# Rebuilding Metrostation CS, Rotterdam

## Unique experience on large scale application of ground freezing techniques

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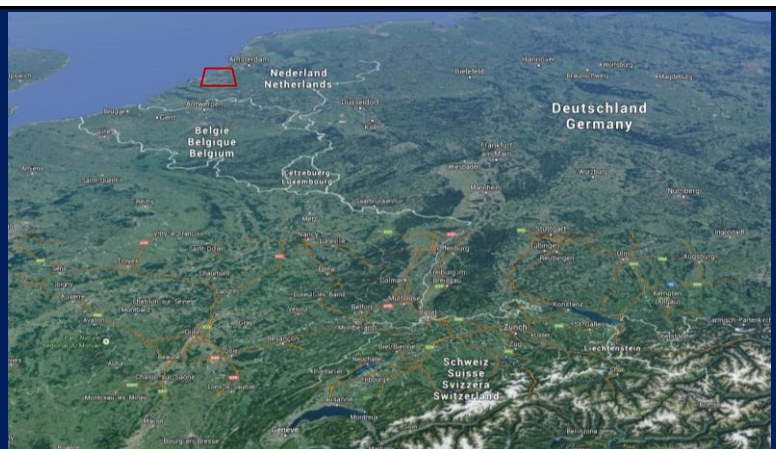







## Stationsplein Rotterdam 2003 - 2014

Major re-building operation as to facilitate public transport in 21st century:

- (inter-) national heavy rail including high speed connection to Amsterdam, Bruxelles, Paris
- regional lightrail (RandstadRail), local public transport (trams, buses)
- underground parking facilities (car, bicycle)

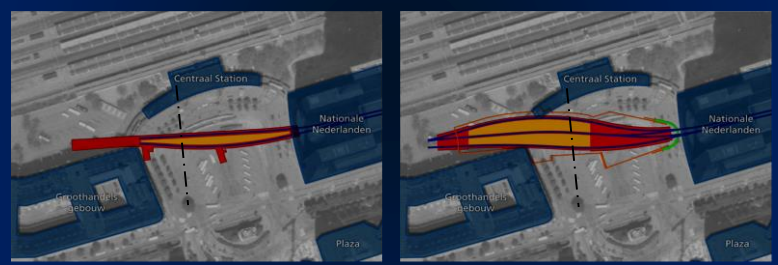



## Stationsplein Rotterdam 2003 - 2014



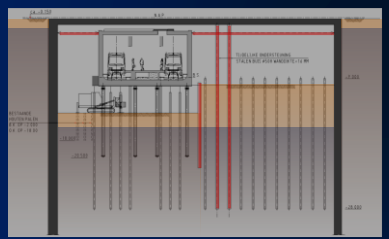

## Rebuilding Underground Infrastructure

**from** **to**



# Rebuilding Underground Infrastructure

**rebuilding** **to**

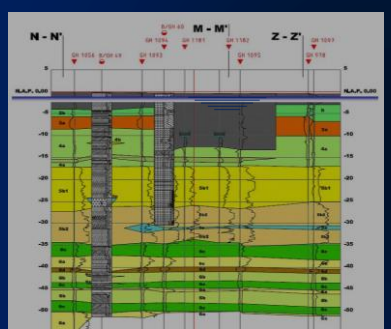




# The Building Pit



# Soil Conditions




Soil stratigraphy (typical for Rotterdam area):

- ~4m sand
- ~12m clay - peat - clay (impermeable, soft)
- ~18m sand (permeable, dense > piled foundations)
- ~15m multi layered (clay - loam - peat - sand)



# Basic Design of Building Pit

Interface boundary conditions:

- neighbouring / sequential infrastructure building projects
- continuity of traffic and public transport to be ensured
- duration of works (many years)
- building in urban area

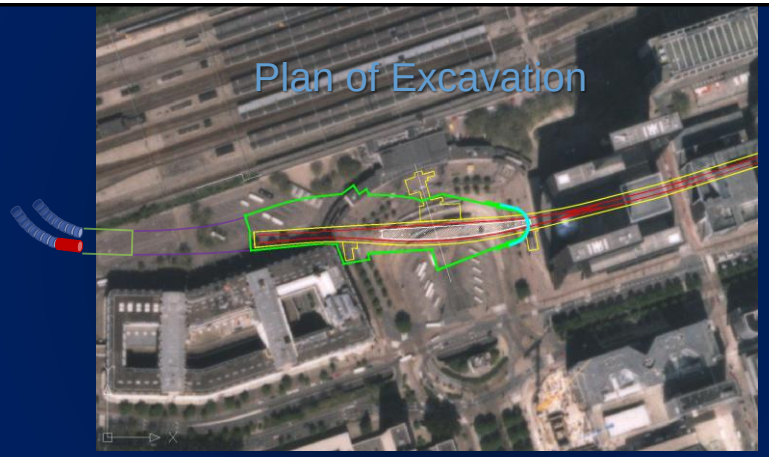
Two contracts:

i. preparatory works (excavation)
ii. re-building underground station CS

Key data:

- area ~ 7500m$^2$, dry excavation to 14m depth
- diaphragm walls to 38m depth, thickness 1.5m / 1.2m / 1.0m for ~90% of excavation circumference (~ 500m')
- including foundation elements for future buildings (to be designed at the time)
- 'wand-en-dak' building method

## Plan of Excavation

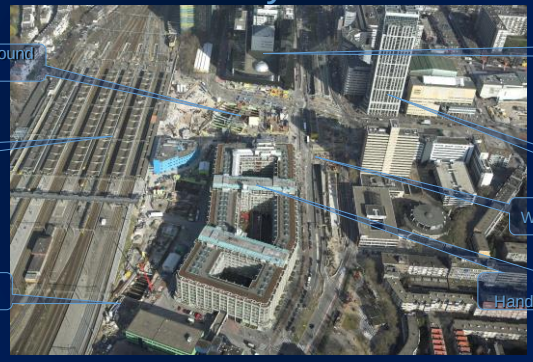




## Impression of the works .....



## Interface boundary conditions .....






## Diaphragm walls near Groot Handelsgebouw .....

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## Underneath existing underground tunnel (in full service!) .....



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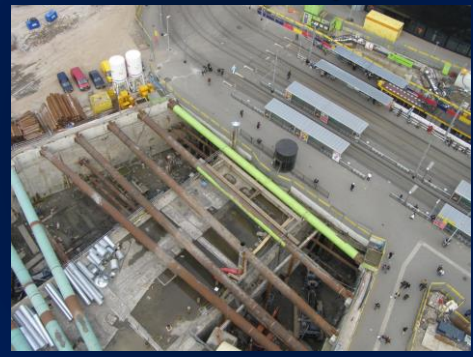
## After more than 40 years .....

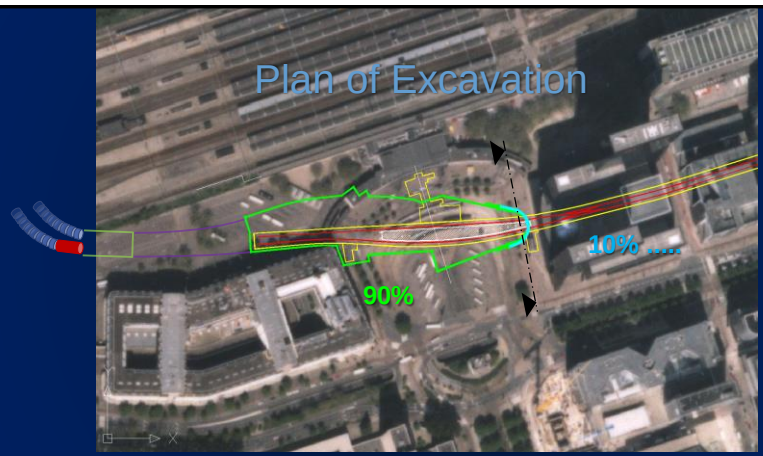




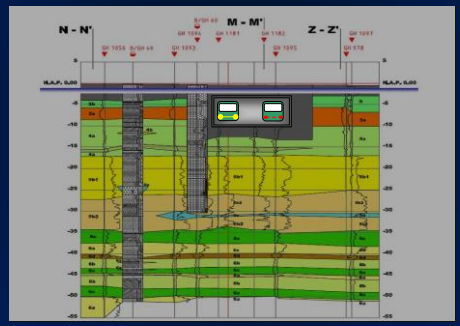
## The Collar Construction



## Plan of Excavation



## The Collar Construction



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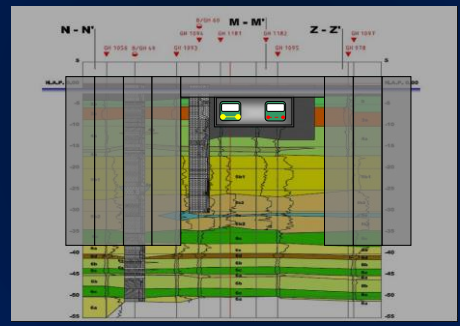




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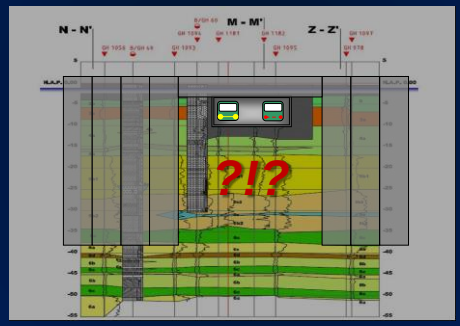





## History

- Stationsplein anno 2000

# History

- Stationsplein anno ~1960



# History (1) – Building of Erasmus line

Building method:

- floating tunnel sections
- founded on pre-installed concrete piles
- backfill of channel with sand



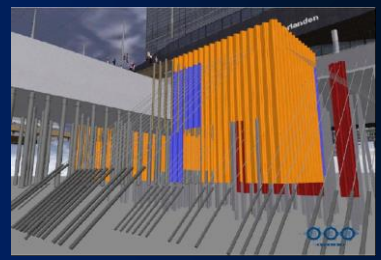
# History (-1)

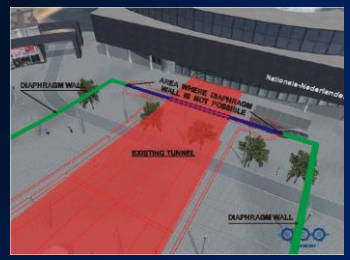
- Beginning of 20th century: Railway station & Zoo



# How to deal with this?

- Diaphragm wall considered not feasible: special design ‘collar construction’ around existing underground tunnel required





## Collar Construction Design Requirements

- Watertightness – risk of damage to existing underground tunnel underneath office building Delftse Poort
- Underground traffic not to be affected
- Structural requirements, a.o. retaining height ~15m (including water pressure)



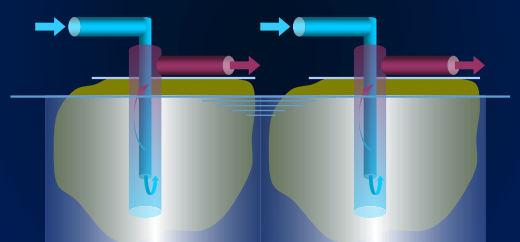
## (May 2003)

- Risk Analysis Session (Geotechnics) reveals that conceptual design of collar construction needs to be improved
- Conceptual design based on jetgrouting - negative experience
- Additional risks as identified: underground obstacles, long duration of works inside excavation pit
- To be investigated: feasibility of ***ground freezing*** techniques?!



## Ground Freezing Principle

- Use cooling agent to retract heat from ground water: frozen soil!





## (2003 & 2004)

- Feasibility study on application of ground freezing (Rotterdam Public Works in cooperation with CDM Consult GmbH, Bochum)
- Conclusion from study: ground freezing is feasible, for various design concepts
- Decision required: which design concept –based on application of ground freezing technology- to be adopted?
- Design review session (1): expert opinion in-house Rotterdam Public Works

# (2004)

Design review session (1):

- Review on structural aspects, safety, costs, overall feasibility

Outcome of design review session (1):

- collar construction to be generated by means of vertical freeze pipes to ~38m depth
- further optimization of collar construction design is required
- collar construction will be part of Contract (ii) re-building of underground station



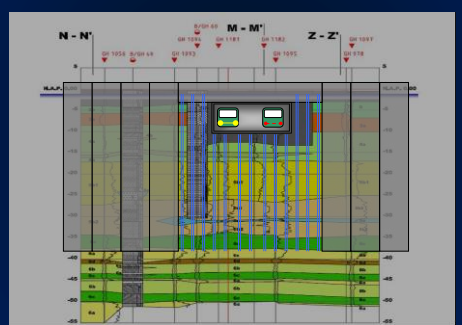
# (2004)

Risk Analysis Session (Ground freezing technology), topics to be investigated:

- groundwater flow (as induced by dewatering activities within nearby building projects)
- safety (workers & travelling passengers)
- scenario analysis (e.g. what to do when freezing system fails)
- underground obstacles (positioning of freeze pipes)

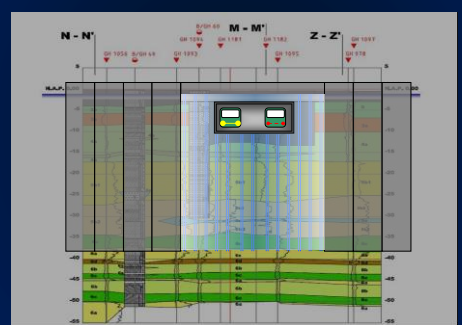


# The Collar Construction






# The Collar Construction



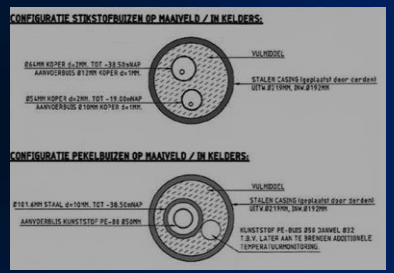
# (2005)

- Design review session (2) –external expertise- all disciplines (structural, geotechnics, ground freezing, contractual)
- Final design optimizations of collar construction: shape (arch), two rows of freeze pipes, two freezing techniques ($LN_2$ & brine), reinforcement of existing tunnel, lay-out of freeze pipes and piping in tunnel, ground freezing side-effects (creep behaviour, frost heave), heating pipes .....?!?
- Contract part (i) has commenced, including some preparatory works (freeze pipe casings) for installation of freeze pipes
- Preparations for Contract part (ii) – detailed specifications for ground freezing



# The Collar Construction

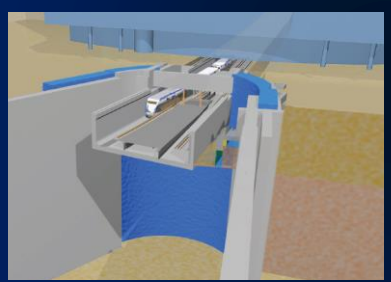
- Minimum thickness 2.5 m (frozen soil volume > ~4000 $m^3$)
- Ca. 100 (freezing) pipes: 50% brine, 30 % $LN_2$ en 20% temperature monitoring
- Pipes to be inserted into pre-installed casings
- Anticipated duration of ground freezing works: two months (freeze-up) + 1.5 years (maintenance)






# The Collar Construction

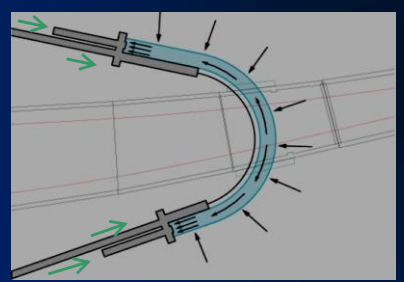
Arch shape retaining wall .....



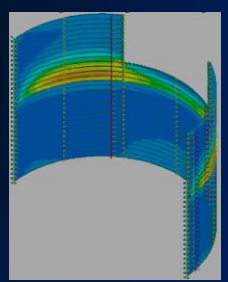


# The Collar Construction

Simple structural concept .....



..... complex FE calculations req'd



## (2005-2006)

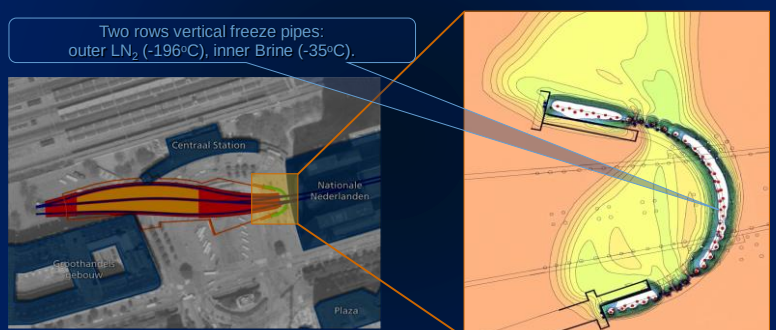
- End 2005: award of Contract (ii), however Contract (i) has not been completed (ground freezing preparatory works still ongoing)
- Main contractor TBI/Voormolen (> Haverkort Voormolen > Mobilis) have subcontracted ground freezing works to Max Bögl
- Preparations (engineering, operation manuals) for ground freezing operation by Contractor (in accordance with detailed Contract specifications)
- Acceptance of documents & procedures, preparations in the field



## Thermal Calculations



## Thermal Calculations






## Thermal Calculations

Typical for ground freezing engineering, a.o. accounting for:

- Combined freezing using Brine and $LN_2$
- Possible groundwater flow v = 4.0m/day (design value) during freeze-up period
- Varying soil properties (layers)
- Effect due to existing underground tunnel (heat source)
- Scenario analyses, a.o. temporary malfunction of freezing equipment during maintenance period

# Thermal Calculations (cont'd)

Special topic: Installation of new pile foundation near collar construction (bearing capacity of piles as installed into frozen soil is unknown/uncertain)

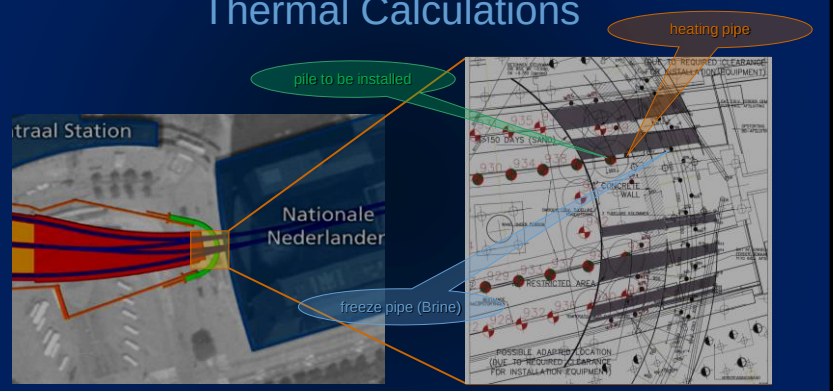
Solution: pile installation in unfrozen (thawed) soil, using heating pipes

Options (Contractor's choice/responsibility):

- thawing of soils
- control of freezing process, as to limit growth of frozen soil body towards pile installation area



# Thermal Calculations



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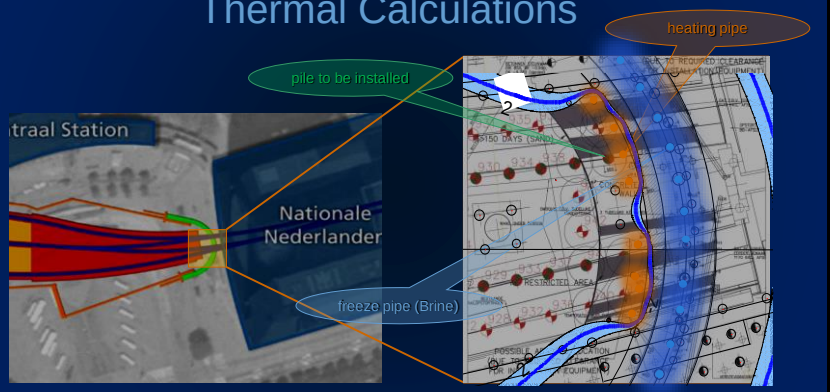





# Contract

## Contractual Aspects & Risk control

General

- Design (Feasibility - Concept - Final – Detail) by Rotterdam Public Works
- 'Traditional' contract (Contractor to perform the Works according detailed Contract Scope of Work & Specifications for Ground Freezing Operation)
- Archiving (as-built) / Quality Control using 'VISI'-system
- Extensive Monitoring Scope of Work, to be executed by Contractor (on-line access & real-time/live when required)
- Rotterdam Public Works responsibilities:
  - Building coordination
  - Pro-active when unforeseen events occur
  - Risk Management – dedicated team



## Contractual Aspects & Risk control

Special topics related to Collar Construction

- Design responsibility with Rotterdam Public Works
- Contractor to be responsible for execution of ground freezing works (mob/installation, freeze-up, maintenaince, removal/demob)
- Required: combination of thermal calculations (by Contractor) and temperature monitoring (by Contractor)
- Minimum requirements for thermal calculations and monitoring as per Contract Specifications
- .....



## Contractual Aspects & Risk control

Special topics related to Collar Construction (cont'd)

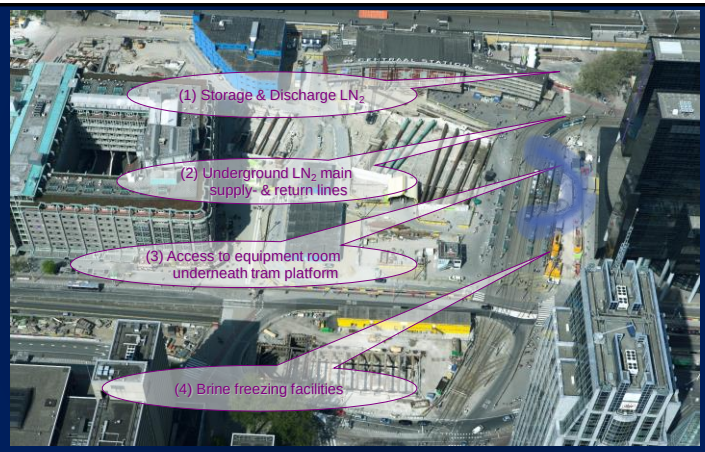
- .....
- Contract Specifications for Ground Freezing Operation:
  - location/position (3D) of freeze pipe and temperature monitoring pipes, as-built from Contract (i) and to be installed as per subject Contract (ii)
  - limiting values for size and temperature of frozen soil body
  - description of (thermal) engineering
  - design values for groud freezing (soil) parameters
  - boundary conditions (a.o. safety, procedures, permits, working hours)

N.B.: regular monitoring program in seperate part of Contract



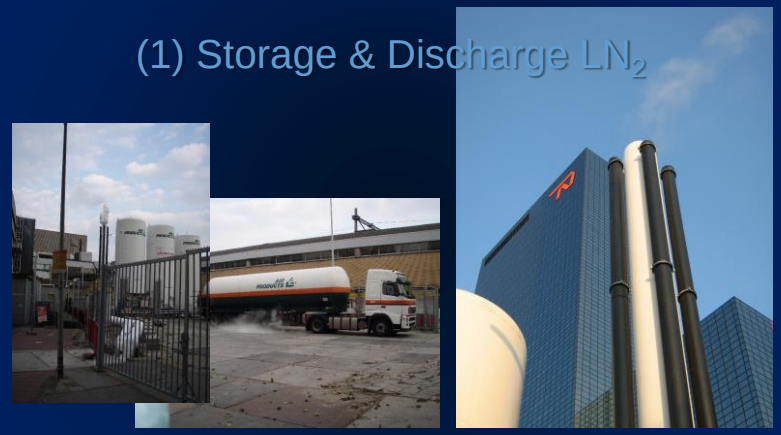
## Start Freezing Operation

March / April 2007






## (1) Storage & Discharge $LN_2$





## (2) Underground $LN_2$ main supply- & return lines



## (3) Access to equipment room underneath tram platform

## (4) Brine freezing facilities

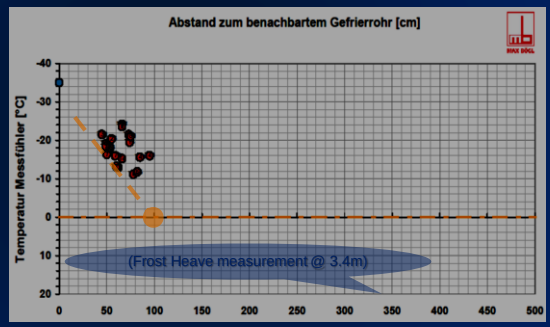


## Monitoring Data



## Thickness (radial) of frozen soil body Peat layer

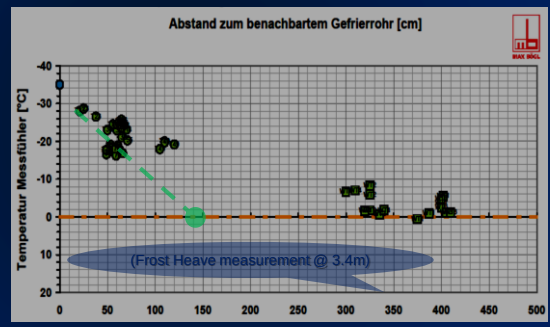
October 2007:
~1,0m





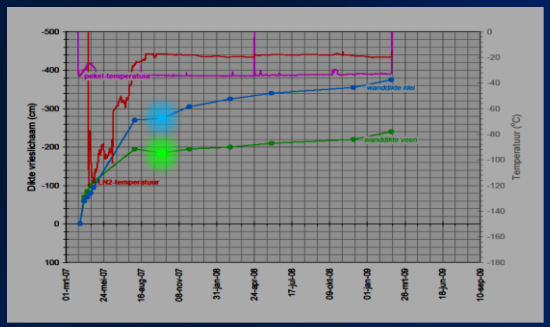

## Thickness (radial) of frozen soil body Clay layer

October 2007:
~1.4m



# Thickness (total) of frozen soil body

October 2007:
~1.9m (peat)
~2.8m (clay)

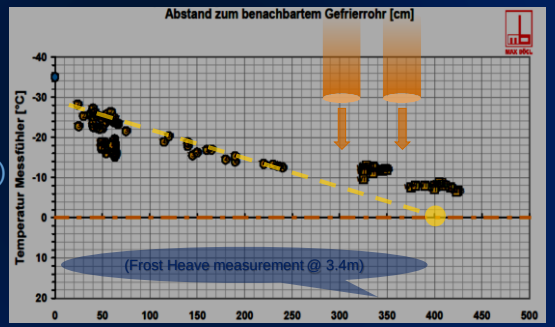





# Thickness (radial) of frozen soil body Sand layer

October 2007:
>4m

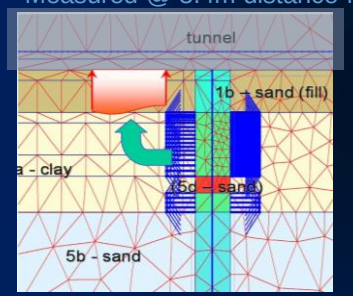
(pile installation ...)

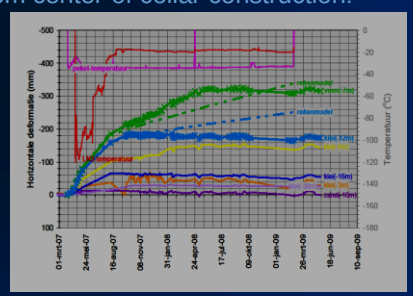





# Frost Heave deformations

Measured @ 3.4m distance from center of collar construction:

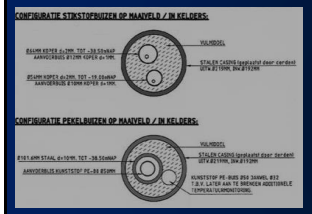


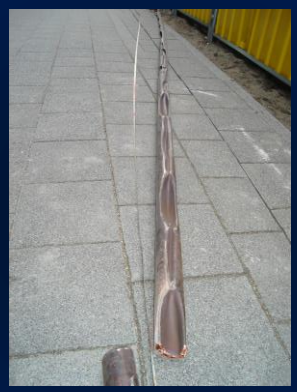






# Unexpected events ..... (1)

December 2006



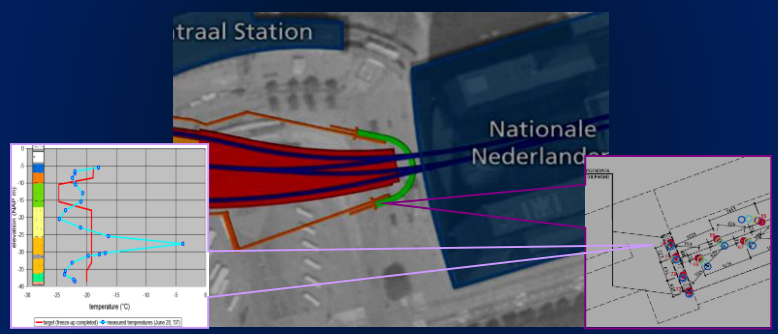


# Unexpected events ..... (2)

April / May 2007



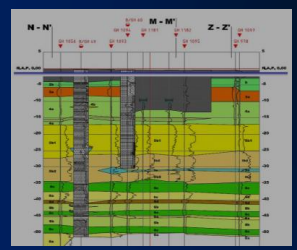
# ‘Hot Spot’ during freeze-up

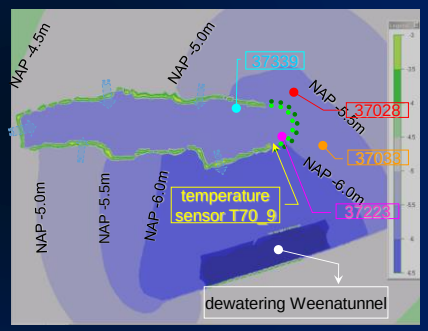




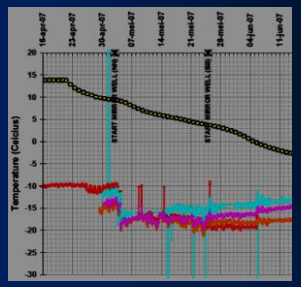

# ‘Hot Spot’ during freeze-up

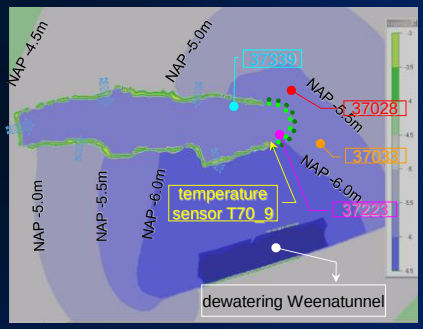
Monitoring data &
3D groundwater model



# ‘Hot Spot’ during freeze-up






# ‘Hot Spot’ during freeze-up


- Water pressure head distribution around building pit, due to dewatering at Weenatunnel project
- Leakage of water through diaphragm wall
- Nett outward flow of water at collar construction location



# ‘Hot Spot’ during freeze-up


- As the frozen soil volume grows, outward flow is more and more obstructed
- Consequently, pressure head difference over collar construction increases with time
- Eventually, pressure head difference causes flow velocities becoming too high to allow for freeze-up



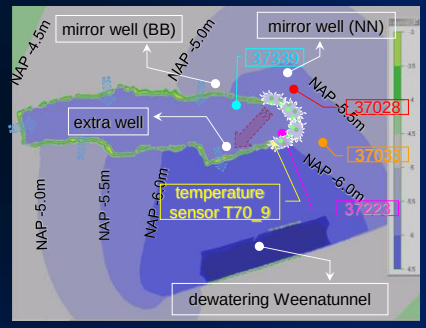
# ‘Hot Spot’ during freeze-up

Solution:

Additional mirror well inside excavation

Aim:

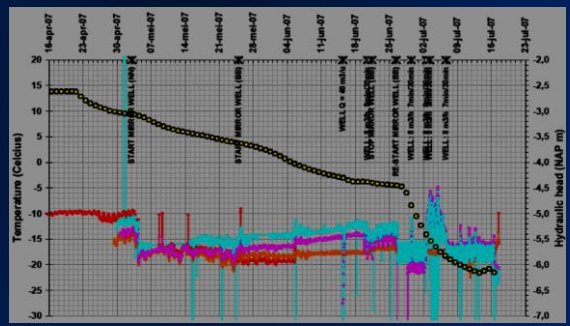
Reduction of excess groundwater pressure head at collar construction location



## ‘Hot Spot’ during freeze-up

Effective?

Yes!






## Watertightness of collar construction



## Watertightness of collar construction

Concern from freeze-up experience:

- uncertainty regarding completion of freeze-up phase
- start of excavation works only after freeze-up has been completed
- consequence of remaining gap in collar construction: failure/collapse due to ‘thermal erosion’
- re-start of freezing process is difficult when (part of) excavation is completed

How to ensure/prove 100% (not: 99.999%) closure of collar construction?

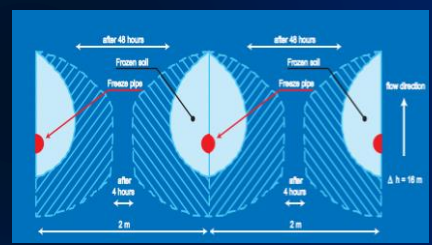
‘Thermal Erosion’ ?



## Watertightness of collar construction

Thermal Erosion:

- heat transport through groundwater flow, resulting in .....
- thawing of frozen soil, resulting in .....
- increase of groundwater flow, .....



# Watertightness of collar construction

Prove by pump test - Philosophy:

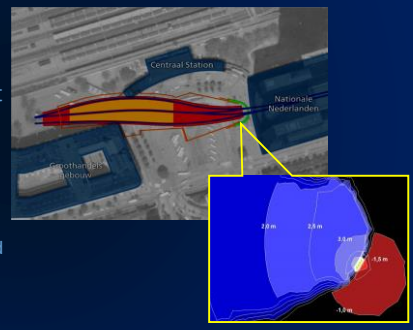
- generate conditions that will certainly cause thermal erosion to occur, in case initial gaps are present
- monitor / measure the effects that are associated with thermal erosion developing
- if subject effects do not show up, then conclusion –without any doubt- is: collar construction is 100% watertight

Which effects can be monitored / measured? When to occur?



# Watertightness of collar construction

- Assessment of development of thermal erosion in time: thermal calculations combined with groundwater flow (by CDM Consult GmbH)
- Effects that can be detected, based on 3D groundwater calculations (by Rotterdam Public Works):
  - change of groundwater pressure head inside building pit
  - change of water discharge volume






# Watertightness of collar construction

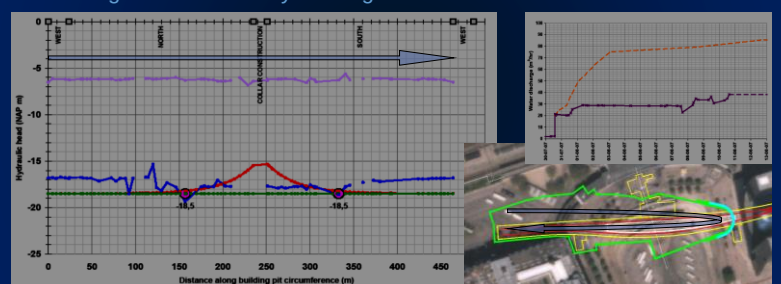
Pump test - Protocol:

- generate hydraulic pressure head difference of 16m (NAP -1.5m / NAP -18.5m) over collar construction by means of pumping
- daily (!) evaluation / analysis of monitoring data
- daily (!) approval / confirmation / acceptance of intermediate results and conclusions by all parties (Rotterdam Public Works, (Sub-)Contractor) that no thermal erosion is detected
- test duration two (2) weeks, then conclusion that collar construction is 100% watertight



# Watertightness of collar construction

Monitoring data after 10 days: no signs of thermal erosion



# Collar Construction Closed – Start Excavation Works

August 2007



# Unexpected events ..... (3)

April 2008





# End of Freezing Operation

February 2009

## Concluding Remarks (1)

- Groud freezing technology has succesfully been applied for generating a vital part of a retaining wall of a large building pit; freezing duration nearly two years
- Rotterdam Public Works have obtained necessary knowledge on ground freezing during design and contract preparations; this proved to be an adequate basis for coordination of the works and performance during unexpected events
- Extensive monitoring and knowledge on groundwater conditions (using validated (!) 3D computermodelling) appeared to be essential information; area of interest to be extended to sufficient distance around the building site



## Concluding Remarks (2)

- 'Mirror' wells have proven to be suitable measures for control of groundwater regime
- Unique protocol to prove 100% watertightness of collar construction has been developed
- Full scale testing –on critical items/equipment- to be considered to further reduce risk profile, and / or for Contractor to demonstrate his experience
- Conditions for terminating ground freezing operation shall be clearly defined, as to avoid unnecessary delays



## Concluding Remarks (3)

- Warming pipes have been applied as to facilitate the installation of pile foundations in unfrozen soil, also in vicinity of the collar construction; bored piles have not been allowed, as the bearing capacity of such piles – when installed in frozen soil- could not be guaranteed (by Contractor)
- Yet to be analyzed: valuable monitoring data on e.g. frost heavy effect for varying soil properties
- Risk analysis has been an adequate tool to identify hazards and to define mitigating measures regarding the –cost effective- application of ground freezing techniques in subject complex project conditions



## Opening Underground Station CS

September 2009

## Weekend September 26th-27th, 2009






## Weekend September 26th-27th, 2009



## Monday September 28th, 2009 (05:55)



## Opening Rotterdam Centraal

March 2014

# March 13th, 2014





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Rotterdam Public Works – Engineering Department – Section Geotechnics
http://www.rotterdam.nl/infraprojecten (Dutch language)

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Mobilis (former TBI/Voormolen)
Max Bögl

Building Coordinating Team
RET
Projectmanagement Projectbureau RandstadRail
Expert Review Panel
Homefront




# Rebuilding Metrostation CS, Rotterdam

## Unique experience on large scale application of ground freezing techniques

Ir. Vladimir Thumann
Sr. Geotechnical Engineer, Seaway Heavy Lifting
/ Rotterdam Public Works, Engineering Department