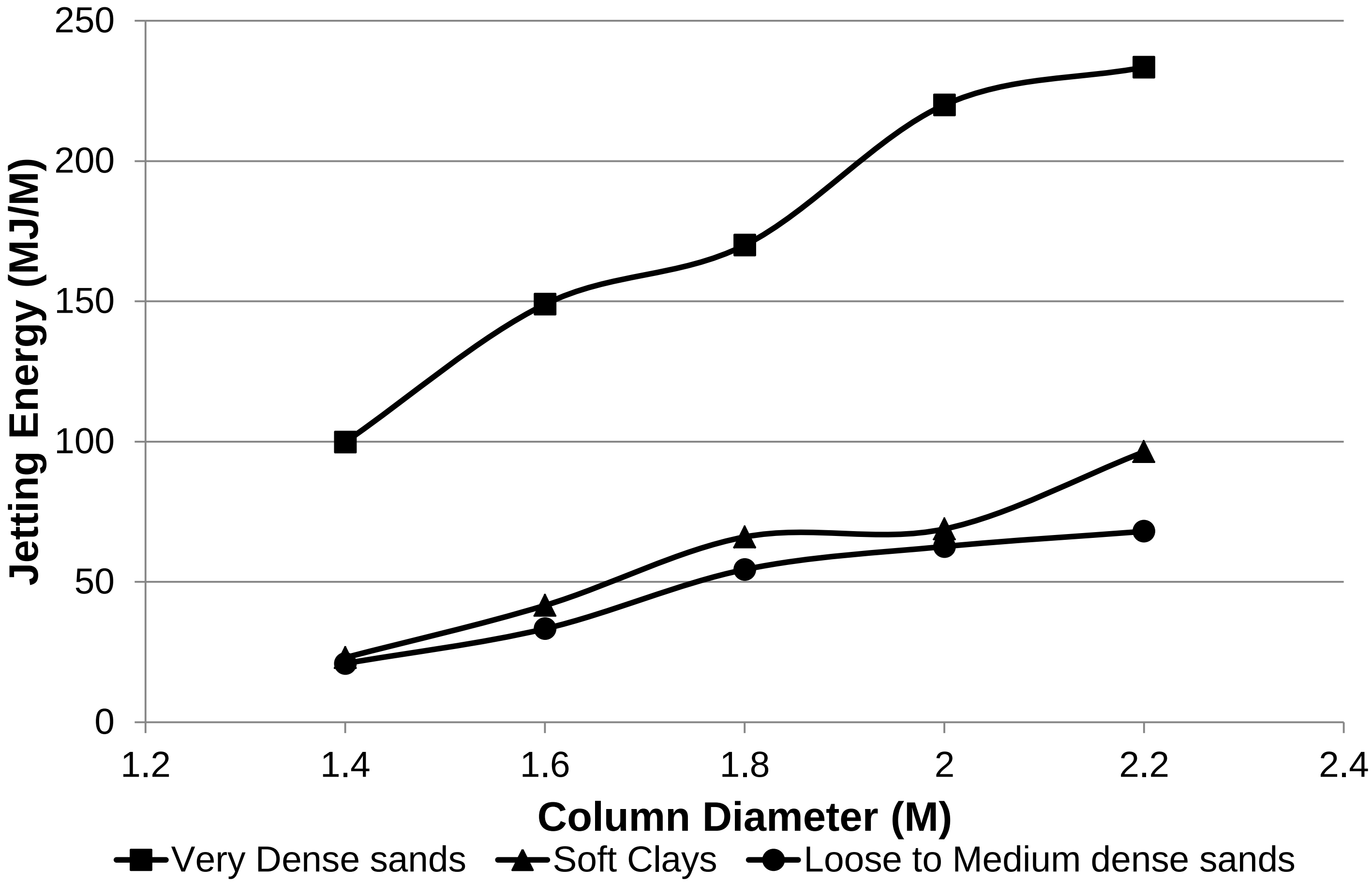
Contours of Energy (MJ/m)



Contours of Column Diameter



Predicting Jet Grout Jetting Parameters



Each jetting system is different and so needs calibration. Trials should not just try and create the design diameter but should test a range of parameters and diameters to develop the energy curve

IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Recent aspect in jet grouting development

Tsutomu Tsuchiya, Chemical Grouting Co., Ltd, Japan

Recent Aspect in Jet Grouting Development

(To Achieve Exact Column Depending on Purpose)

Tsutomu Tsuchiya

Chemical Grouting Co., Ltd.

Content

1. Histories of Jet Grouting in Japan

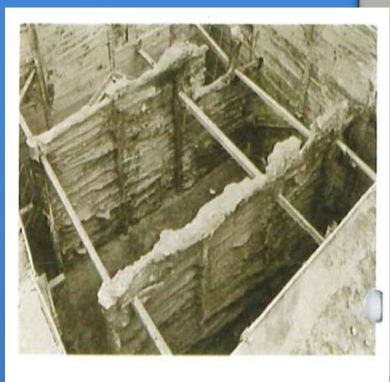
2. Work for Required Performance

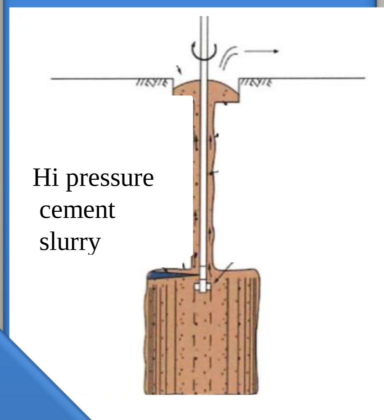
3. New Jet Grouting System

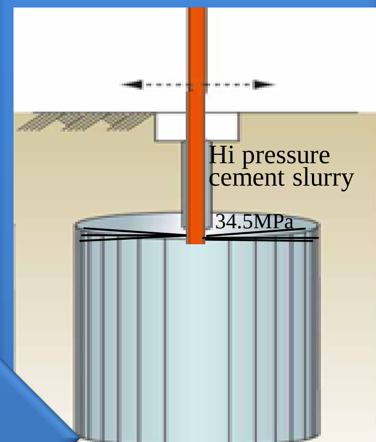
4. Implementation Cases

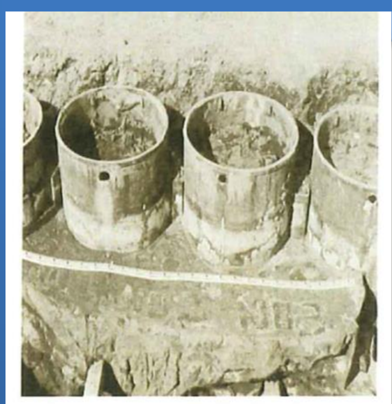
1. Histories of jet grouting in Japan

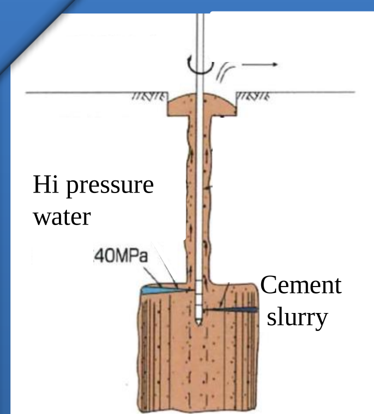
1 step (early197 0s～)	2step (late1970s～)	3step (1990s～)	Today (presence)

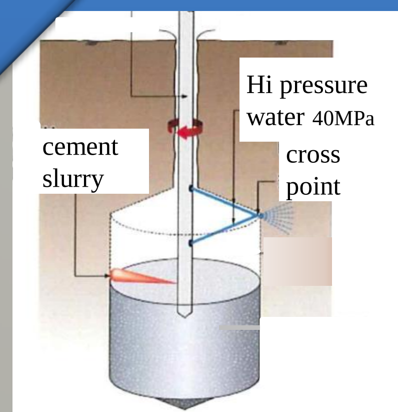












Need

- Rationality
- Quality
- Green
- Durability
- Diversity
- Economy

2. Work for Required Performance

1. **Improving the Energy Efficiency**

   a) **In-house manufacture of tools and machines**

   b) **Strict Regulation for tools and machines**

2. **Improving the Column Quality**

   a) **Factors to Control Diameter**

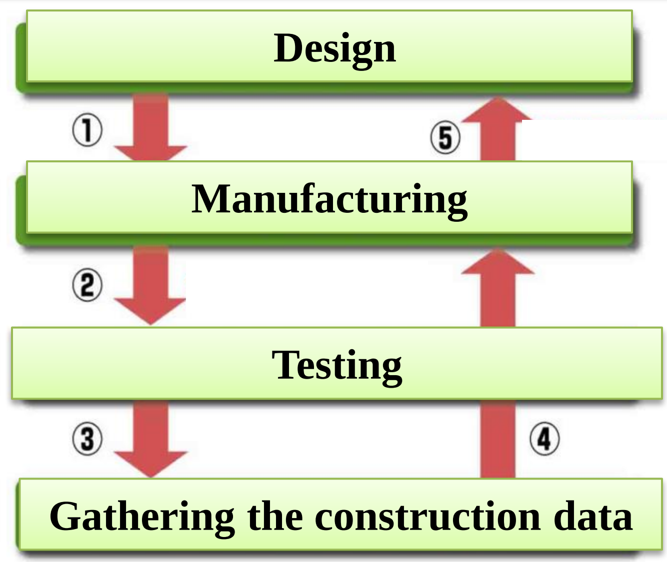
   b) **Factors to Control Strength**

2-1 Improving the Energy Efficiency

*<u>In-house design and manufacturing capability</u>
with our “Techno Center”

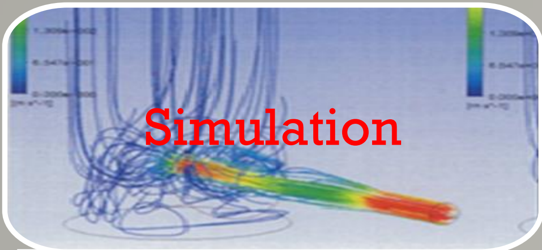
<u>Techno Center</u>

<u>Total Management</u>



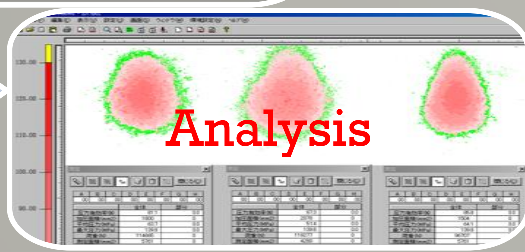
a) In-house Manufacture of Tools and Machines

＊ Total Management in the Techno Center



1) Initiate simulation program
- Computer simulation of test cases

2) Test
- Empirical testing of selected test case



3) Analyze Raw Data
- Confirming the results

4) Improve Jet grouting system
- Tools
- Innovative Machines

⇒ High performance Light Tools

Small Swivel

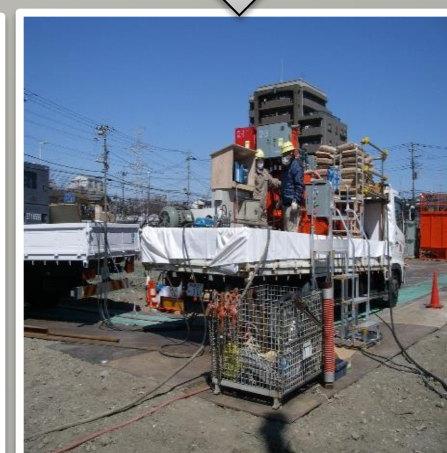
Φ45mm Rod

Φ70mm Injector

⇒ Efficient Compact Machines

Mini-Machine

Mini-Pump



b) Strict Regulation for Tools and Machines

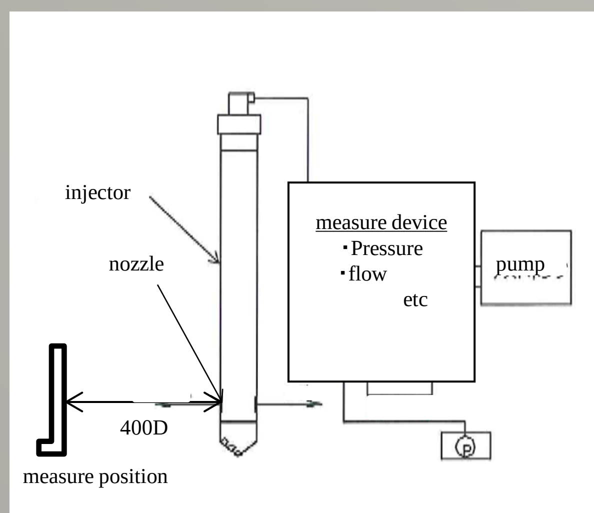
＊ Adapting the Most up-to-date Measuring Devices

1. **Nozzle**

1) figure test
・6 Factors
2) Spray test
・2 Factors

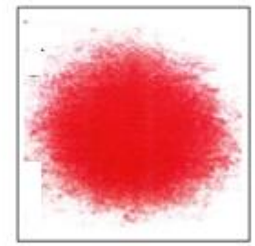
2. **Injector**

1) figure test
・6 Factors
2) Spray test
・2 Factors

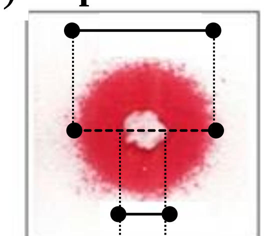


Mesurement Position：400D D:nozzle diameter

・For Mixing (nozzle/injector)

・For Far Distance (nozzle/injector) **Hi-pressure area**

Super hi-pressure area

2-2 Improving Column Quality

*Factors to Control Diameter and Strength

a)Factors to control Diameter

- Energy to Erode a Soil
- Shear Strength of Soil

b) Factors to Control Strength

- Cement Content / Unit Volume
- Fine Fraction Content of Soil

a) Factors to Control Diameter

*How to Formulate of Column diameter

Soil Eroded by Jet Flow Shrouded by Air

$$h = f(P_{\sigma}, E) \qquad \cdots ①$$

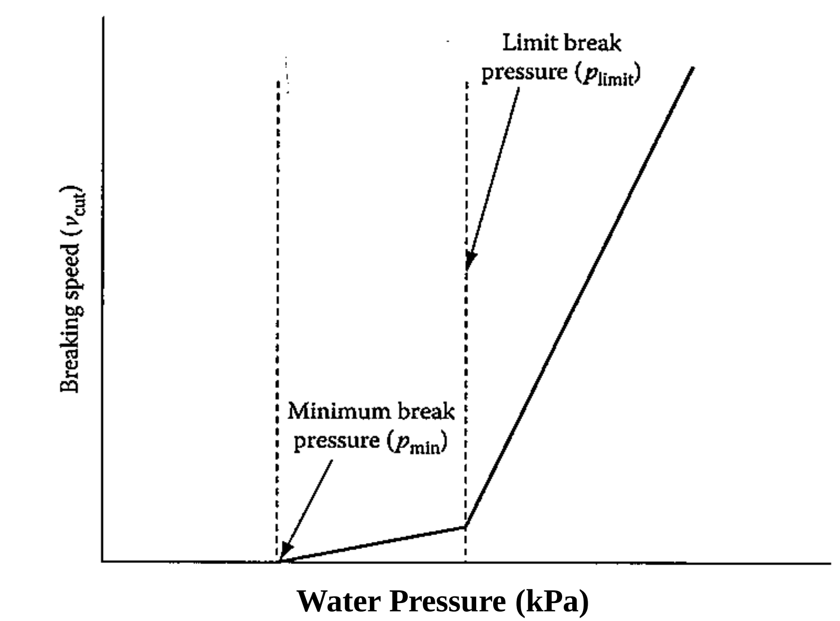
(Basic formula)

- h : eroded distance
- $P\sigma$: soil strength
- E : eroding energy

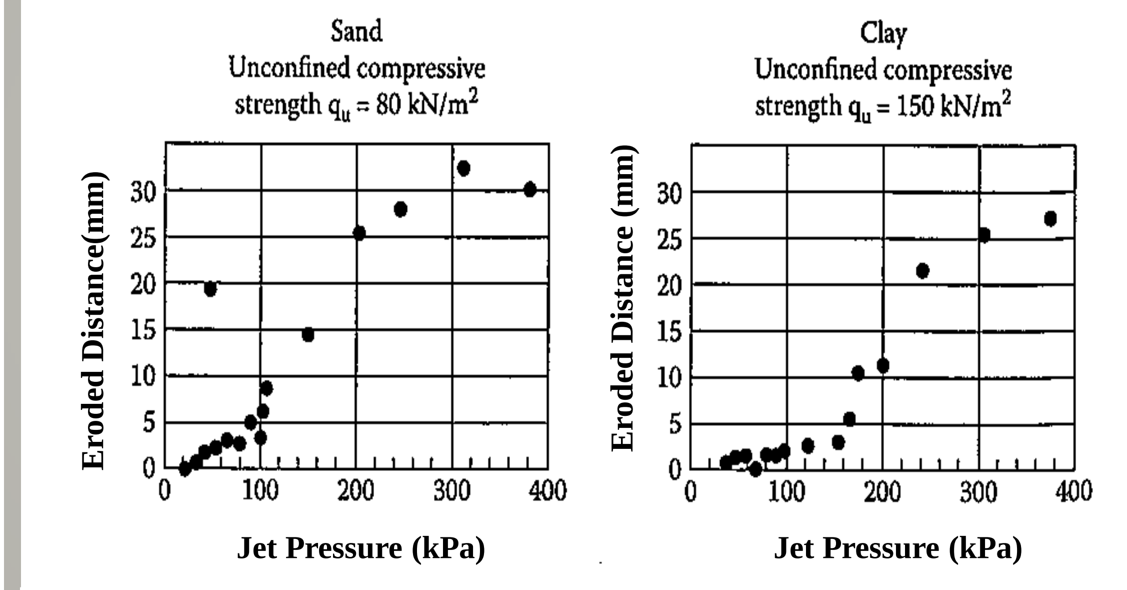
$$h = f(P_{\sigma}, P, Q, t) \qquad \cdots ②$$

- h : eroded distance
- P : jet pump pressure
- Q : flow rate
- t : construction time

*Shear Strength vs. Erosion



Jet Pressure vs. Soil Erosion



Erosion Distance vs. Jet Pressure for Sand and Clay

$$P_{\sigma} = f(\sigma_c) \quad \cdots ③$$

Soil Eroded by Jet Flow Shrouded by Air (Rotation)

$$h_r = f(\sigma_c, E_r) \quad \cdots ④$$

h_r : eroded distance(radius)
σ_c : shear strength
E_r : eroding energy

$$h_r = f(\sigma_c, P, Q_r, t_r) \cdots ⑤$$

h_r : eroded distance(radius)
σ_c : shear strength
P : jet pump pressure
Q_r : flow rate
t_r : construction time

$$h_r = f(\sigma_c, P, V_{tr}, d_0, N) \cdots ⑥$$

(Resolving the item to the elements)

h_r : eroded distance(radius)
σ_c : shear strength
P : jet pump pressure
V_{tr} : rotation speed
d_0 : nozzle diameter
N : repeat number

*Empirical Formula for Diameter

P_m : jet pump pressure(kgf/cm^2)
V_{tr} : rotation speed(cm/s)
d_0 : nozzle diameter(cm)
N : repeat number
k : coefficient

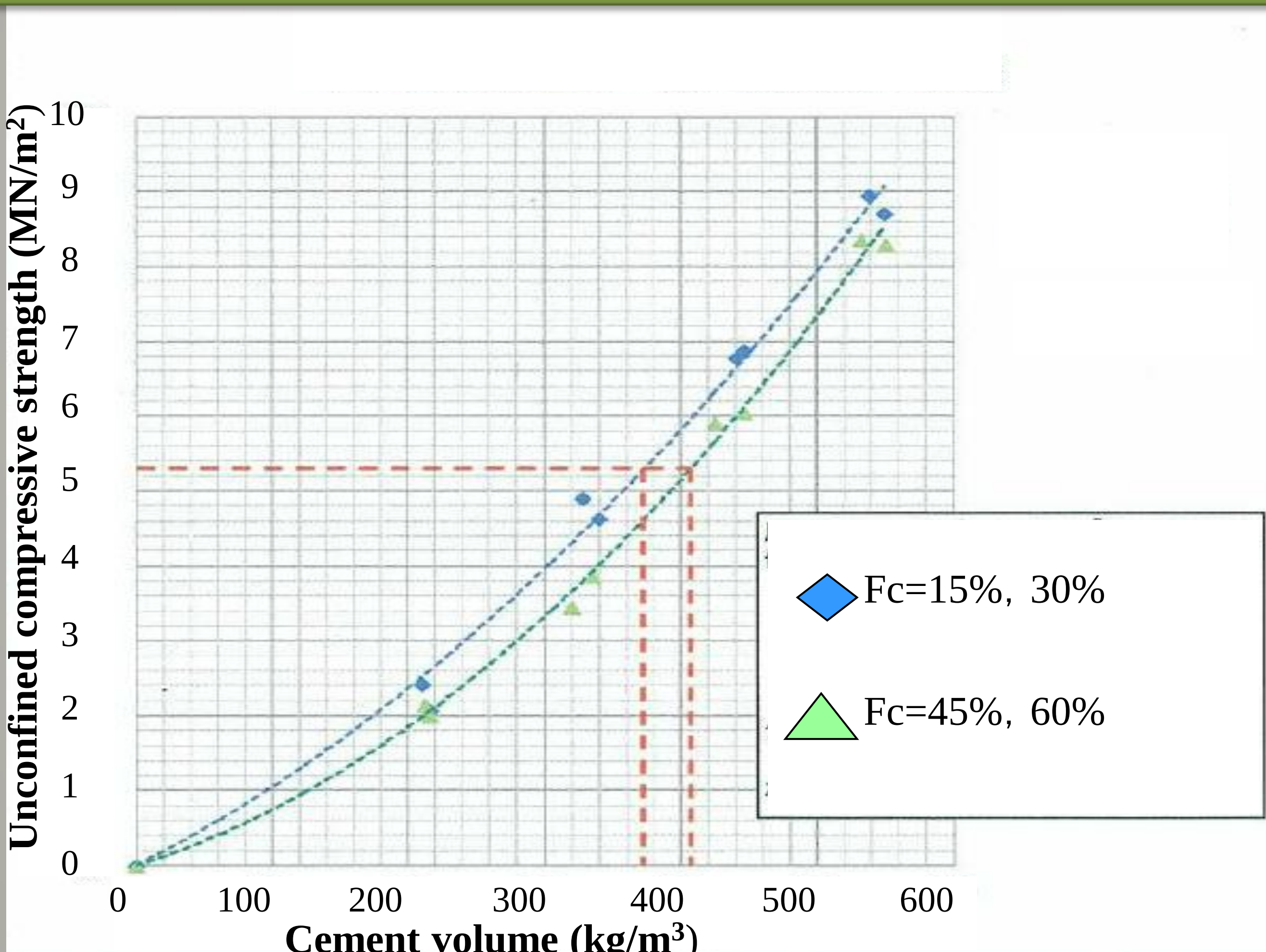
- $h_r = k \cdot f(\sigma_c, P_m, V_{tr}, d_0, N)$ ···⑦

- $h_r = 150 \cdot \sigma_c^{-0.58} P_m^{0.35} \cdot V_{tr}^{-0.43} \cdot d_0^{0.83} \cdot N^{0.29}$ ···⑧

REFERENCE : the latest chemical grouting method 3 " column jet grouting method and the application" Yasiho, Yoshida 1978

b) Factors to Control Strength

Unconfined Compressive Strength (Cement Volume and Fine Fraction Content)



3. New Jet Grouting System

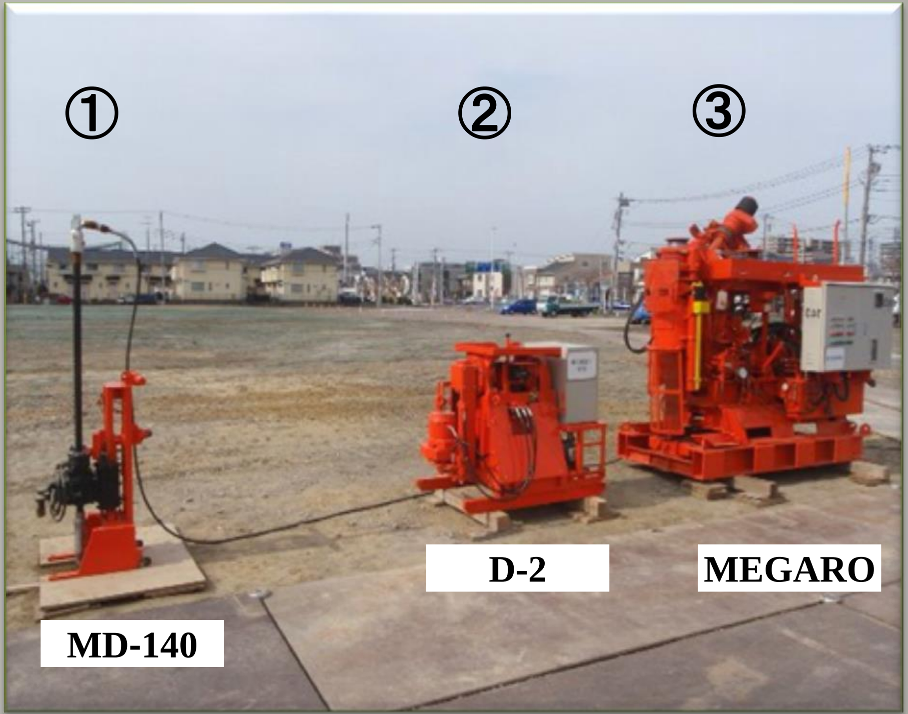
New Jet Grouting System

*Equipment Capabilities (Range of Application)

- **Small Type (Max Diameter 3.0m)**
  Pressure 20～40MPa
  Flow 100～200L/min
  Step Time 6～24min/m

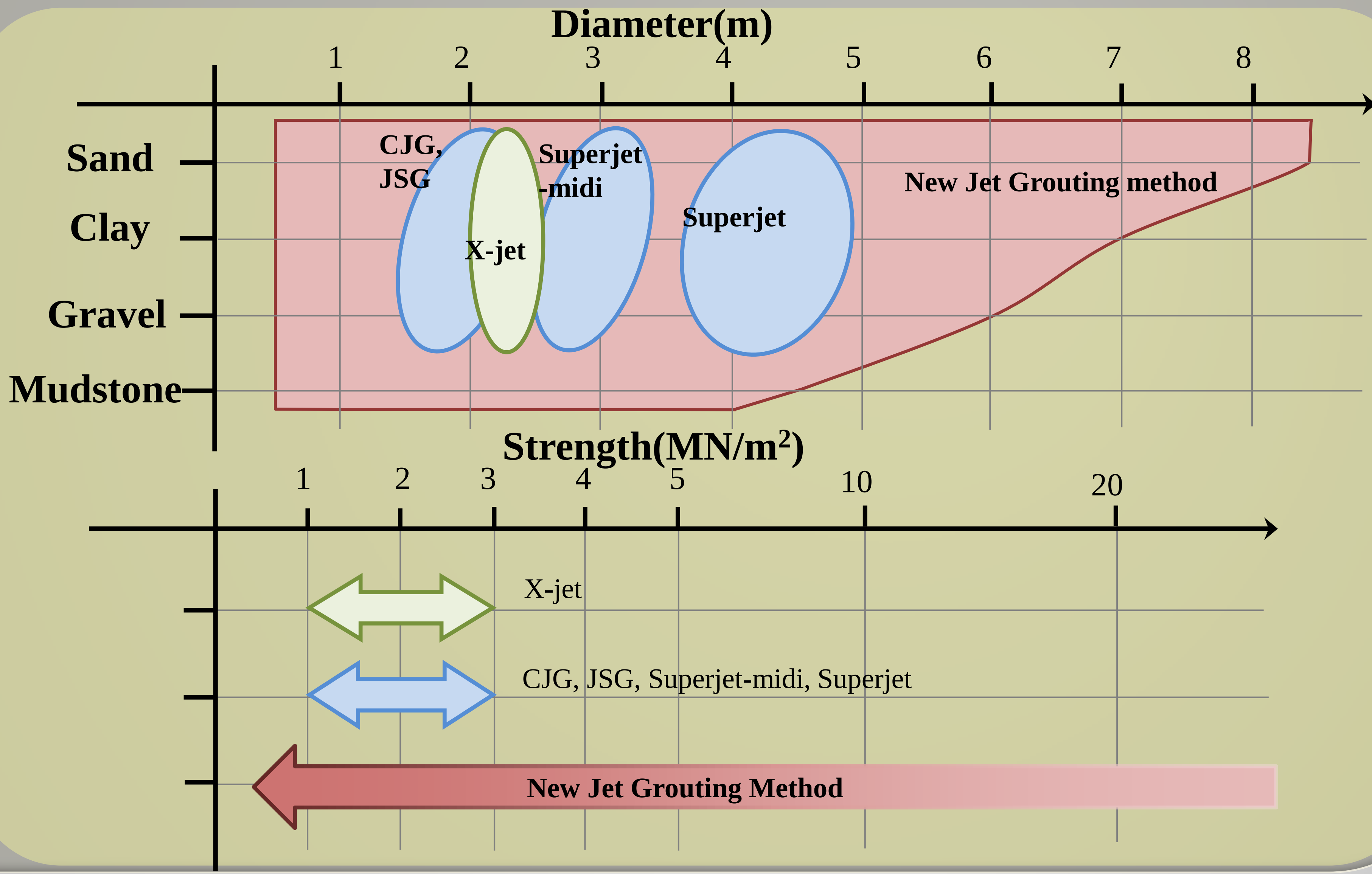
- **Middle Type (Max Diameter 5.0m)**
  Pressure 20～40MPa
  Flow 200～400L/min
  Step Time 6～24min/m

- **Large Type (Max Diameter 8.5m)**
  Pressure 20～40MPa
  Flow 200～600L/min
  Step Time 6～24min/m



- **①·② Machines For Small and Middle**
  (Injector :φ70mm, Rod:φ45/60mm)
- **③ Machines For Large**
  (Injector, φ90mm or φ140mm)

*Applicable Range
(in comparison with traditional method)



4. Implementation Cases

① High quality

1) High-strength
2) Low-strength

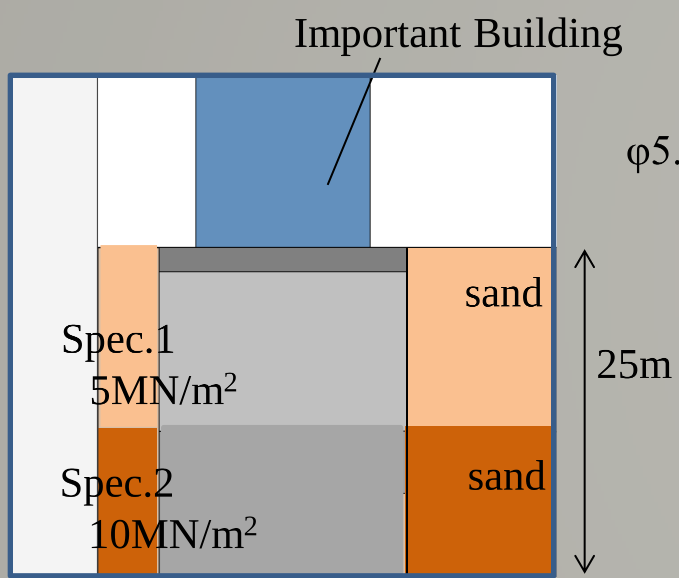
② Difficult Site

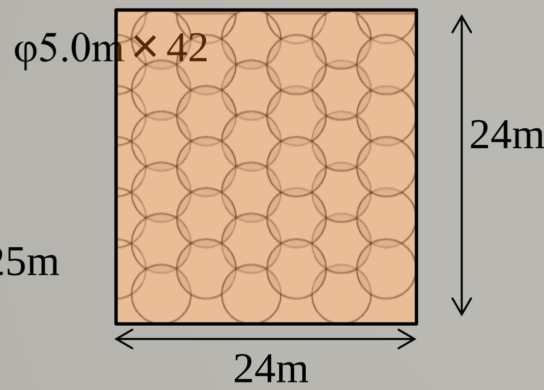
1) Narrow Site

③ New Application

1) Environment Remediation
2) Re-use System
3) Horizontal Jet Grouting

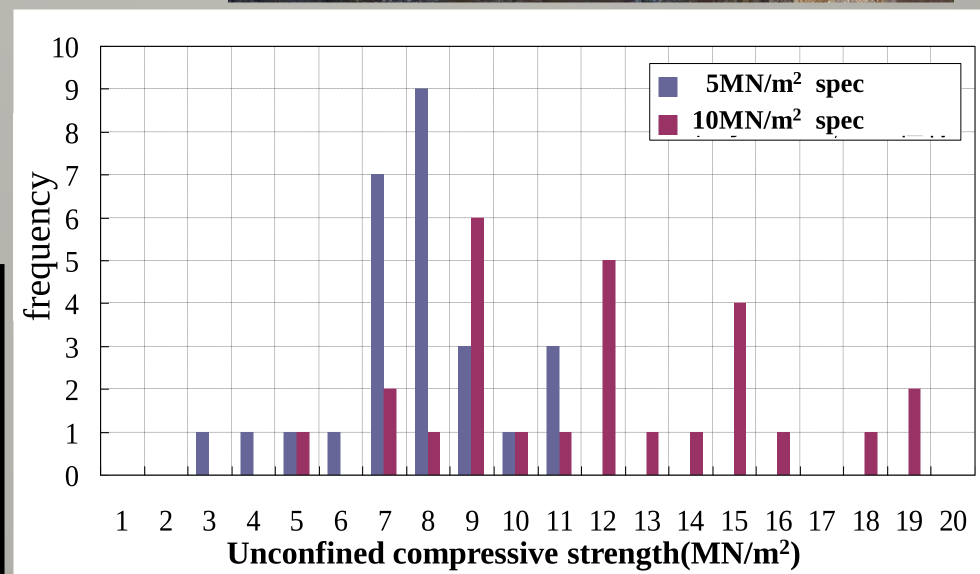
*① High-quality 1）High-strength (Foundation in Important Facility)





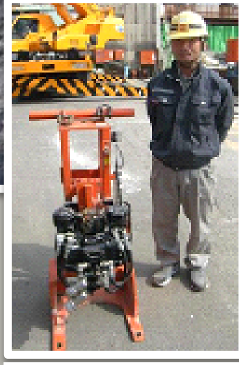
Unconfined compressive strength

	5MN/m² spec	10MN/m² spec
data	27	27
average strength	7.2 MN/m²	11.4 MN/m²
variation coefficient	25%	33%



*① High-quality　2）Low-strength Site

Item	Spec.
Machine	**MD-140**
Pump	**PP35**
Diameter	Φ2.0m～Φ2.5m
Pressure	35MPa
Flow	30　L/min
Step Time	8min/m
Cement Density	20～30kg/m3
Strength	0.05MN/m2～0.1MN/m2

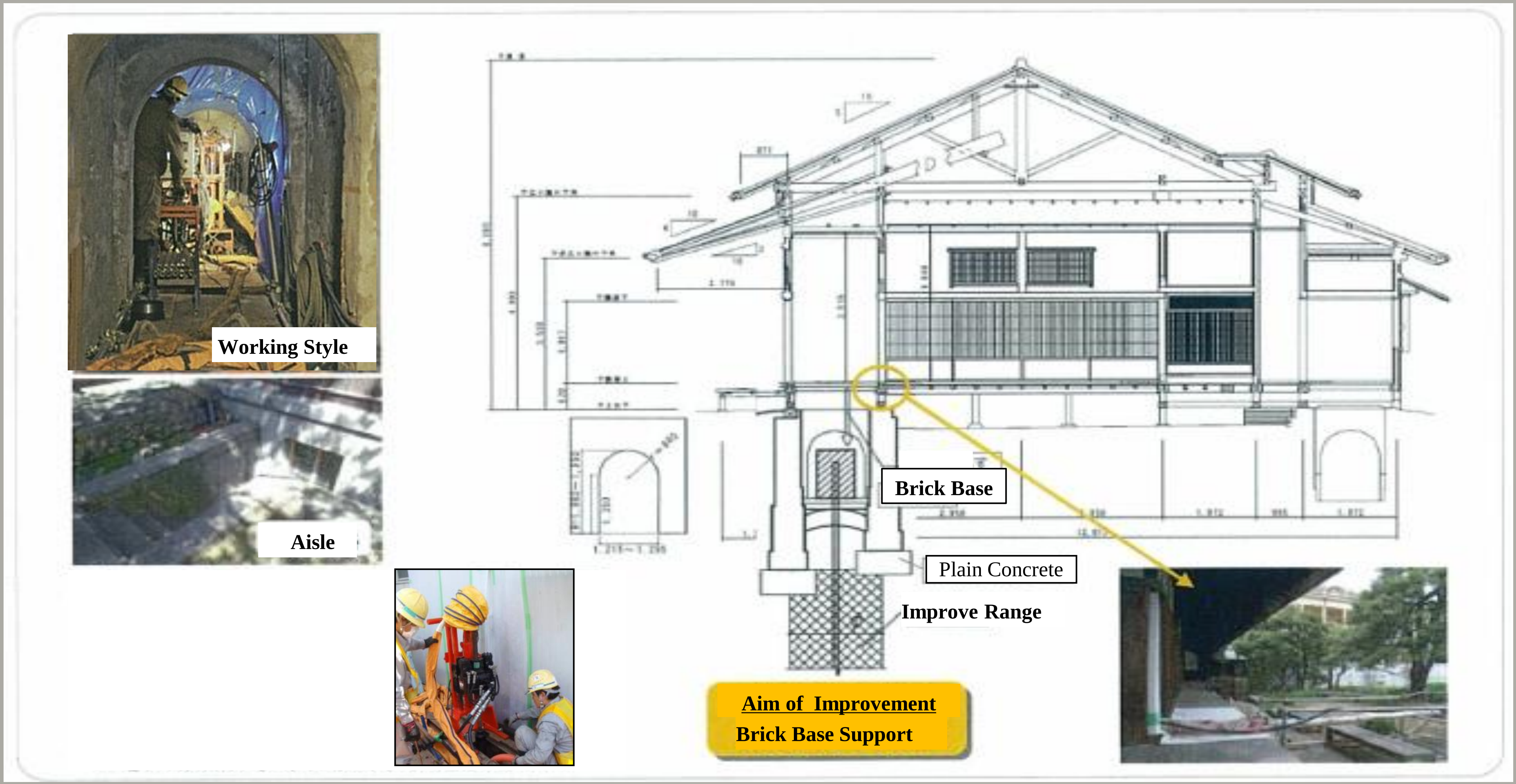


Compact Machine (MD140)

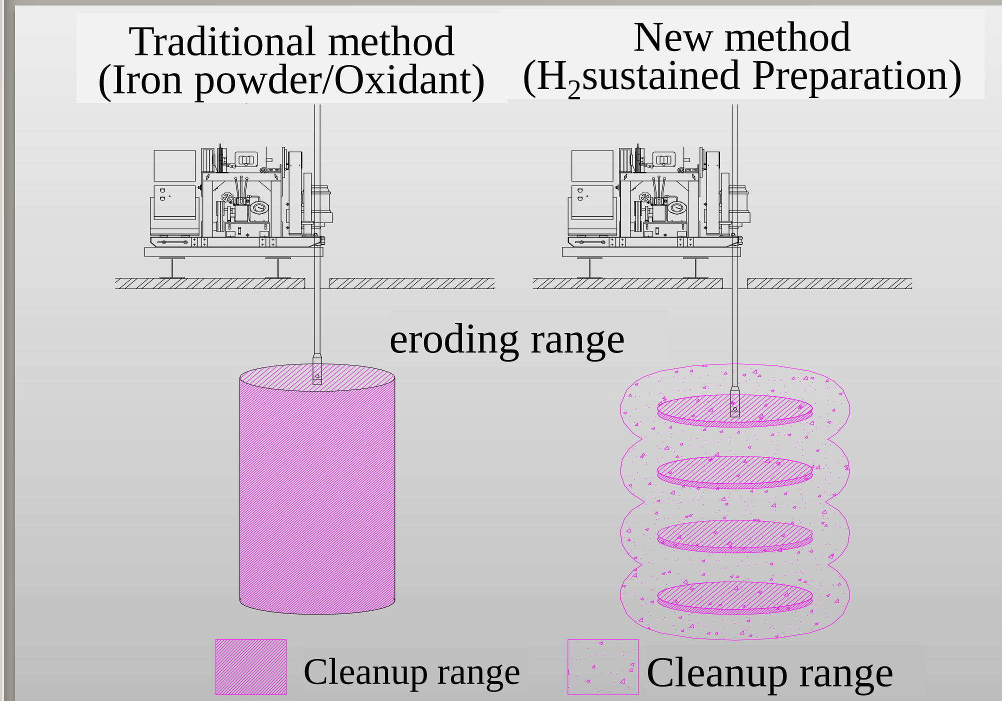
Compact Pump (PP35)

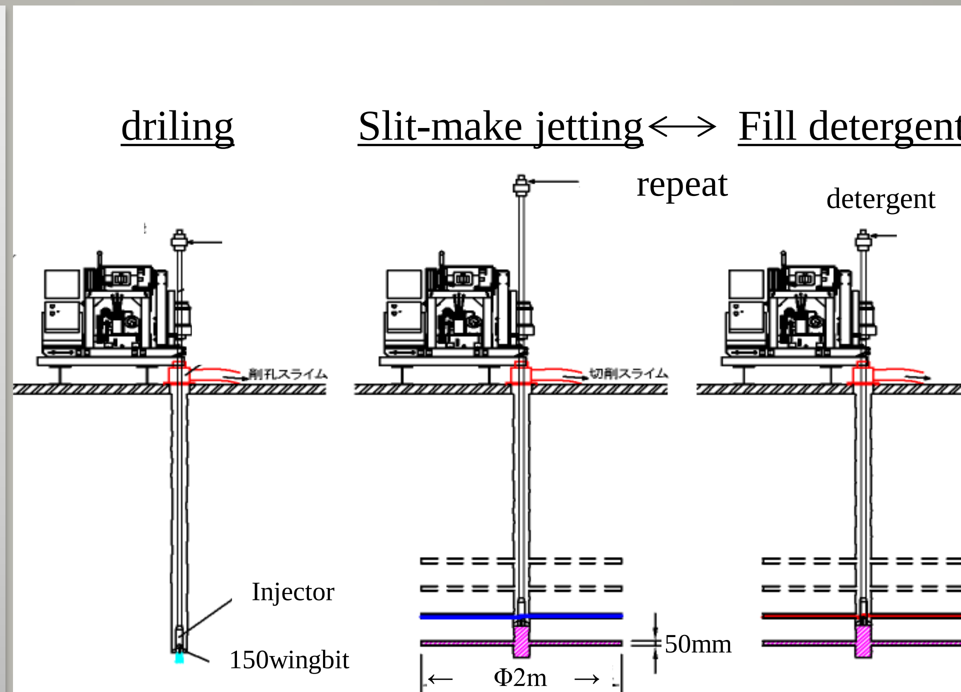
Compact Plant (4T-track×2)

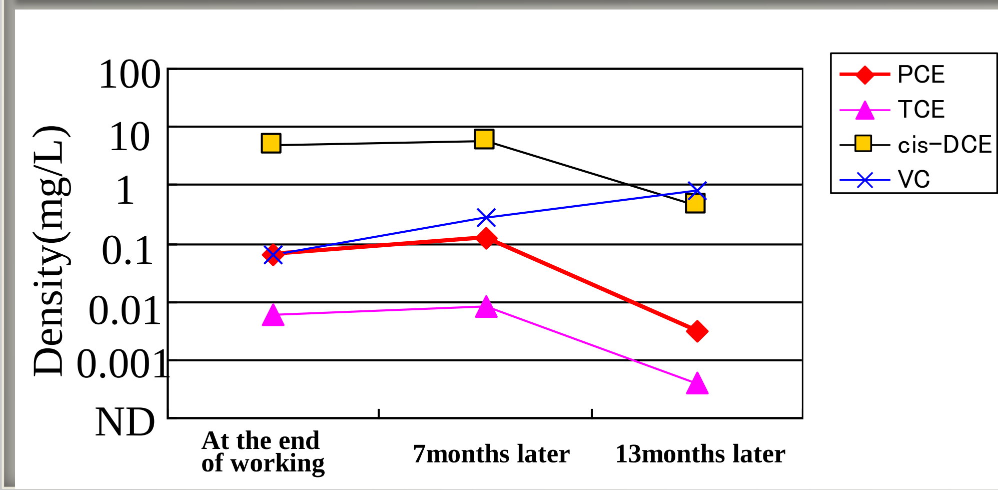
*② Difficult Site 1）Narrow Site(Cramped Site)



*③ New Application　1）Environment Remediation







*③ New Application　2）Re-use System

1. 3 Type of Re-use Jet System

・Which material is re-used ？How is re-used?

1）Water (As Jet)

2）Water(As Jet)＋soil（ As Backfill ）

3)Water(As Jet)＋soil（As Jet）

1)Re-use water as jet

2)Re-use water as jet and soil as backfill

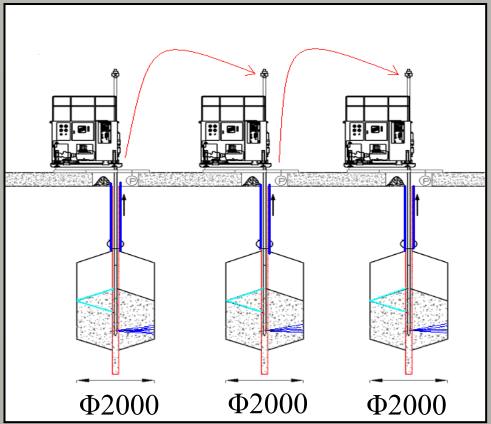
2. New Machines

1）Centrifugal classifier

2）X-type Injector

1) Centrifugal classifier

2) X-type Injector



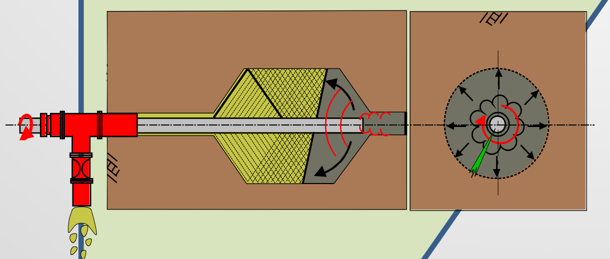
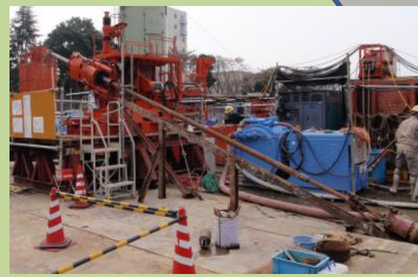
3)Re-use water and soil as jet

* ③ New Application　3）Horizontal Jet Grouting

Horizontal Jet Method	Parajet Method	Curvex Jet Method
Attainment, 1998～December, 2001	**Upgrade 2003～**	**Development 2009～**





Thank you very much for your attention.

IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Design of jet grout base plugs and strength of jet grout elements

W. Sondermann, Keller Grundbau, Germany

Design of jet grout base plugs and strength of jet grout elements

W. Sondermann

Keller Grundbau GmbH, Germany

Content

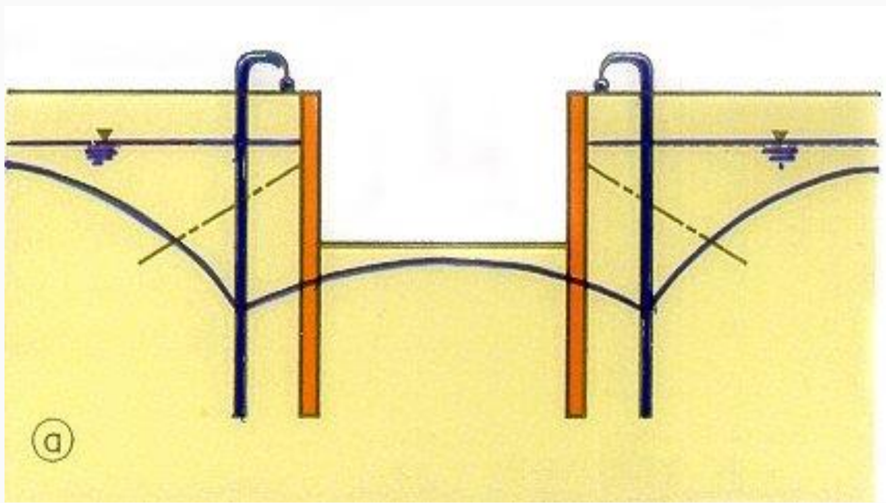
Design considerations for jet grout base plugs

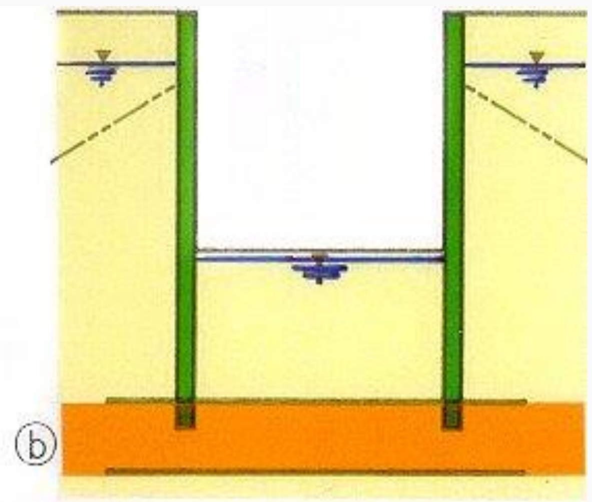
- Systems for base plugs
- Design of depth
- Thickness
- Tie back system
- Layout of base plug
- Installation sequence

Strength of jet grouting elements

- Variations of subsoil conditions
- Testing of insitu strength
- Design strength verifications

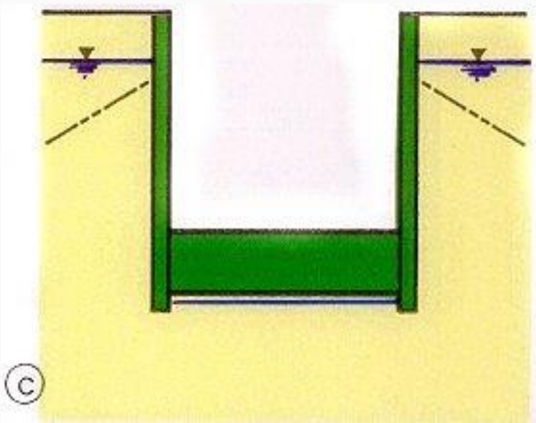
Deep excavations in water-bearing soils (horizontal barriers)

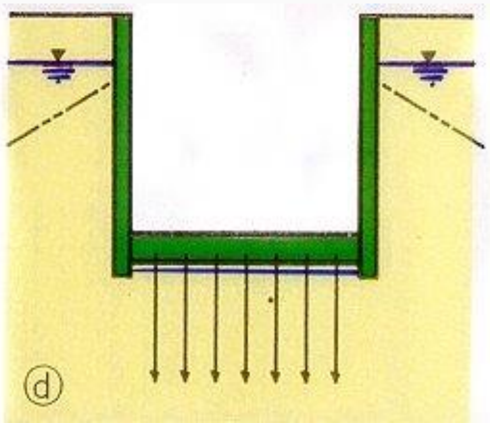


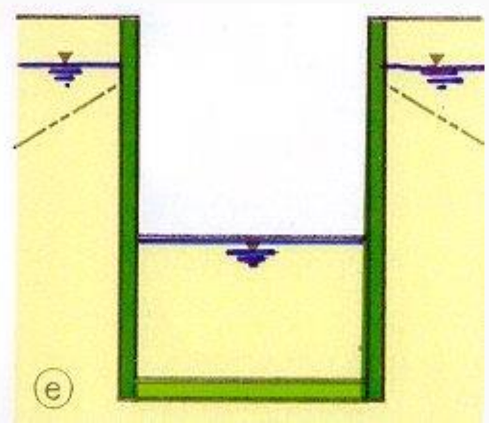


- avoidance of ground water lowering by...

- impermeable shoring extending into existing impermeable layers,





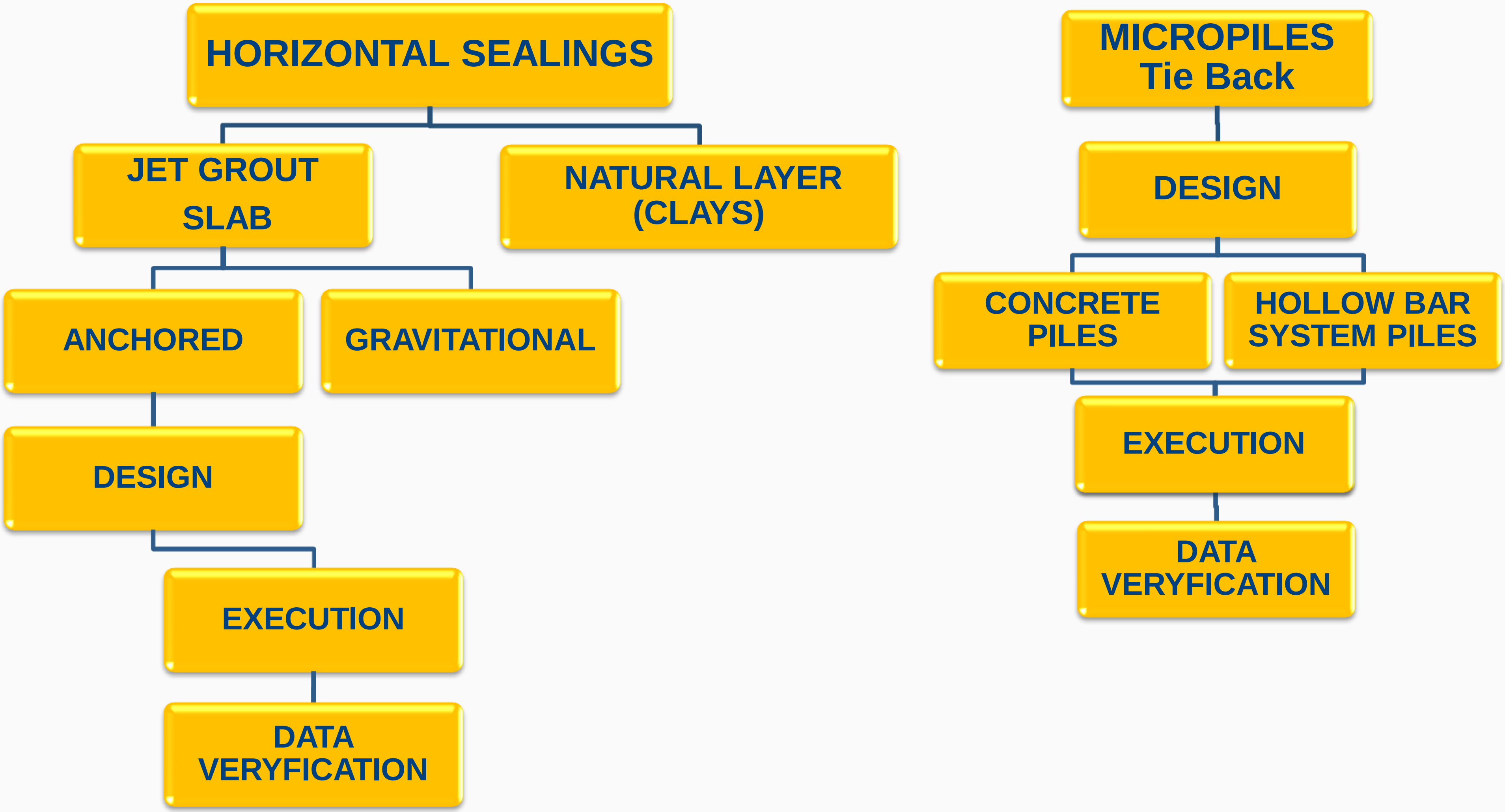


- uplift-safe under water concrete slab,

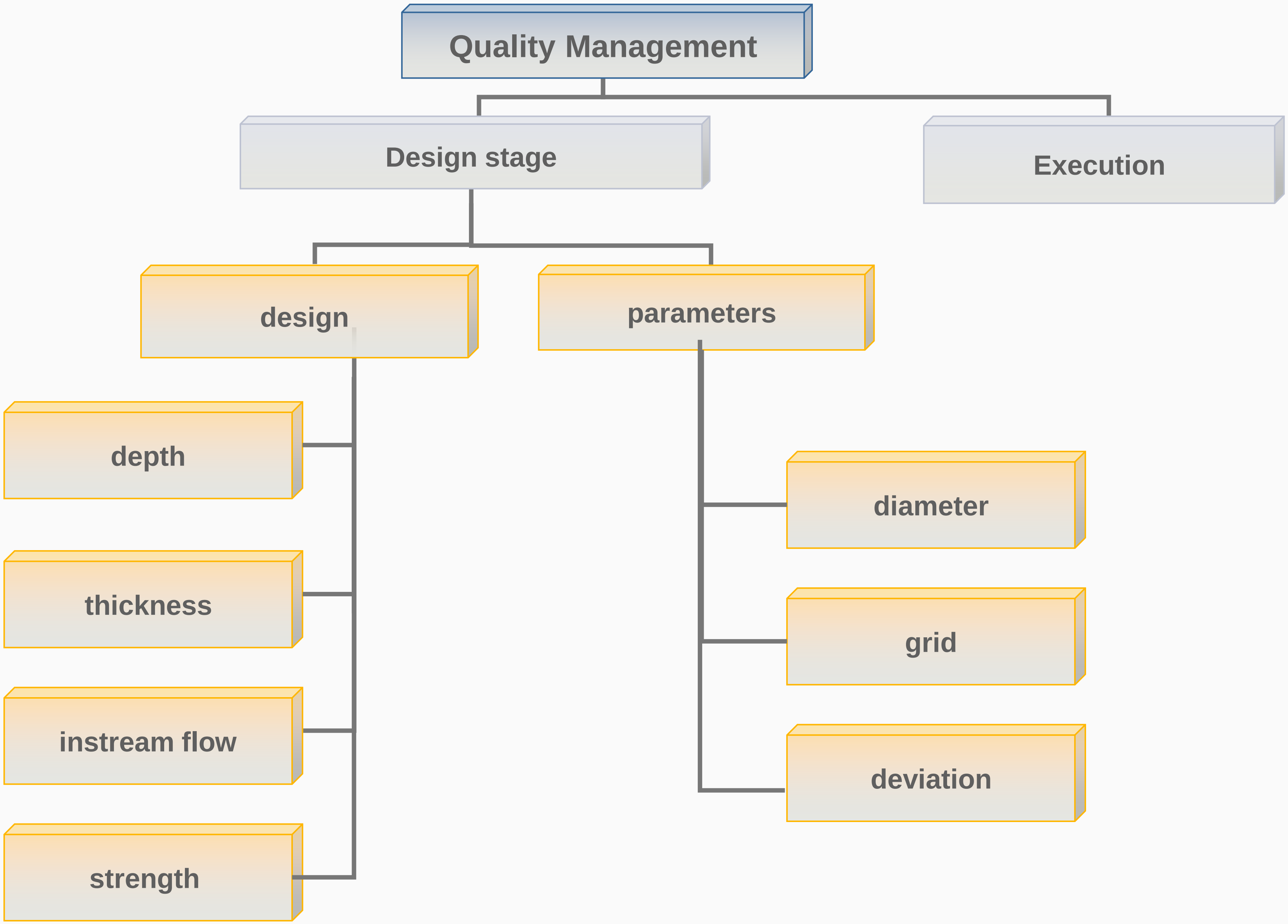
- anchored under water concrete or jet grouted slab

- uplift-safe grouted slab

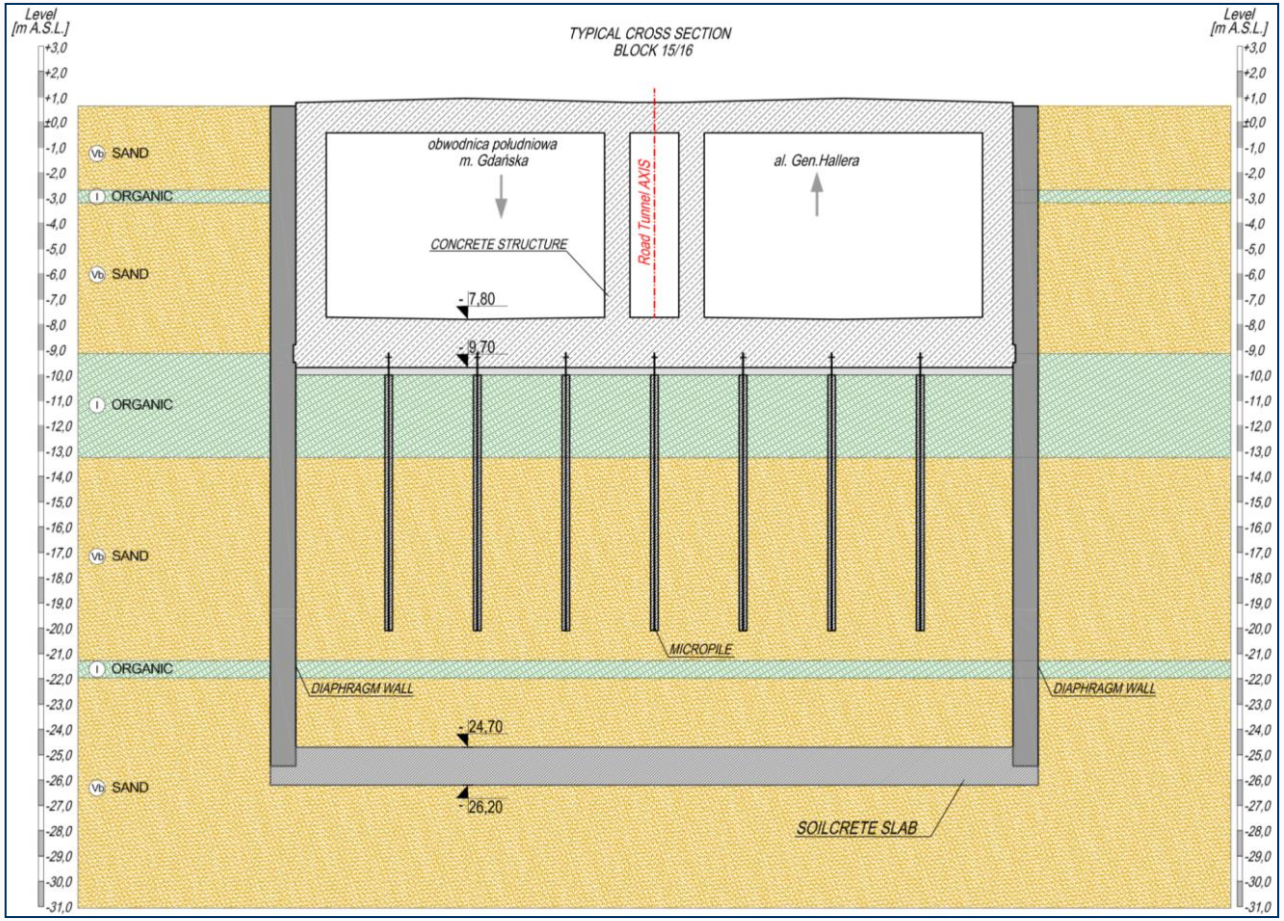
Structural Analysis



Quality Management



Type– Deep gravity jet grout base plug



Components of the system:

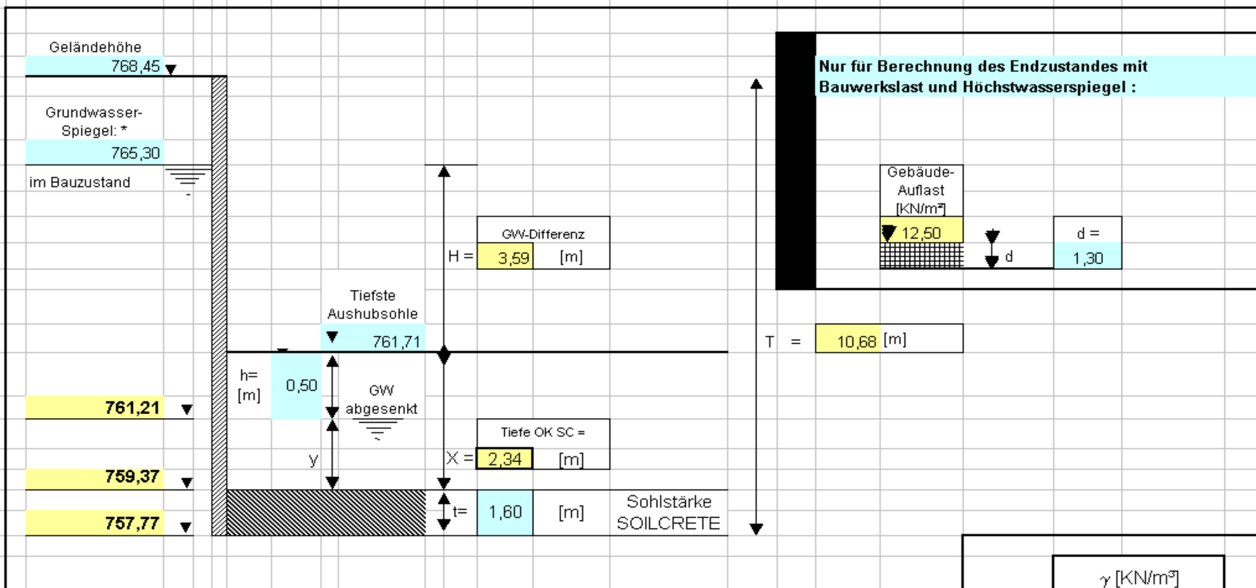
- Vertical walls (secant piles, D-walls,..) 0.8 m to 1.2 m thick; depth according to uplift
- Base plug as sealing membrane 1.0 to 1.5 m thick (compressive strength again erosion effects), depths according to analysis of uplift / gravity balance

Design: depth of base plug

Berechnung der Tiefenlage von Dichtsohlen

Baustelle:	Musterbaustelle	Sachbearbeiter :	ho	Datum 07.09.2001

Eingaben :	
Ergebnisse :	



G = Gebäude-Auflast :	$G = h * \gamma_{Beton}$	
G =	32,50	[KN/m²]

Gebäudeauflast :	32,50
Bauhöchstwasserstand:	
Sicherheit im Endzustand mit Bauwerkslast und bei Höchstwasser :	s = -0,01

γ [KN/m³]	
21,0	γ Boden
17,0	γ SC

DATENEINGABE

Bodenbeschreibung :	Tiefe von	Tiefe bis	[stgm]		γ [KN/m³]	γ_d [KN/m³]	ω_u [%]	Korndichte ρ_s [g/cm³]
Kies	0,00	-20,00	20,00		21	20,00	5%	2,65
sandiger Schluff weich			0,00			0,00		
			0,00			0,00		
Mittlere Bodenwerte			20,00		21,00	20,00	5%	2,65

Porenanteil n =	1 - γ_d / ρ_s	=	0,25
γ_{total} [KN/m³] =	γ_d + n * 10,(	=	22,5

Auftrieb P_w = (H + x + t) * 10

Eigengewicht Überlagerung g = t * $\gamma_{SOILCRETE}$ + y * γ_{total} + h* γ

g >= 1,05 * P_w ....Sicherheit 1,05

(H + x + t) * 10 * s   t * $\gamma_{SOILCRETE}$ + y * γ_{total} + h* γ

Tiefe OK SOILCRETE unter tiefster Aushubsohle :	x =	2,34
Tiefe UK SOILCRETE unter tiefster Aushubsohle :	x + t =	3,94
Tiefe UK SOILCRETE unter Geländehöhe :	T =	10,68

(Version 5.5.2000)

BODENKENNWERTE - Streubereich :

γ_d [KN/m³]	Trockenraumgewicht		
γ sc	bei Kies, Sand, Schluff :	21,0	[KN/m³]
	bei Humosen Böden, Torf	18,0	[KN/m³]

γ [KN/m³]	Feuchtraumgewicht	
	Kies	21,00
	Sand	20,00
	Schluff, Ton	19,00
	Torf	10,00

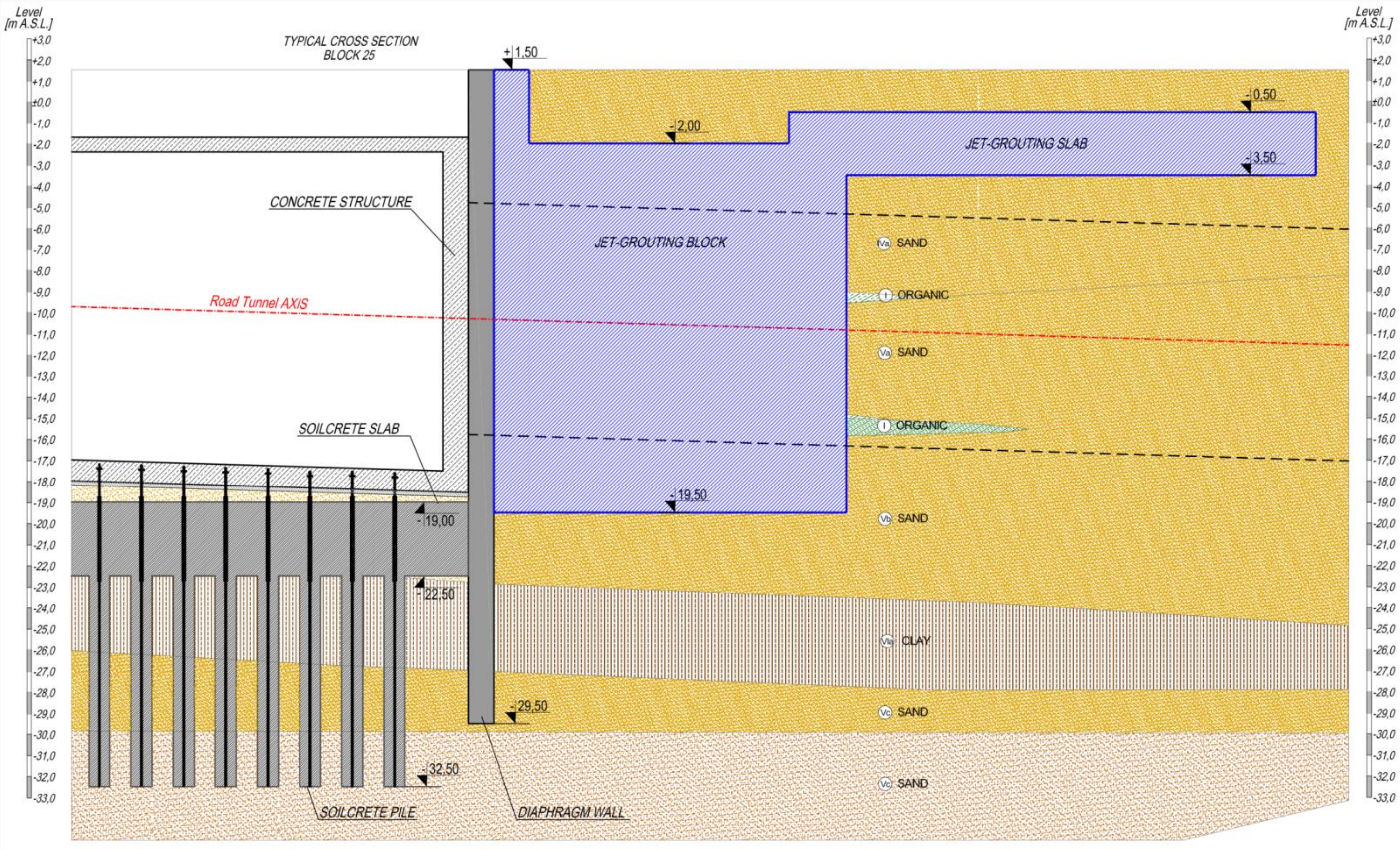
ω_h [%] erdfeucht	Wassergehalt	bei Kies :	5%
		bei Sand :	10%
		Schluff, Ton :	20%

Korndichte ρ_s [g/cm³]	bei Quarz - Kies, -Sand	2,65
	bei Kalk-, Dolomit-Kies, -Sand	2,70
	bei Schluff, Ton	2,75
	bei Torf	1,10

Porenanteil n	dichtgelagerter Kies	0,2
	lockerer Kies	0,25
	Sand	0,3
	Schluff	0,35
	Ton	0,40 - 0,45
	Löß	0,40 - 0,50

Sicherheit s	gem ÖN B 4435 T2 für Bauzustand :	1,05
	für Endzustand :	1,10

Type – Anchored jet grouting sealing plug

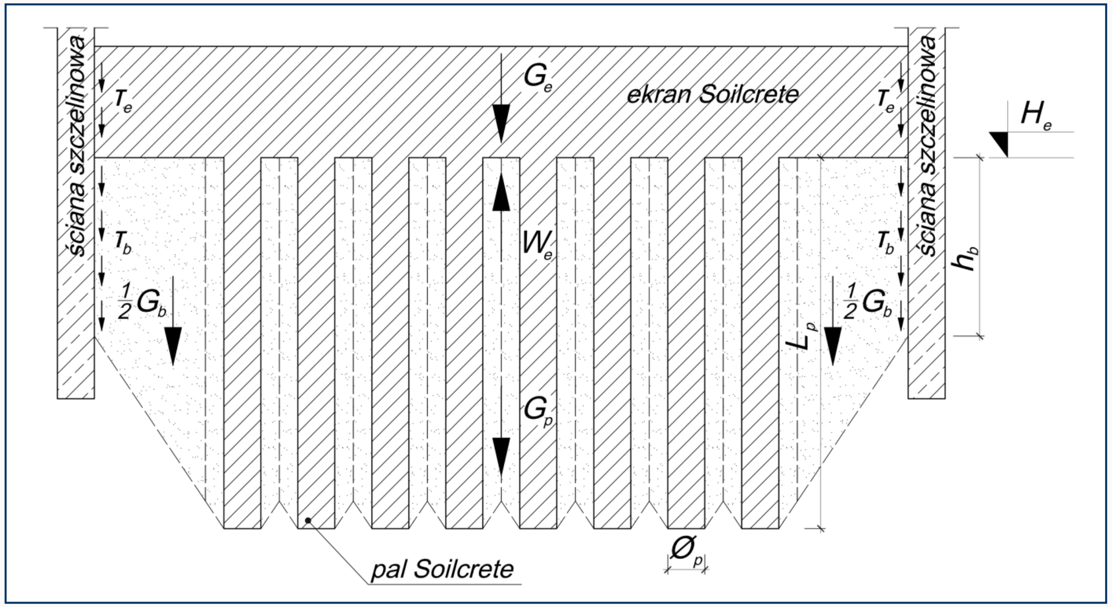


Components of the system

- Vertical walls (secant piles, D-walls,..) 0.8 m to 1.2 m thick; depth acc. structural analysis
- Tie back anchoring –length according to analysis of uplift / gravity balance
- Jet grouting plug as **sealing membrane and strut ,** thickness and strength according to full arching action analysis of system

Base Plug Structural Analysis

Global equilibrium – construction phase

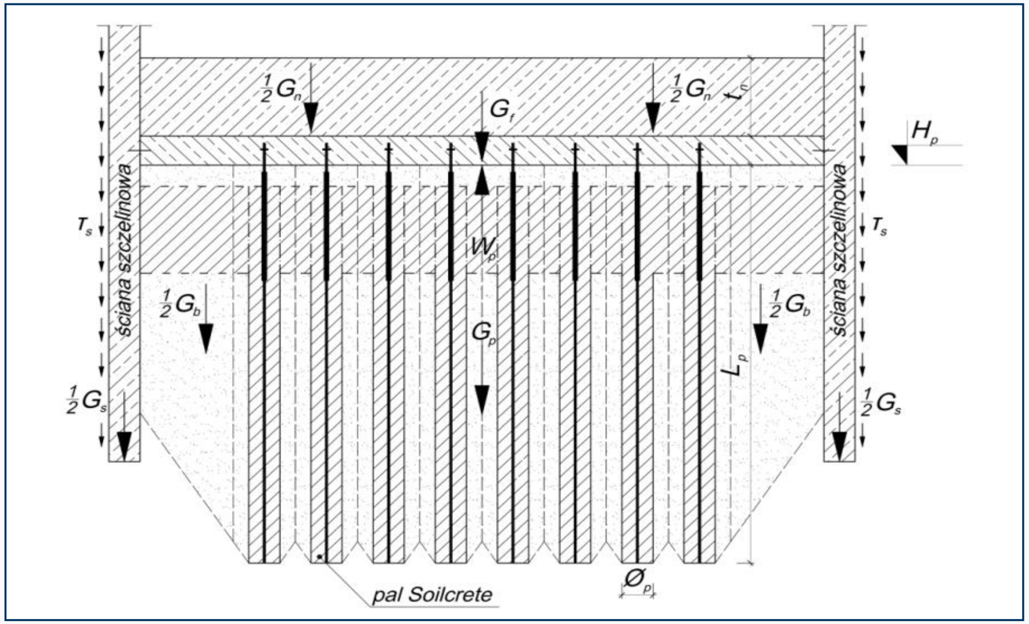


$$\frac{G_{e,k} + G_{p,k} + G_{b,k} + T_{e,k} + T_{b,k}}{W_{e,k}} > 1{,}10$$

$W_{e,k}$	- hydrostatic uplift force acting on the bottom of plug
$G_{e,k}$	- weight of jet grouting plug
$G_{p,k} + G_{b,k}$	- enclosed soil mass
$T_{e,k}$	- friction between jet grouting plug and diaphragm wall
$T_{b,k}$	- friction between soil mass and diaphragm wall

Base Plug Structural Analysis

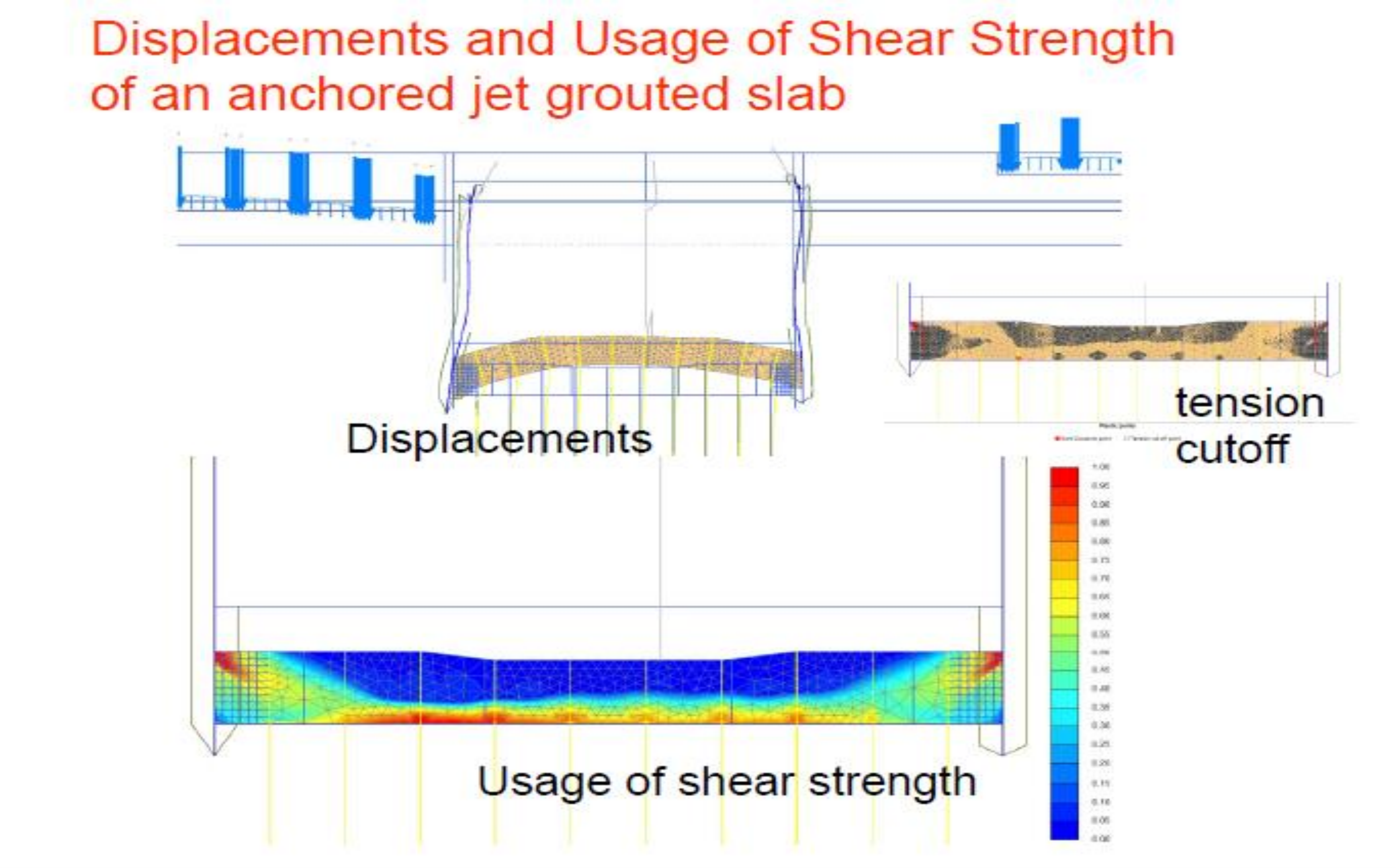
Global equilibrium – final stage



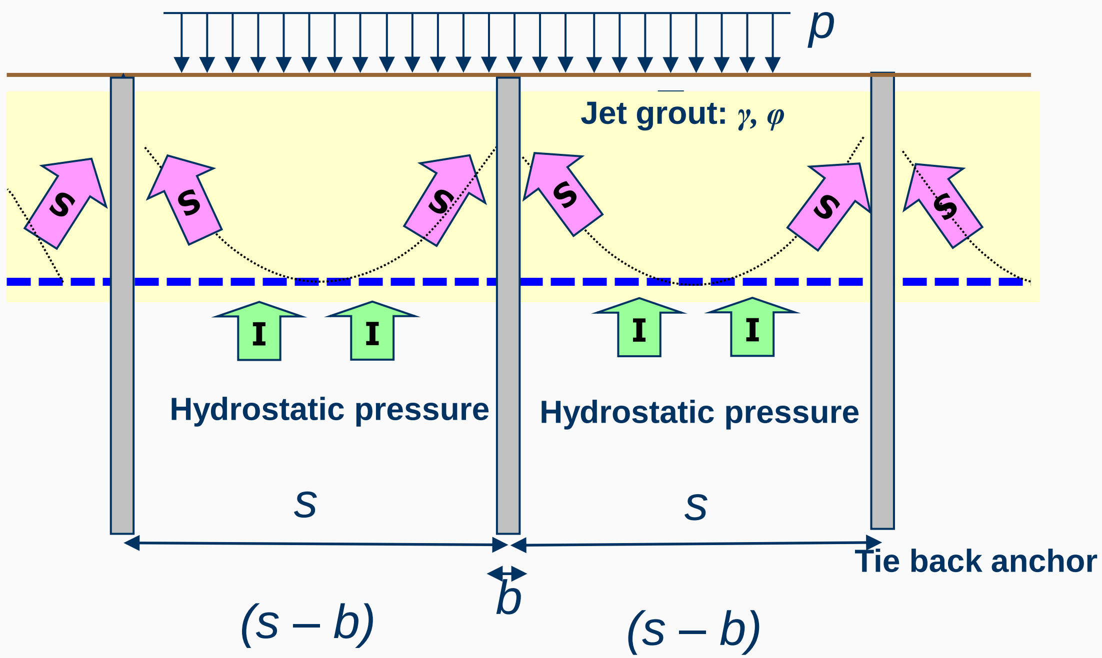
$$\frac{G_{f,k} + G_{s,k} + G_{n,k} + G_{p,k} + G_{b,k}}{W_{p,k}} > 1{,}10$$

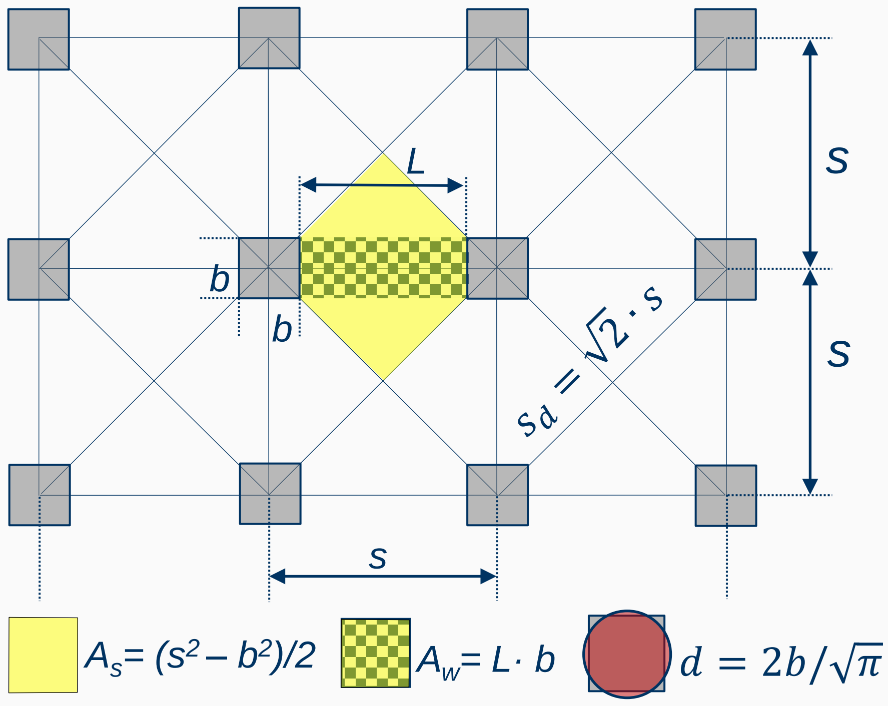
$W_{e,k}$	- uplift force acting on the bottom of slab
$G_{f,k}$	- weight of foundation slab
$G_{p,k} + G_{b,k}$	- enclosed soil mass
$G_{s,k}$	- weight of diaphragm walls (with buoyancy)
$G_{n,k}$	- weight of bottom slab in technical building

Structural Analysis jet grout element



Structural Analysis jet grout element





Structural Analysis:

Geometry
Fill properties
Load

1: „arching"

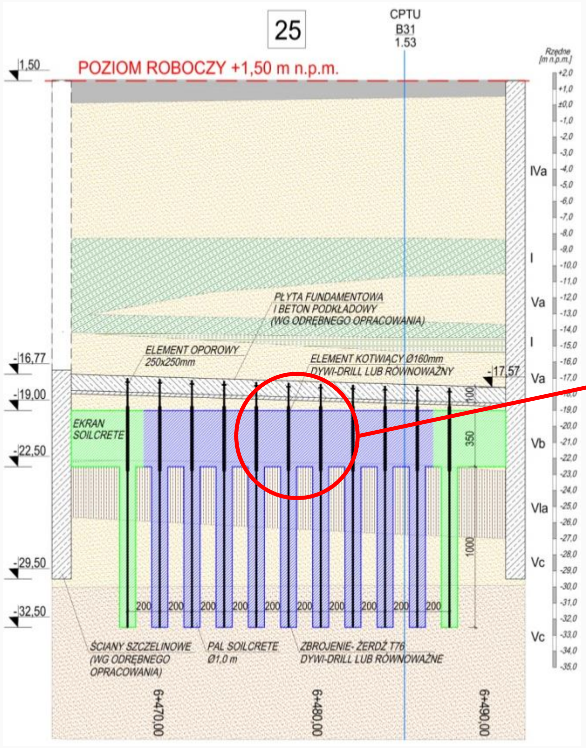
Load I

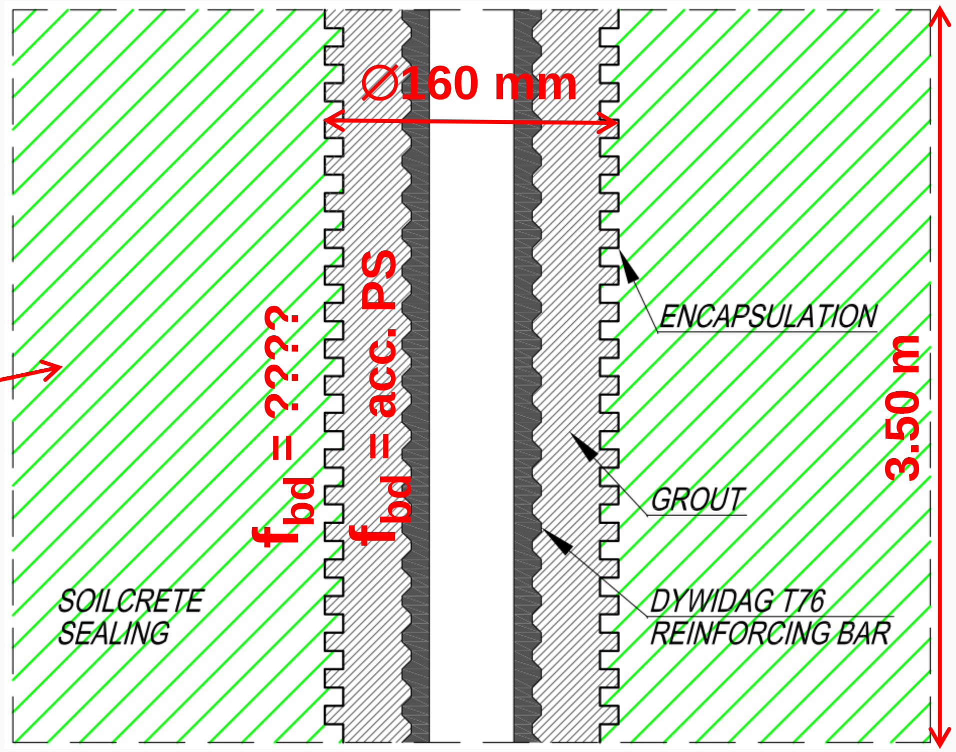
Arching
S

Stress analysis jet grouting material

Base plug Structural Analysis

Interaction between base plug and tie back anchoring:





Base plug Structural Analysis

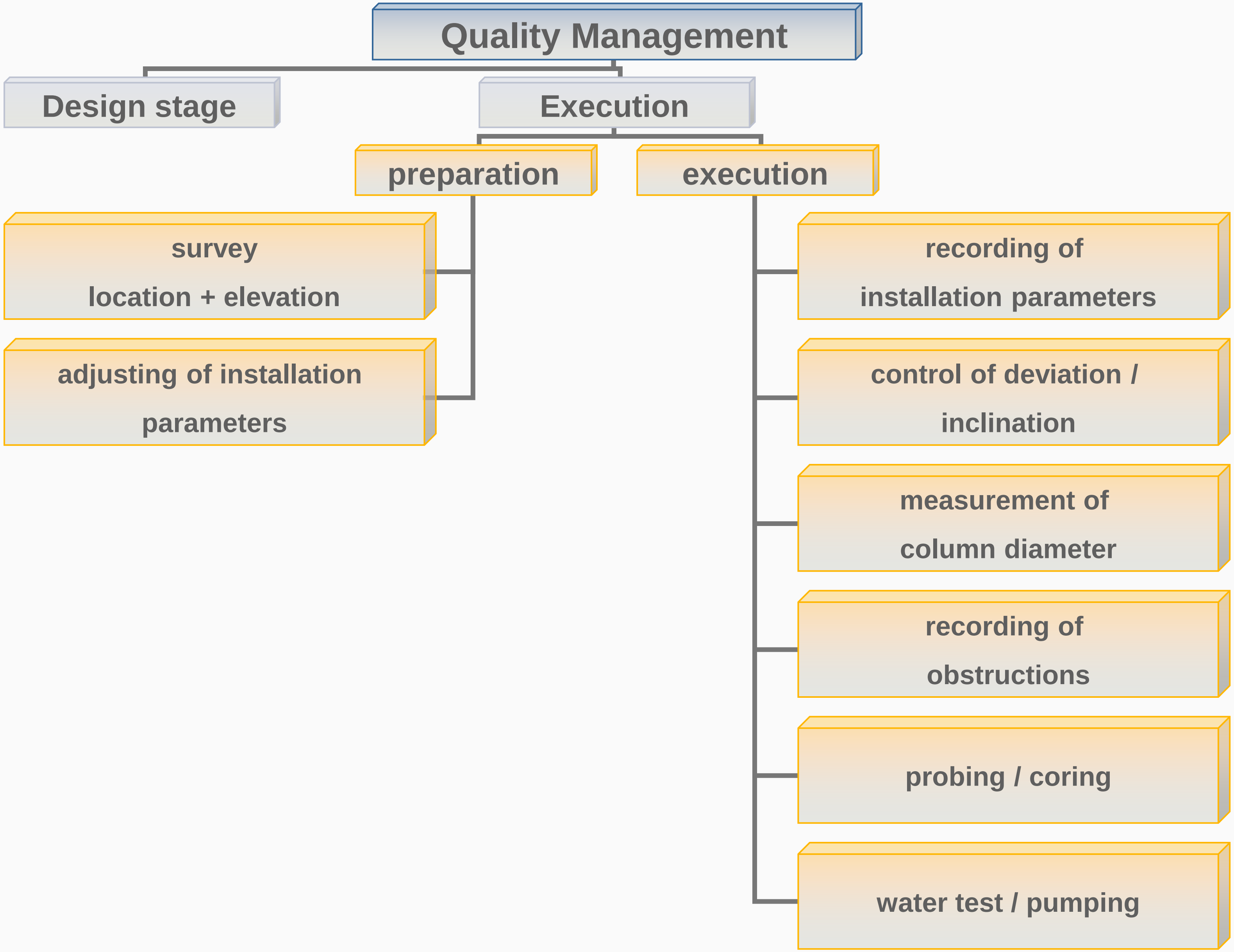
Internal capacity (reinforcing hollow bar)

Internal capacity of hollow bars according to steel standards.

Internal capacity (grout-to-steel bond stress)

Bonding capacity of imbedded steel element in jet grouting depending on strength of jet grouting material.

Quality Management



Influencing factors of jet reach

- In general lower reach of jet in soil with higher resistance (strength)
- Kinetic energy input determines erosion volume primarily (cutting efficiency)
- Air shrouding minimizes friction and increases reach in saturated soil
- Effective air velosity app. 170 m/s for optimal cutting efficiency
- High air pressure and volume involving increasing risks during execution

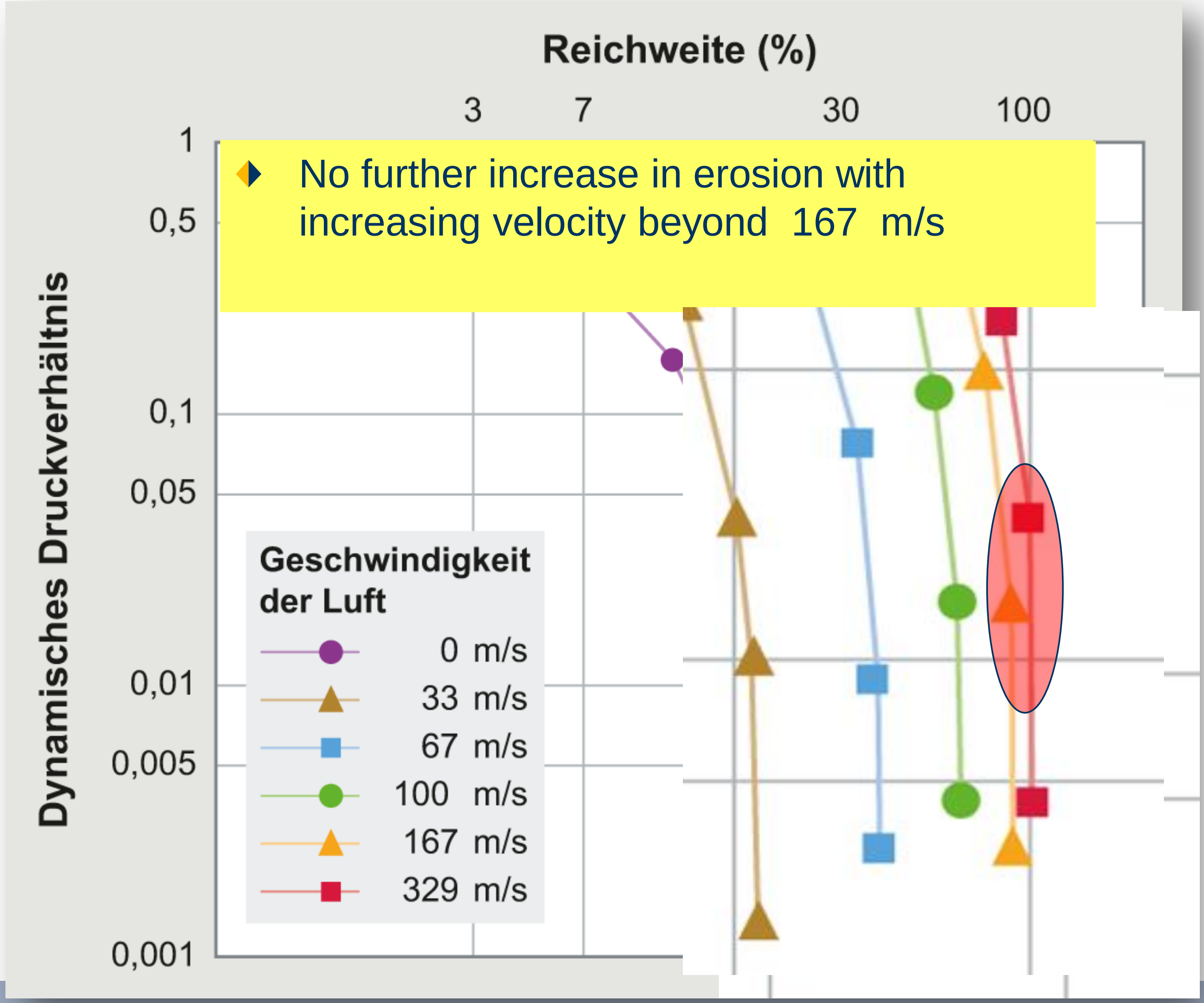
  => Blockage of drilling canal leading to heaval

  => Uncontrolled usage of air increasing drilling canal unregularly, irregularity in spoil discharge

High flow rate (abrasion) und quantity increasing wear and tear of monitor and nozzle (grout and air)

Air shrouding (quantity & velocity)

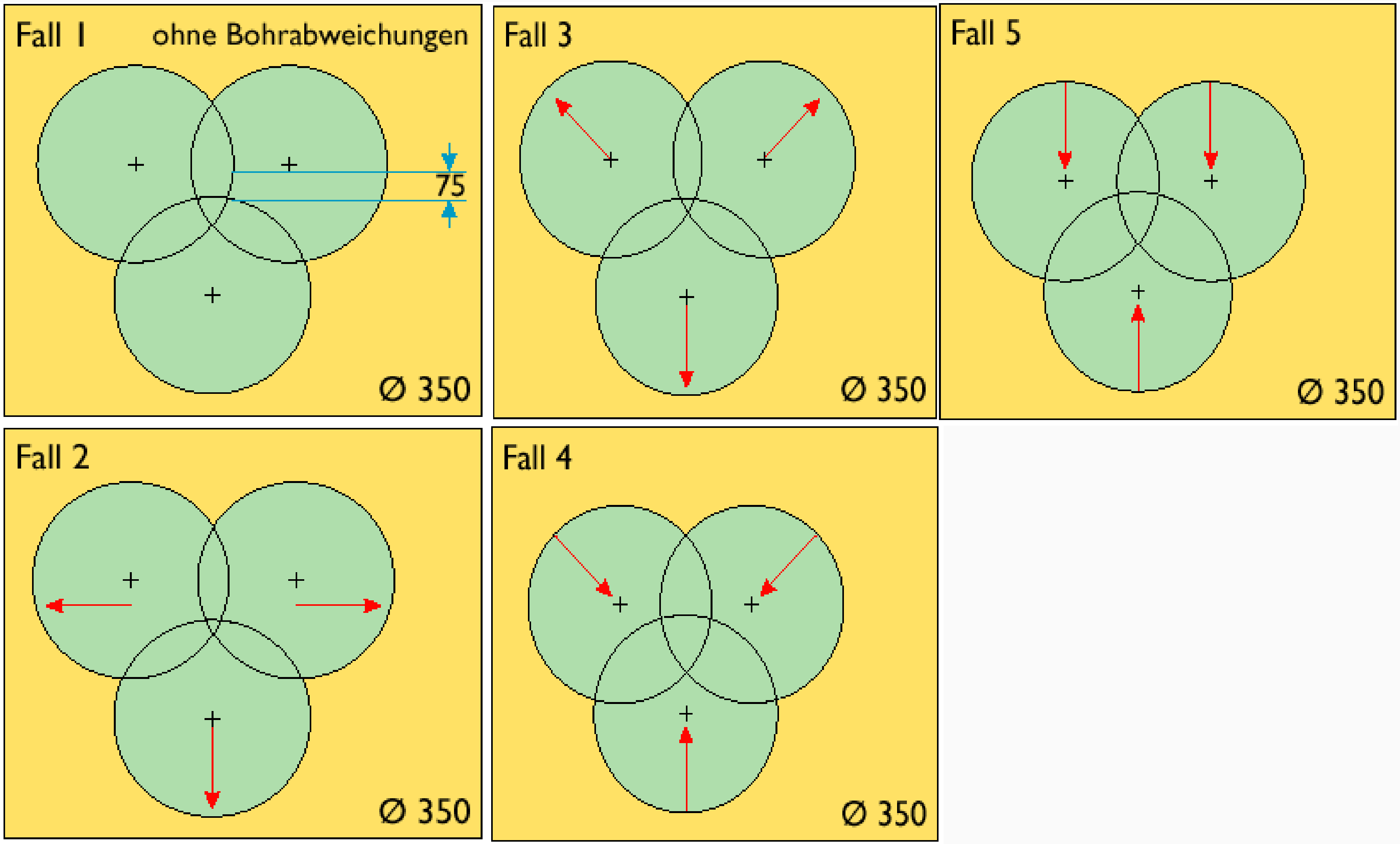
Erosion effectiveness depending on air velocity



Defects in Jet Grout bodies may occur due to:

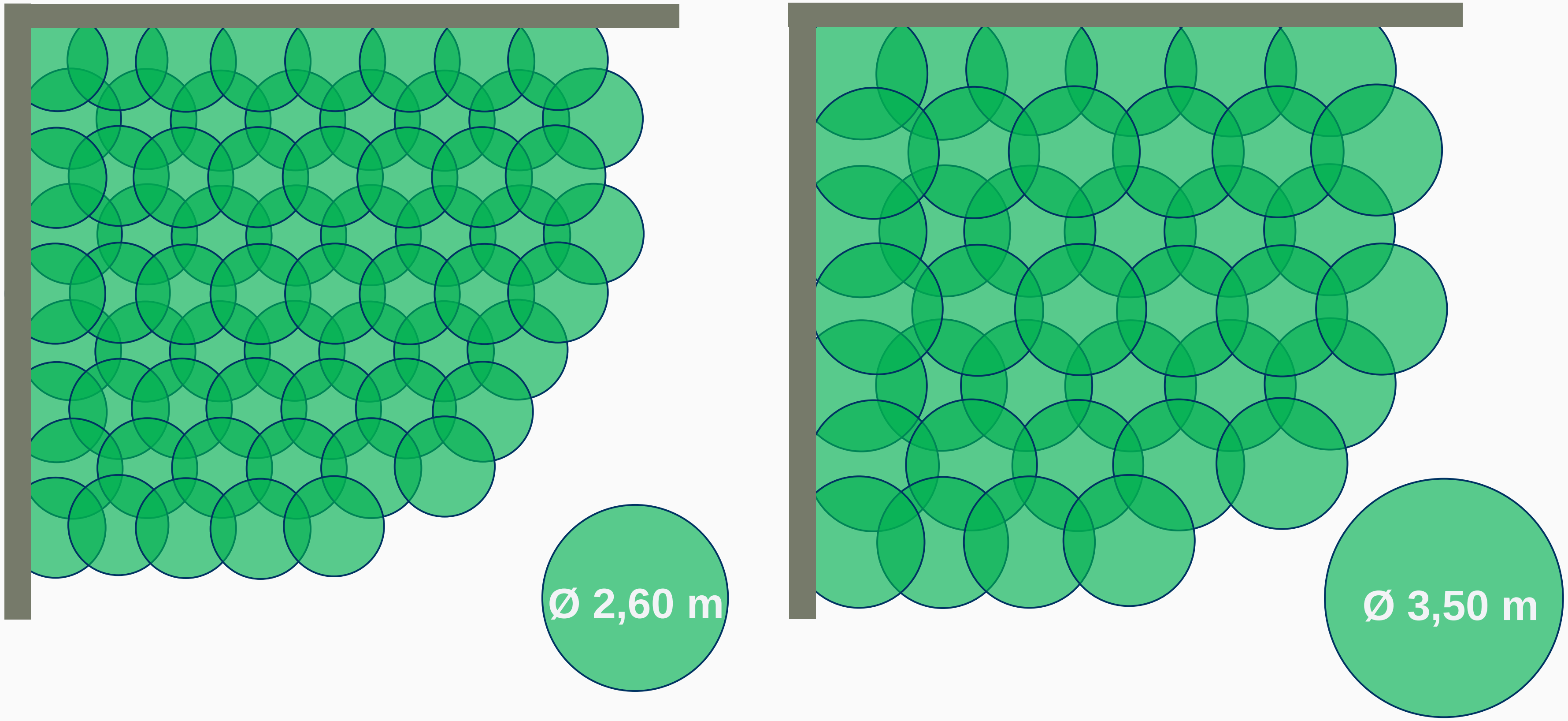
1. Insufficient overlapping of individual J.G. columns
2. Jet shadows caused by natural or man made obstructions
3. Inhomogeneity's of the ground (marl or clay layer imbedded in sand, peat layers etc…)
4. Instability and subsequent collapse of J.G. columns
5. Process deficiencies and interruptions, mistakes

Consideration of deviations at design stage

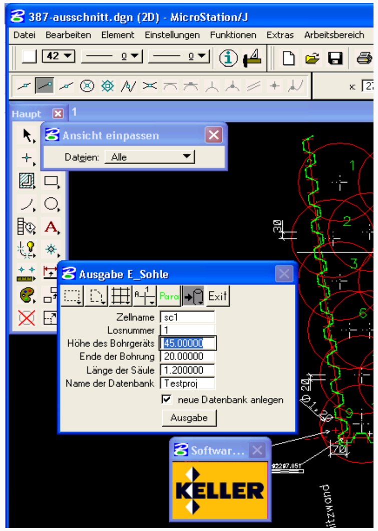


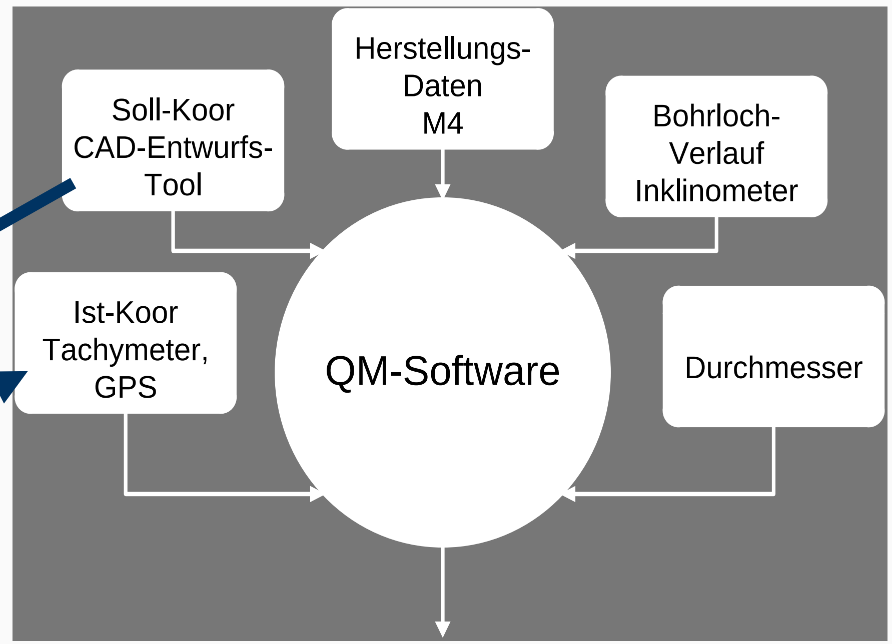
Diameter of jet grout columns

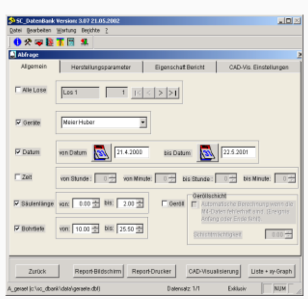
Increase in diameter reduces the overlapping volume and minimizes the joint-area in between columns

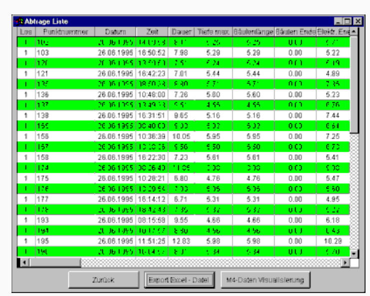


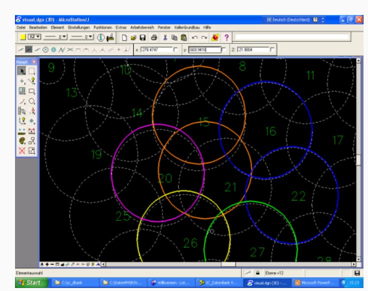
QM-System Jet grouting applications

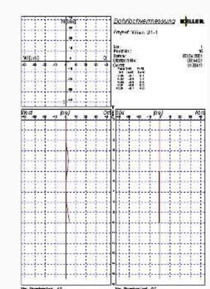




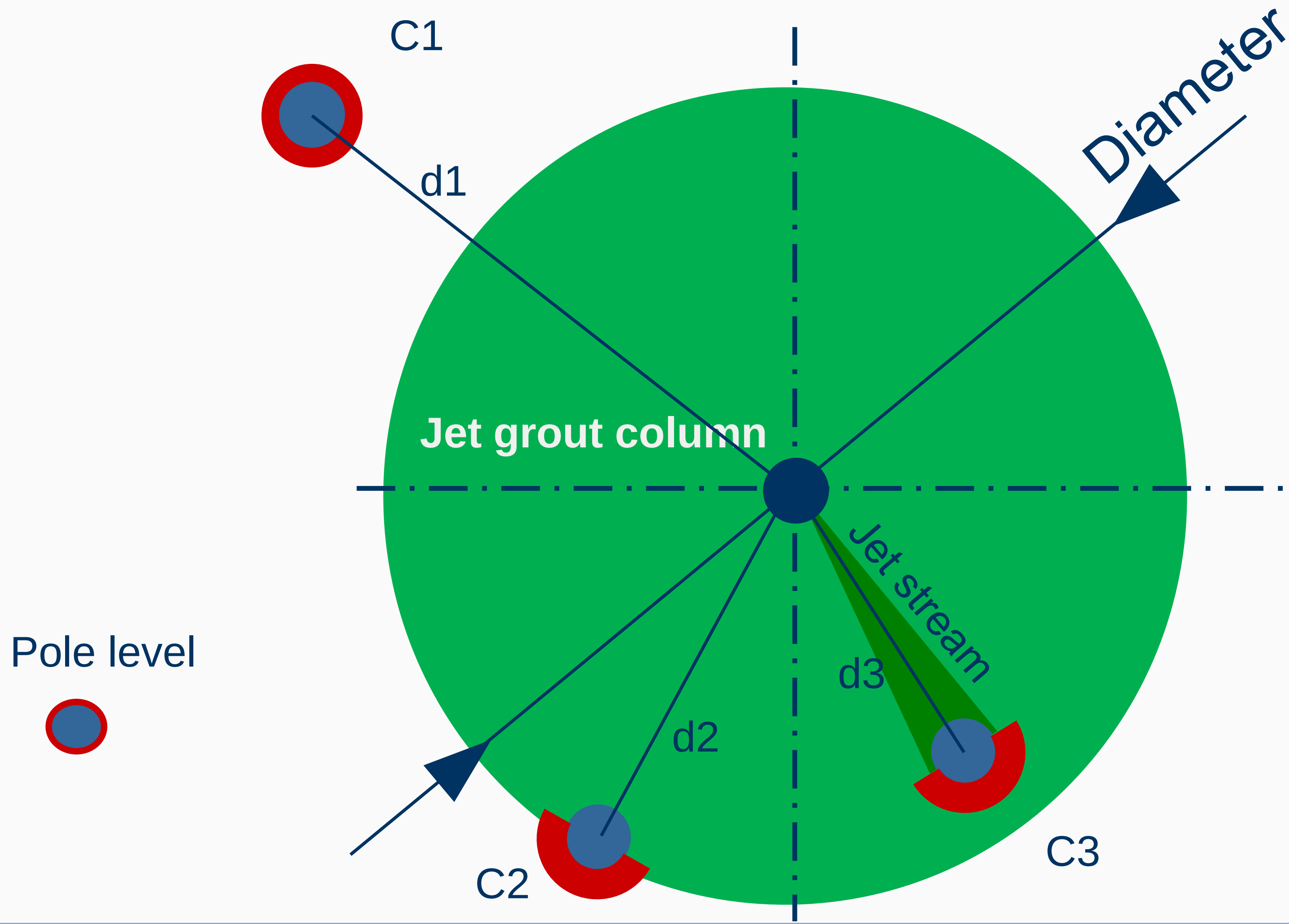






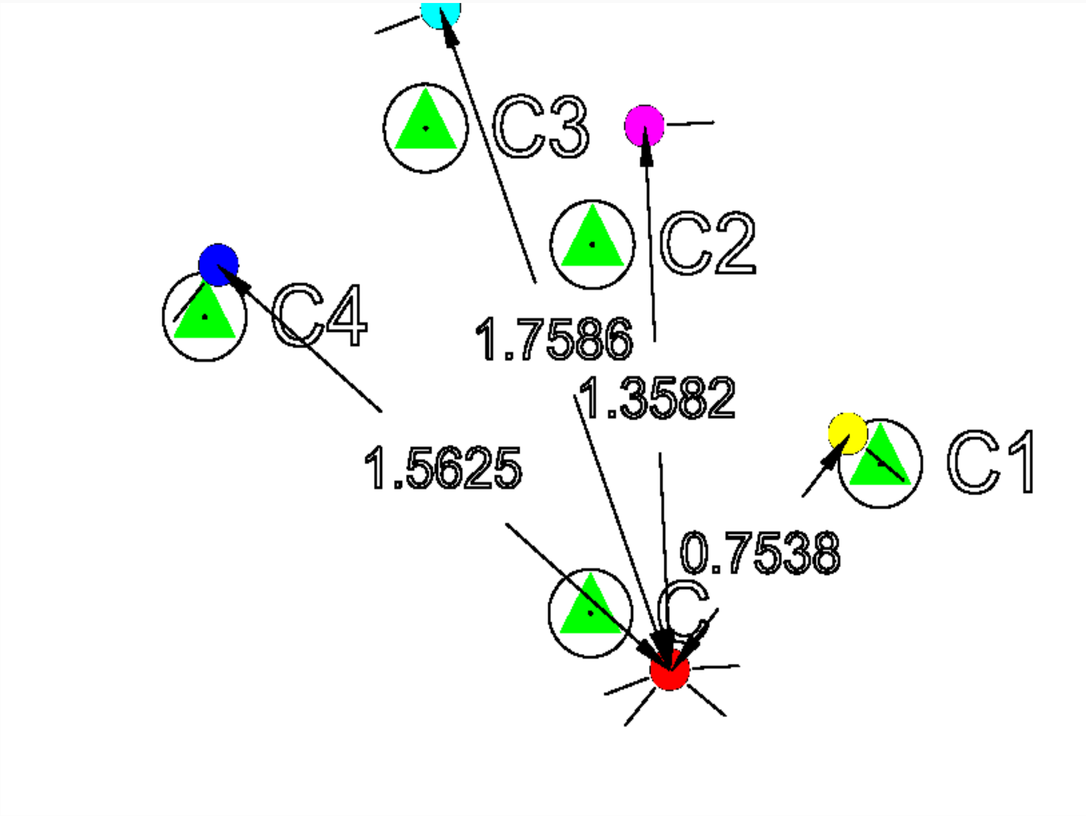


Pole level method



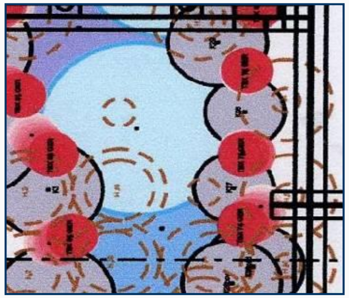
Verification of column diameter

Layout of pole levels to verify jet effectivness

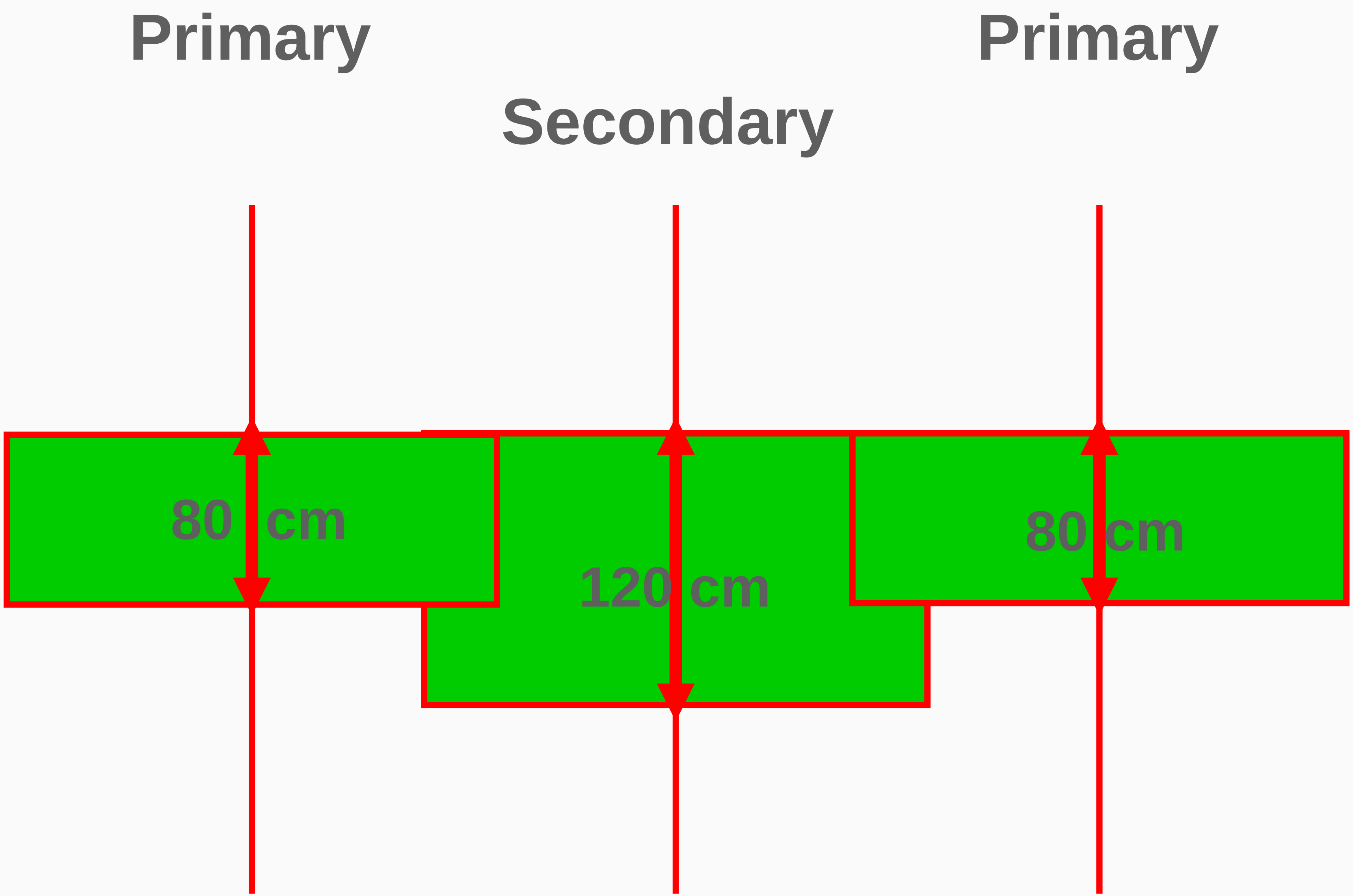


Diameter verification

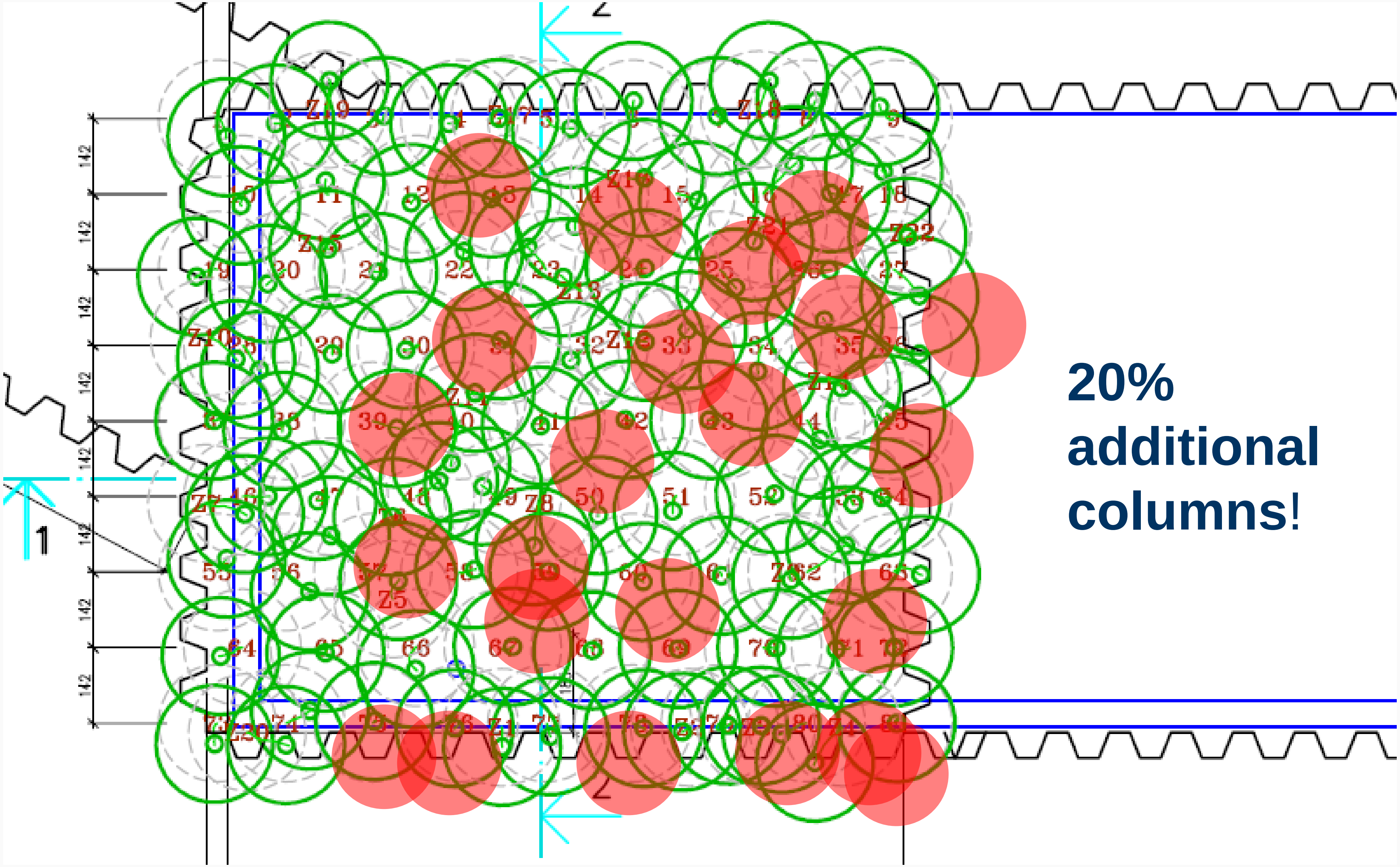
using hydraulic measurement device



Quality assurance execution sequence

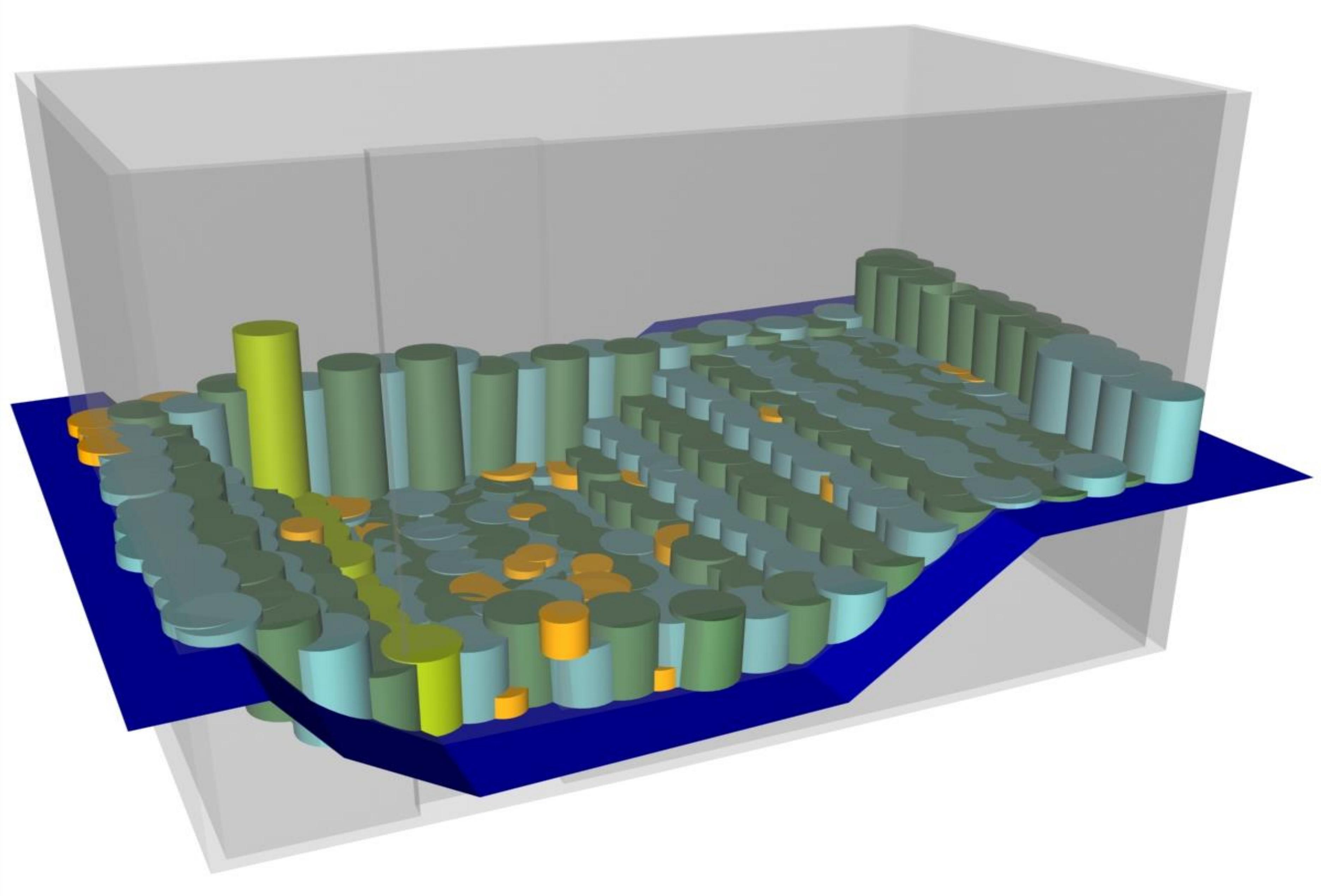


Impact of deviation on overlapping



20% additional columns!

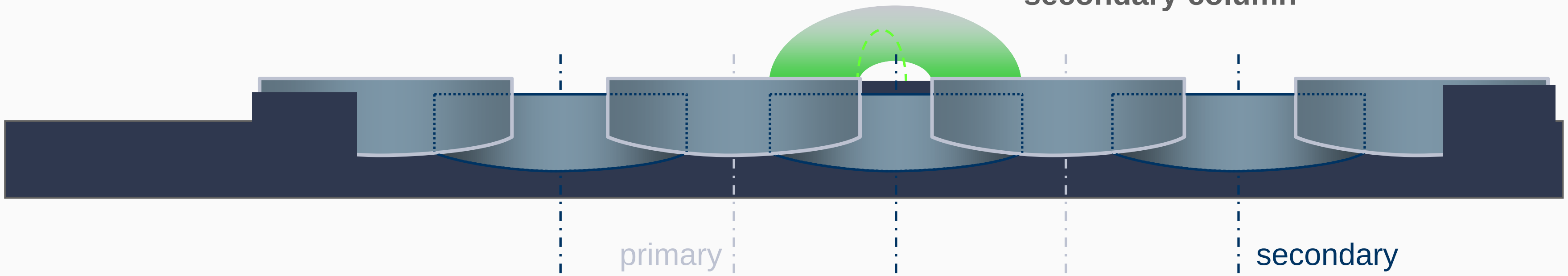
3 D overview of actual column installation



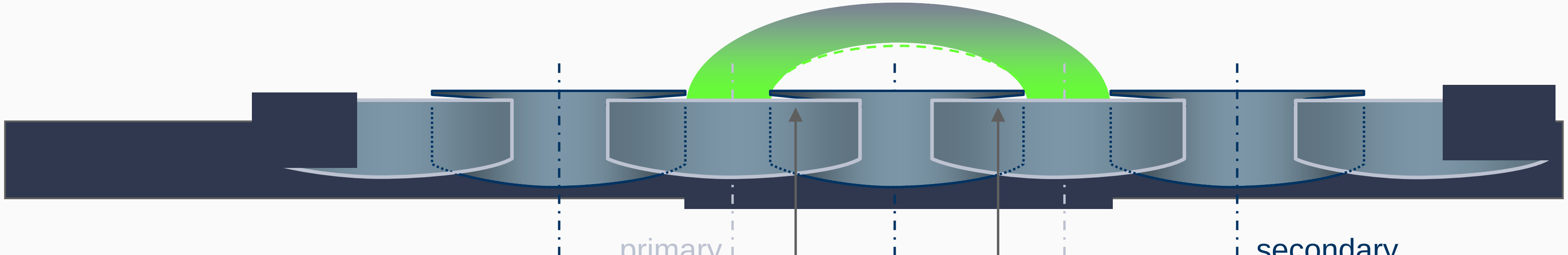
Installation of primary and secondary rows:

arching with and w/o overlap

w/o overlap

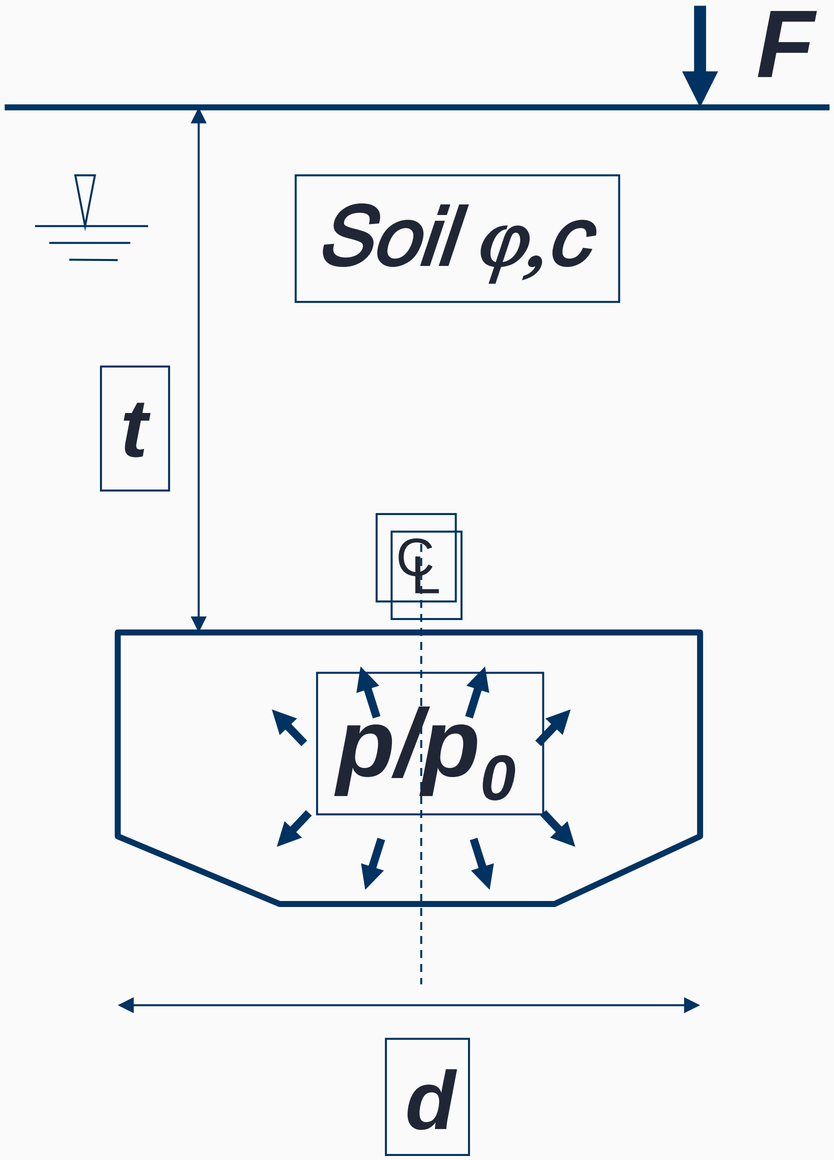


with overlap



Stability of jet grout column

- diameter impact



$$stability\ s = f\left(p/p_0, t, d, \varphi, c, F, \ldots\right)$$

p/p_0 = pressure ratio in column

t = overburden

d = column diameter

φ, c = shear strength

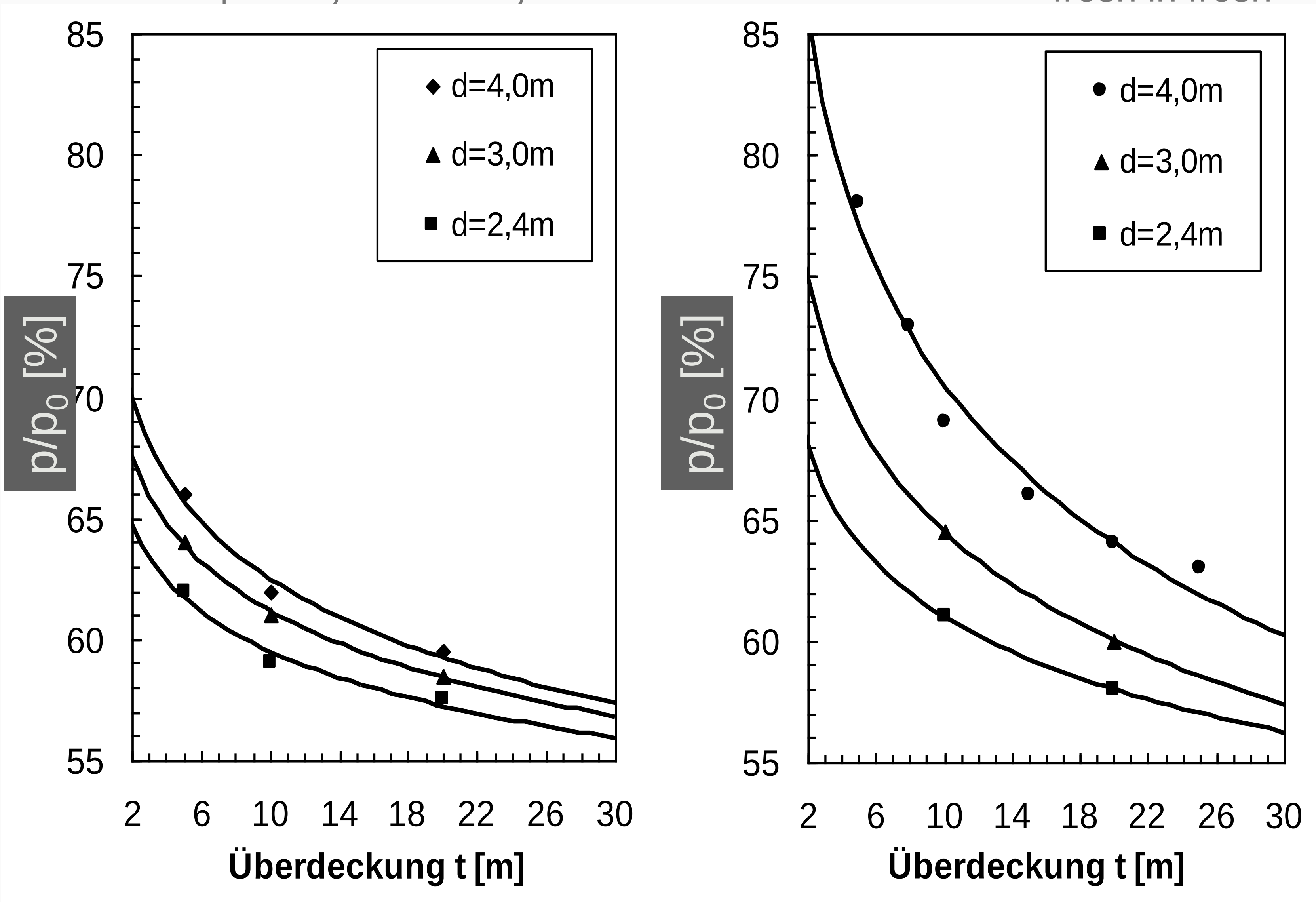
F = surface load

Instability

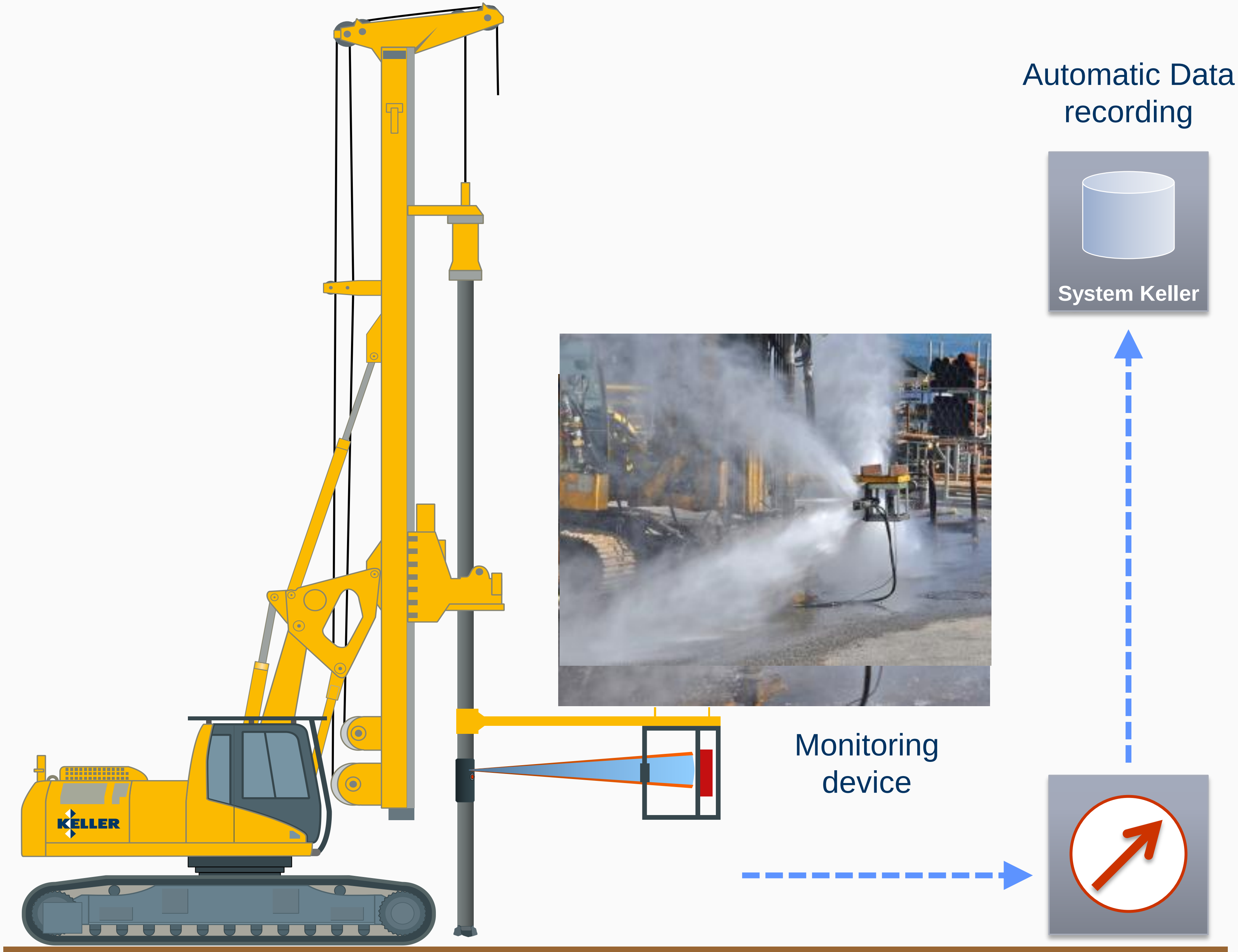
Critical supporting pressure for…

… primary/secondary row

… primary column row fresh in fresh



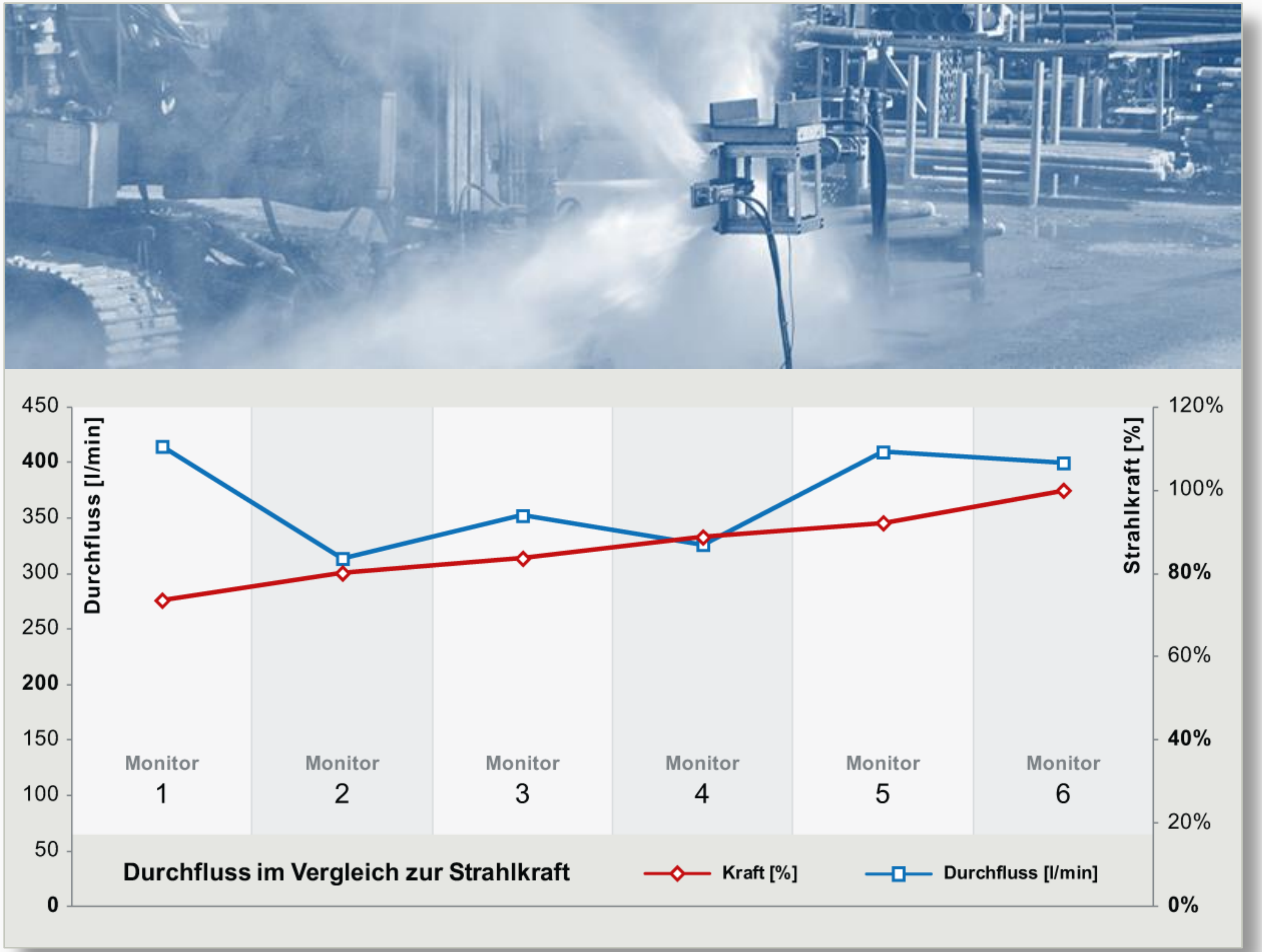
Effectiveness check of monitor and nozzle



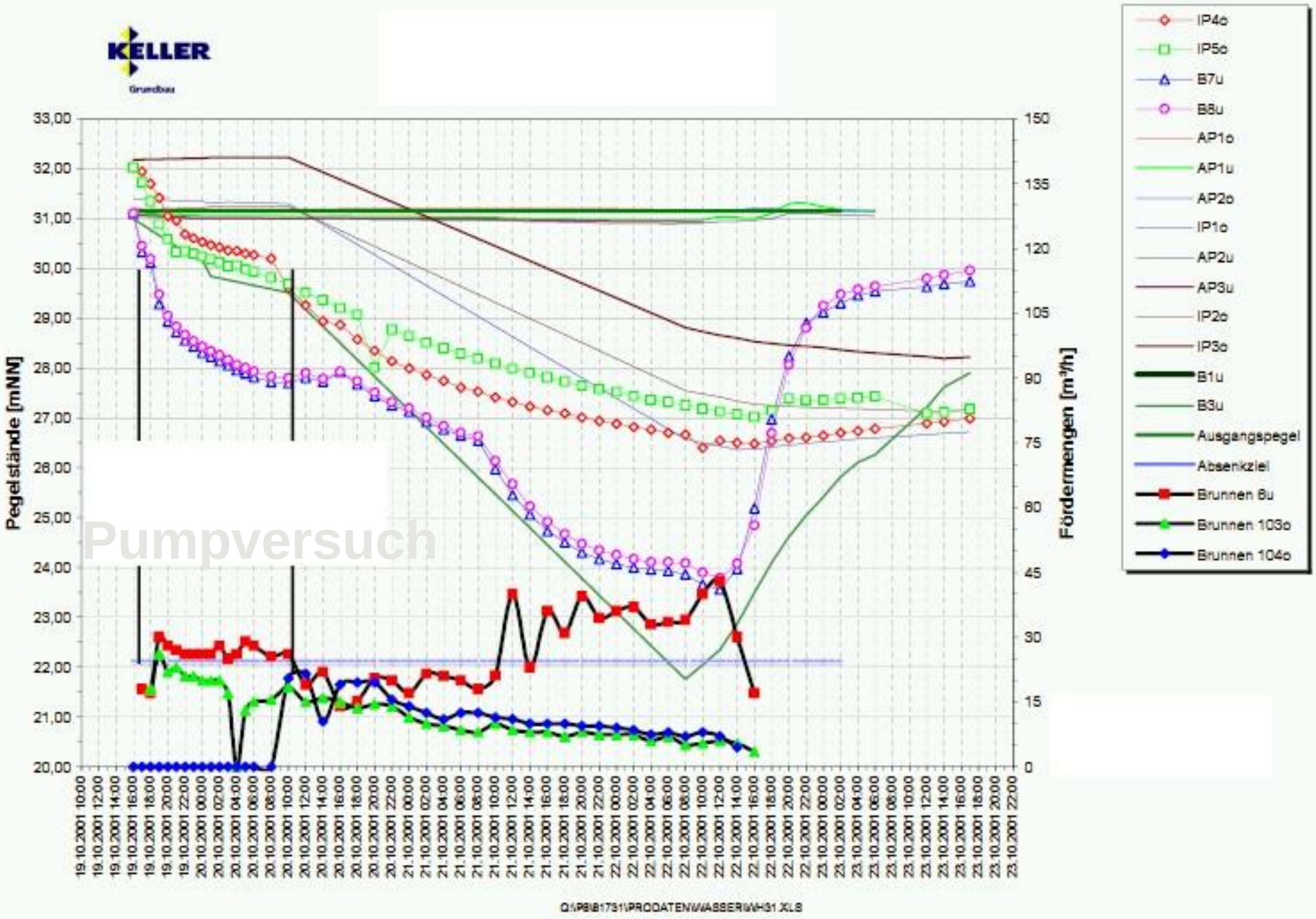
On-site test device

Verification of efficiency

Efficiency of monitor and nozzle

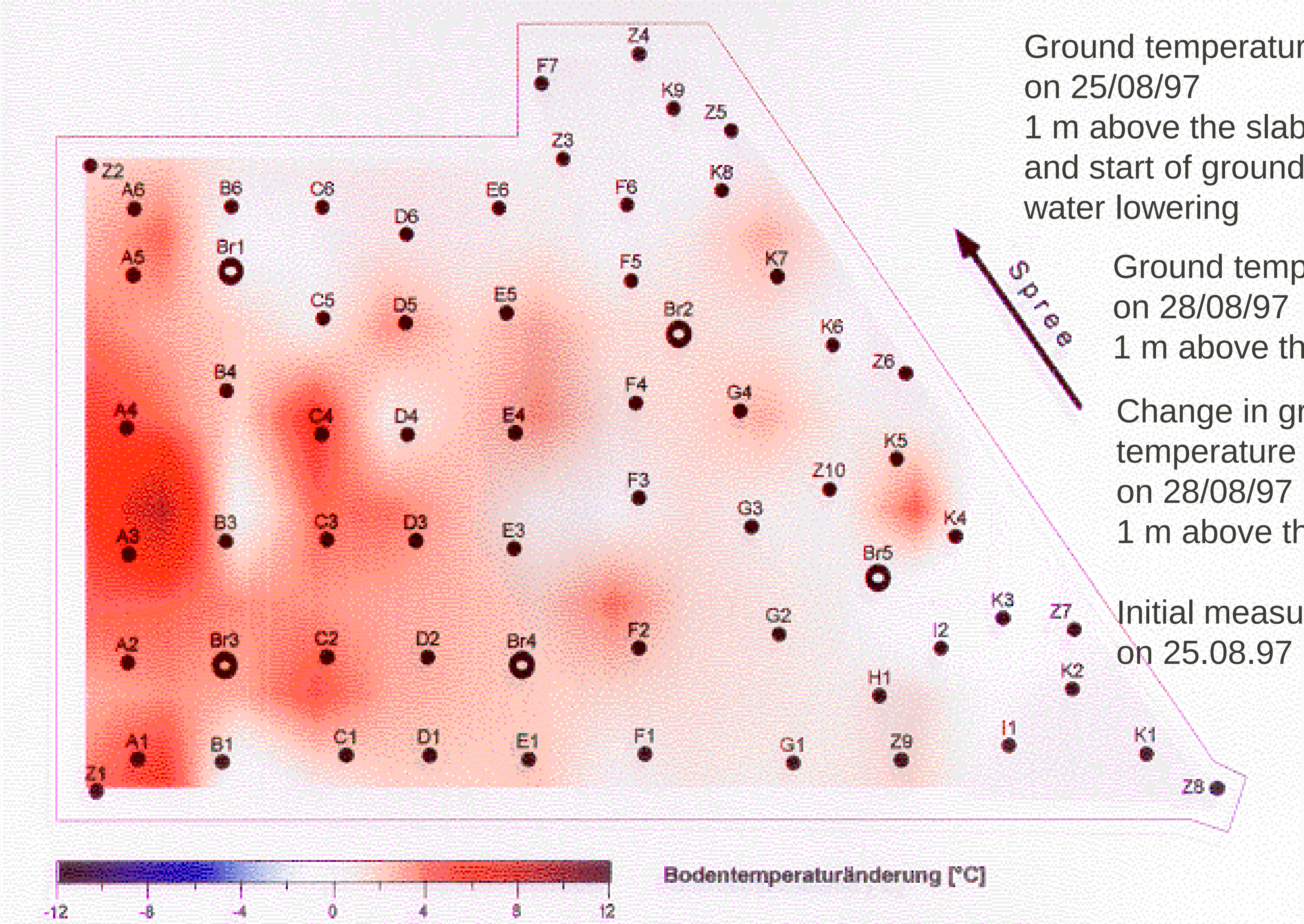


Quality assurance before excavation



Leak detection by temperature measurement

during draw down of water table



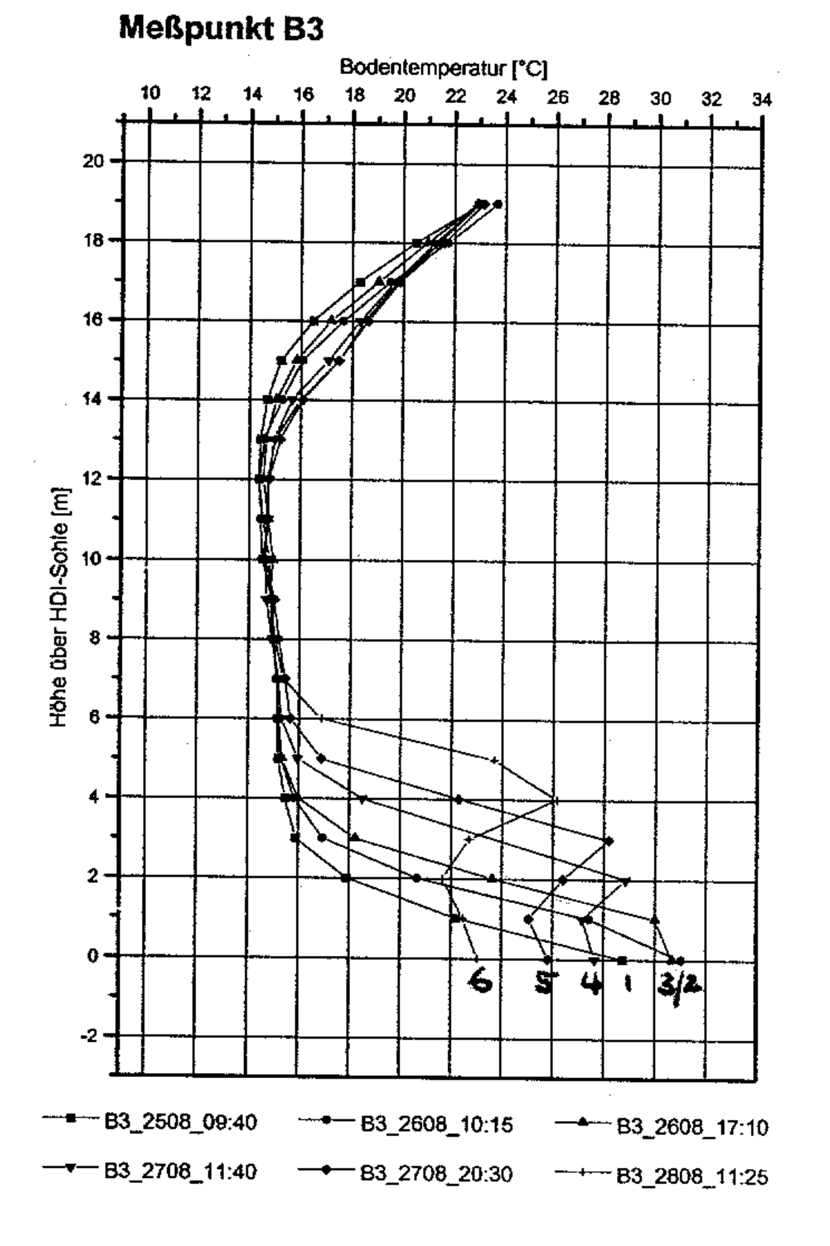
Ground temperature on 25/08/97 1 m above the slab and start of ground water lowering

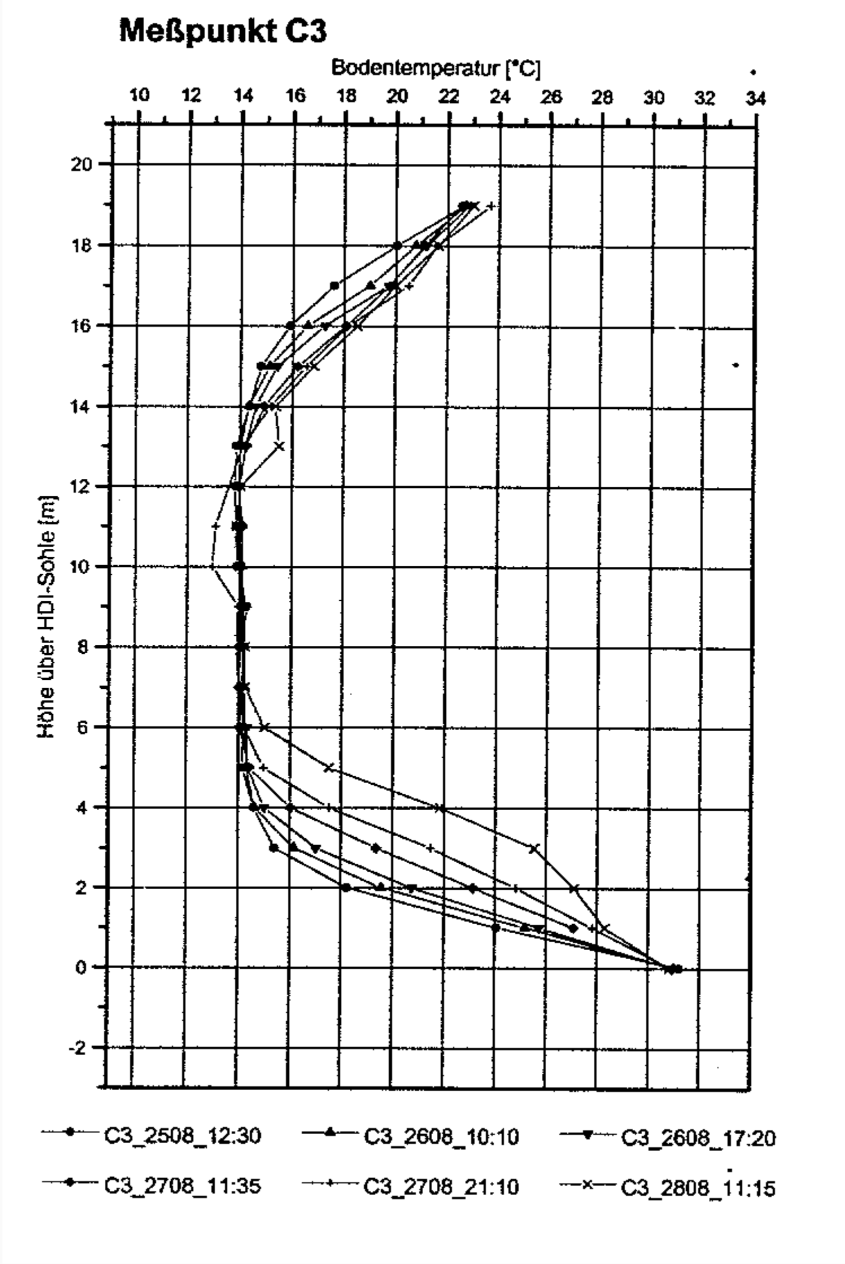
Ground temperature on 28/08/97 1 m above the slab

Change in ground temperature on 28/08/97 1 m above the slab

Initial measurement on 25.08.97

Leak detection by temperature measurements





Cement content jet grouting material

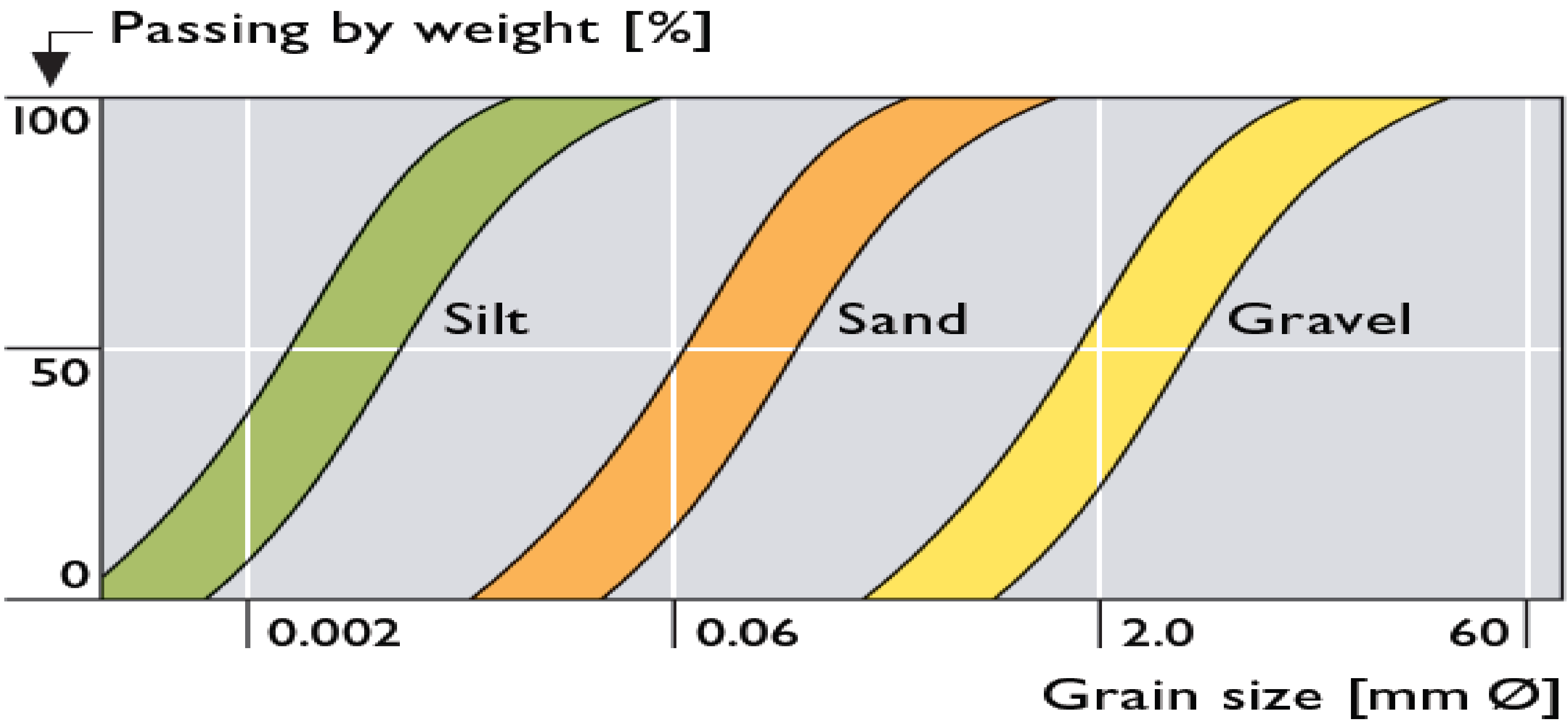
Cement Content :

$$Cem_{Soil} = \frac{1500 \cdot \left(\rho_{Suspesion} - \rho_{Water}\right) \cdot Q_{Suspesion}}{v_z \cdot 10 \cdot \frac{\pi \cdot D^2}{4} + \left(Q_{Water} + Q_{Suspension}\right)}$$

Cem_{Soil}:	Cement content jet grouted soil[kg/m³]
$\rho_{Suspension.}$, ρ_{Water} :	unit weight suspension, water[t/m³]
v_z:	withdrawal speed [cm/min]
$Q_{Suspension}$, Q_{Water}:	pump rate suspension, water [l/min]

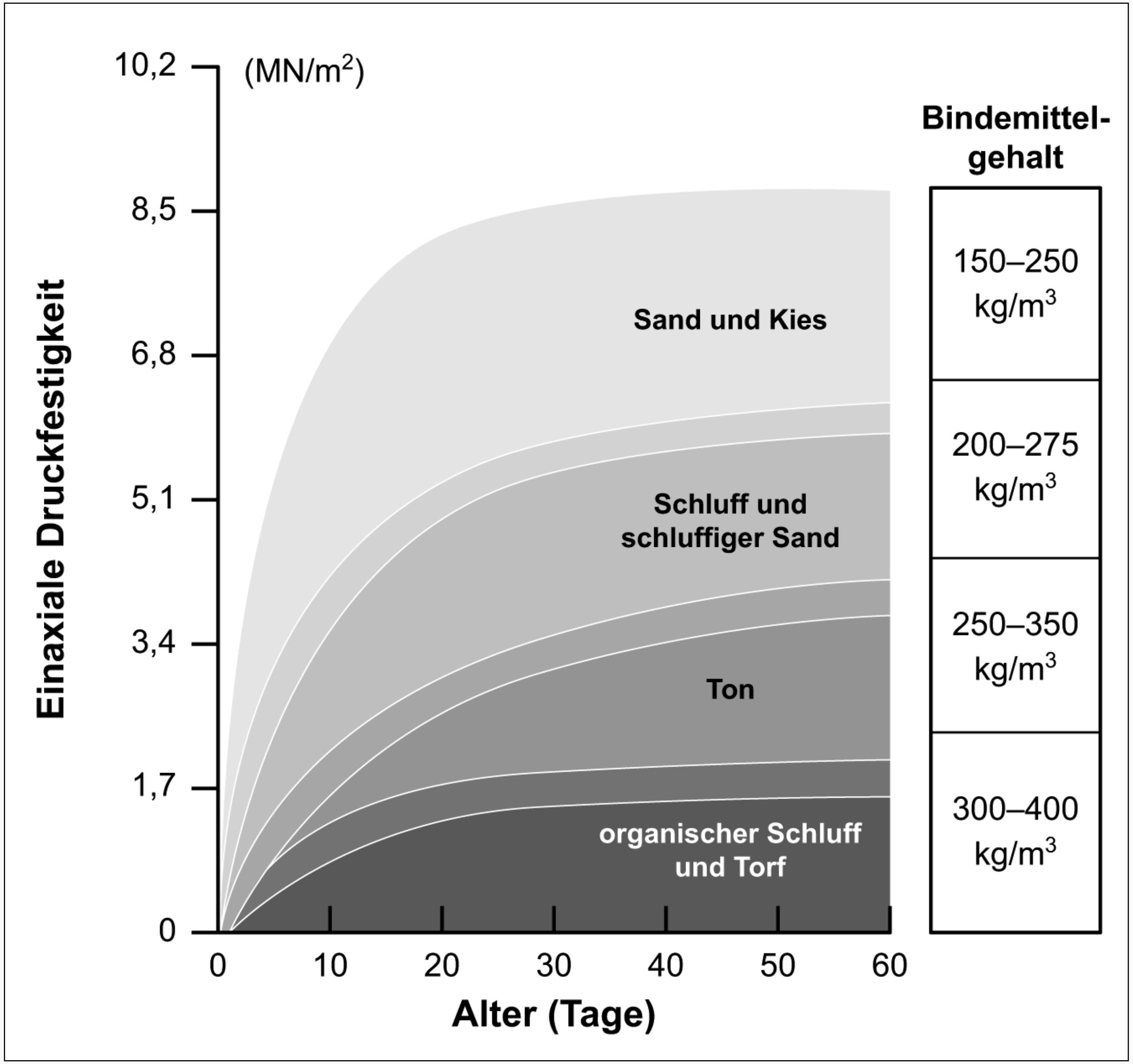
Compression strength

Compressive strenght of Soilcrete®

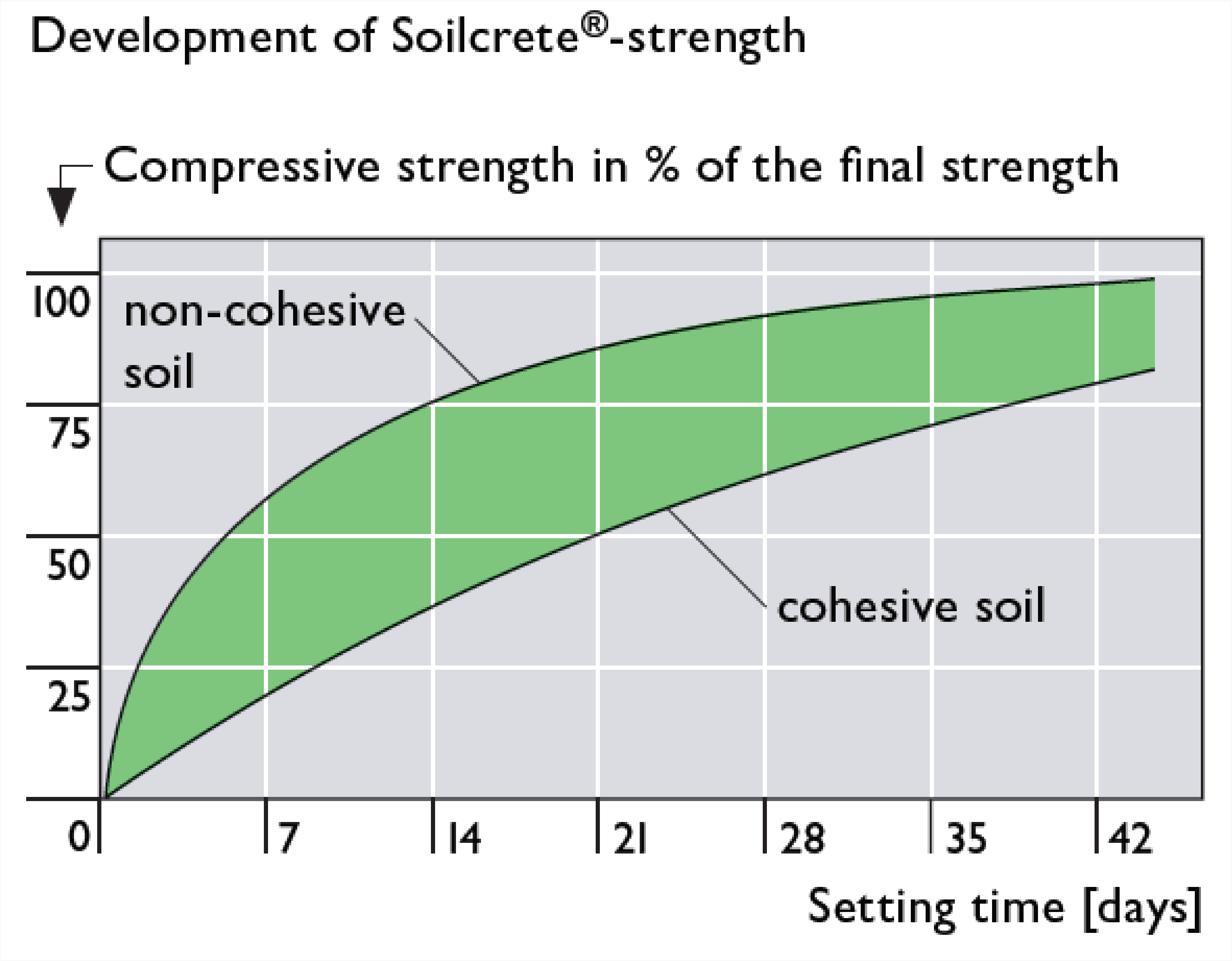


Type of soil	Silt	Sand	Gravel
Compressive strength [N/mm²]	≤ 5	≤ 10	< 25

Strength of jet grouted soil mortar



Strength as function of soil and age



EC specifications

For example: Italian regulations

The strength of the jet grouted material is generally represented by uniaxial compressive strength. However, in particular cases it may be appropriate to adopt the Mohr-Coulomb failure criterion, assessing the shear strength parameters by means of laboratory tests.

If direct experimental data are missing, the **design value of the uniaxial compressive strength** can be estimated from correlations available in literature. This value must be then verified by experimental measurements conducted in field trials.

For example: Italian regulations

MECHANICAL PROPERTIES OF THE JET GROUTED SOIL

If experimental values are available, it is suggested to identify a characteristic value σ_k of the uniaxial compressive strength and to reduce it with a partial safety factor γ_σ :

$$\sigma_d = \frac{\sigma_k}{\gamma_\sigma}$$

	Clay	Sand	Gravel
γ_σ	1.4	1.5	1.6

When a statistically meaningful sample of experimental data is available, a log-normal probabilistic distribution can be assumed and the design value of the uniaxial compression strength can be calculated as the value corresponding to the 5% fractile of the distribution, calculated with the following expression:

$$\sigma_d = \exp\left\{\ln(\overline{\sigma}_c) - 0.5 \cdot \ln\left[1 + \left(\frac{s_{\sigma_c}}{\overline{\sigma}_c}\right)^2\right] - 1.65 \cdot \sqrt{\ln\left[1 + \left(\frac{s_{\sigma_c}}{\overline{\sigma}_c}\right)^2\right]}\right\}$$

EC specifications

For example: German regulations

Resistance (1)

The characterising value ot strength is the cylindrical uniaxial strength f_m tested with h/d = 2; this strength is the base to determine resistance values of normal stress and shear stress

During design the necessary characteristic strength $f_{m,k}$ is assessed

- ... *acceptability tests before ececution of work*
- *control tests during execution*

One test contains at least 4 single samples with its cylindrical uniaxial strength tested

It has to be shown:

minimum criterion: $f_{m,min} \geq f_{m,k}$

mean value criterion: $\alpha \cdot f_{m,mean} \geq f_{m,k}$

$\alpha = 0{,}6$ with $f_{m,k} \leq 4$ N/mm²
interpolate to
$\alpha = 0{,}75$ with $f_{m,k} = 12$ N/mm²

EC specifications

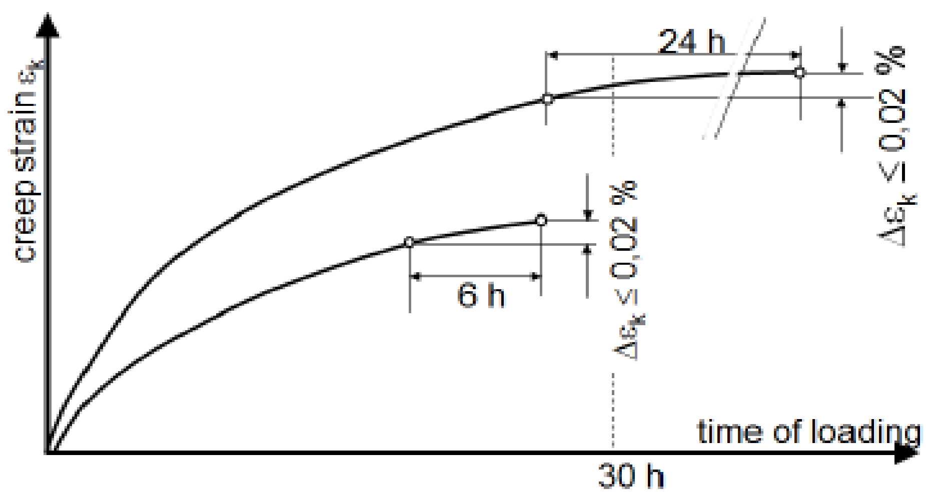
For example: German regulations

Resistance (2)

For jet grouting or deep mixing cubatures in clay and with low strength values of $f_{m,mean}$ < 4 N/mm² creep behaviour has to be investigated.

creep behaviour has always to be investigated for silica grout cubatures

creep criteria to be fulfilled at 50 % of $f_{m,k}$



Quality Control – Strength / Filtration Ratio

quantity and dimentions of cement grout samples	average (standard deviation) meassured compression strength after 28 days [MPa]	min. assumed compression strength after 28 days [MPa]	ANCHORED SOILCRETE SLAB
162 cubic samples 15 x 15 x 15 cm	7,85 (2,11)	5,00	
quantity and dimentions of cement grout samples	average meassured filtration ratio after 28 days [m/s]	min. assumed substitute filtration ratio after 28 days [m/s]	
52 cylindrical samples Ø100mm x 15cm	$0{,}245 \cdot 10^{-7}$	$k \leq 4{,}0 \cdot 10^{-7}$	

quantity and dimentions of cement grout samples	average (standard deviation) meassured compression strength after 28 days [MPa]	min. assumed compression strength after 28 days [MPa]	GRAVITATIONAL SOILCRETE SLAB
64 cubic samples 15 x 15 x 15 cm	4,79 (2,25)	1,00	
quantity and dimentions of cement grout samples	average meassured filtration ratio after 28 days [m/s]	min. assumed substitute filtration ratio after 28 days [m/s]	
40 cylindrical samples Ø100mm x 15cm	$0{,}264 \cdot 10^{-7}$	$k \leq 4{,}0 \cdot 10^{-7}$	

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IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Design issues for jet grouted structures

A. Flora, Università di Napoli Frederico II, Italy

DESIGN ISSUES FOR JET GROUTED STRUCTURES

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PRESENTATION OUTLINE

1. Jet grouting technology and columns characteristics

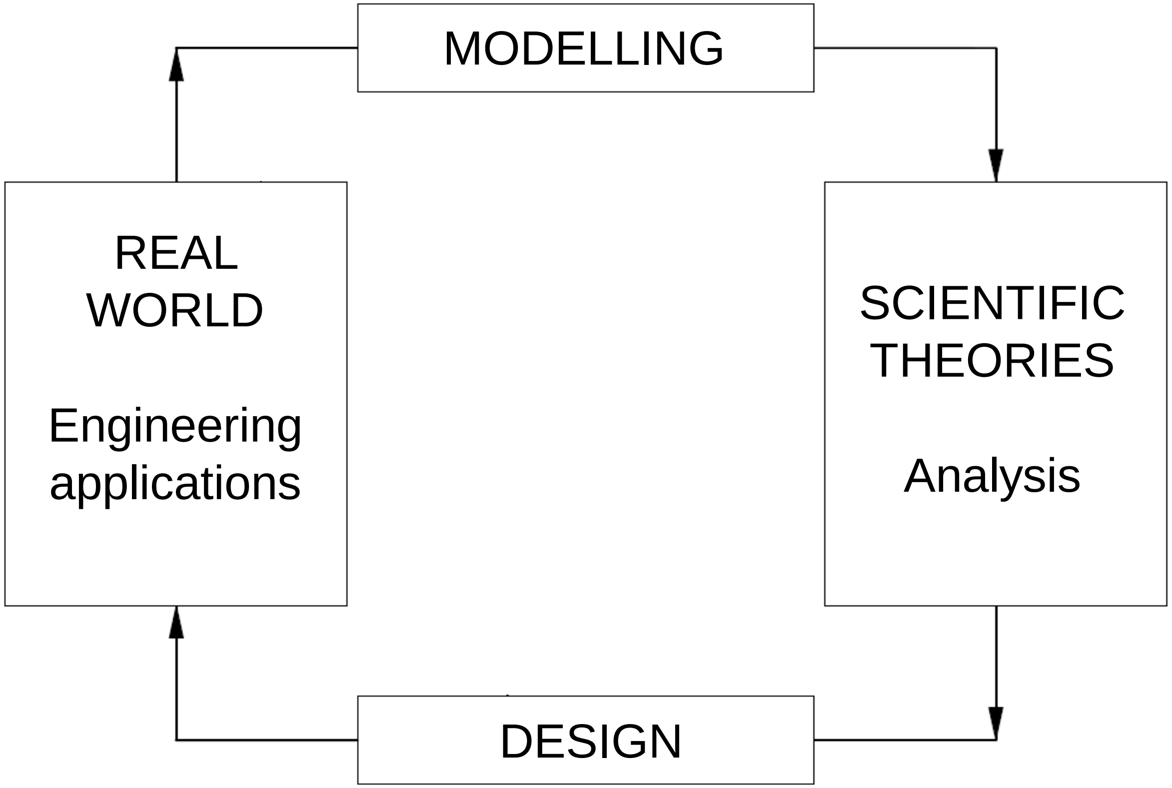
2. Design strategy

3. An example

4. Conclusions

ENGINEERING DESIGN

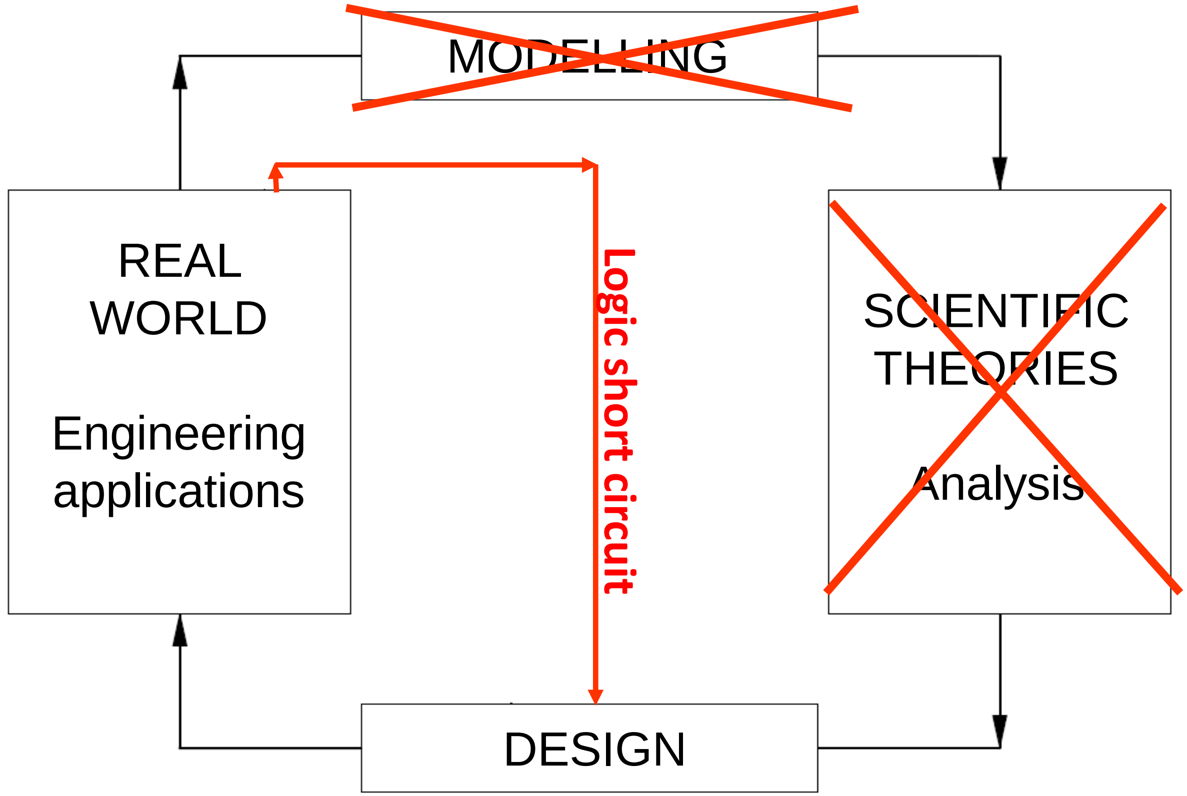
Should be always based on the scientific method



ENGINEERING DESIGN

Should be always based on the scientific method
What about ground improvement techniques?

Sometimes…



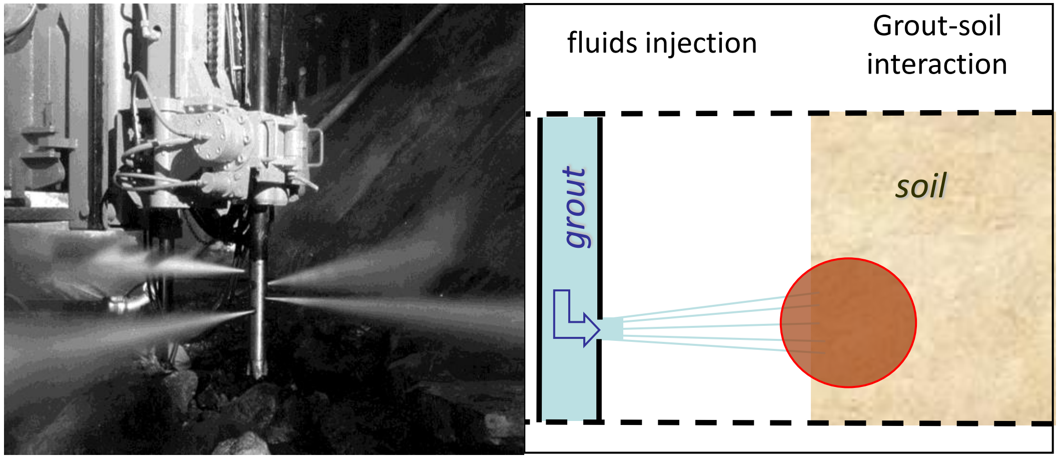
often a grey area in design!

JET GROUTING: THE TECHNOLOGY

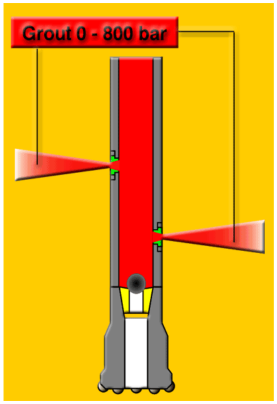
High velocity soil erosion and cementation system.

Large or very large columns formed from small holes.

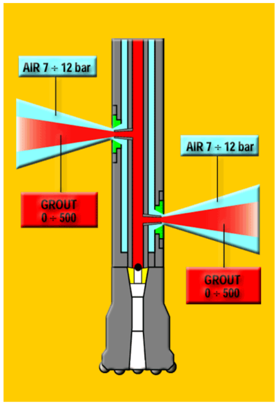
Often convenient alternative to more traditional techniques



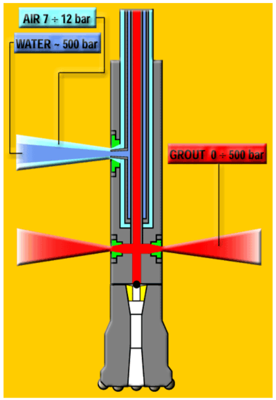
Single fluid



Double fluid



Triple fluid



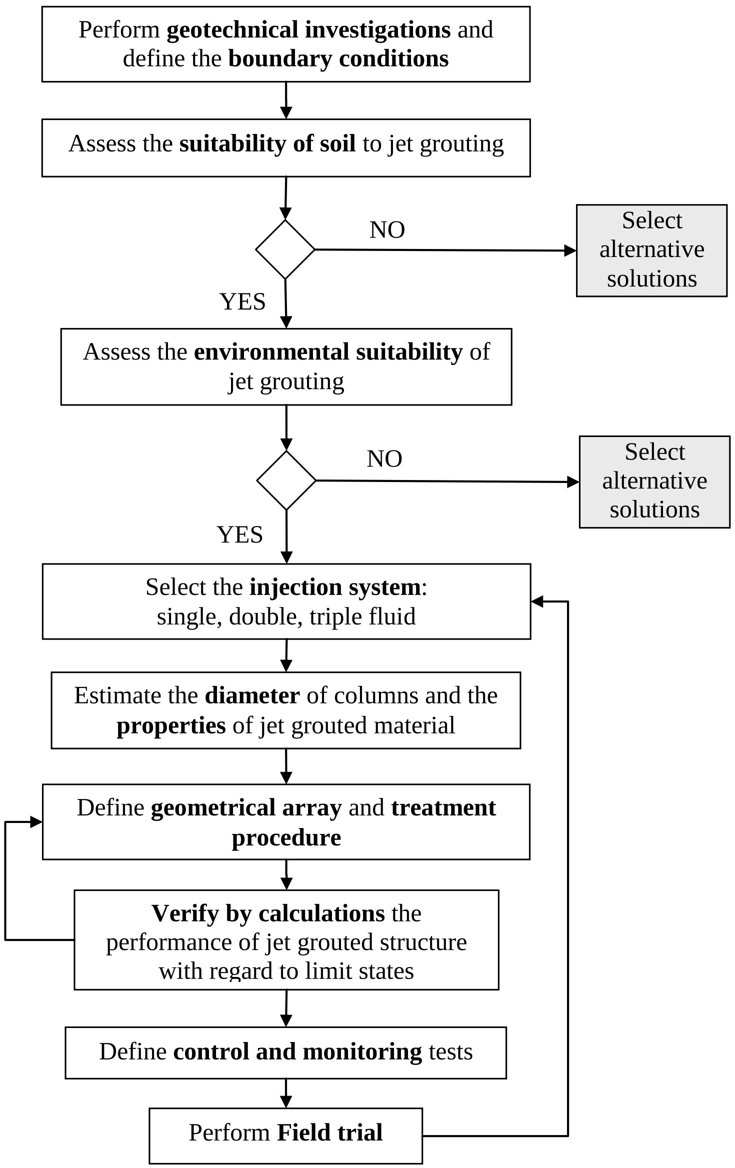
+ …. evolutions ….

DESIGN OF JET GROUTED STRUCTURES

The design of jet grouted structures should go through all the steps usually adopted in civil engineering design.

There are steps to be added to the usual design process, strictly related to the quantification of the technological effects. These steps are:

- the choice of the **jet grouting procedure**;
- the quantification of **treatment parameters**;
- the prediction of **dimensions** and **mechanical properties** of the jet grouted columns;
- the analysis of possible **undesired collateral effects** on the surrounding constructions and on the environment.



DESIGN OF JET GROUTED STRUCTURES

SINGLE COLUMN:
- Diameter
- Position of column axis
- Mechanical properties of improved soil

GROUP OF COLUMNS:
- Performance

→

ISSUES TO BE FACED
- Variability
- Ability to predict
- Ability to control the outcome

The first key step is the **design of the single column**. For all the variables (diameter, position of axis, mechanical properties), it is essential to know:

- Mean value
- Possible variability
- Nature of variability (systematic or random)
- Statistical distributions of random variables

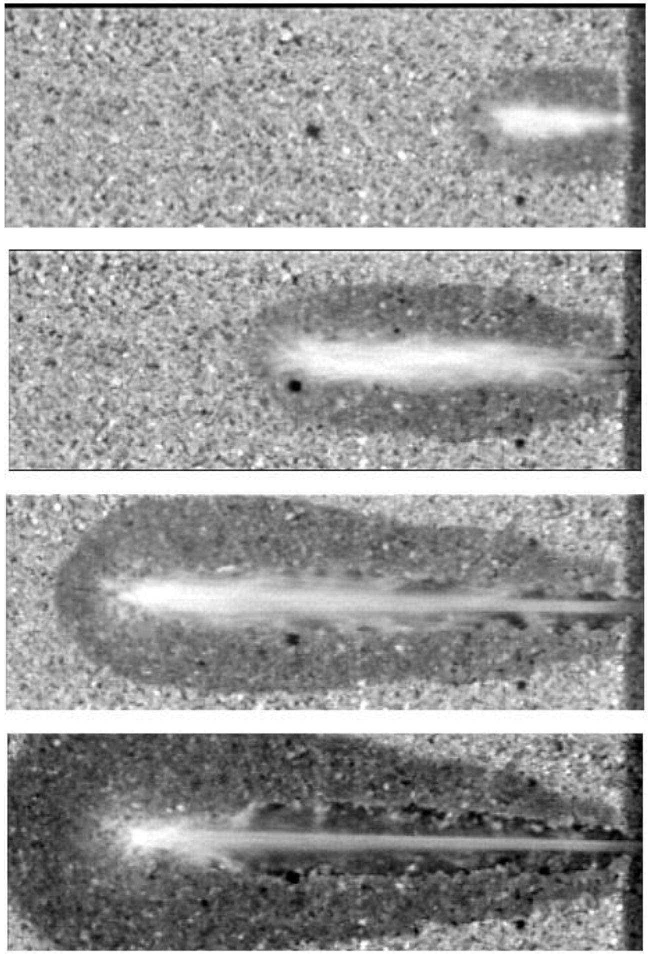
DESIGN OF JET GROUTED COLUMNS

Prediction of mean diameter

The soil is eroded, remoulded and permeated by the jet.
The column diameter is the outcome of jet-soil interaction

The distance to which the jet is able to interact with the soil depends on:

- **Jet characteristics** (type of fluid, shrouding fluid, diameter and number of nozzles, injection parameters)
- **Soil characteristics** (shear strength, permeability)



Sequence of frames taken during high speed injection in a sandy soil (after Bergscheider, 2002).

MEAN DIAMETER OF JET GROUTED COLUMNS

D_{mean} is directly proportional to the jet erosive capacity, expressed via the specific jet energy E'(x), and inversely proportional to soil resistance to erosion (S). Formally, the following relation must therefore hold:

(1) $$D_{mean} \propto E'(x)^{\beta} \cdot S^{\delta}$$

Eq. (1) must hold also for a reference column diameter D_{ref}, obtained using a reference specific kinetic energy E'_{ref} (x) in a soil having a reference resistance to the erosive capacity S_{ref}. Considering β and δ constant, it can be therefore written:

(2.a) $$\frac{D_{mean}}{D_{ref}} = \left(\frac{E'(x)}{E'_{ref}(x)}\right)^{\beta} \cdot \left(\frac{S}{S_{ref}}\right)^{\delta}$$

(2.b) $$D_{mean} = D_{ref}\left(\frac{E'(x)}{E'_{ref}(x)}\right)^{\beta} \cdot \left(\frac{S}{S_{ref}}\right)^{\delta}$$

In order to use eqs. (2), it is necessary:

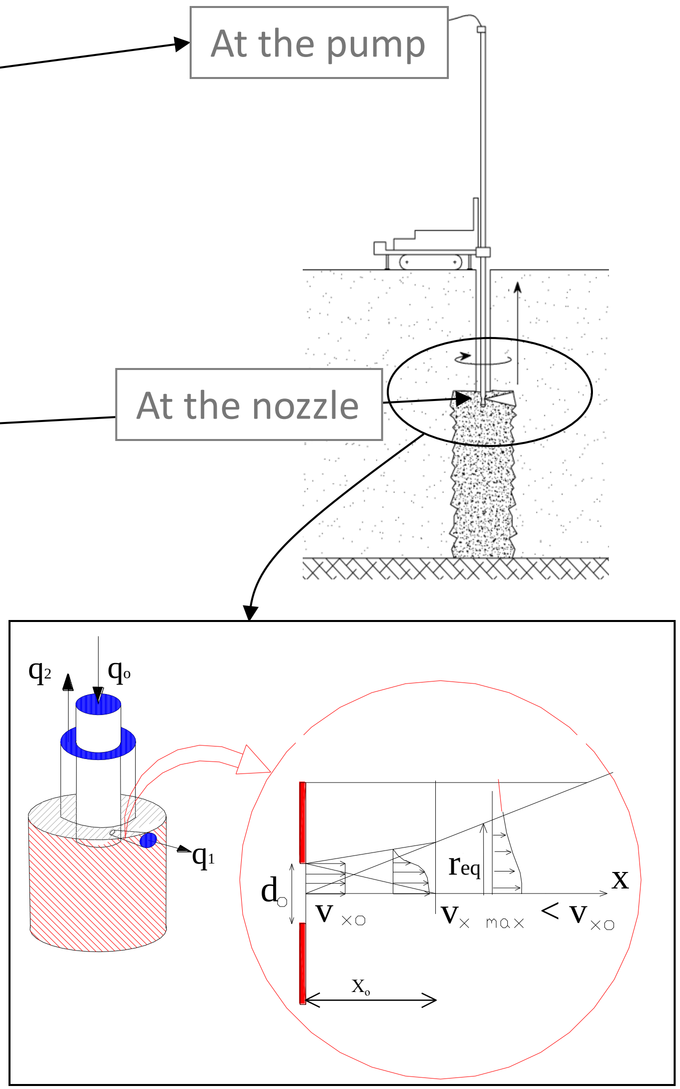
- to find an expression for E'(x)
- to choose an expression for S
- to calibrate D_{ref}, β, δ on experimental data

MEAN DIAMETER OF JET GROUTED COLUMNS

Jet characteristics: Specific treatment energy [MJ/m]

(3) $$E'_p = \frac{p \cdot Q}{v}$$

(4) $$E'_n = \frac{1}{2}\frac{m \cdot v_0^2}{L} = \frac{\pi}{8} \cdot \frac{M \cdot \rho \cdot d_0^{\ 2} \cdot v_0^{\ 3}}{v}$$



where:

p = fluid pressure

Q = fluid flow

v = mean uplift velocity of the monitor

m = fluid mass ($m = \frac{\pi}{4} \cdot \frac{M \cdot d^2 \rho \cdot v_o}{v_r}$)

v_0 = outflow fluid velocity at the nozzle

ρ = fluid density

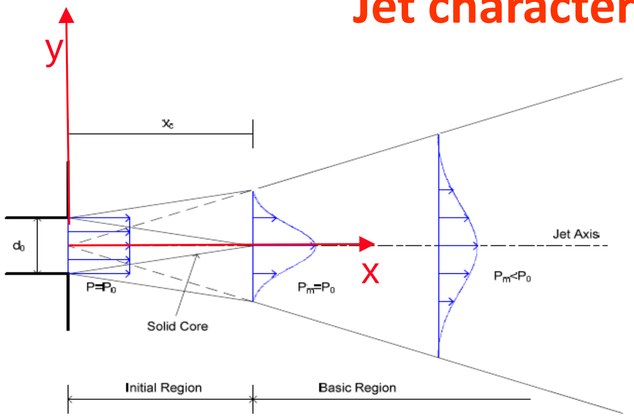
L = length of treatment

d = diameter of nozzle

M = number of nozzles

MEAN DIAMETER OF JET GROUTED COLUMNS

Jet characteristics: Specific treatment energy [MJ/m]



Eqs. (3) and (4) are not fully satisfactory.

The kinetic energy E(x) at any generic distance x from the nozzle can be calculated as the integral in time of the hydrodynamic power (Flora et al., 2013):

$$E(x) = M \cdot \int_{\Delta t} W(x) \cdot dt = \frac{\pi \cdot M \cdot \Lambda \cdot \rho \cdot d^3 \cdot v_o{}^3 \cdot L}{13.3 \cdot x \cdot v_r}$$

The specific energy per unit length of column available at a distance x from the nozzle (E'(x)=E(x)/L) can be conveniently expressed as a function of the specific energy at the nozzle (eq. 4) as:

(5.a) $$E'(x) = 0.6 \cdot \Lambda \frac{d}{x} \cdot E'_n$$

Since $E'_n \propto E'_p$ (most times, E'n ≈ 0.9 E'p), it can be also expressed as a function of the energy at the pump :

(5.b) $$E'(x) = 0.54 \cdot \Lambda \frac{d}{x} \cdot E'_p$$

MEAN DIAMETER OF JET GROUTED COLUMNS

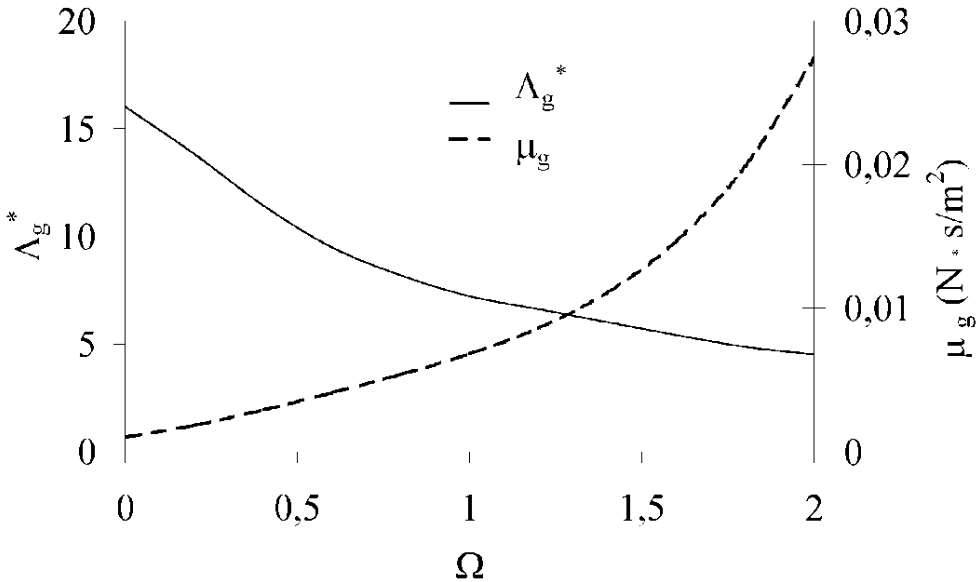
Jet characteristics: Specific treatment energy [MJ/m]

The hydrodynamic parameter Λ depends on the properties of the fluid of the jet and of the surrounding fluid. It can be conveniently expressed as:

(6) $$\Lambda = \alpha_E \cdot \Lambda^*$$

In which Λ^* is the hydrodynamic parameter for a submerged jet (i.e. the fluid surrounding the jet is water) and α_E is introduced to account for different boundary conditions (jet in air). For a grout with a given cement-water ratio by weight Ω, it can be expressed as:

$$\Lambda_g^* = \Lambda_w^* \cdot \sqrt{\frac{\mu_w}{\mu_g} \cdot \frac{\rho_g}{\rho_w}}$$



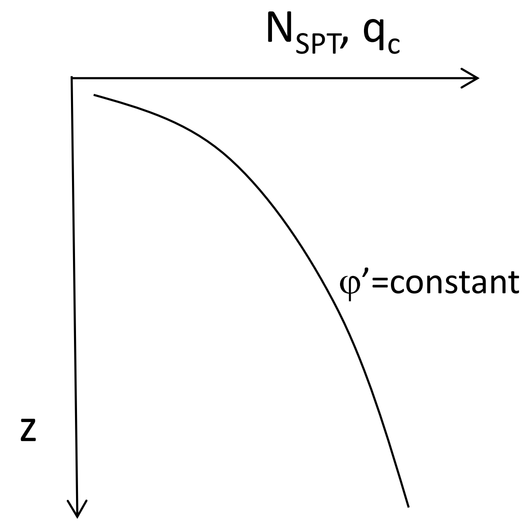
MEAN DIAMETER OF JET GROUTED COLUMNS

Soil characteristics

Soil resistance to erosion S can be simply related to its shear strength, expressed considering the results of popular geotechnical in situ tests (namely SPT and CPT, having as results respectively the blow count N_{SPT} and the tip penetration resistance q_c).

(7.a) $$\frac{S}{S_{ref}} = \frac{N_{SPT}}{N_{SPT\,ref}}$$ *for coarse grained soils*

(7.a) $$\frac{S}{S_{ref}} = \frac{q_c}{q_{c\,ref}}$$ *for fine grained soils*



MEAN DIAMETER OF JET GROUTED COLUMNS

Then, the mean diameter can be calculated combining eqs. (2, 5, 7) (Flora et al., 2013):

(8.a) $$D_{mean} = D_{ref} \cdot \left(\frac{\alpha_E \cdot \Lambda^* \cdot E'_n}{7.5 \cdot 10} \right)^{0.2} \cdot \left(\frac{q_c}{1.5} \right)^{-0.25}$$

For fine grained soil (E'_n in MJ/m and q_c in MPa)

(8.b) $$D_{mean} = D_{ref} \cdot \left(\frac{\alpha_E \cdot \Lambda^* \cdot E'_n}{7.5 \cdot 10} \right)^{0.2} \cdot \left(\frac{N_{SPT}}{10} \right)^{-0.25}$$

For coarse grained soils (E'_n in MJ/m)

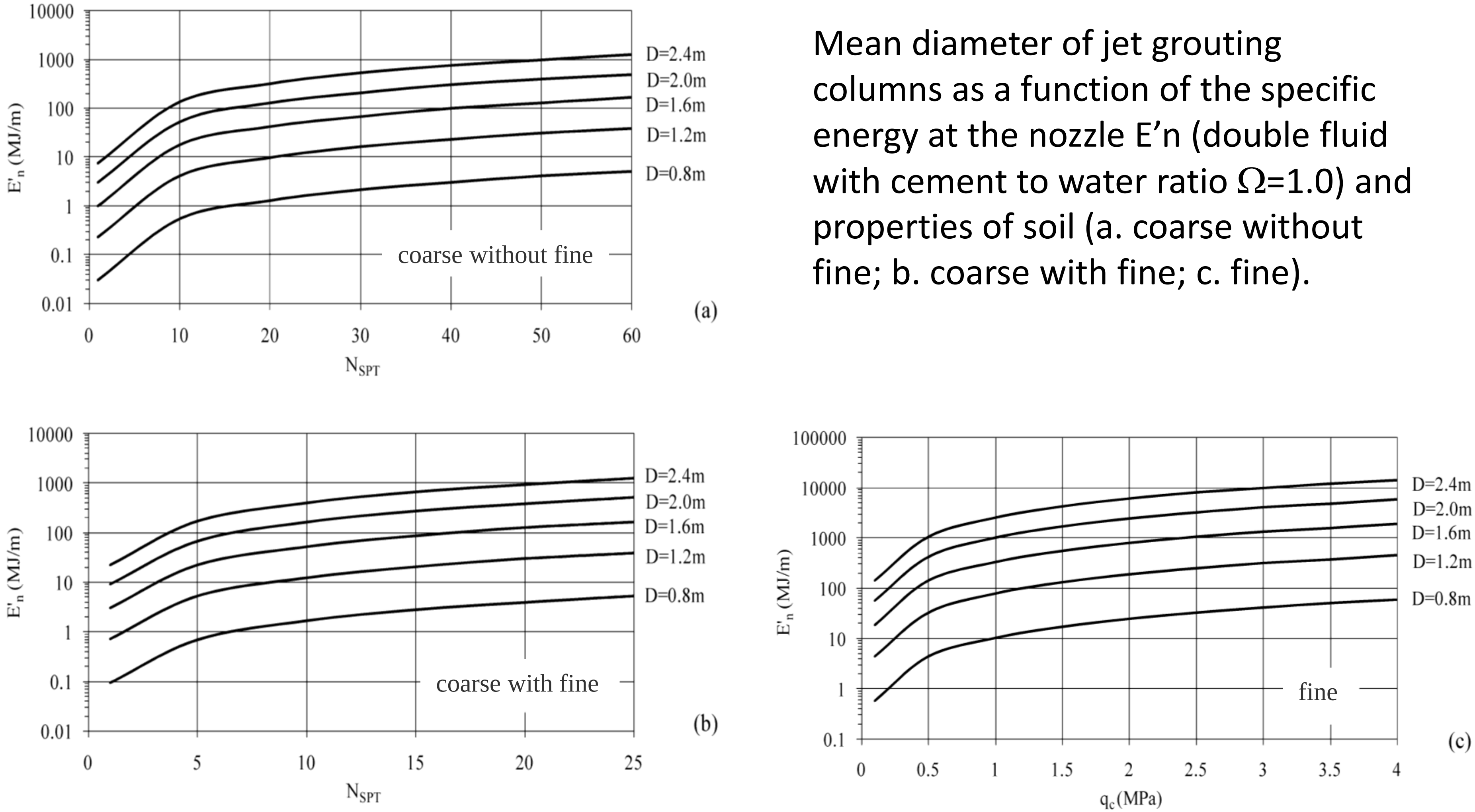
Eqs. (8.a) and (8.b) have been written assuming

- $\Lambda^*_{ref=}$7.5 (for a cement to water ratio by weight Ω=1)
- α_{ref}=1
- $E'_{n,ref}$=10 MJ/m
- $q_{c,ref}$=1.5 MPa, $N_{SPT,ref}$=10

All the parameters of eqs. (8) have been calibrated on a large number of field trials data

Soil type		ASTM D2487 classification	D_{ref} (m)	α_E single fluid	α_E double and triple fluid
Coarse grained	without fine	Gravels and sands with less than 5% fines	1.00	1	6
	with fine	Gravels and sands with more than 5% fines	0.80		
Fine grained		Silts, clay and organic soils	0.50		

MEAN DIAMETER OF JET GROUTED COLUMNS



Mean diameter of jet grouting columns as a function of the specific energy at the nozzle E'n (double fluid with cement to water ratio Ω=1.0) and properties of soil (a. coarse without fine; b. coarse with fine; c. fine).

UNCERTAINTIES AND DEFECTS

Defects can be either systematic or random.
Their nature must be known to be correctly taken into account

POSSIBLE REASONS OF DEFECTS:

- Machine positioning
- Treatment parameters
- Jetting procedure

} **Can be relatively easily taken care of**

- Variability of diameter
- Axis deviation
- Variability of mechanical properties

} **Difficult to control. Mostly unavoidable**

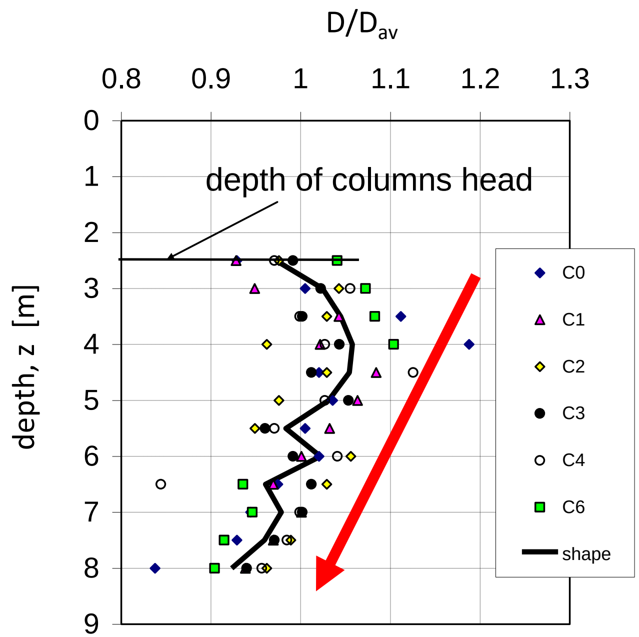
VARIABILITY OF DIAMETER

SYSTEMATIC VARIABILITY:

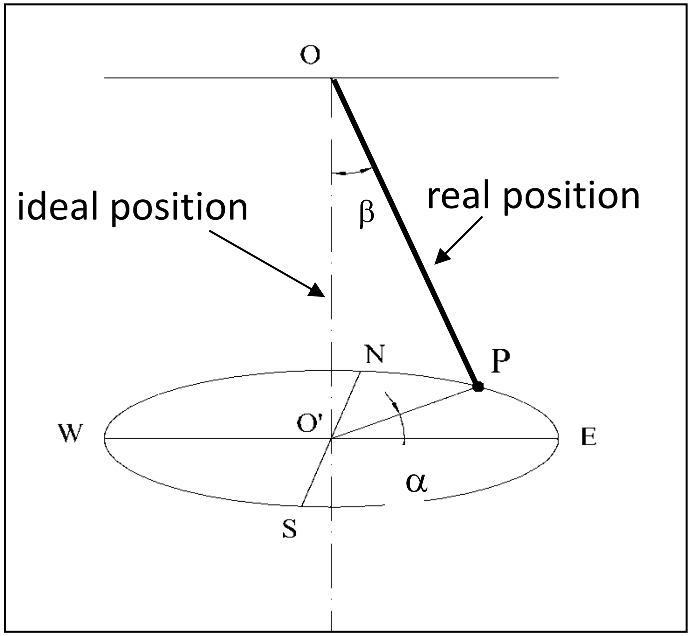
- Reduction of D with depth
- Variation of D with soil properties

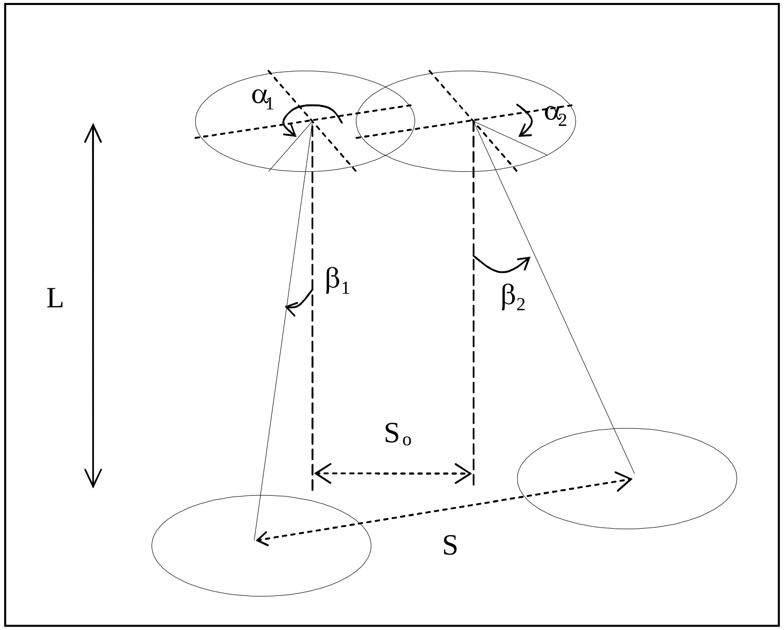
RANDOM VARIABILITY:

- Variation of D in a given soil regardless of depth



VARIABILITY OF THE POSITION OF THE COLUMN





β: angle of deviation from ideal axis position (inclination)

α: azimuth of axis position

Most critical when partial overlapping of adjacent columns is required

STATISTICAL PARAMETERS OF INTEREST

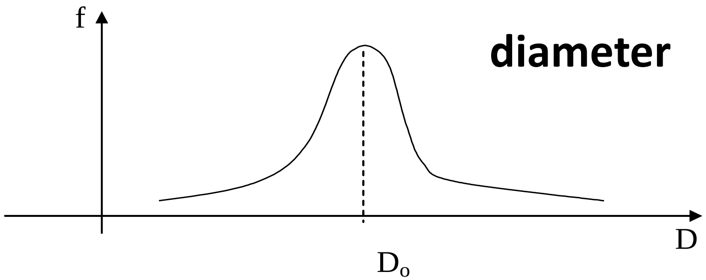
$\mu_x = \frac{1}{n}\sum_{i=1}^{n} x_i$	Mean value	[physical dimensions of x]
$Var(X) = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu_x)^2$	Variance	[physical dimensions of x^2]
$\sigma_x = SD(x) = \sqrt{Var(X)}$	Standard Deviation	[physical dimensions of x]
$\delta_x = CV(X) = \frac{\sigma_x}{\mu_x}$	Coefficient of variation	[dimensionless]

UNCERTAINTIES AND DEFECTS: WHAT DO WE KNOW?

Field data have suggested possible distributions of the random variables

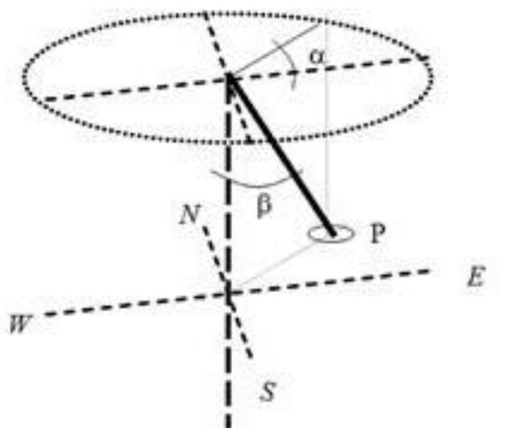
COLUMNS DIMENSIONS:

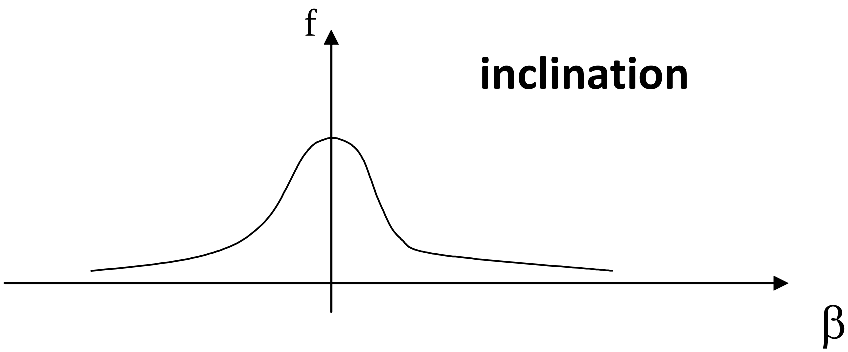
- Diameter: **normal distribution**

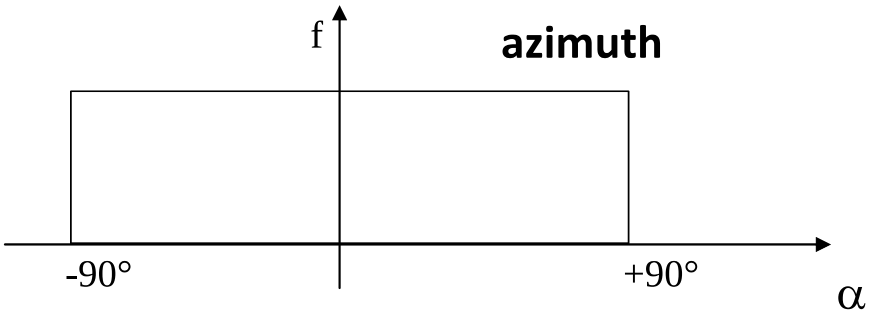


COLUMNS AXIS POSITION:

- Inclination β: **normal distribution**
- Azimuth α: **uniform distribution**





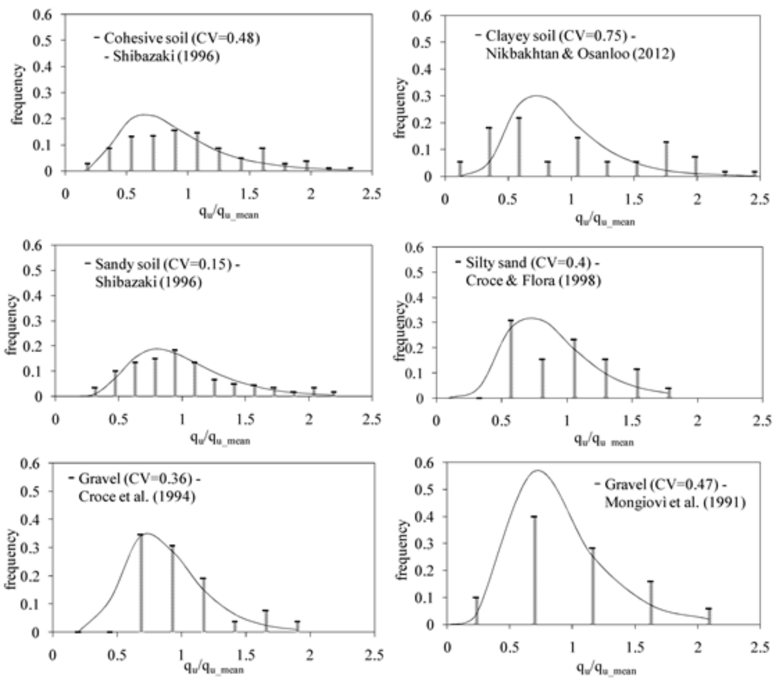


UNCERTAINTIES AND DEFECTS: WHAT DO WE KNOW?

Field data have suggested possible distributions of the random variables

MECHANICAL PROPERTIES:

- Uniaxial compressive strength (σ_c)
- Cohesion and friction angle (c, φ)



Log-normal distribution

Given a mean μ and a standard deviation SD of the values measured on specimens, the mean and standard deviation of the values pertaining to columns are:

$$\mu(\text{column}) = \mu(\text{specimens})$$

$$\text{SD}(\text{column}) = \frac{1}{\sqrt{a}}\,\text{SD}(\text{specimen})$$

a: ratio between the area of the cross section of the column and that of the tested specimen.

Considering the typical diameters of jet grouting columns (say from 1 m to 3 m) and of the cored specimens (from 0.08 to 0.10 m), the parameter “a” ranges from 100 to 1500.

The variability of the mechanical properties of a column is much smaller (from 1/10 to about 1/40) than that of specimens taken from it.

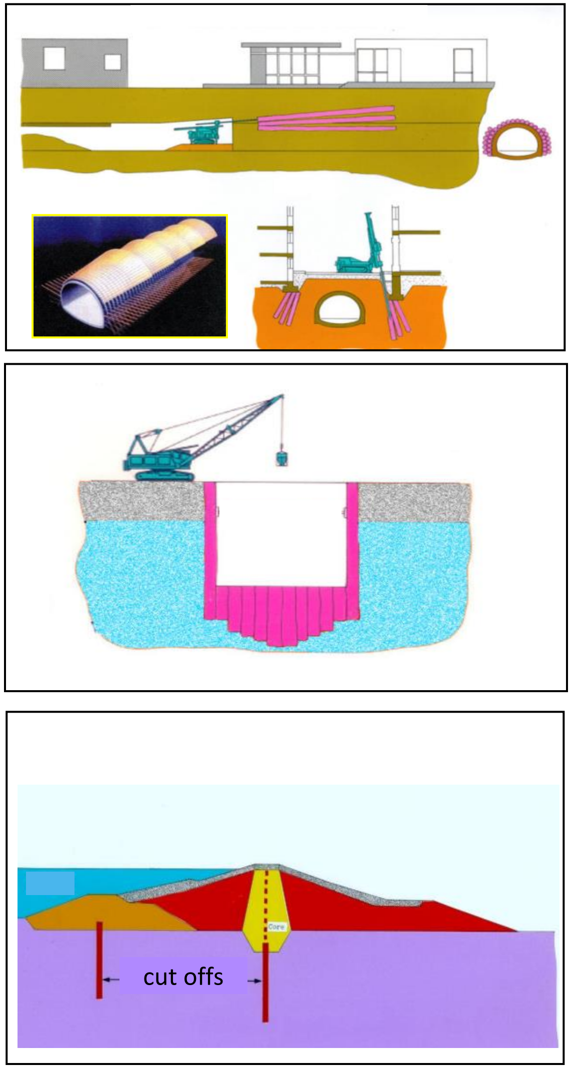
DESIGN STRATEGY FOR JET GROUTED STRUCTURES

The variability of geometrical and physical properties affect the performance of jet grouted structures and must be considered.

This can be done with two different approaches:

- **Deterministic**
- **Probabilistic (or semi probabilistic)**

Typical applications



DETERMINISTIC APPROACH

GEOMETRICAL AND MECHANICAL PROPERTIES OF COLUMNS

COLUMNS DIMENSIONS:

- Diameter

EC7: when deviations in geometrical data have a significant effect, design values of geometrical data (a_d) shall be either assessed directly (not possible in our case) or be derived from the nominal values as:

$$a_d = a_{nom} \pm \Delta a$$

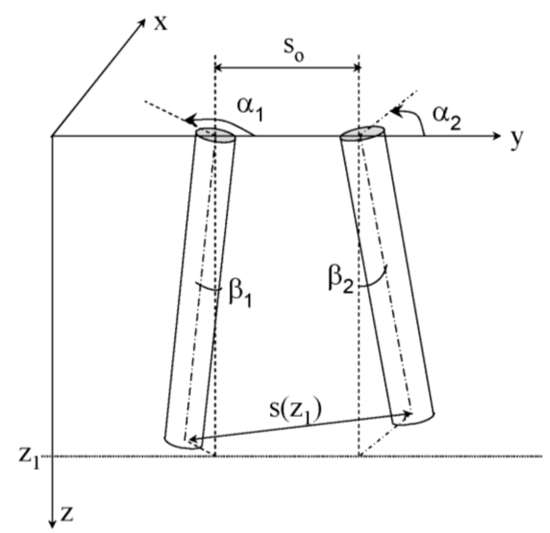
$$D_d = \frac{D_k}{\gamma_D}$$

COLUMNS AXIS POSITION:

- Azimuth α
- Inclination β

α_d: Least favourable (but physically realistic) choice, depending on the problem under analysis

β_d: Least favourable (but physically realistic) choice, depending on the problem under analysis



MECHANICAL PROPERTIES:

- Uniaxial compressive strength (σ_c)
- Cohesion and friction angle (c, φ)

$$\sigma_{c,d} = \frac{\sigma_k}{\gamma_\sigma}$$

DETERMINISTIC APPROACH

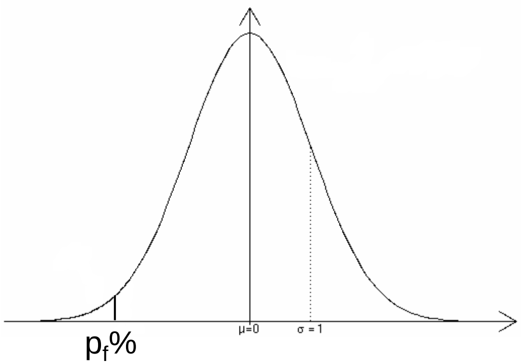
CONSIDERATIONS ON THE CHOICE OF PARTIAL FACTORS

If we assume for instance $D_k = D_{mean}$, and $\sigma_k = \sigma_{c,mean}$, the partial factors can be tuned on experimentally observed probabilistic distributions, associating them to a given probability of having more critical values

For the diameter D of the column, for instance:

$$D_d = \frac{D_k}{\gamma_D} \qquad D_d(p_f\%) = D_{mean} \cdot (1 - g(n) \cdot CV(D))$$

$$\gamma_D = \frac{1}{1 - g(n) \cdot CV(D)}$$



Where g(n) takes into account the number of available data n:

$$g(n) = \left(b(p_f\%)\sqrt{\frac{1}{n}+1} \right)$$

$b(p_f\%)$ is the value of g(n) for $n=\infty$ → $b(5\%)=1.645$

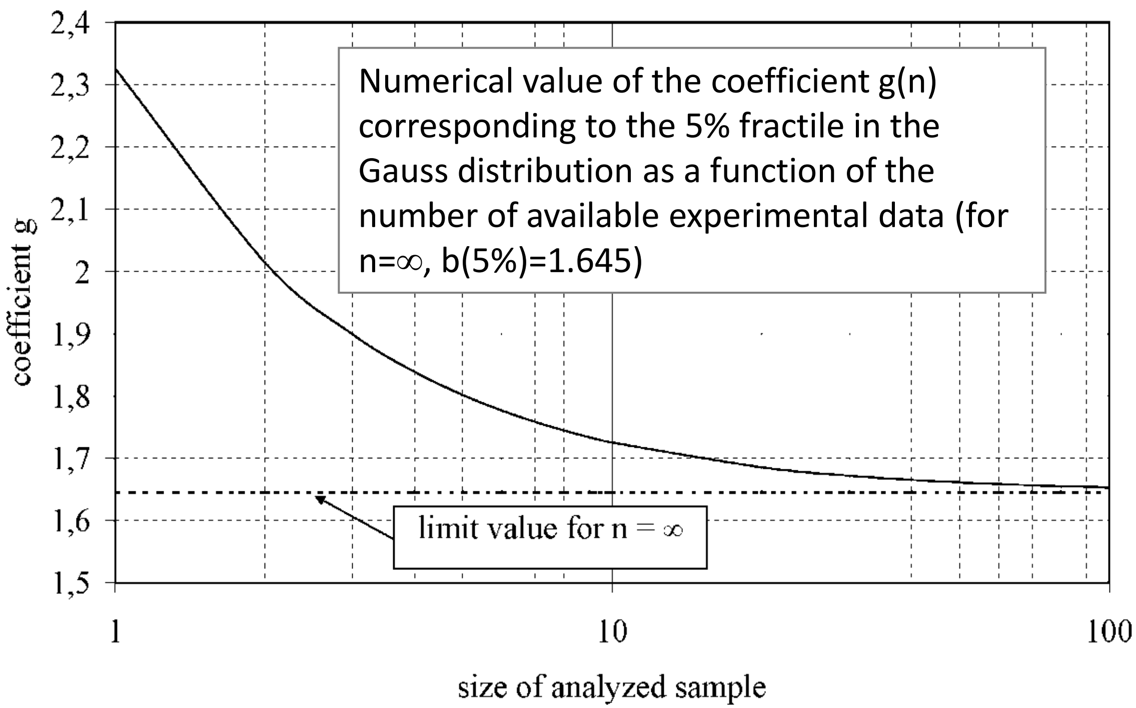
DETERMINISTIC APPROACH

CONSIDERATIONS ON THE CHOICE OF PARTIAL FACTORS

$$\gamma_D = \frac{1}{1 - g(n) \cdot CV(D)}$$

$$g(n) = \left(b(p_f\%) \sqrt{\frac{1}{n} + 1} \right)$$

The number n of available experimental data largely affects the uncertainty



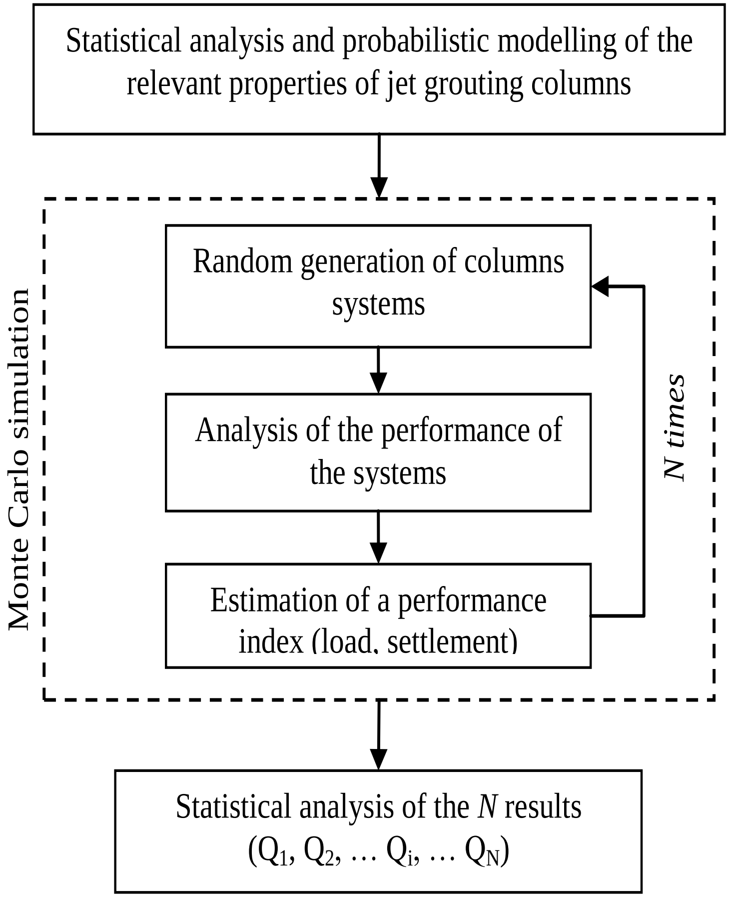
Experimental information on the scatter of diameters (Croce, Flora and Modoni, 2013)

	Soil heterogeneity		
	low	medium	high
CV(D)	0.02-0.05	0.05-0.10	0.10-0.20

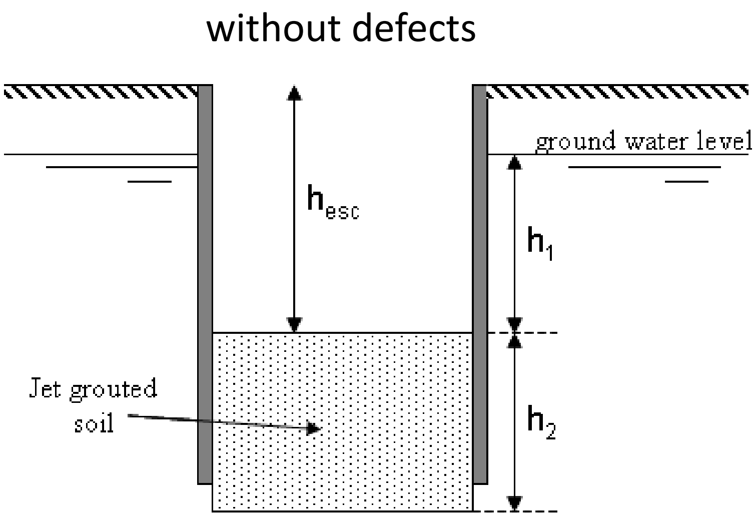
PROBABILISTIC APPROACH

Monte Carlo simulation technique

1. Define the random variables (D, α, β)
2. Quantify their statistical characteristics
3. Generate the values of the random variables
4. Evaluate the problem deterministically for each set of variables
5. Extract probabilistic information from N such calculations

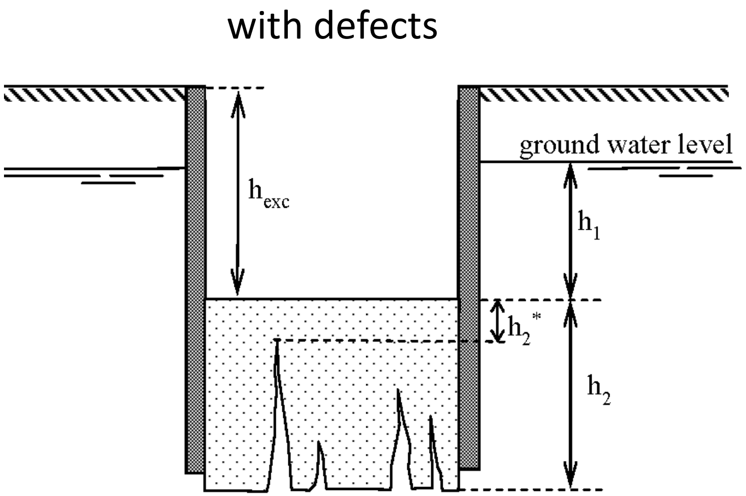


The example of jet grouted water sealing bottom plugs



USEFUL FOR:

- Water tightness
- Diaphragms propping

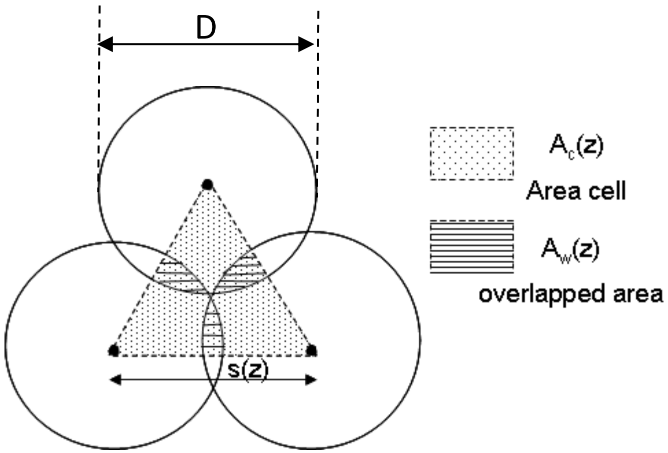


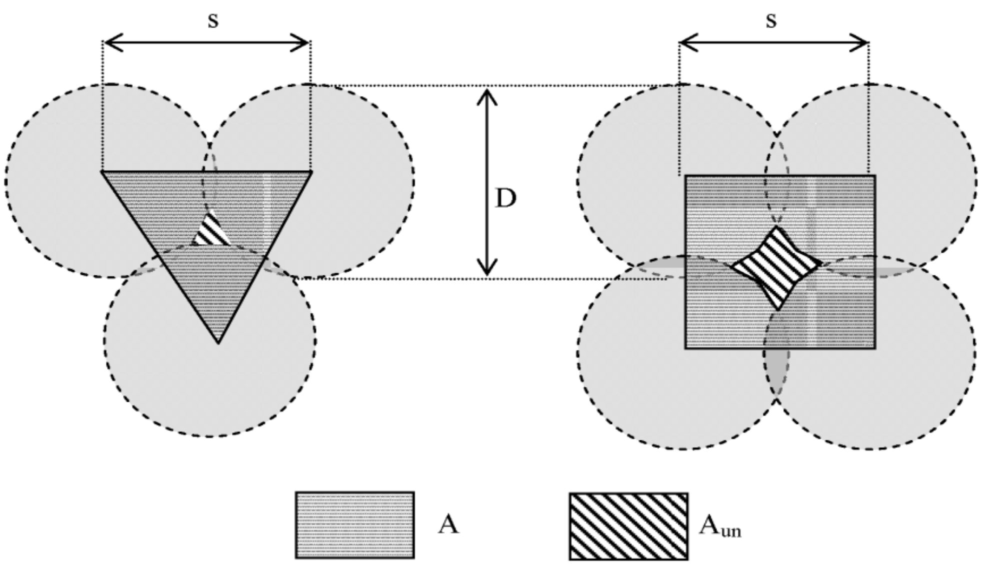
DESIGN ISSUES:

- $h_2>0$ (water tightness)
- Safety against uplift

The example of jet grouted water sealing bottom plugs

Triangular array



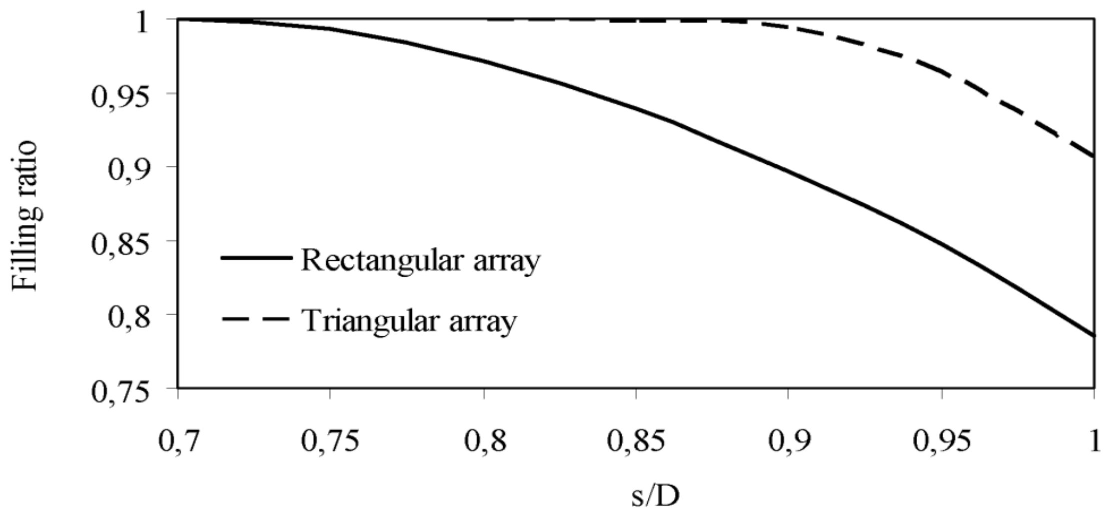


To have a fully treated cross section in ideal conditions with a triangular array:

$$s(z)_{max}=0.87 \cdot D$$

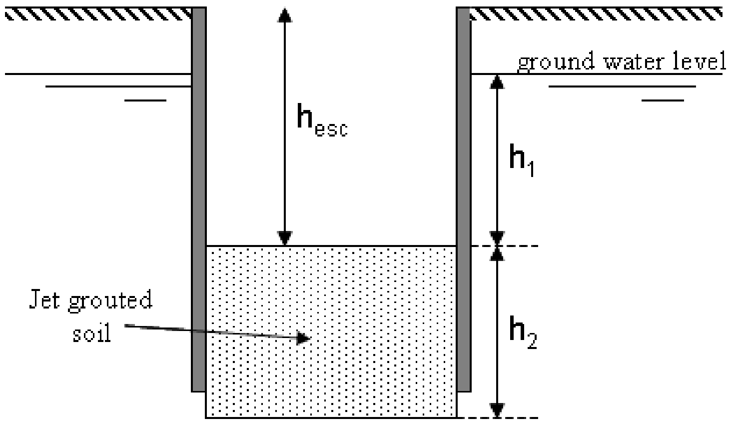
Filling ratio:

$$F(s/D)=\frac{A-A_{un}}{A}$$



The example of jet grouted water sealing bottom plugs

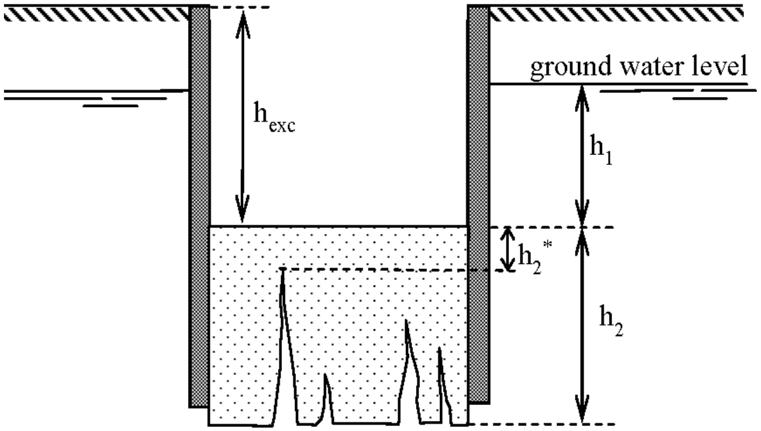
Without geometrical defects (ideal)



Stabilising action $R=\gamma_{jg}\cdot h_2$

Destabilising action $E=\gamma_w\cdot(h_1+h_2)$

With geometrical defects (possible)



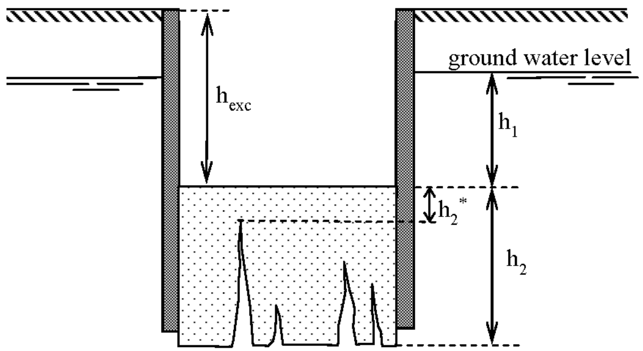
$$R = \gamma_{jg} \int_{hexc}^{hexc+h_2} F(z)\cdot dz$$

$$E = \gamma_w \left(h_1 + \int_{h_{exc}}^{hexc+h_2} F(z)\cdot dz \right)$$

Equilibrium requires for the design values E_d and R_d → $E_d \leq R_d$

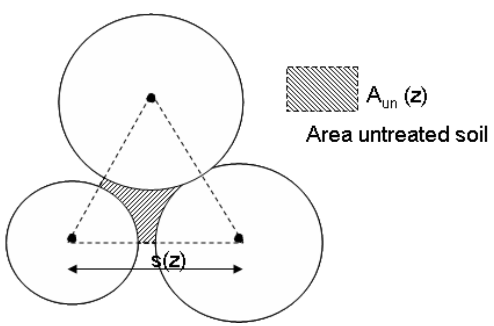
The example of jet grouted water sealing bottom plugs

Design: **deterministic approach**



$$R = \gamma_{jg} \int_{hexc}^{hexc+h_2} F(z) \cdot dz$$

$$E = \gamma_w \left(h_1 + \int_{h_{exc}}^{hexc+h_2} F(z) \cdot dz \right)$$



Steps:

- assign design values of the columns diameter D_d and inclination β_d;
- assume a minimum tolerable ratio R_d/E_d;
- assign a value of the columns spacing at ground level (s_0) and a length of the columns (h_2) able to guarantee water tightness and equilibrium of the plug

Design values of the geometrical variables:

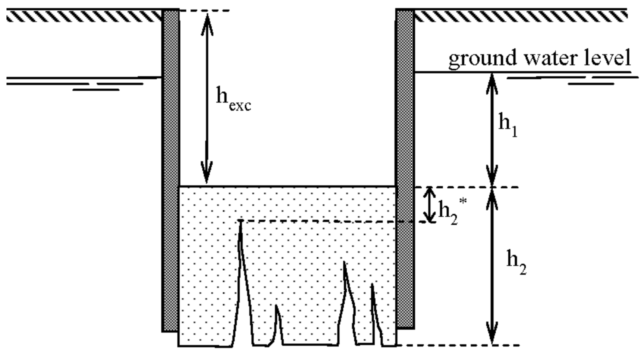
Column Diameter $D_d = \dfrac{D_k}{\gamma_D}$

Application	Available experimental information	γ_D, Soil heterogeneity		
		low	medium	high
Isolated columns, thin structures	poor	1.10	1.15	1.25
	good	1.00	1.05	1.10
Massive treatments	poor	1.05	1.10	1.20
	good	1.00	1.00	1.05

Croce, Flora & Modoni (2013)

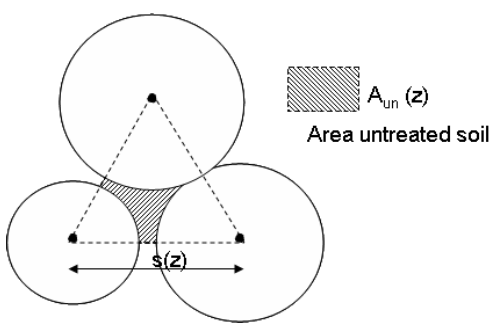
The example of jet grouted water sealing bottom plugs

Design: **deterministic approach**



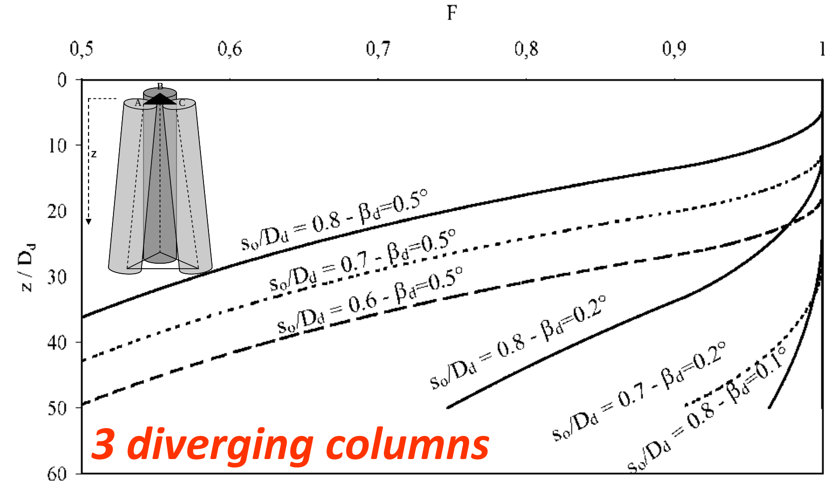
$$R = \gamma_{jg} \int_{hexc}^{hexc+h_2} F(z) \cdot dz$$

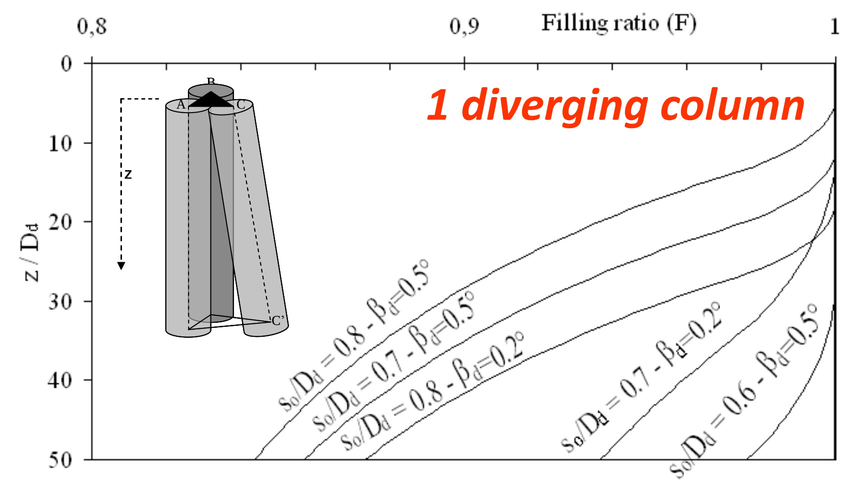
$$E = \gamma_w \left(h_1 + \int_{h_{exc}}^{hexc+h_2} F(z) \cdot dz \right)$$



Design values of the geometrical variables:

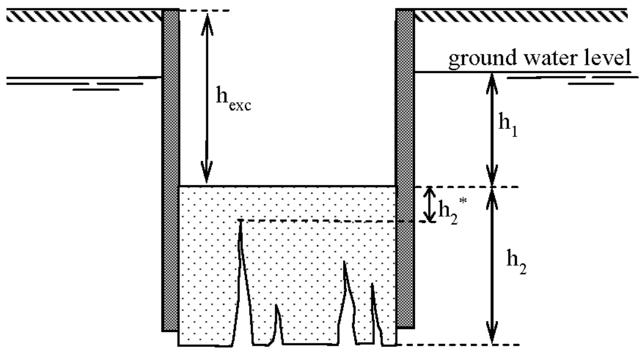
Columns inclination β, conservative assumptions. ***Two possible hypotheses are:***





The example of jet grouted water sealing bottom plugs

Design: probabilistic approach



$$R = \gamma_{jg} \int_{hexc}^{hexc+h_2} F(z) \cdot dz$$

$$E = \gamma_w \left(h_1 + \int_{h_{exc}}^{hexc+h_2} F(z) \cdot dz \right)$$

Approach	D_k	γ_D	β (°)	CV(D)	SD(β) (°)
Probab.	1.5 2 2.5	-	-	0.1 0.2	0.3
Determ.	1.5	1.2	0.3	-	-

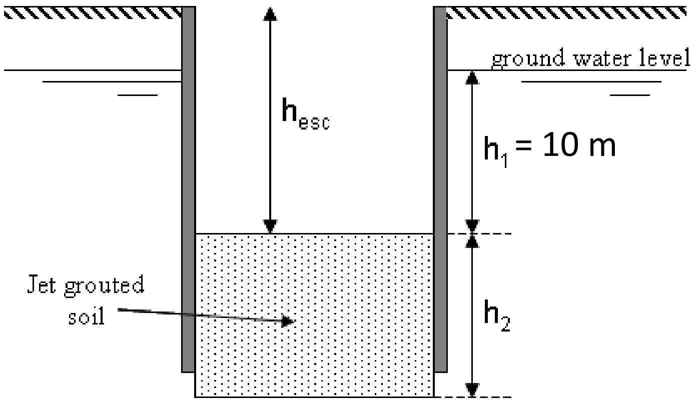
Steps:

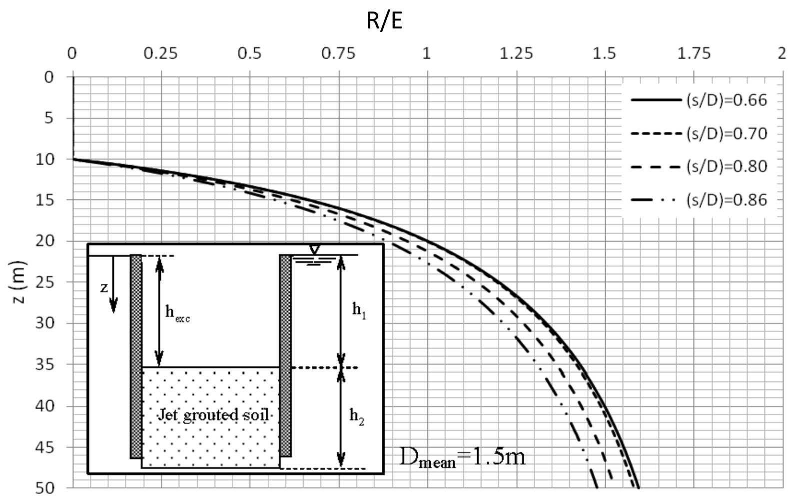
- define probabilistic distributions of statistical variables (D and β);
- assume a tentative value of the columns spacing at the ground level (s_0);
- carry out a Monte Carlo analysis, performing a large number (>1000) of simulations;
- compute the length of columns h_2 able to guarantee equilibrium for a given fractile of the obtained results (in this example, 1%).

Column characteristic		Probabilistic model	Statistical parameters
Diameter of column		Normal	Mean value, Stand. Dev.
Orientation of column	Azimuth (α)	Uniform	-
	Inclination (β)	Normal	Mean value, Stand. Dev.
Strenght/stiffness of jet grouted soil		Log-normal	Mean value, Stand. Dev.

The example of jet grouted water sealing bottom plugs

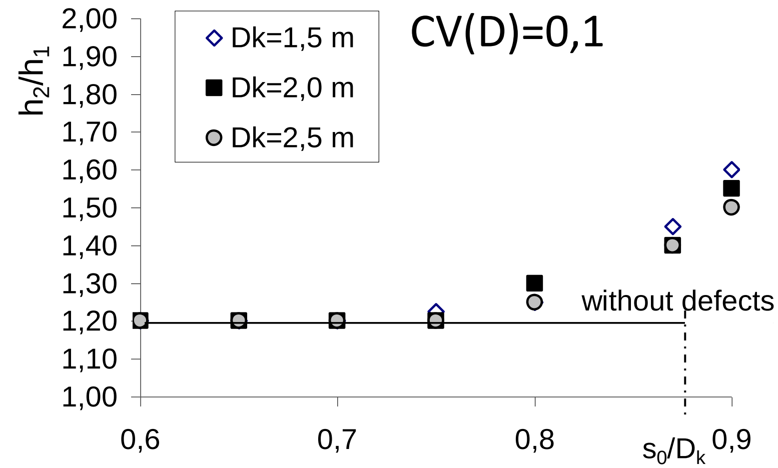
Design: **probabilistic approach**

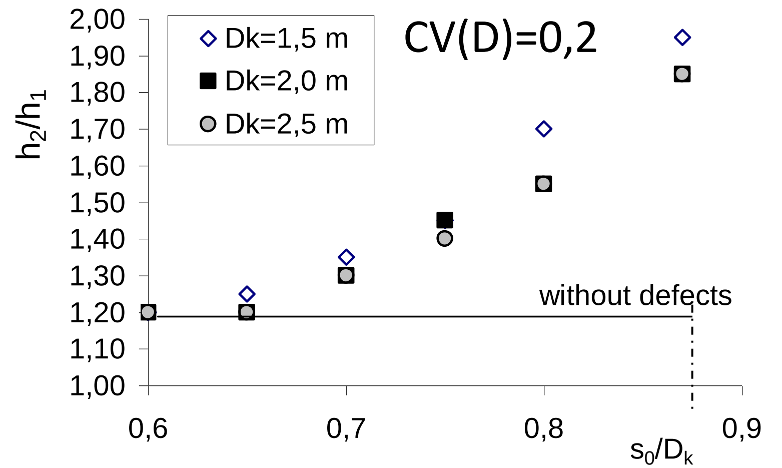




Example of results for h_1=10 m and different values of the relative spacing s/D. CV(D)=0.2; SD(b)=0.3°, probability of failure=5%.

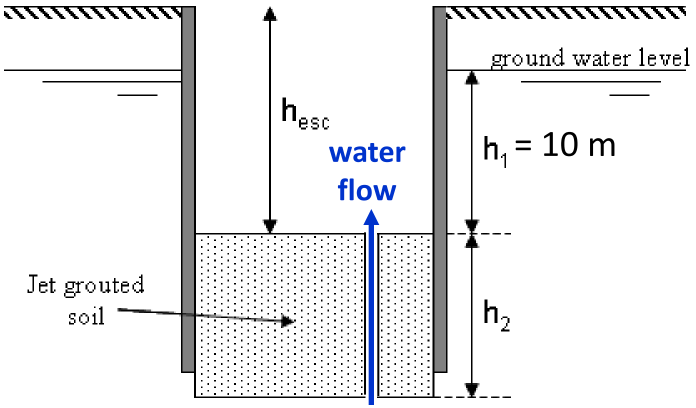
R_d/E_d=1,1





The example of jet grouted water sealing bottom plugs

Design: **probabilistic approach**



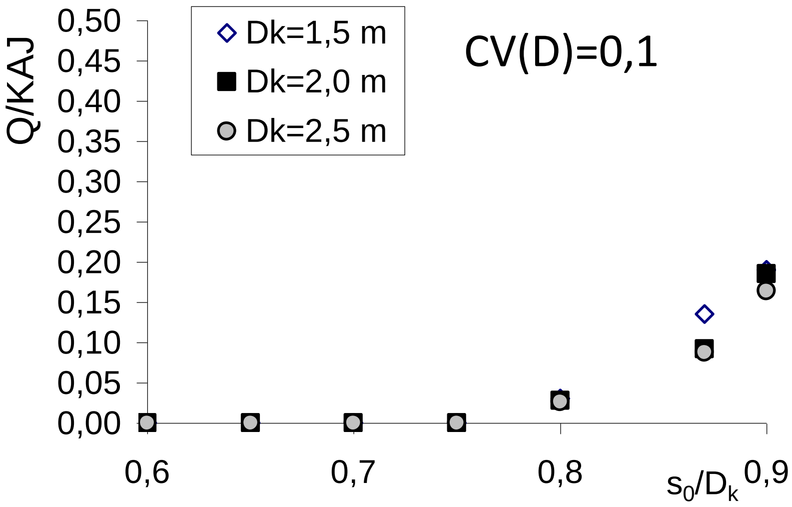
Untreated area at the top of the plug (single cell):

$$A_{un,top} = (1 - F(h_{exc})) \cdot A$$

Water flow through the untreated area at the top of the plug (single cell):

$$Q = k \cdot j \cdot A_{un,top}$$

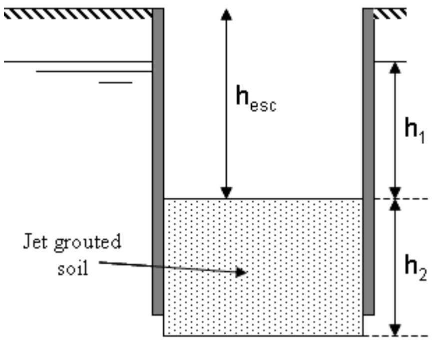
R_d/E_d=1,1

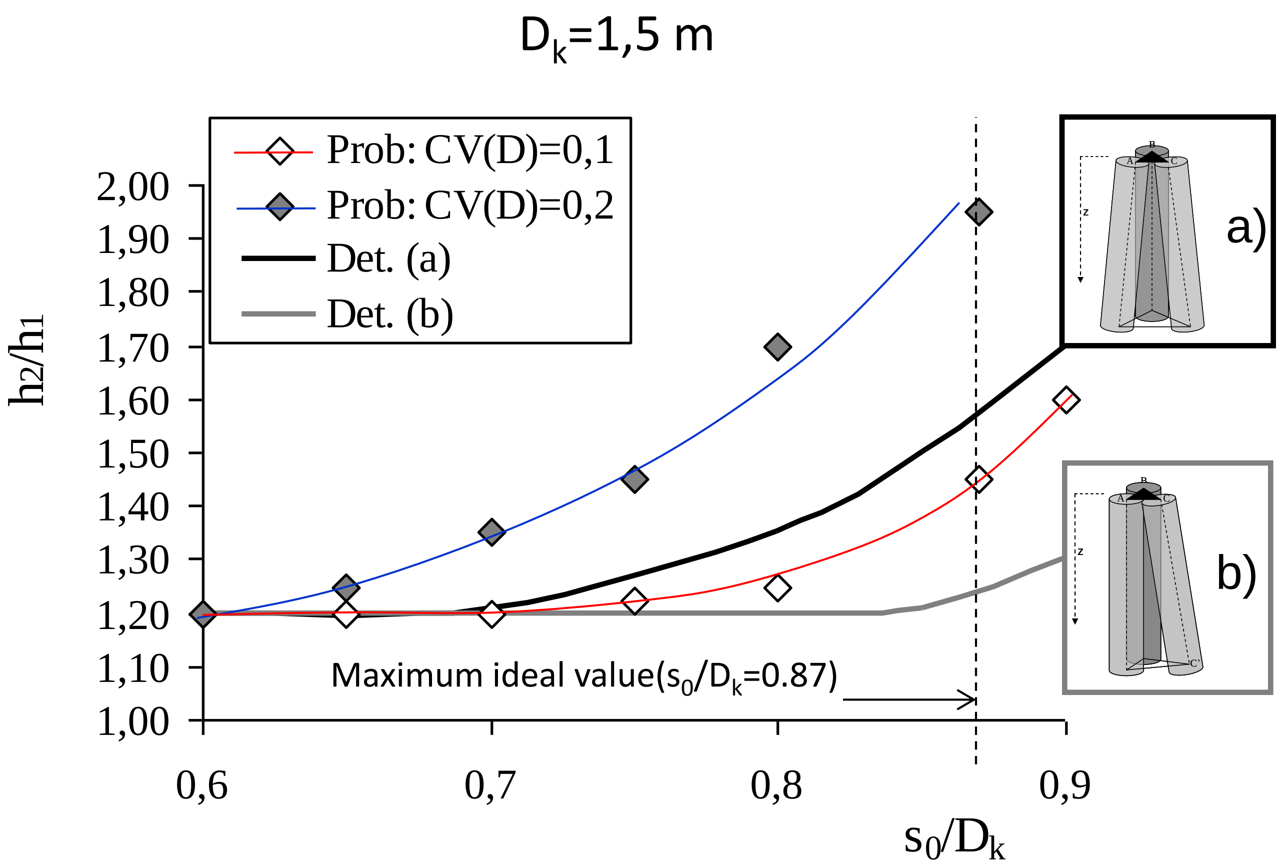


Depending on the hydraulic gradient **j** and on soil permeability **K**, the total water flow **Q_{tot}(=$Q \cdot A_{tot}/A$)** may be tolerated for cost effectiveness or even used to release water pressure

The example of jet grouted water sealing bottom plugs

Comparison between probabilistic and deterministic approaches (imposing R_d/E_d=1,1)





With the deterministic approach, the results largely depend on the (subjective) assumption on columns inclination and azimuth, as well as on the value of the partial factor γ_D

The probabilistic approach, with a very low probability of failure (1%) gives similar but more sound results

CONCLUSIONS

1. The design of jet grouted structures must start from the design of single columns. Mean values and statistical distributions of the geometrical and mechanical properties of the columns must be known with some confidence.

2. Defects of jet grouted columns are unavoidable. They strongly affect the performance of jet grouted structures, and must be quantitatively taken into account at the design stage.

3. Both deterministic and probabilistic design approaches are possible.

4. In the design of water proofing bottom plugs, the assumption of an ideal shape and position of the jet grouted columns is not conservative, unless an extremely small spacing (overconservative design) is assigned.

5. The probabilistic approach has the advantage of providing a rational and cost effective way to design jet grouted structures assigning a desired probability of failure.

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- Flora A., Lirer S., Lignola G.P., Modoni G. (2011). Mechanical analysis of jet grouted supporting structures. *Proceedings of the VII International Symposium on Geotechnical Aspects of Underground Construction in soft ground*, Rome.
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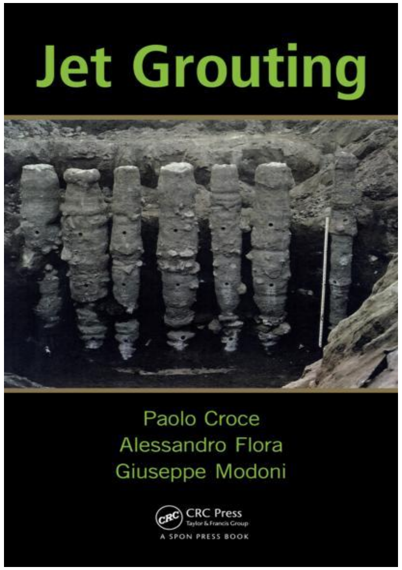
- Flora, A., Modoni, G., Lirer, S., and Croce P. (2013) The diameter of single, double and triple fluid jet grouting columns: prediction method and field trial results*, Géotechnique*, 63, No. 11: 934 –945.
- Lignola, G.P., Flora, A. and Manfredi, G. (2008) A simple method for the design of jet grouted umbrellas in tunnelling. *Journal of Geotechnical and Geoenvironmental Engineering*, *ASCE* 134(12): 1778-1790.



IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Sandwich wall beneath Amsterdam Central Station

O. Langhorst, Movares, The Netherlands

ISSMGE TC211 Ground Improvement

Sandwich wall beneath Amsterdam Central Station

September 1, 2013

Onno Langhorst

Adviesbureau Noord/Zuidlijn Amsterdam   VOF Stationseiland Amsterdam   CSO   Smet/Keller

Presentation Topics

1 Introduction and geotechnical longitudinal section

2 Requirements and construction method

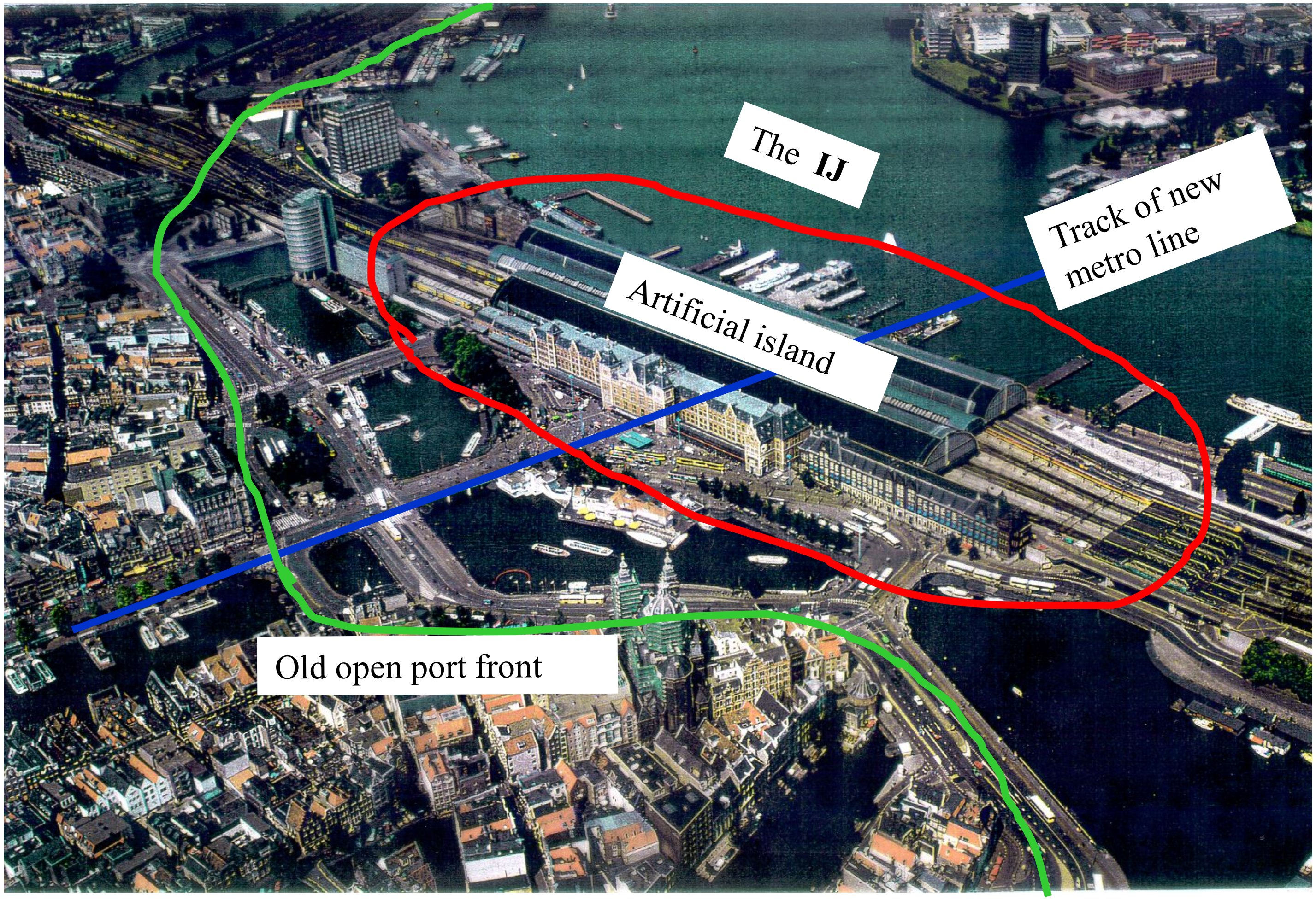
3 Design and construction process

4 From jetgrout trial to final work

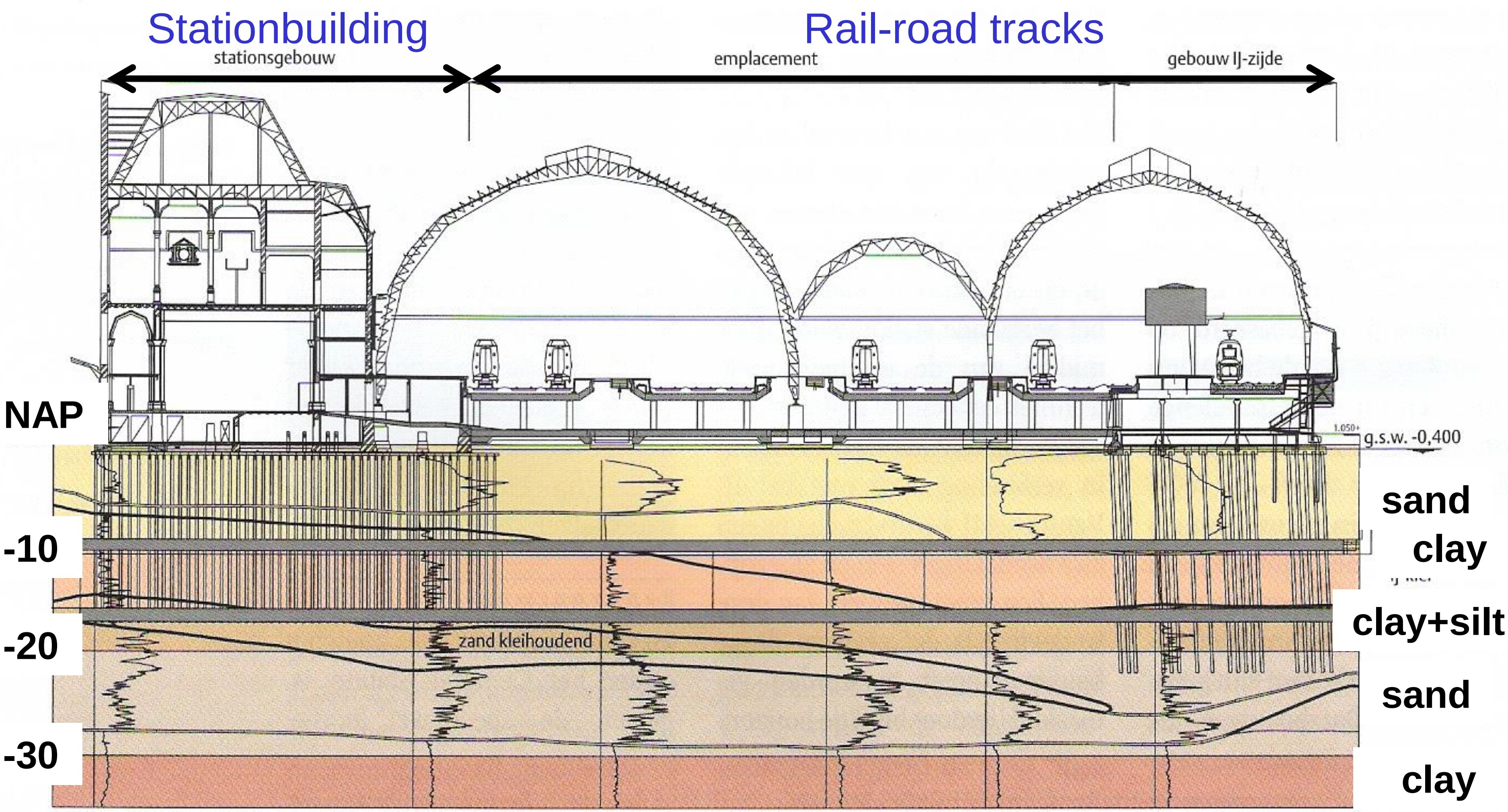
5 Execution jetgrout parameters and measurements

6 Conclusion

Overall picture of the island with Amsterdam Central Station



Longitudinal section of the existing station

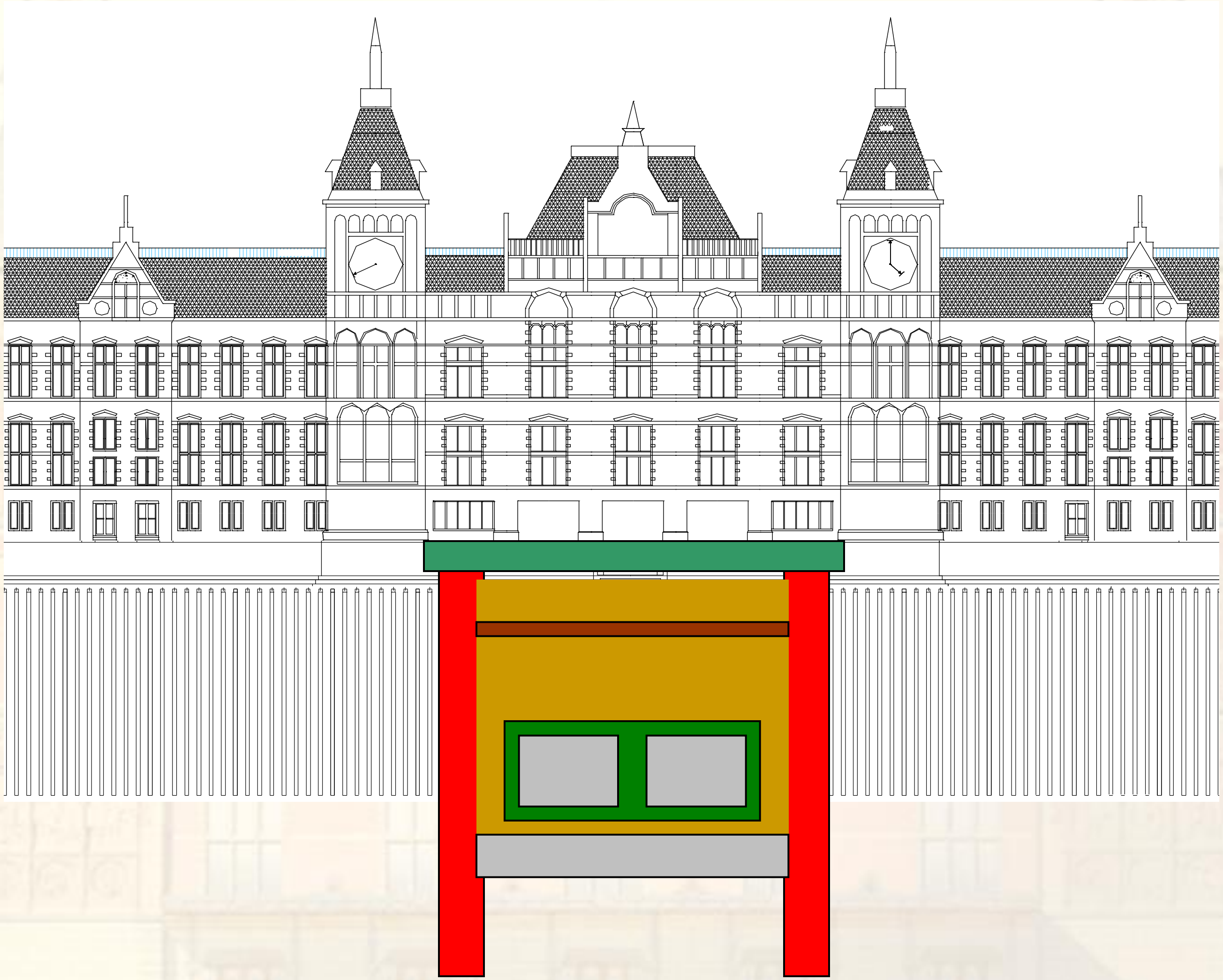


Adviesbureau Noord/Zuidlijn Amsterdam VOF Stationseiland Amsterdam CSO Smet/Keller

Requirements for the building pit

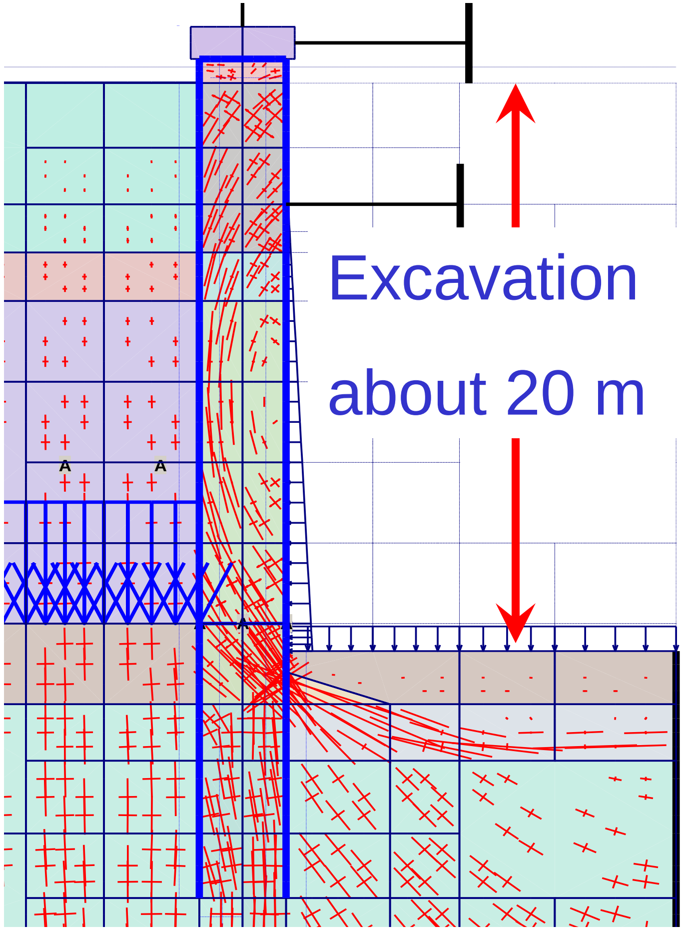
- Minimize disruption to the train operations during construction;
- Minimize inconvenience to the passengers during construction;
- Limit the damage to the existing structures, especially the station building, which is a monument.

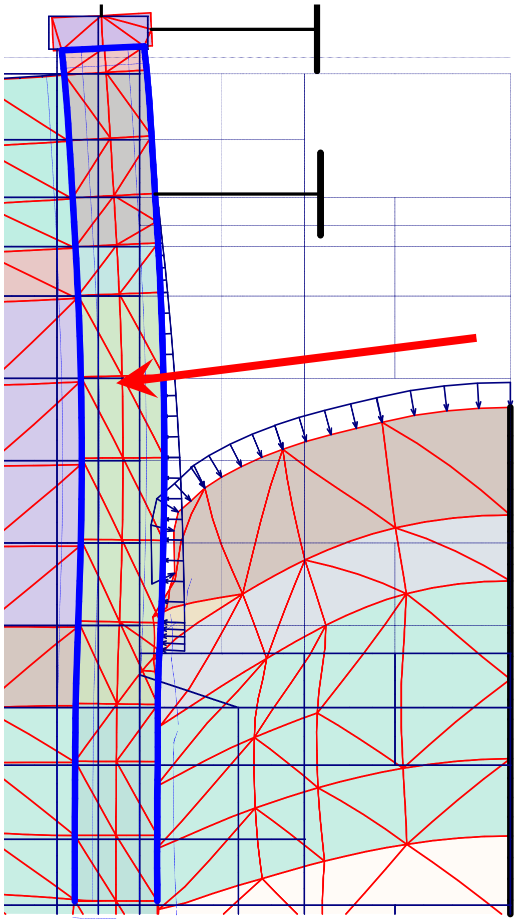
The construction proces



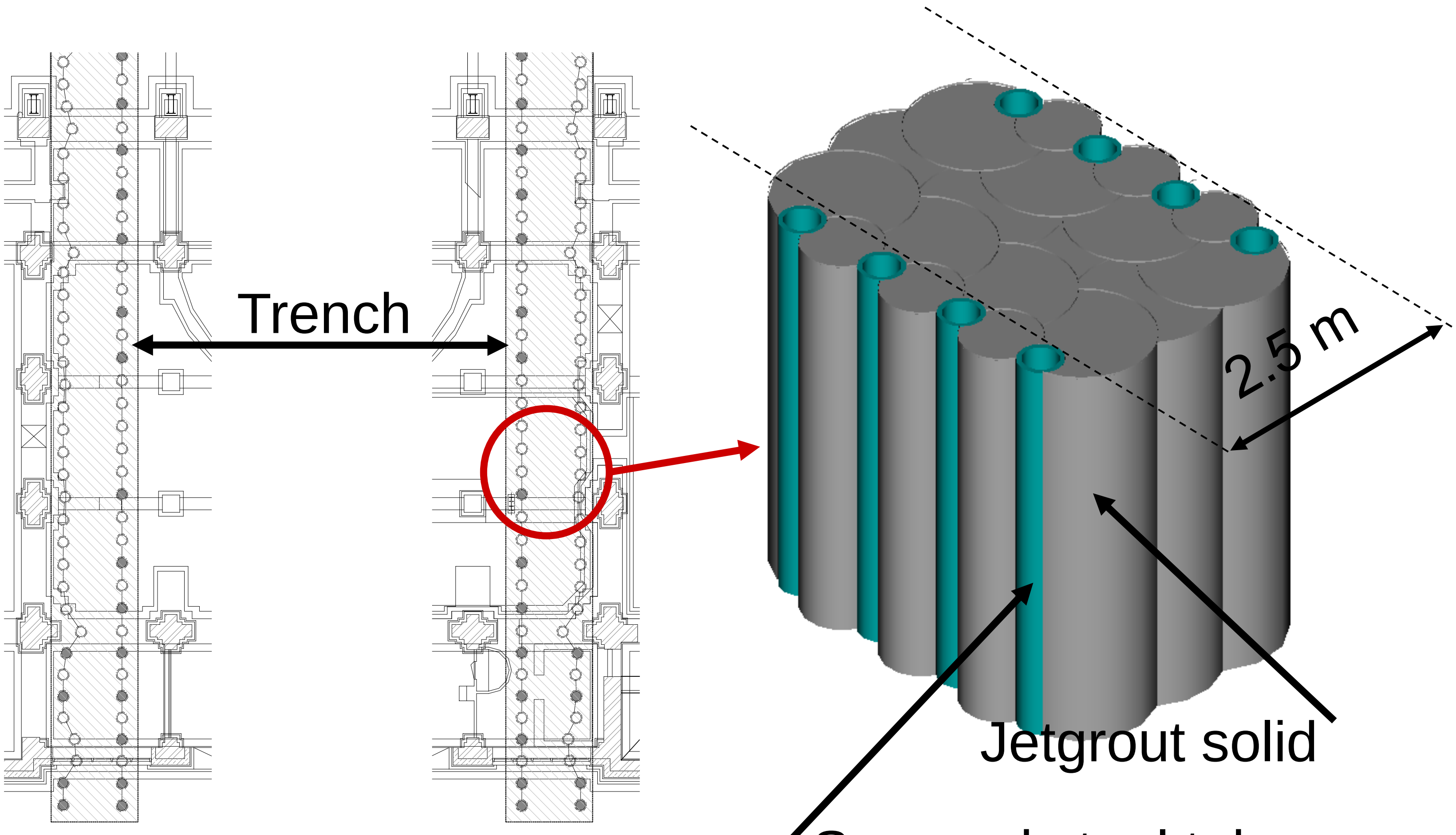
The final result

Deformation of the sandwich wall has been calculated with PLAXIS





Specific topics of the building pit (trench)



Screwed steel tubes

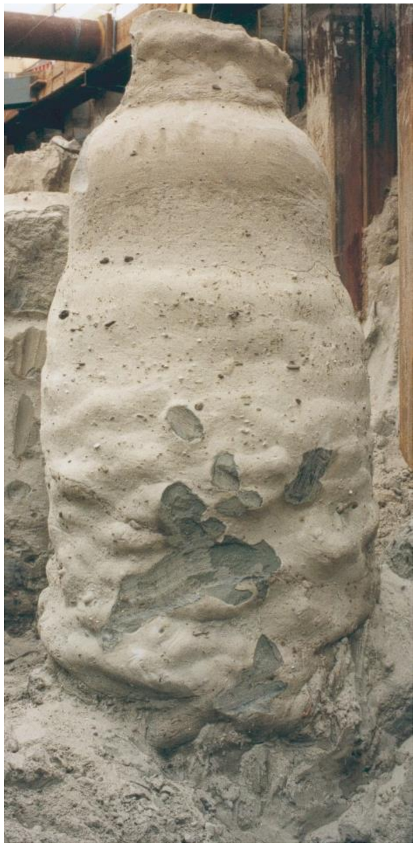
Station floorplan with trenchwalls

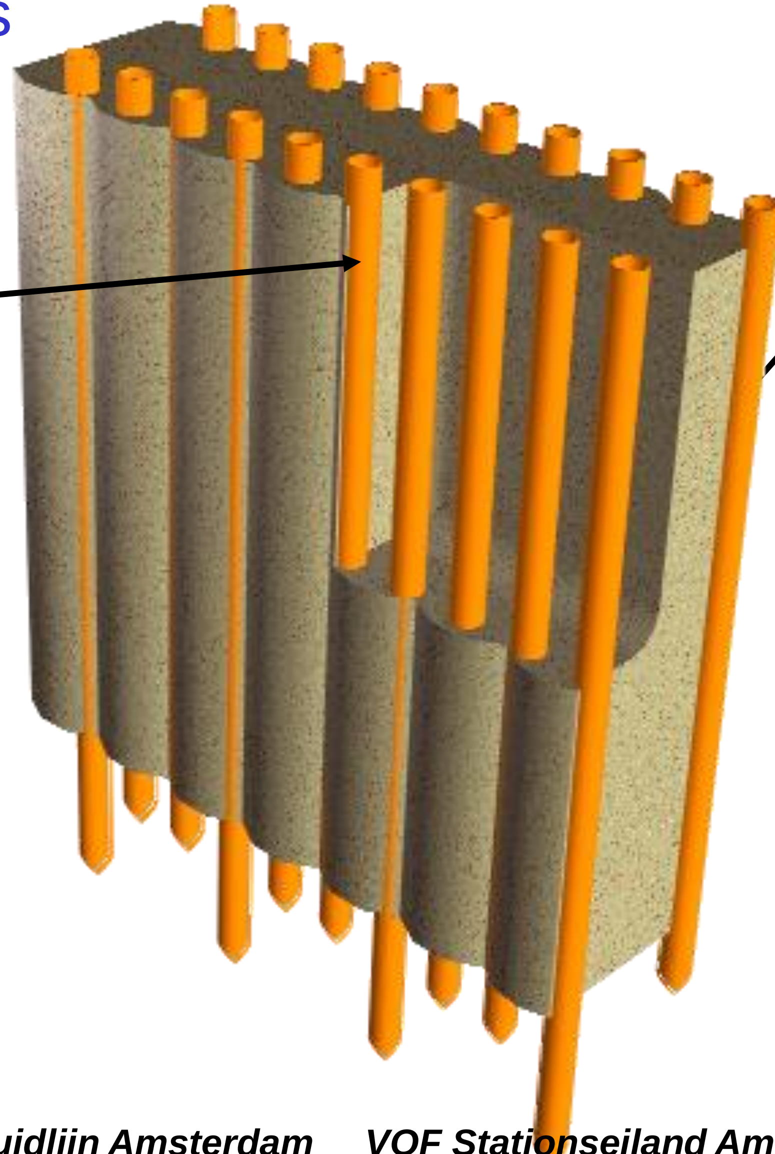
Isometric view

The sandwich wall elements

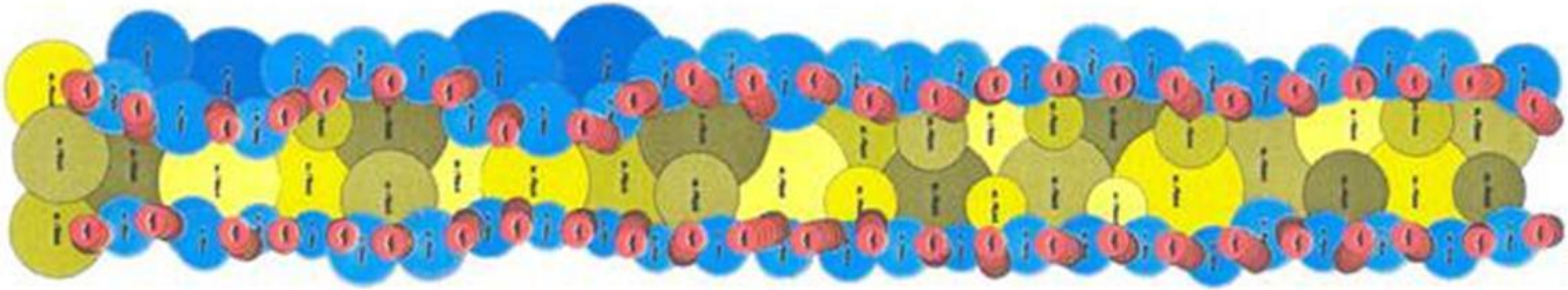
Jetgrout columns

Steel Tubex piles with rings





Sandwich wall

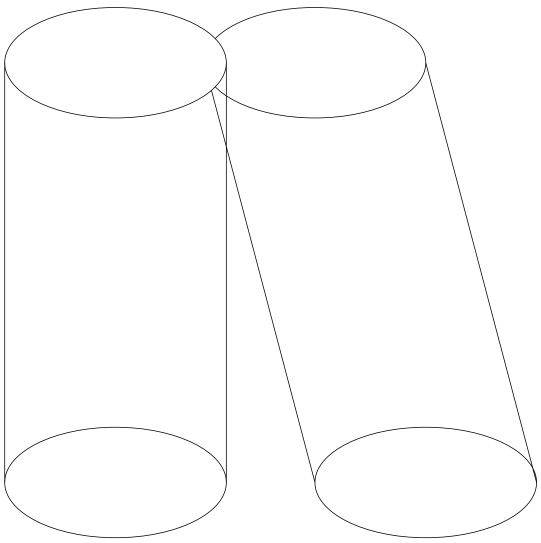


- 160 Tubex piles
  length 30 - 60 m, diameter 0,457 m

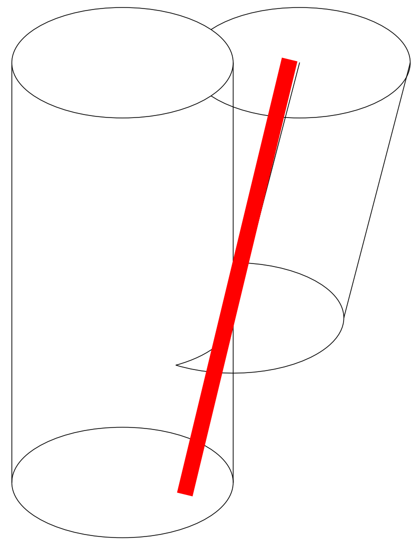
- 162 jetgrout (peripheral) columns (mono-jet)
  length 30 m, diameter 0,8 m - 1,2 m

- 122 jetgrout (fill) columns (bi-jet)
  length 30 m, diameter 1,4 m - 2,2 m

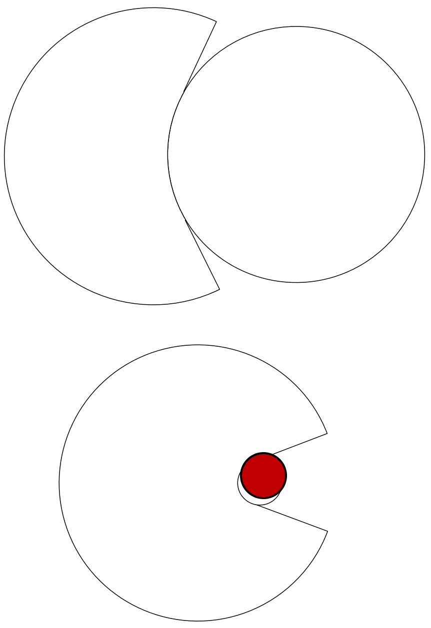
Deviations jetgrout proces



Deviation inclination

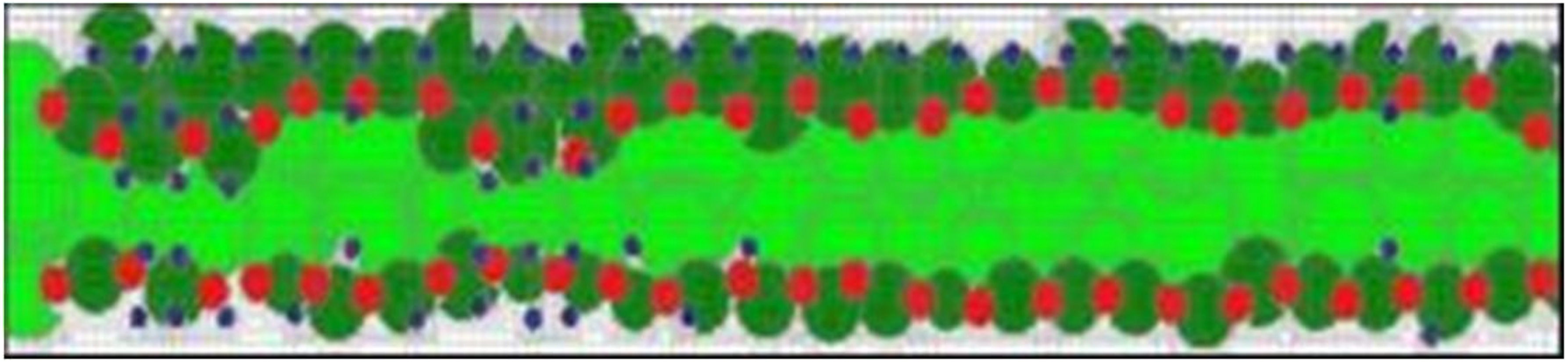


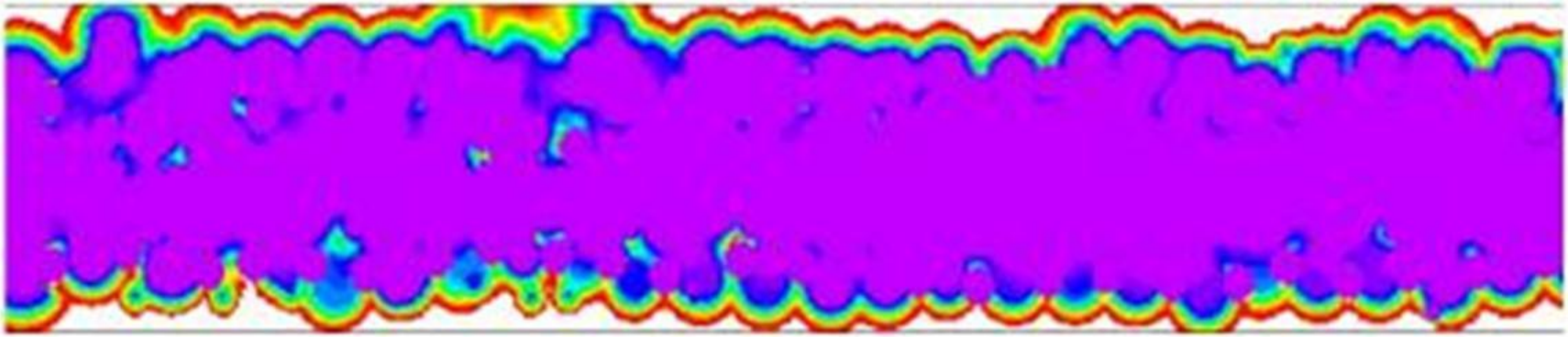
incorrectly drilled



Shadow effect

Monte Carlo analyse





Risk profile

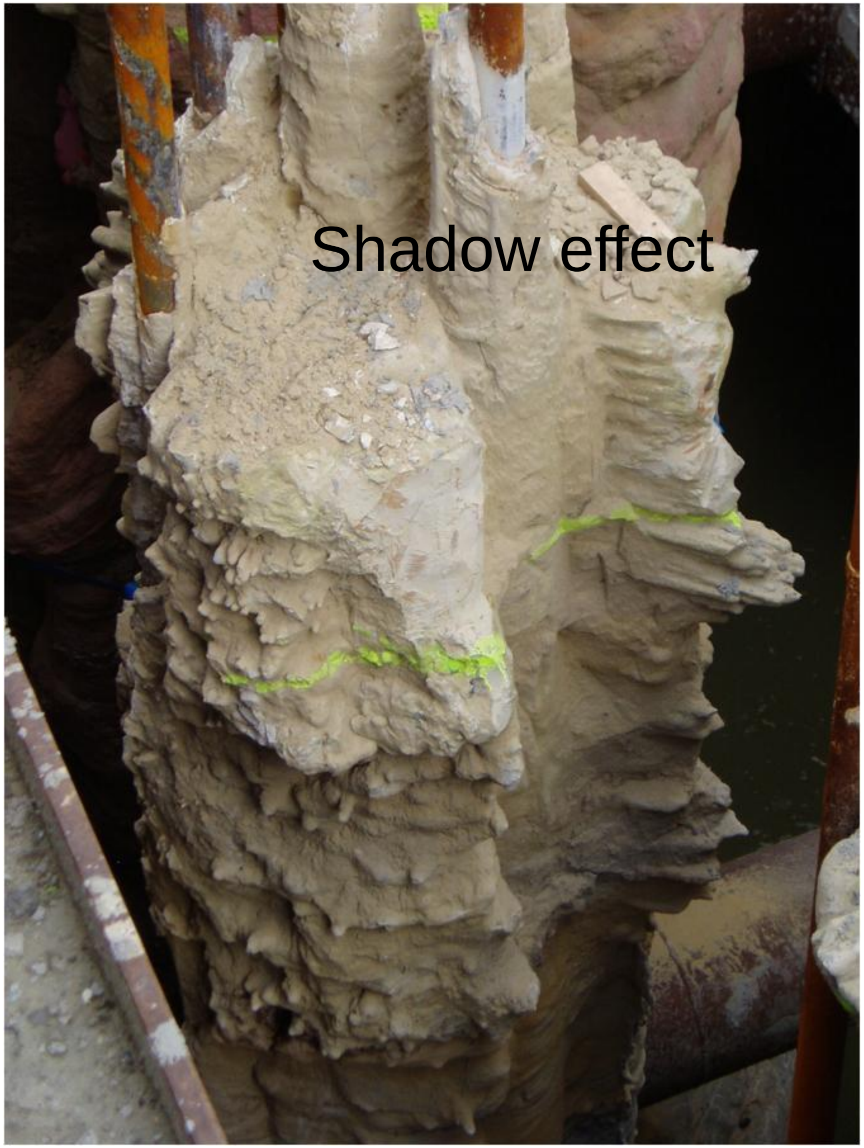
Risk / fail	Consequence	Cause
Constructive	•Large deformation of the wall	•Grout strength too low •Inadequate overlap with Tubexpiles •Missing large grout volumes
Impermeability	•Groundwater lowering outside the pit •Groundwater lowering inside the pit which is not controllable	•Inadequate overlap between Tubex - jetgrout •Inadequate overlap between grout columns
Compactness of the ground	•See impermeability •Earth movement	•See impermeability

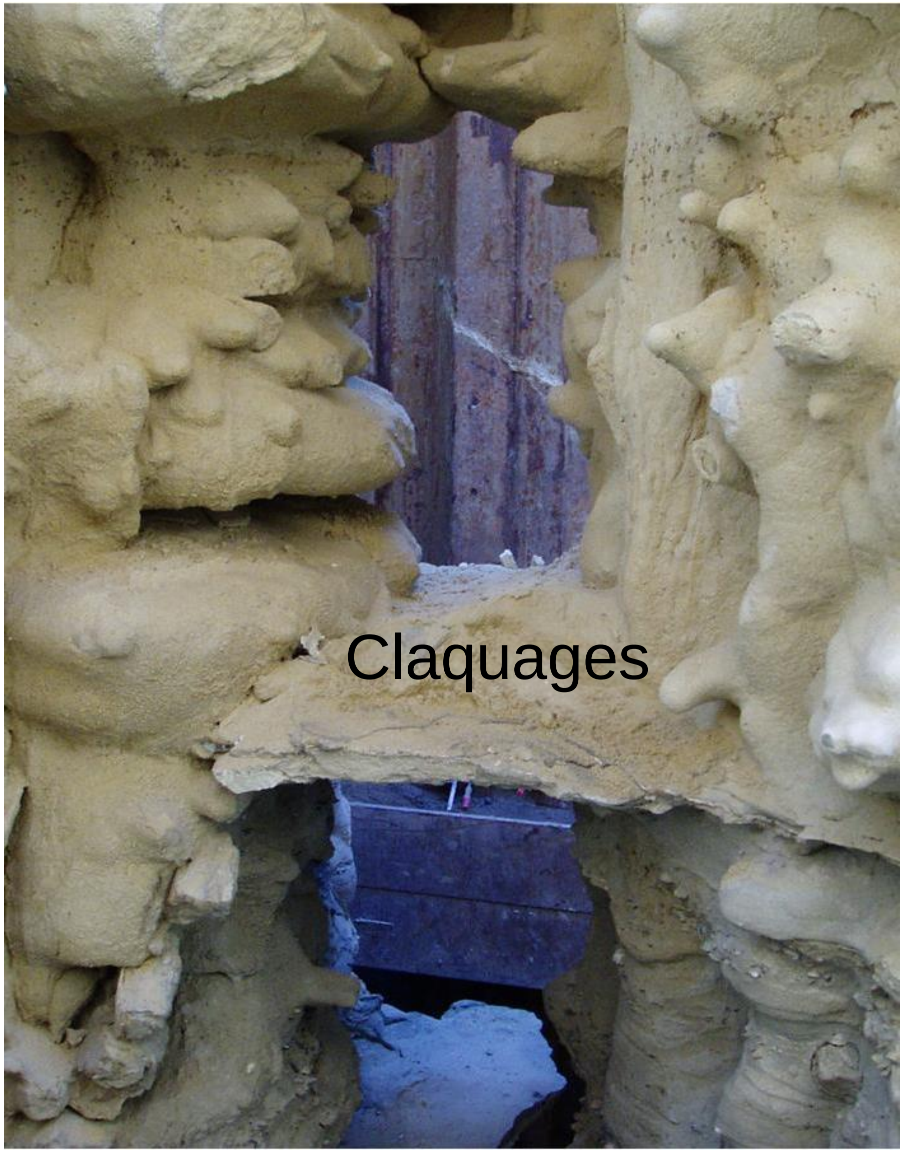
From jetgrout trial to final work

Technical points:

- Pre cutting (diameter);
- Post jetting (strength);
- Section length 5 - 10 m;
- Controlling strength of the mixes and densities on site;
- Compressive strength 1,5 N/mm^2 at 120 days;
- Diameter variation +/- 20%;
- Extensive measurements:
  Inclination
  Borehole caliper
  Hydrophone
  Leakage detection
- Observational method

Test colums





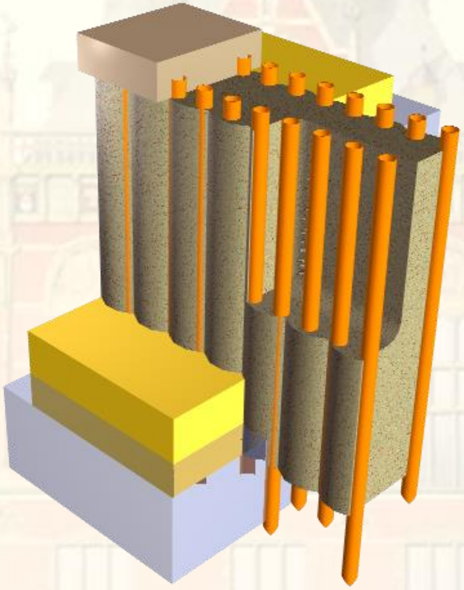
Installation Tubex piles (Top-drill)

Steel Tubex piles with rings

Jetgroutprocess Observational method:

Design sandwichwall

Modification execution proces → Measurements



↑ ↓

Verification ← Interpretation

- Steering group (preconditions)
- Implementation support team

The Steering Group

Adviesbureau Noord/Zuidlijn Amsterdam *[1]

- Hans de Wit, Johan Bogaards

VOF Stationseiland Amsterdam *[2]

- Onno Langhorst, Bauke Schat

Consultants

- Bob Essler, Jan Maertens

Principal Contractor CSO *[3]

- Bas Obladen, Carlos Bosma

Jetgrouting Subcontractor Smet Keller

- Yves Sleuwaegen, Henk Dekker

*[1] cooperation between Royal Haskoning, Witteveen en Bos, Ingenieursbureau Amsterdam

*[2] cooperation between Movares Nederland BV and Arcadis Infra

*[3] cooperation between Strukton betonbouw and van Oord ACZ

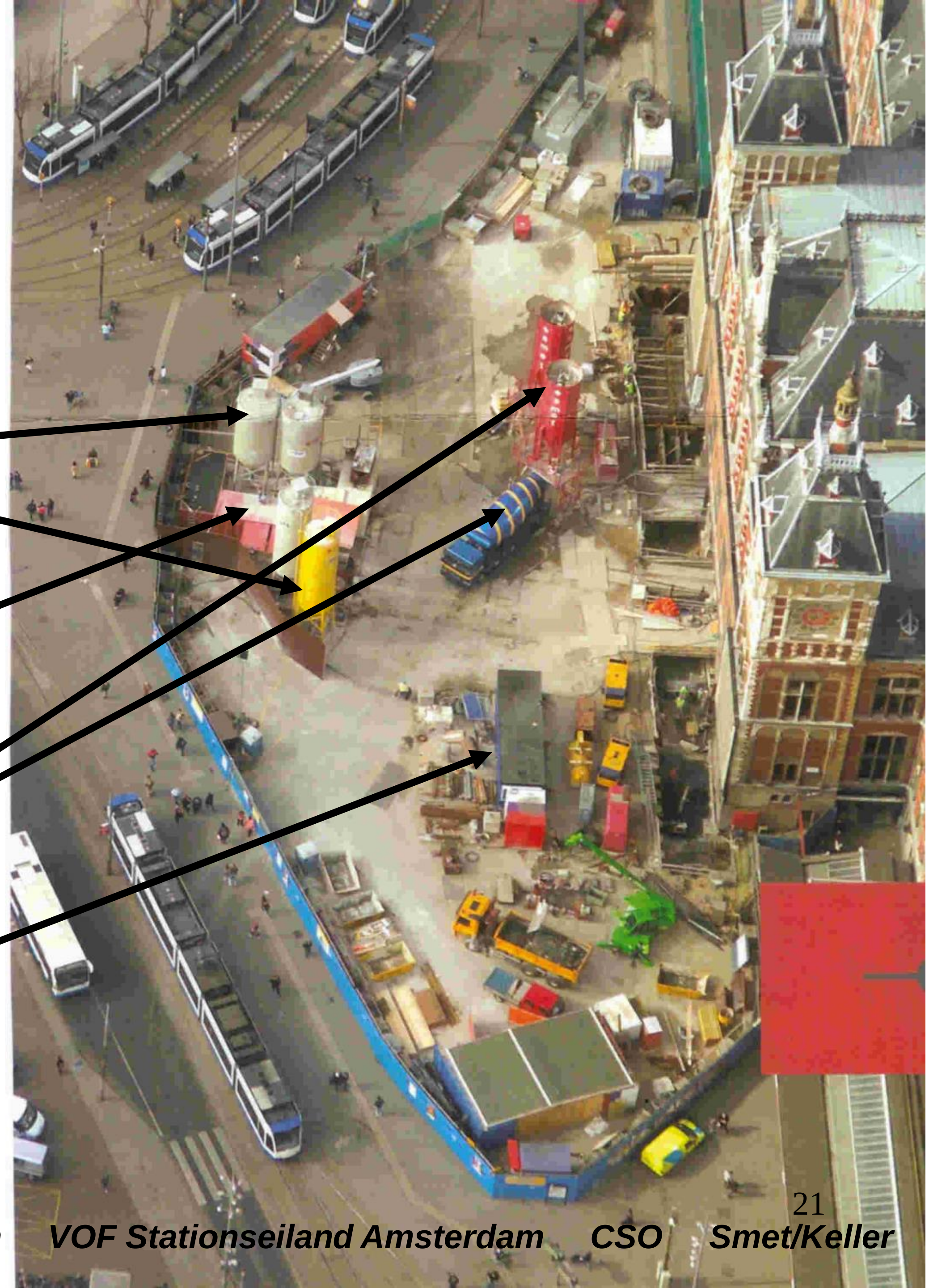
Building site

Cement silo's

Groutpump, mixers
en watercontainers

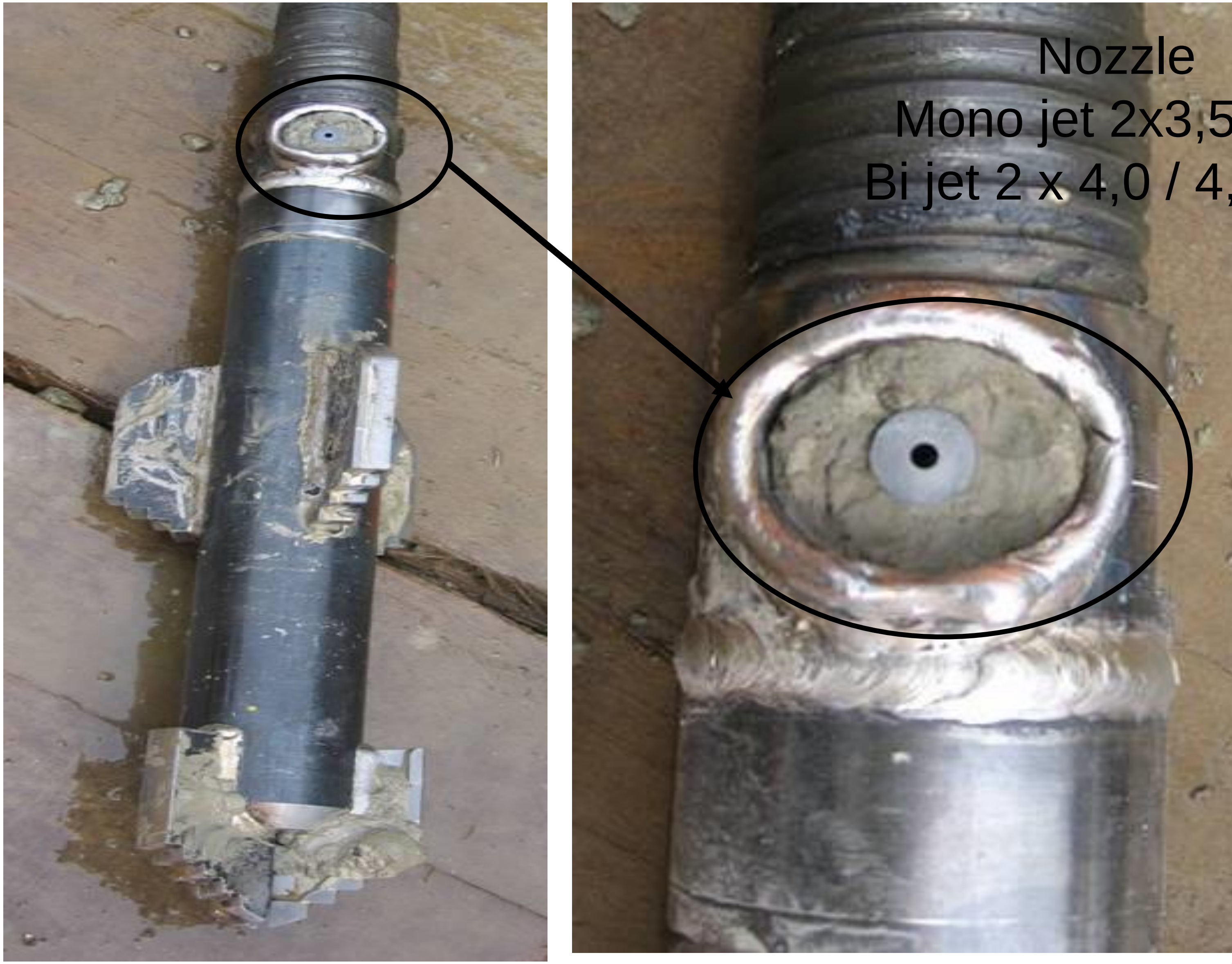
Spoil disposal

Monitoring unit

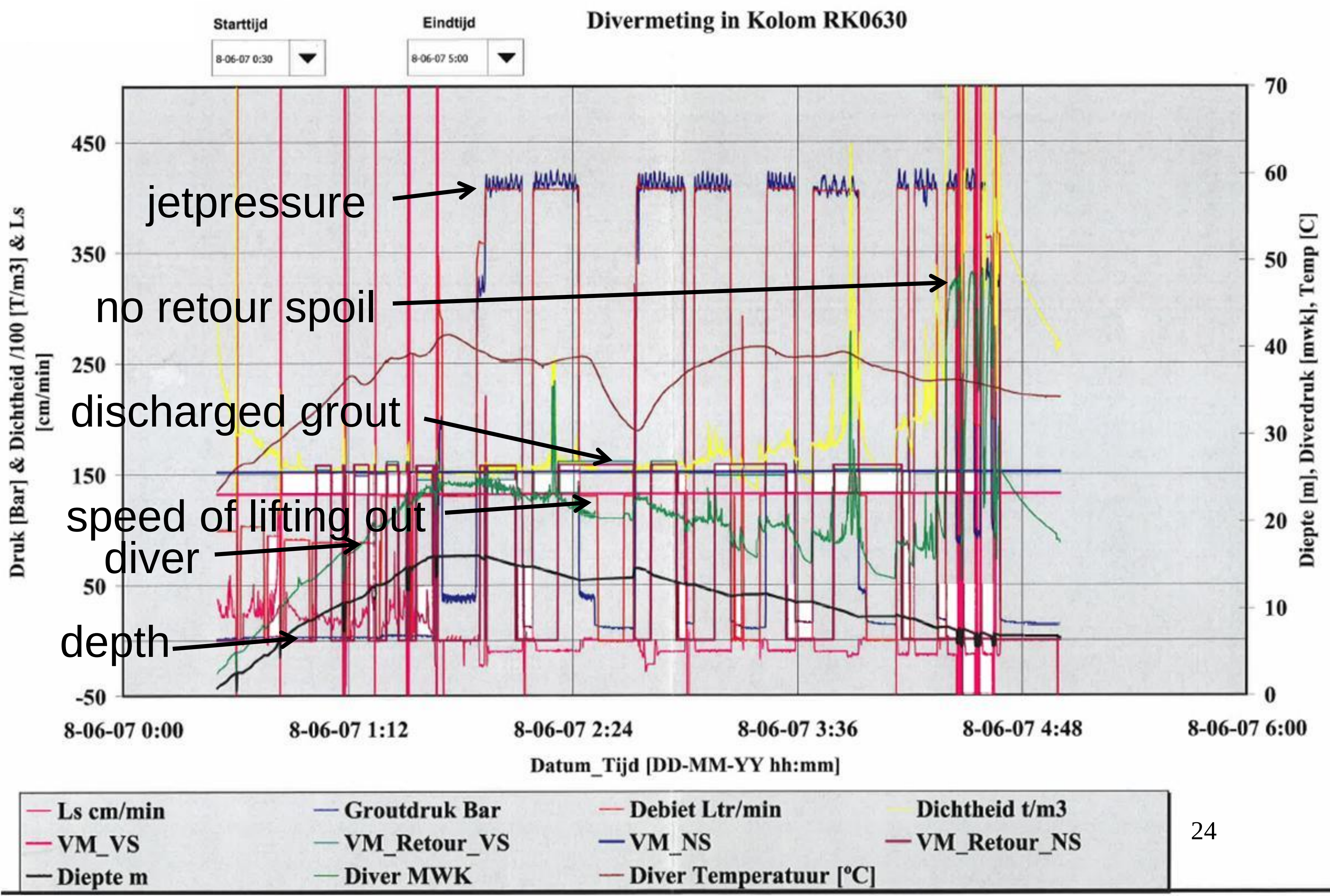


Jetgrout machine

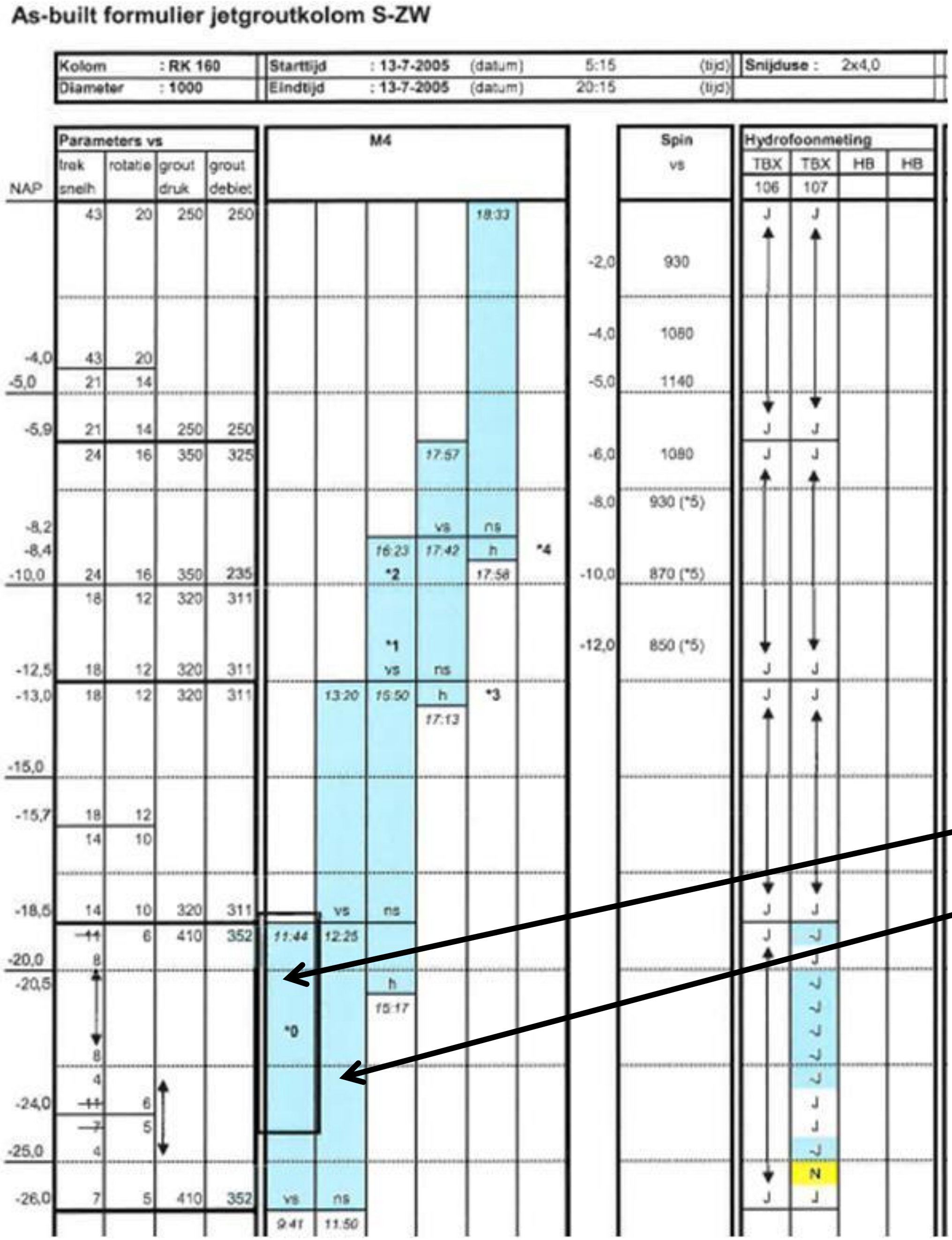
Drill bit and nozzles



jetgrout process



As built results



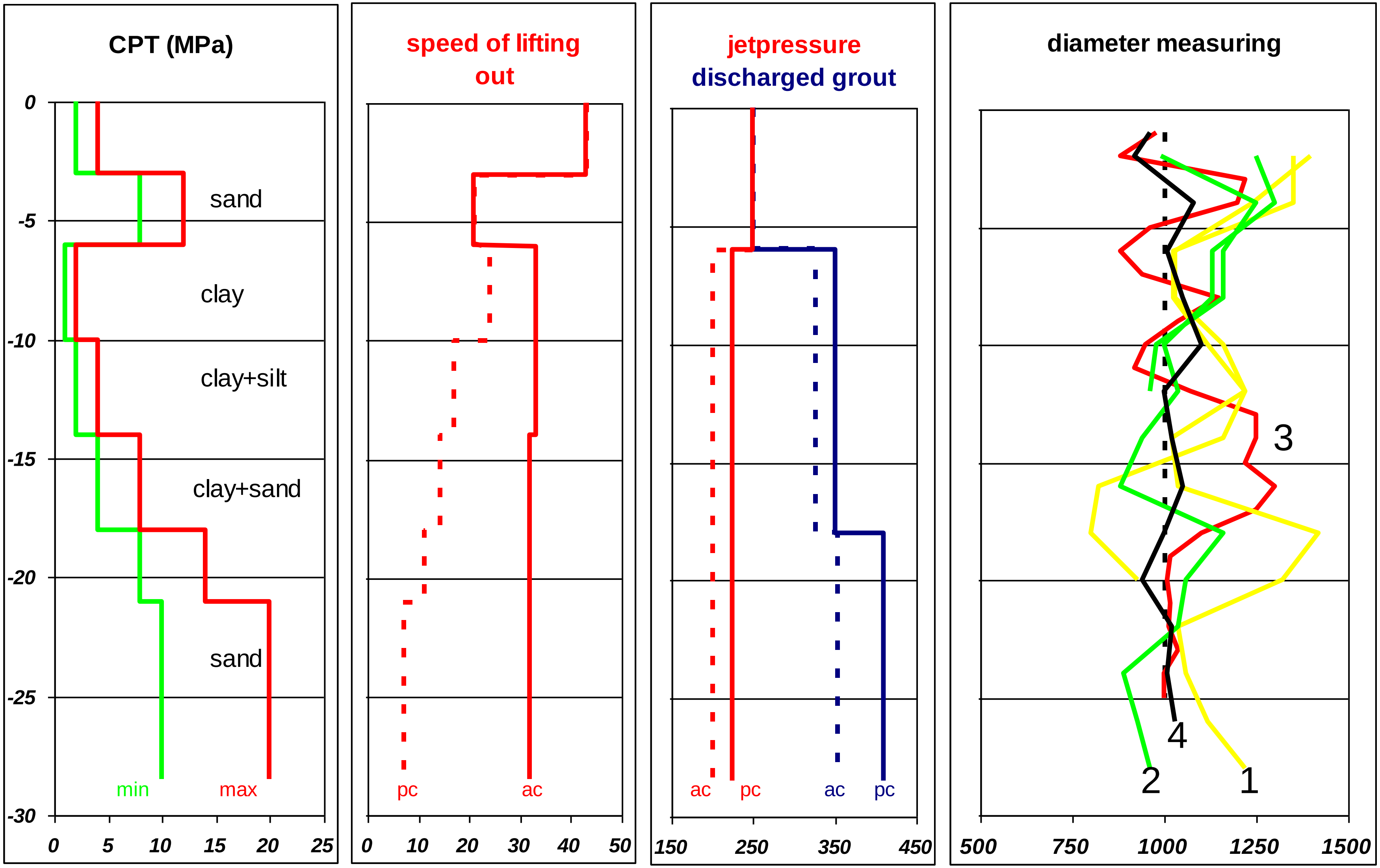
Smet: Lutz

Keller: M4

pre cutting (1e section)

after cutting (jetgrout)

Jetgrout parameters and diameter

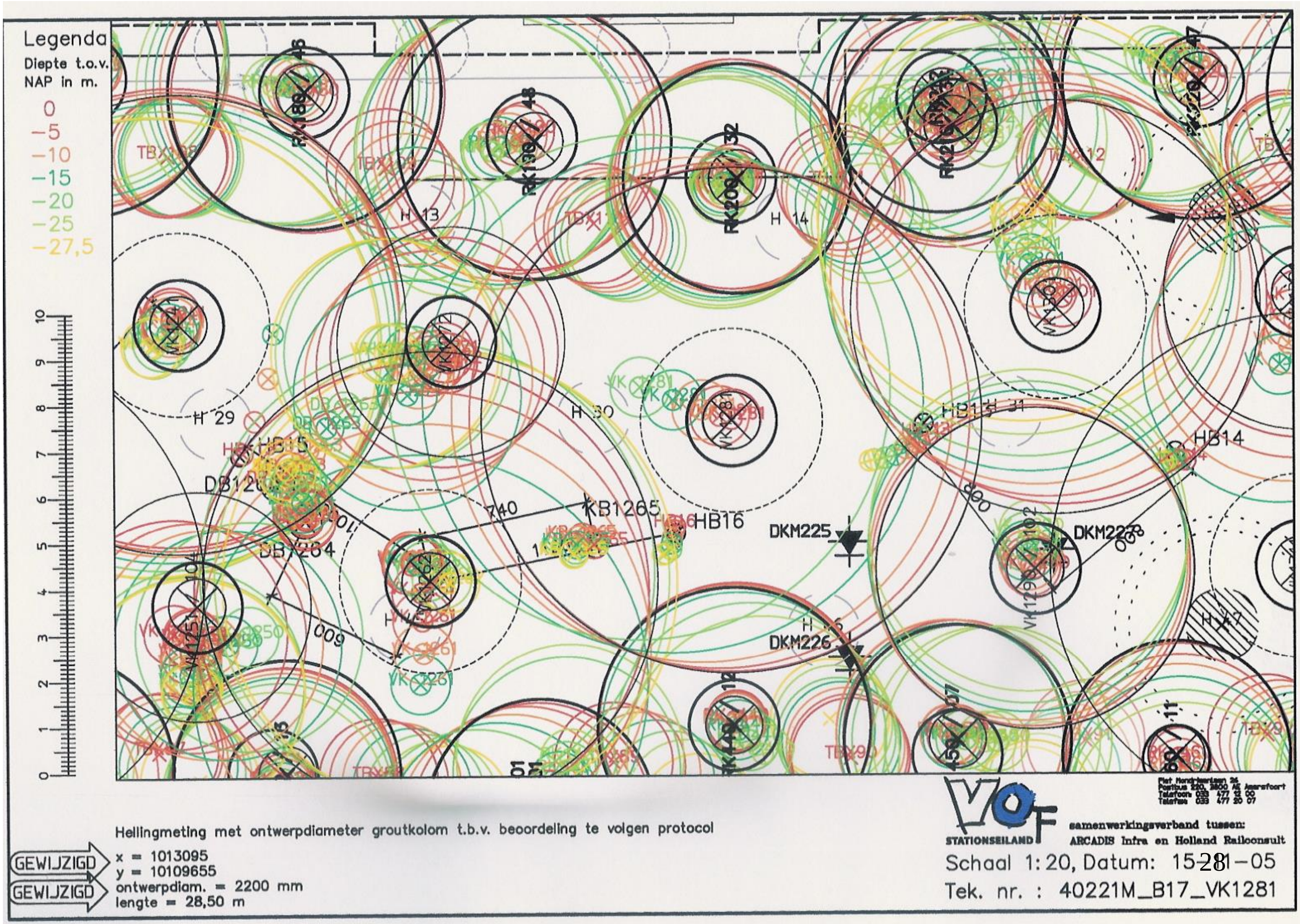


Inclination measurements

inclination

< 0,5%	0,5 -1,0%	1,0-1,5%	1,5-2,0%	>2,0%
24%	36%	21%	12%	7%

Visualization of the measured deviations:

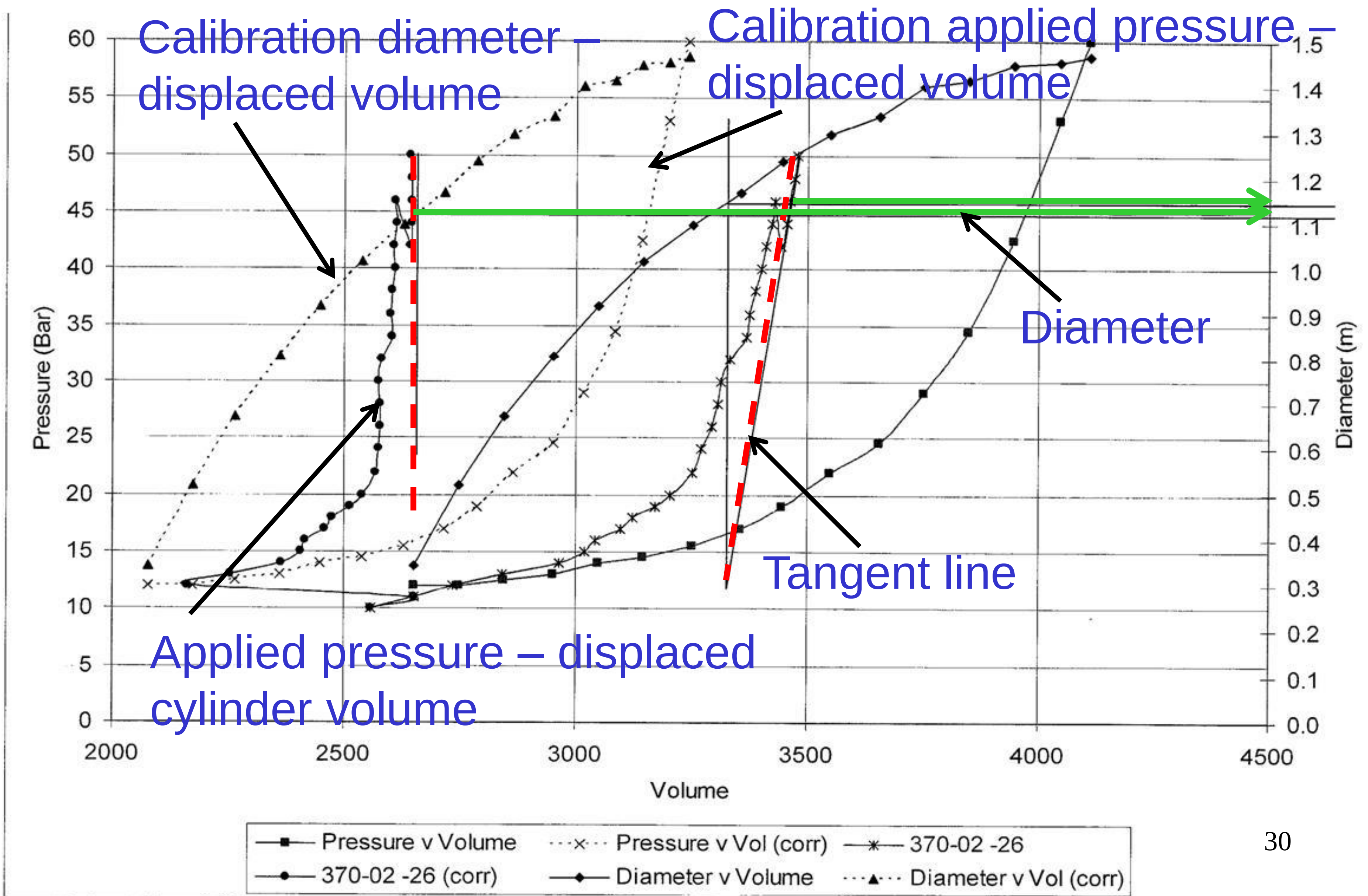


Borehole caliper (diameter measurements)

Fold caliper
(∅800-1200mm)

Slide caliper
(∅1400-2200mm)

Typical results measurements with calliper



Return slurry

Return slurry (density)

Samples of spoil return to determine the strength

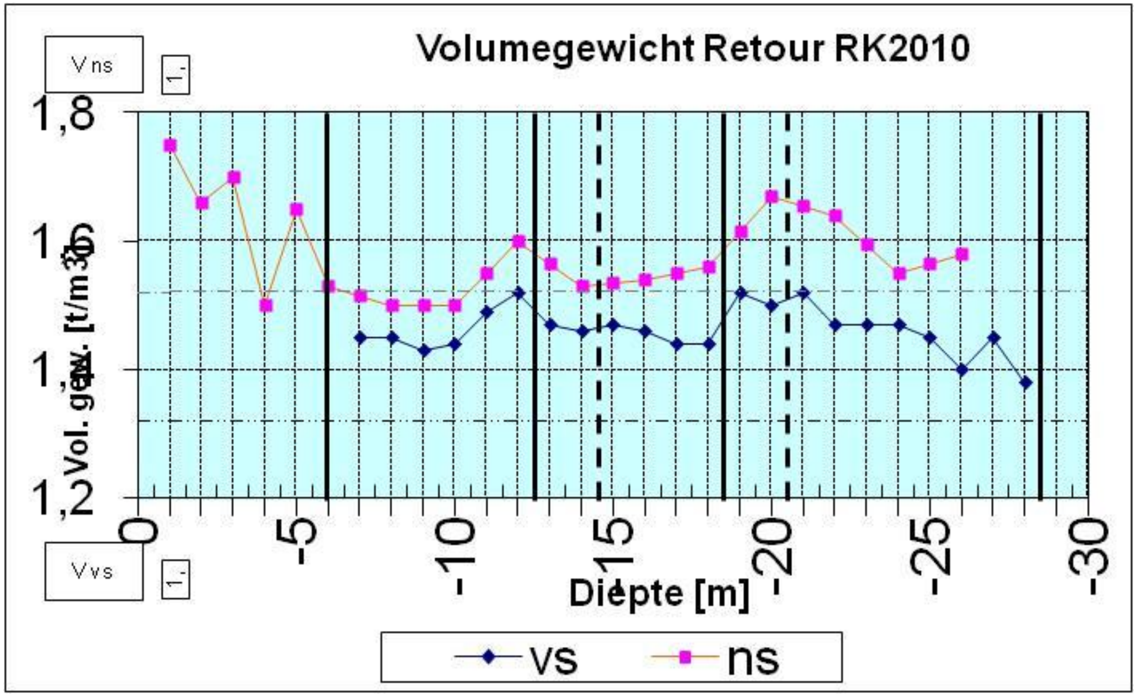
Not always representative for the situ strength

days	strength
7	5 MPa
28	11 MPa
120	15 MPa

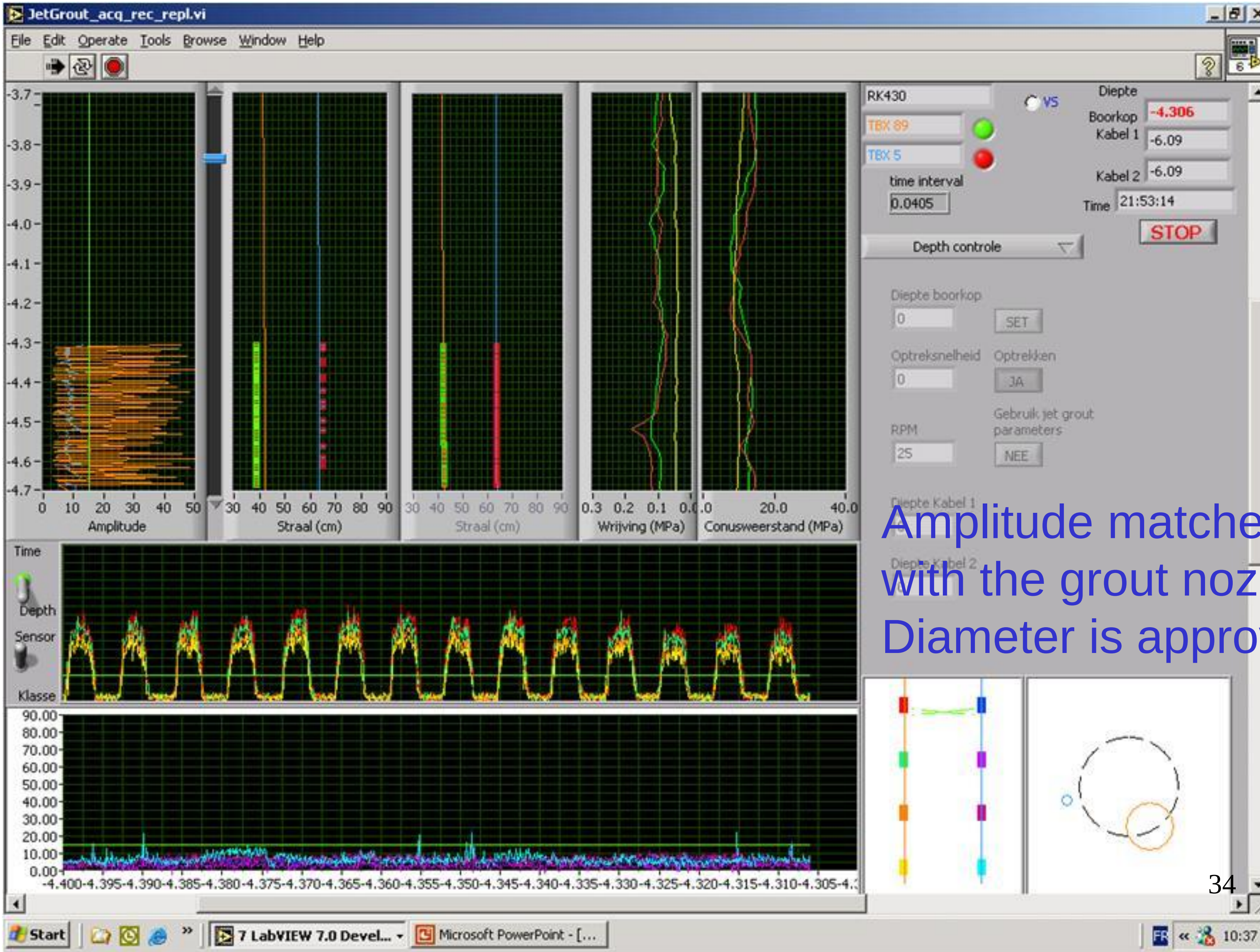
Return slurry (estimation diameter)

Density of spoil return is determined by weighing 2 litres of spoil

Gives an idea about the replacement % column diameter



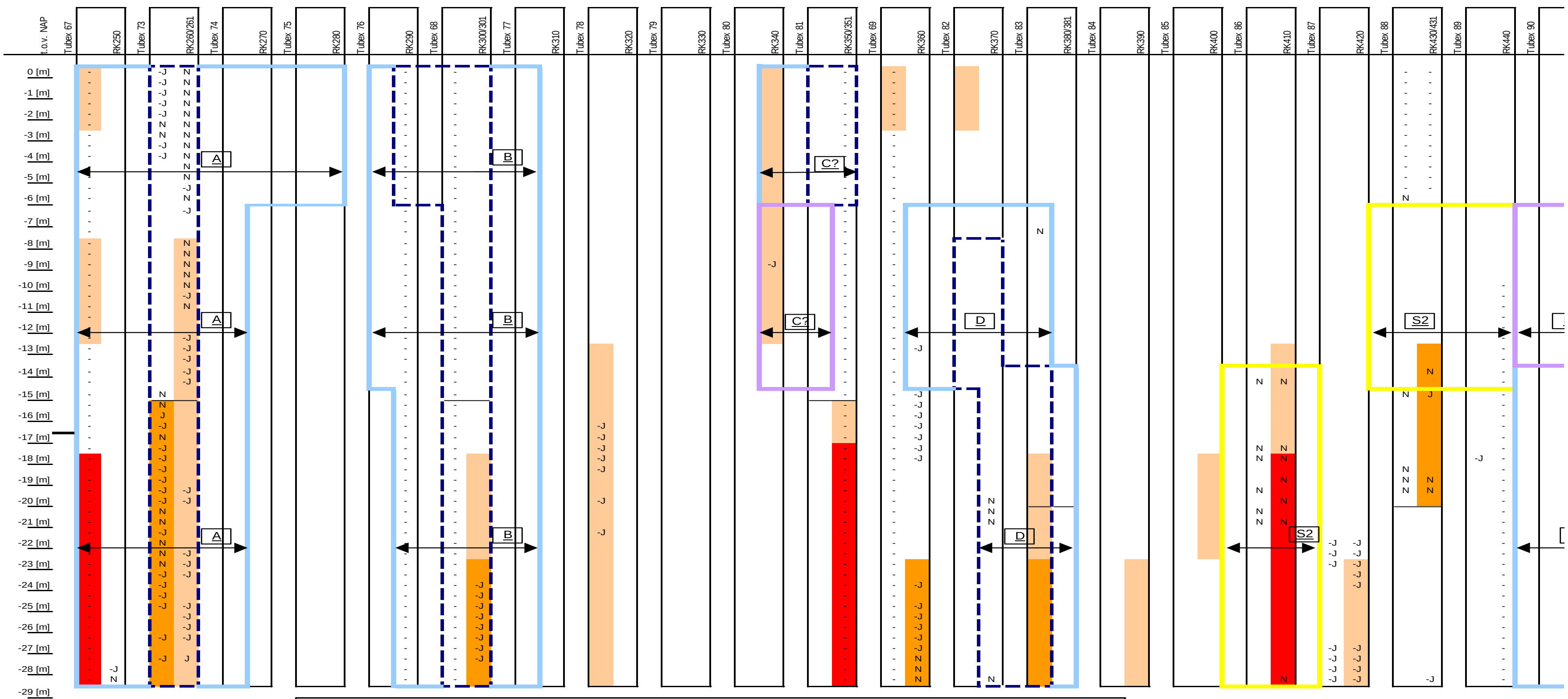
Hydrophone measurements



Amplitude matches with the grout nozzle Diameter is approved

Sectional view of a wall of the first row of completed peripheral columns

Beoordeling jetgroutrandkolommen S-ZW RK250 t/m 480 **versie 14-9-2005**



LEGENDA

G-tec
- -J : Zwakke aanstraling gemeten door G-tec
- N : Geen aanstraling gemeten door G-tec
- \- : Geen meettesultaten Hydrofonen beschikbaar

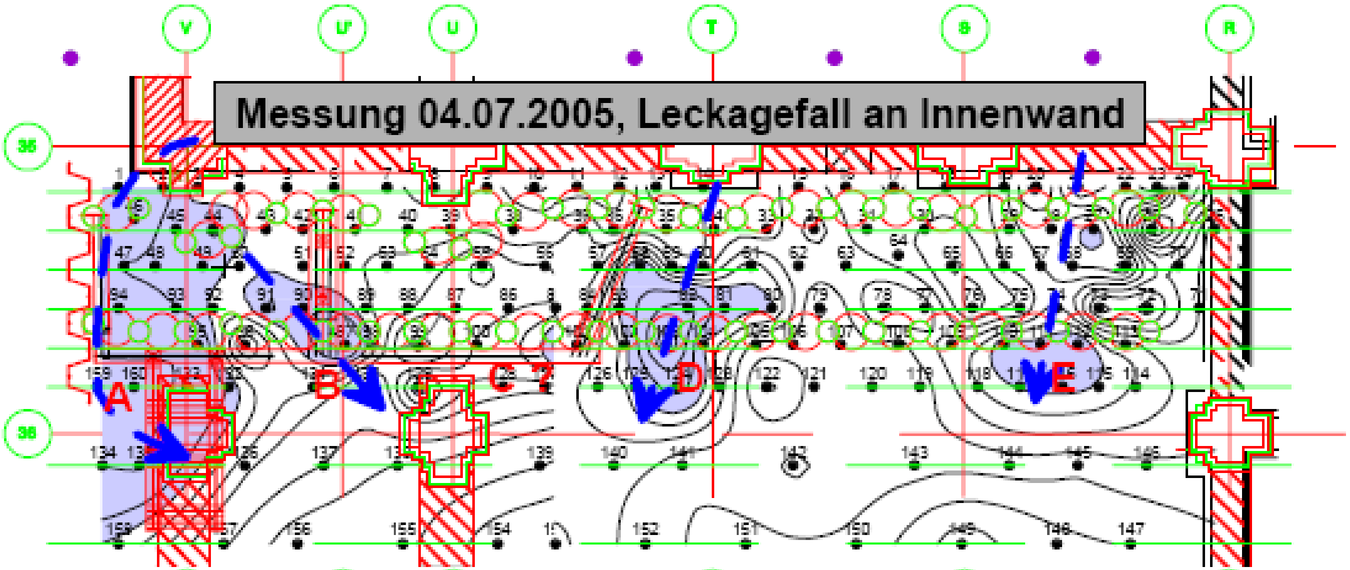
min/max diameter Op basis van gerealiseerd groutpatroon met minimale / maximale diameters groutkolommen:
- (licht oranje) : Bij minimale diameter geen overlap en bij maximale diameter wel overlap met tubex-paal.
- (oranje) : Bij minimale diameter geen overlap en bij maxmale diameter net aan overlap met tubex-paal.
- (rood) : Bij minimale en maximale diameter geen overlap met tubex-paal.

Texplor (2-9-2005)
- (lichtblauw) : Risico-zone van lekkage op basis van EFT-metingen
- (donkerblauw) : Meest waarschijnlijke zone van lekkage op basis van EFT-metingen
- (paars) : Zone met zwakke vorm van lekkage op basis van EFT metingen
- (geel) : Zone met zeer zwakke vorm van lekkage op basis van contourlijnen EFT-metingen
- ___ : Kolom in twee delen gemaakt

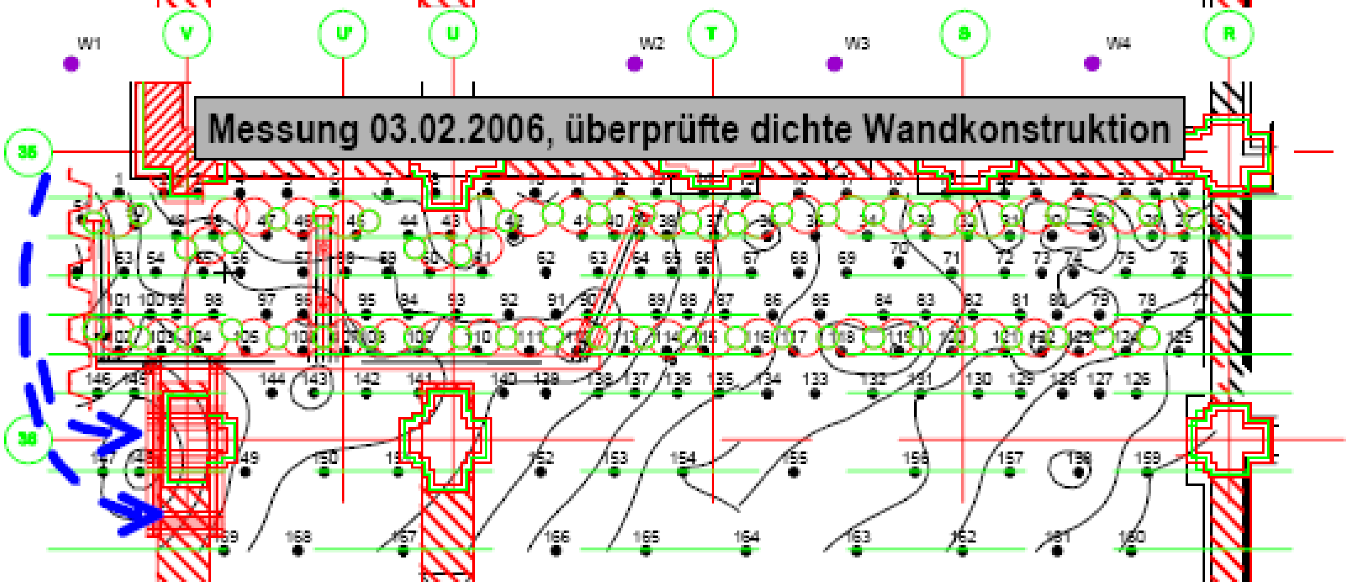
STATIONSEILAND

Leakage detection location (Texplor)

Leakage detection measurements (Texplor)

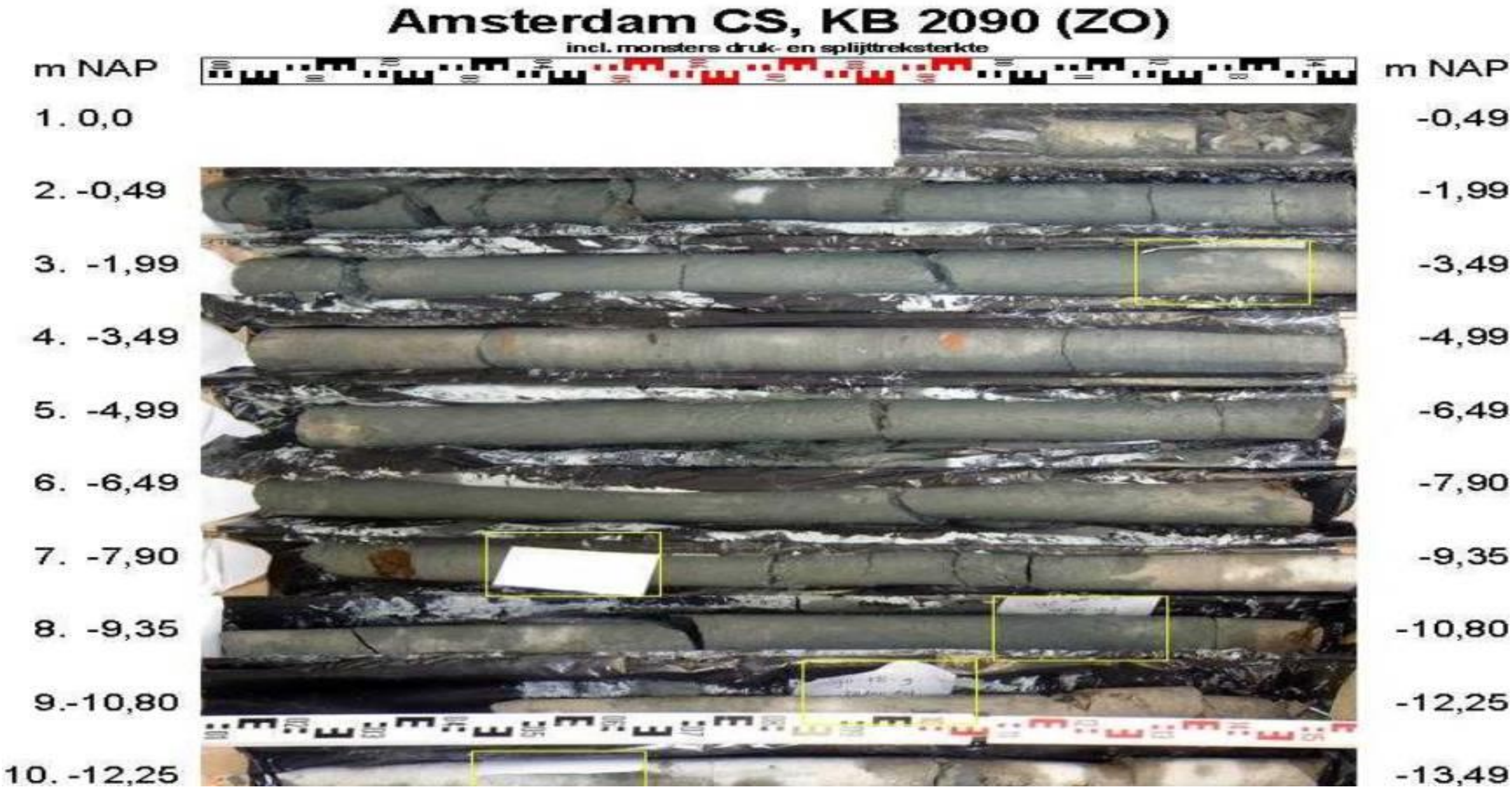


1 row of jetgrout columns between Tubex piles



Wall section of the sandwich wall is complete

Core drilling

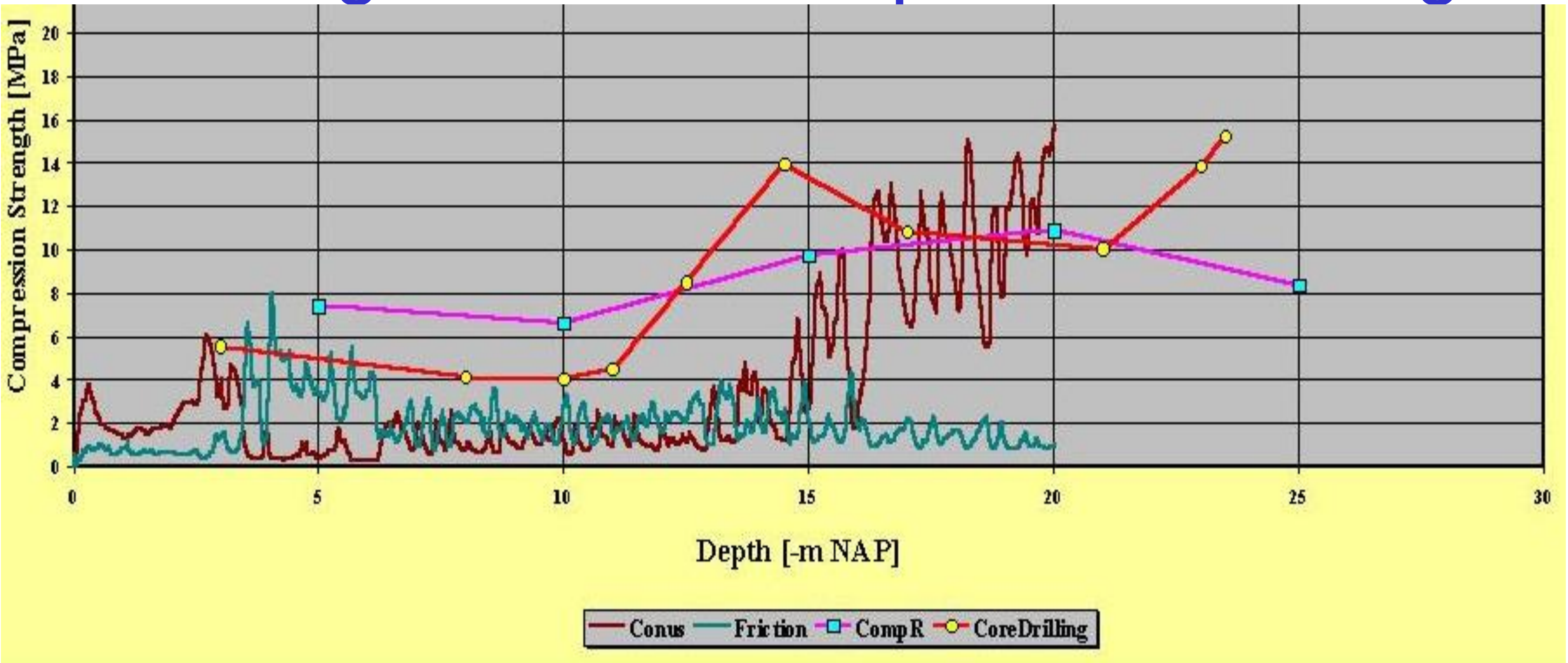


Total 12 core drillings

0-15 m: 4 x 48 samples (sand / clay) 7/28/56/120 days

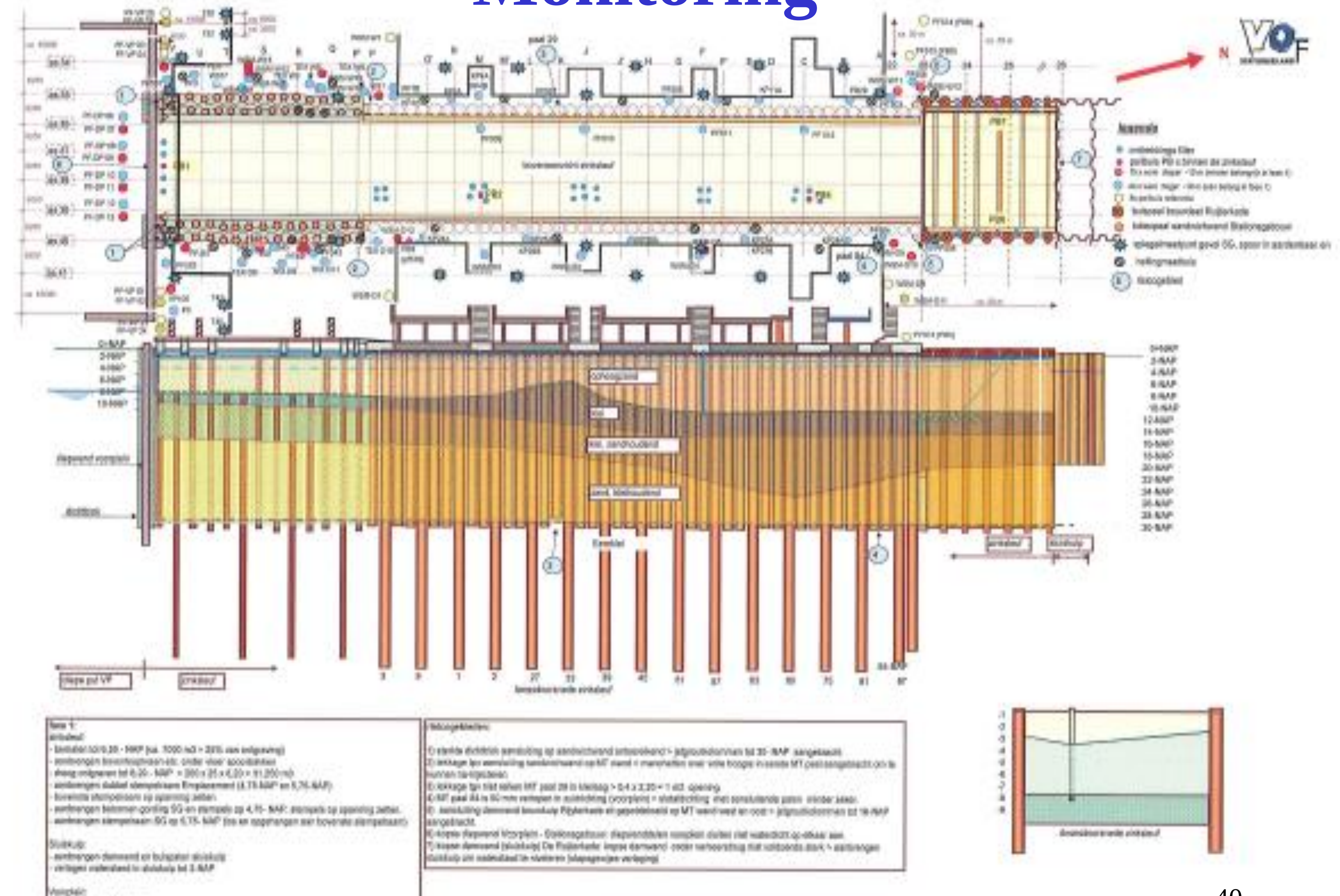
15-30 m: 4 x 48 samples (sand) 7/28/56/120 days

Influence ground on compression strength

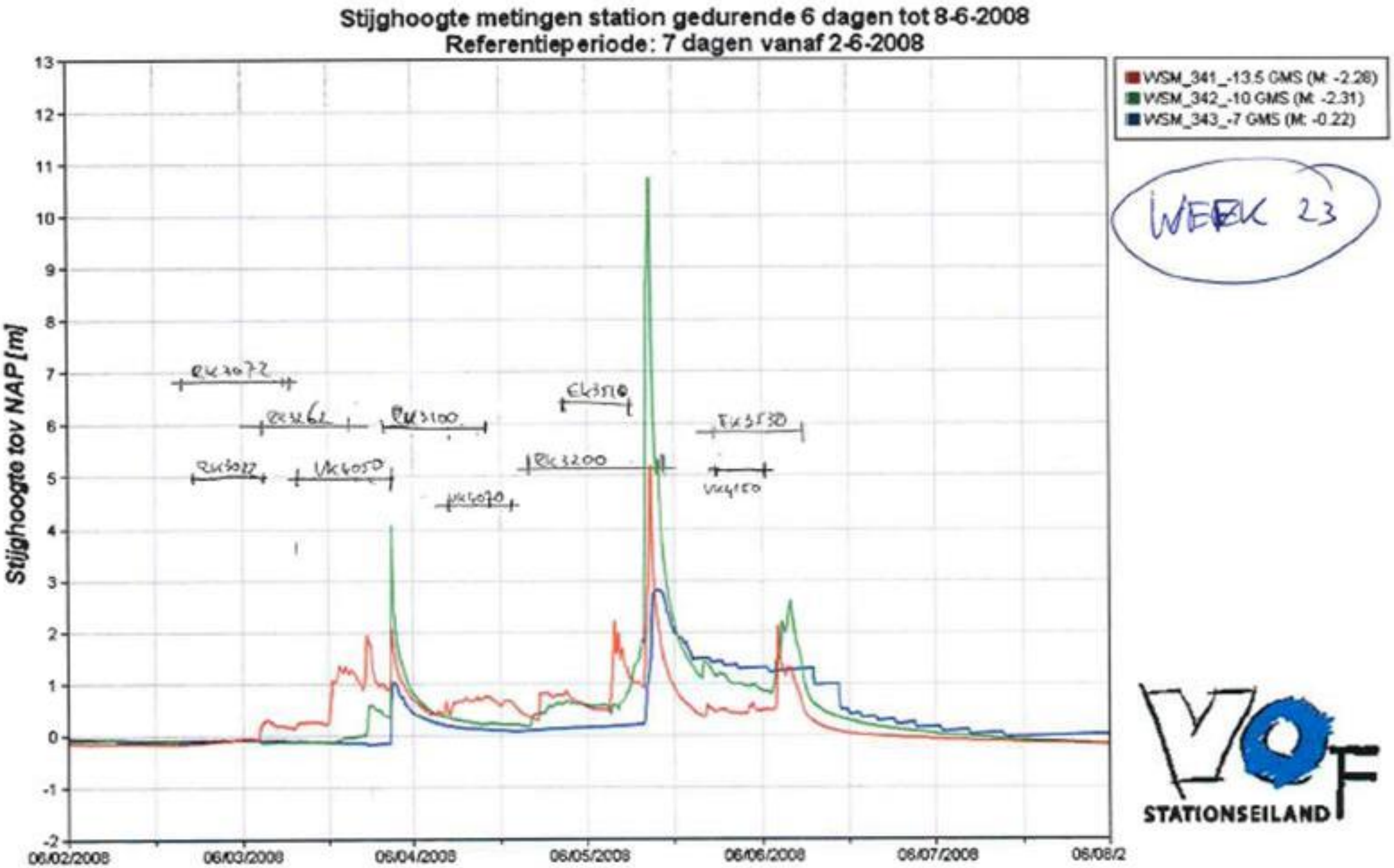


120 days	Strength 0-15 m gem	Strength 0-15 m Xd	Strength 15-30 m gem	Strength 15-30m Xd
mono-jet	6,1	2,1	11,6	3,8
bi-jet	7,0	3,9	10,9	2,9

Monitoring



Water (over) pressure



Sandwich wall

Conclusion

- The jetgrouting trial raised a number of points of interest in terms of technical content and procedure for the final work;
- Observational method (anticipate) the jetgrouting process, if necessary, to be adjusted;
- The intensive process controll was necessary and fruitful for a constructive and impermeable sandwich wall;
- Optimum quality of the desired end product

IS-GI 2012 SHORT COURSE 4

COMPENSATION GROUTING & JET GROUTING

Quality assurance of jet grouting

B. Lecomte, Solétanche-Bachy, France

1st of Septembre, 2013

TC 211 – Short courses on Jet-Grouting

QUALITY ASSURANCE OF JET-GROUTING

Basile LECONTE

SOLETANCHE BACHY

SUMMARY

1 – Introduction - What means « Quality Assurance » ?

2 – Usual controls in jet-grouting and interests

3 – Means of control

4 – Conclusions

WHAT MEANS « QUALITY ASSURANCE » ?

The « Quality Assurance » is defined as part of the « Quality Management ».

Different ways to define the « Quality Assurance » =>

-*The « Quality Assurance » aims to make the client confident that the quality requirements will be satisfied.*

- *The « Quality Assurance » gathers all the arrangements taken in order to give to the client the assurance that the requirements of the contract will be satisfied according to good practices OR all the arrangements taken to provide a product which complies with the client expectations.*

But also :

- *The « Quality Assurance » gathers* all the *arrangements taken to comply with the own internal rules of the company (as contractor => Internal Procedure / rules more restrictive than the contract requirement => Part of the Quality Management System).*

WHAT MEANS « QUALITY ASSURANCE » ?

On a jobsite, The « Quality Assurance » has many levels of application :

- Administrative (documents codification, issuing and classification …)

- Site organisation (Organisation chart, internal and external meeting …)

- Site execution (method statements, ITP, supervision, reports, drawings …)
- Site closing (as-built, final report …)

- …

This presentation will deal with the controls implemented during the execution stage and related to the construction of a jet-grouting element (main works or trials).

The list of controls we are going to see is not exhaustive, other controls can be carried out. Also, depending on the scope of work and contract requirements, all these controls are not always implemented (ex : no need to check the borehole deviations for small shallow columns).

The controls to be done are listed in the ITP.

WHAT MEANS « QUALITY ASSURANCE » ?

Example of ITP (not complete)

ACTIVITY / CONTROL POINT	RESPONSIVE	REFERENCE	MEAN	TARGET	TOLERANCE	FREQUENCE	REMEDIAL ACTION	HP	CP	SP	SR
GENERAL ACTIVITIES											
Column setting out	FO	Drawings	Survey / Measure tape	Column coordinates	+/-2cm	Each column	Set out again		X		
DRILLING											
Drilling depth displayed on the computer	OP	Rod length / measure tape	Visual	0,5%	+/- 0,5%	Once a week	Calibrate the depth sensor again			X	
Rig setting - position	FO / OP	Columns setting out marks	Rig moving	Drill bit on the marks	+/-3cm	Each hole	Adjust the rig position			X	
Rig setting – Mast verticality or mast angles	FO / OP	Drawings	Spirit level / Mast inclinometer / survey	Designed angles	+/-0,2°	Each hole	Set again / adjust mast inclination			X	
Verticality / inclination	SC	Theoretical column coordinates at ground level	Slope indicator + grooved pipe	Designed position at depth	variable	Each hole	Remedial hole / adjust column diameter			X	
JETTING											
No. of nozzles	FO / OP	Method statement	visual	Method statement requirement	none	Each column	Add or remove nozzle			X	X
Nozzle(s) diameter	FO / OP	Method statement	Drilling bit / calliper	Method statement requirement	0,1mm	Each column	Change nozzle			X	X
Jetting depth (bottom and cut-off level)	OP	Drawings	Computer display / number of rods	Drawings depth	0,1m	Each column	Drill again or lift up the rods			X	X
Jet fluid pressure at the rig	OP	Method statement	Visual (gauge, computer display)	Method statement requirement	+/- 10bars	Continuously	Adjust the pump flow to meet with the required pressure			X	X

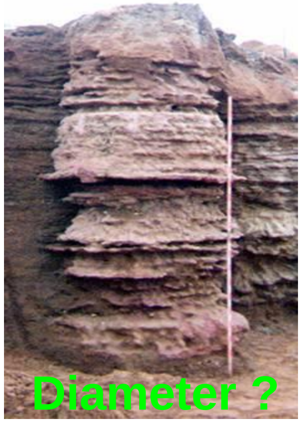
WHAT MEANS « QUALITY ASSURANCE » ?

Generally on a jet-grouting jobsite, the main requirements (concerns) of the client / Engineer are the following :

- **Diameter** (dimensions) of the jet-grout elements (estimation, accuracy, variations …)
- **Strength** (UCS) and **Young Modulus** (E) of the jet-grout elements (struting, underpining, lagging with arch effect …)
- **Overlapping** between adjacent columns (diameter, verticality …)
- **Continuity** of the jet-grout elements (mask effect, collapse, non-jeted length …)

All these aspects haven't the same importance depending on the scope of work :

- Underpining
- Cut-off wall (watertightness)
- Ground improvement (settlements)
- Foundation
- Retaining wall
- Struting
- Slab



=> Of course, the ITP has to be adapted to the scope of works !!

USUAL CONTROLS IN JET GROUTING AND INTERESTS

BEFORE JETTING :

CONTROL	INTERESTS / PURPOSES
Column setting out at GL	- Locate the drilling starting point with accuracy (<2cm) - Clearly (tag, stake ..) identify the drilling starting point
Rig Setting up **=> position and mast verticality or angles**	- Ensure that the rig is set up with accuracy (<3cm, <0,2°) at the drilling starting point (inclination, orientation, verticality of the boom) - Limit the drilling deviation
Cutting analysis	- Confirm the geology - Adjust if needed the depth / length of treatment (cut-off) - Identify or confirm some layers with organics
Drilling parameters **=> depth, torque, Drilling speed, …**	- Ensure that the jet grout element is at the right depth (0m = nozzle) - Compare the drilling report with the expected geology - Detect some voids, fractures ... (spoil return)
Drilling deviations	- Position the column at depth (as-built) - Adjust the column diameter (cut-off)
Checking of the monitor nozzle(s), drill bit size and type and rods and hoses diameter	- Ensure that the jetting parameters will be applicable - Facilitate the drilling (nature of the ground) and limit the deviations - Provide a good spoil return (annular space) - Anticipate and estimate the pressure losses (pump capacity)
Cement performance / grout strength / mixing and ground water quality	- Ensure that the performances of the cement are in accordance with the expert expectations - Estimate the impact of a pollution on the grout setting (mixing water or ground water)

USUAL CONTROLS IN JET GROUTING AND INTERESTS

WHILE JETTING :

CONTROL	INTERESTS / PURPOSES
Grout composition **=> density,** bleeding, viscosity	- Ensure the final strength of the column - Anticipate any change in the relashionship between Pressure and Flow (grout density or nozzle wear) - Anticipate any problem linked to the bleeding (plug the pump ..)
Jetting parameters **=> Pressure, Flow, Lifting speed, rotation speed**	- Ensure that the correct jetting energy (and constant) is applied on the entire length of the column (consistency of the column diameter) - Confirm that the correct nozzle are used - Be able to adjust the jetting parameters if needed (substitution ratio, utilities ..)
Spoil aspect, density and bleeding	- Make an estimation of the diameter (in appropriate ground conditions) - Estimate any variation in the column diameter (ground condition variations) - Appreciate the overlapping between adjacent columns (hard-fresh) - Confirm the geology (Clay / Sand / gravel) - Estimate the bleeding inside the column and the need to compensate it with spoil or grout (underpining)
Spoil return	- Avoid any clacage and damage on the existing structures around the site
Pressure losses along the circuit	- Verify the estimation made at tender stage and eventually adjust je jetting parameters (pump capacity) - Be able to work looking at the pressure instead the flow (flow is the same everywhere but not the pressure)
Visuel check of the vicinity of the site	- Ensure that no damage are caused on the existing structure - Avoid any spoil ingress inside an adjacent utilities / galery.

USUAL CONTROLS IN JET GROUTING AND INTERESTS

AFTER JETTING :

CONTROL	INTERESTS / PURPOSES
Diameter / dimension of the jet-grouted elements	- Provide adequat bearing capacity / area - Provide a sufficient overlapping between adjacent columns
Strength of the Columns **=> Spoil and core samples**	- Compare the strength between spoil and core samples - Estimate the strength variations (deviation …) - Ensure theta the column can « play » its structural role - Anticipate some variations in the diameter or in the ground conditions (after jetting but to be check all along the site) - Anticipate any « pollution » in the ground (sulfate, organics)
Strength of the grout	- Verify the cement performance consistency and the grout composition (+ density)
Continuity / overlapping	- Confirm the integrity of the jet-grout element (no block with mask effect, no non-jeted length …) - Provide a continous barrier or cut-off wall (watertightness)
Permeability **=> Spoil / core samples, mass permability**	- Control the column permeability - Estimate the mass permeability of a cut-off wall or a jet-grouted block - Estimate the water ingress (flow) in a excavation
Bleeding and filtration effect in the column (settlement)	- Provide a good compensation with grout or spoil (underpining) - Anticipate the compensation volume

MEANS OF CONTROL

GROUT AND SPOIL DENSITY

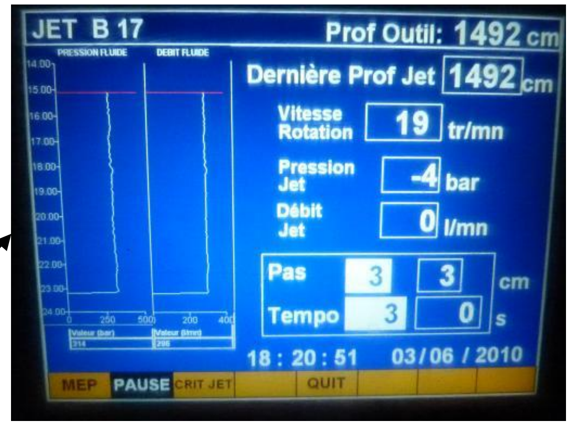
Baroïd / Mud scale

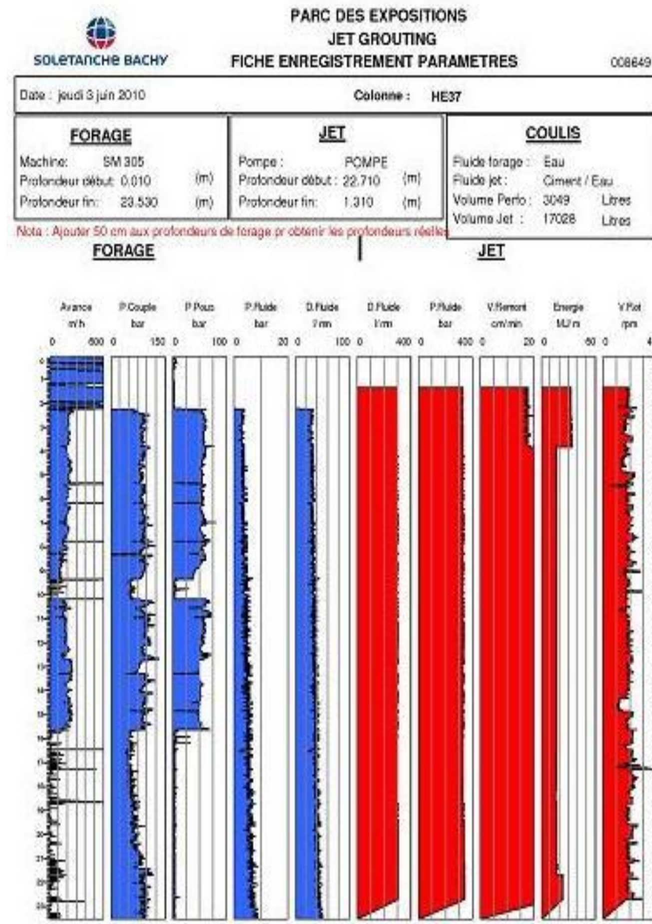
Digital scale + 1 or 2 litres container

Hydrometer

MEANS OF CONTROL

JETTING / DRILLING PARAMETERS - Recording





MEANS OF CONTROL

JETTING / DRILLING PARAMETERS – Flow measurement

Electronical flowmeter

- Need to be calibrated
- Work with water and grout
- < 3% accuracy
- Possible wire or radio transmission to the parameter reccorder on the rig
- Need to be often cleaned

SOIL MEC S.P.A. CESENA - ITALY

7 T500 J JET GROUTING UNIT

ENGINE RPM	GEARBOX RATE	SPM	PISTON ø 3" DELIVERY LT/1'	PISTON ø 3" MAX PRESSURE BAR	PISTON ø 3" 1/2 DELIVERY LT/1'	PISTON ø 3" 1/2 MAX PRESSURE BAR	PISTON ø 4" DELIVERY LT/1'	PISTON ø 4" MAX PRESSURE BAR
1200	1	26	63	650	85	650	112	520
1600		34	84	650	114	650	149	520
1900		41	99	650	135	650	177	520
1200	2	36	87	650	119	650	156	520
1600		48	117	650	159	650	208	520
1900		57	139	650	189	650	246	520
1200	3	49	120	650	164	650	214	520
1600		66	161	650	219	650	286	520
1900		78	191	650	260	650	339	520
1200	4	68	166	650	226	650	295	500
1600		91	221	650	301	570	394	440
1900		108	263	650	358	490	468	380
1200	5	92	225	650	306	490	400	370
1600		123	300	540	408	420	533	320
1900		146	356	490	485	360	633	280

VOLUMETRIC EFFICIENCY = 1
MECHANICAL EFFICIENCY = 0.85

0953-3583 E

Stroke counter at the pump

- One stroke = 1 volume
- Volume of grout pumped at each piston stroke never known with accuracy
- < 10% accuracy

Stroke counter at the rig

- Installed on the rig (pressured line)
- Based on the pressure peaks
- STroke volume to be input in the computer.
- Filtration time to be calibrated to avoid counting the rebounds of pressure.
- Possibility to work with 2 filtration time in case of using prejetting or different jetting parameters in the same column.
- Need to be often cleaned
- < 10% accuracy

The air flow can also be measured at the rig using a classical air flowmeter

MEANS OF CONTROL

JETTING / DRILLING PARAMETERS – Pressure, rotation and lifting speed measurements

- **The pressure** (Air + grout) is measured with a sensor (4-20mA) directly installed on the HP line on the rig. Generally, a gauge is also installed on the rig to double check.

The rotation speed is also measure with a sensor (4-20mA) installed on the rotation head of the rig. It can be adjusted manually or directly by the rig (jetting mode).

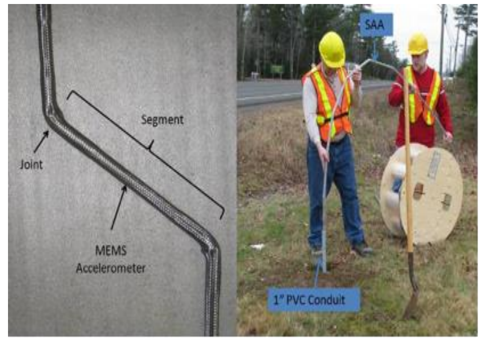
- **The lifting speed** is not measured but controled by an automaton which acts on the hydraulic system of the rig. The automaton is often part of the parameter recorder (computer).

MEANS OF CONTROL

BOREHOLE DEVIATIONS

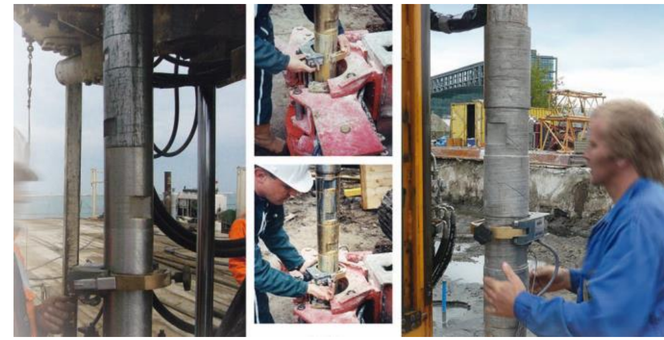
Inclinometer probes

- Generally accurate
- More or less easy to use
- With or without grooved pipes
- With or without compass or gyroscope
- Different diameters (25 to 42mm)
- Possibility to check the deviations inside the rods
- Very usefull when using predrilling (as-built before jetting)
- More or less influenced by the temperature
- For horizontal or vertical holes



Chain of accelerometers

- Composed of segments (33 or 50cm)
- One accelerometre / segment
- One temperature sensor / segment
- Horizontal and vertical
- Small diameter (25mm)
- Possibility to check the deviations inside jet rods
- Very fast method



Instrumented drill rods

- With ou without compass (in case of steel parts)
- Directly installed on the rod string above the monitor
- Generally, exploitation of the measure once the column is contructed (except when using predrilling)
- Adapted to double or single jet

MEANS OF CONTROL

DIAMETER ESTIMATION / MEASUREMENT

Many different means to measure / estimate the diameter of a jet-grout column exist on the market. They often have been developped by the contractors themselves or by instrumentation / equipement companies. Hereinafter are listed some methods / devices that are commonly used to estimate or measured the column diameter.

Simple ways :

- Column exposure

When it is possible (above water table and shallow column), it is possible to clearly determine the column diameter just by exposing it.

- Spoil density

To be able to estimate with a good accuracy a column diameter through the spoil density, three points have to be verified :

- Good knowledge of the ground conditions (bulk density, water content …)
- Good contrast of density between grout and soil (bulk density)
- Spoil representative of the eroded soil

Therefore, this method doesn't work (very well) :

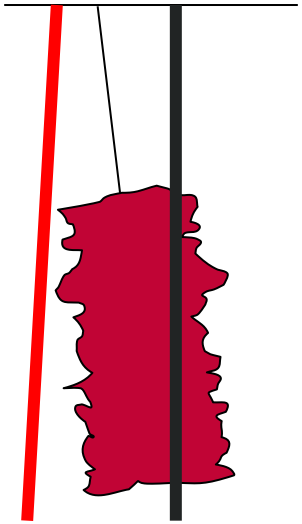
- In Clayey soils because of their low density (to close to the grout density) => small mistake on the density = big mistake on the diameter)
- In very coarse soils (gravels, blocks) because the coarse particules tend to settle down the bottom of the column => spoil density non-representative of the in situ soil.
- When using prejetting

This method is quite accurate in sandy soil (the denser the better) if the spoil is correctly sampled

MEANS OF CONTROL

DIAMETER ESTIMATION / MEASUREMENT

- Coring



Coring can be used to estimate the diameter of a jet-grout column with an variable accuracy depending on the conditions. Indeed, **coring will be accurate in case of shallow columns** (<10m depth). Then, the deeper is the column the less accurate is the method. At least, when trying to estimate the diameter of a deep column, the vertiaclity of the column and the coreholes have to be checked … but even with this V-check, we are often surprised by the results.

Coring involves a minimum strength of the column. The Sonic coring (with no water) will be preferred to the standard coring for soft column.

Also, when coring a column with lot of gravel in it, it happens thet the core barrel remains either empty of full of non-treated ground because with the high rotation speed, the gravels tend to roll inside the core barrel destructuring the cement matrix which is washed away by the water flushing.

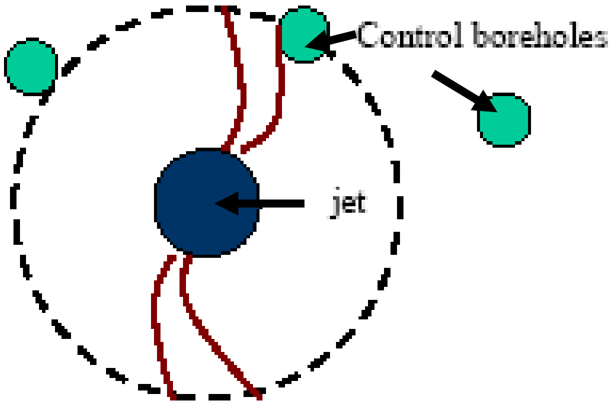
- Caliper

The caliper, also called « umbrella », is composed of 2 or 3 « arms ». An hydraulic jack allows to open the arms.

The device is lowered in the fresh column (just after completion) and the arms are opened at different levels inside the column. The diameter of the column is determine by the opening of the arms (volume of hydraulic oil).

MEANS OF CONTROL

DIAMETER ESTIMATION / MEASUREMENT



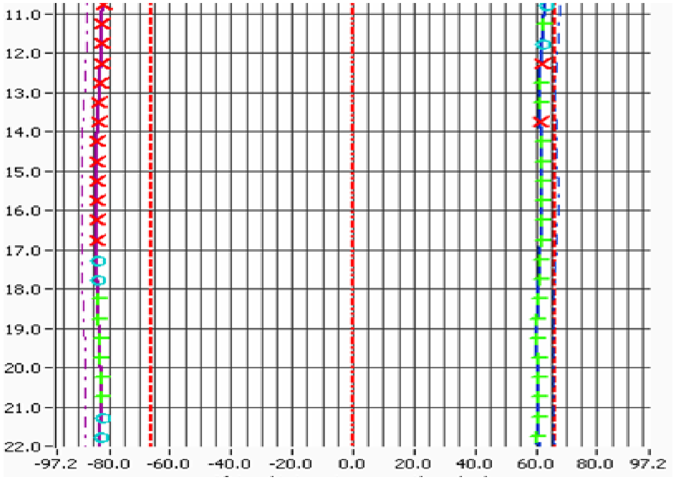
- Vibration measurement

This technic consists in recording the vibrations induced by the high pressure jet.

Some control holes are installed at different locations and distances around the column and the vibrations are record while jetting.

Depending on the vibration intensity, some logs are realized and analysed to determine, regarding the depth, if the control hole was or not in the column.

This method requires to check the deviations of the column and of the control holes.



- Painted Bars

An alternative exists using painted bars. If the paint as been wash away, that means the bar has been touched by the HP jet.

MEANS OF CONTROL

DIAMETER ESTIMATION / MEASUREMENT

- Electrical method – CylJet ®

Cyljet is a patented process of electrical investigation based on the contrast of resistivity between jet-grout column and surrounding ground. It allows having a good estimation of the column diameter (< 10% accuracy) whatever the ground conditions and whatever the depth. The measure of the resistivity is made using a string of electrode (every 33 or 50cm).

The principle is the following :

- Drill a calibration hole in the virgin ground down the bottom level (+2m) of the jet-grout column to be constructed.

- Make a first measure in the virgin ground to draw up a **MEASURED resistivity card of the "virgin ground"** => Calibration process.

- Based on the **MEASURED resistivity card of the "virgin ground"** a **CALCULATED resistivity card of the "virgin ground"** is drawn up by calculation => The geological layers corresponding to this calculated card is called the **MODEL.**

- Construct the jet-grout column

- After a setting time (24h to 7 days depending on the ground conditions), drill through the column up to its bottom level (+2m)

- Make a second measure inside the column to draw up **a MEASURED resistivity card of "Column + Ground"**

- Finally, starting from the **MODEL**, a simulation (by calculation) is made by introducing a "virtual" column with a diameter D. Thereby a **CALCULATED resistivity card of "column + ground"** is drawn up. By iterative calculation, the aim of the method is to adjust the diameter of the column until the **CALCULATED resistivity card "column + ground"** matches with the **MEASURED resistivity card "column + ground"**.

- A profil of the jet-grout column can be issued after only 24-36 hours after the measure in the column.

MEANS OF CONTROL

DIAMETER ESTIMATION / MEASUREMENT

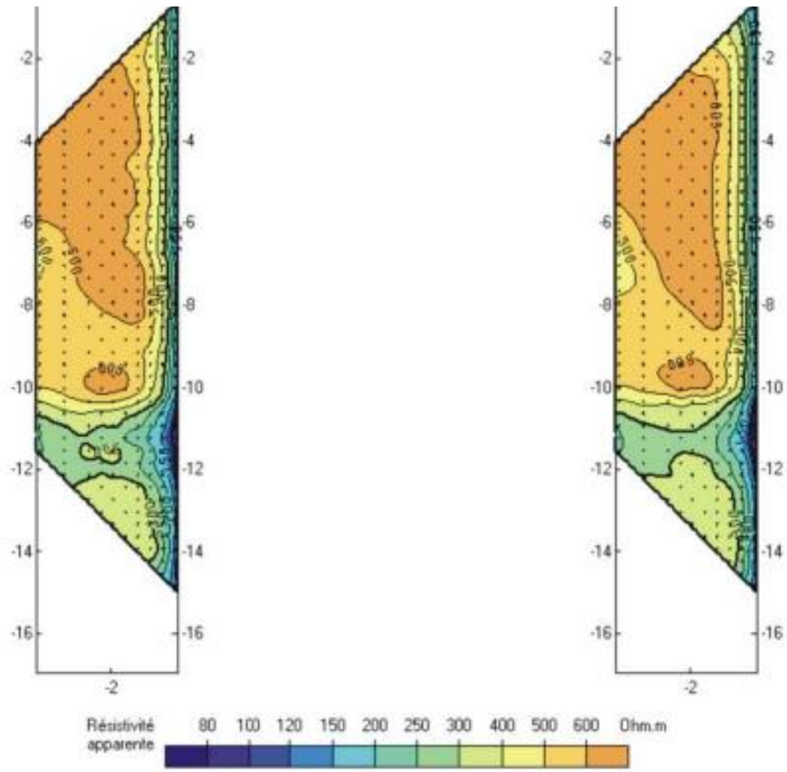
-**Electrical method – CylJet ® - MODEL**

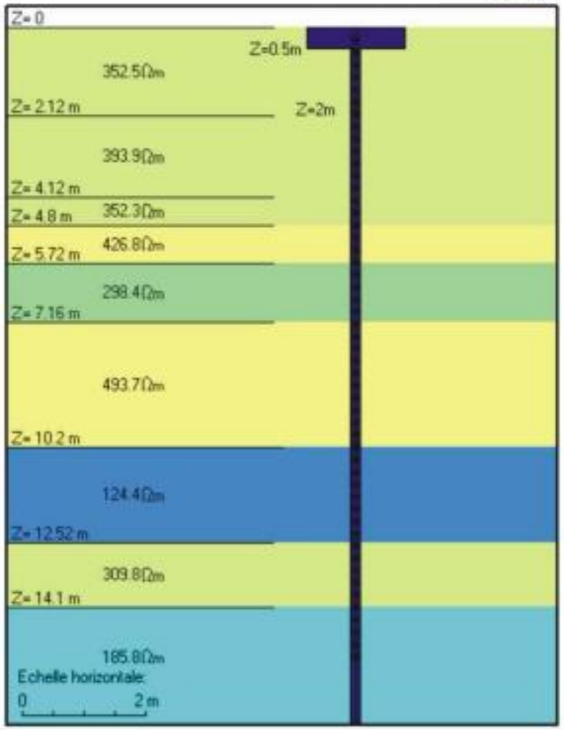
LAC NYOS - Mesures CYLJET - Ce3-1

MEASURED Resistivity card « virgin ground »

CALCULATED Resistivity card « virgin ground »

Corresponding MODEL





Modèle initial pour l'inversion

MEANS OF CONTROL

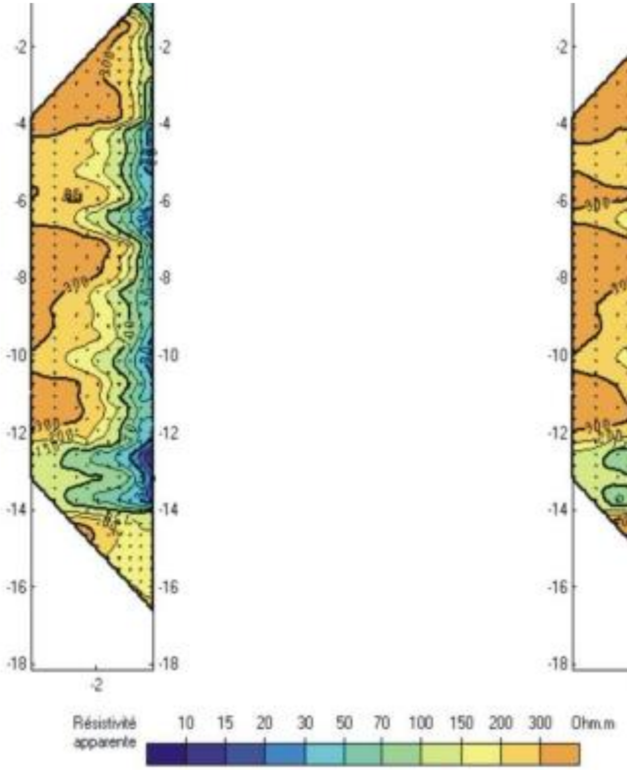
DIAMETER ESTIMATION / MEASUREMENT

-**Electrical method – CylJet ® - COLUMN PROFIL**

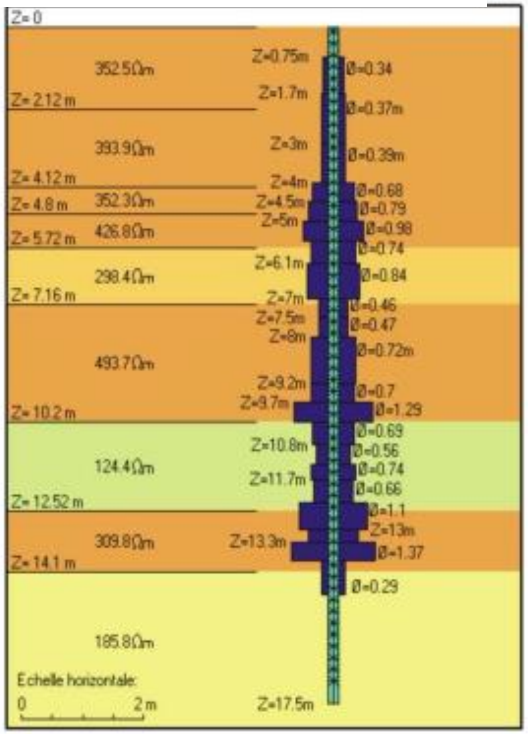
LAC NYOS - CYLJET - Colonne CE3-1

MEASURED Resistivity card « virgin ground)

CALCULATED Resistivity card « virgin ground)



Co **Corresponding MODEL**



Modèle initial pour l'inversion

CONCLUSION

Jet-grouting has been replaced by other cheaper technics as soilmixing in many cases. However, jet-grouting is a very specific technics that keeps an interest for many technical works.

In most cases, jet-grouting elements are not exposed. Therefore, the Quality Assurance is of interest to ensure that the client requirements are met.

Jet-grouting is an empiritical technics and the trial columns allow adjusting the jetting parameters. Unfortunately, in many contracts, no trial columns are budgeted. That's why, especially in jet-grouting, the REX (as part of the quality assurance) is very important and all the site experiences (good or bad) have to be registered in a data basis. That will be inevitably useful for futur projects !!

Thank you for your attention !!!

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