cfms
COMITÉ FRANÇAIS DE MÉCANIQUE DES SOLS ET DE GÉOTECHNIQUE

ACADÉMIE DES SCIENCES INSTITUT DE FRANCE

ACADÉMIE DES TECHNOLOGIES POUR UN PROGRÈS RAISONNÉ, CHOISI ET PARTAGÉ

SIMSG ISSMGE

LES TRAVAUX PUBLICS FÉDÉRATION NATIONALE

Charles-Augustin COULOMB - A geotechnical tribute

Paris, september 25 & 26, 2023

What to remember from 10 years of Grand Paris Express ?

Thierry Huyghues-Beaufond, Hervé Le Bissonnais, Missom Ouedraogo

BUREAU VERITAS Shaping a World of Trust · Geos · SoilCloud · SOLETANCHE BACHY · spie batignolles fondations · SSI 2U · terrasol setec

Société du Grand Paris

The Grand Paris Express

Summary

- Project progress
- A major project to drive environmental progress
- The first feedback from construction sites expériences

Grand Paris Express: responding to key issues

Housing shortage

Territorial and social imbalance

International competition between cities

Pollution

Congested transport infrastructures

A project unprecedented in scope

Grand Paris express

In figures

68 stations
and 6 technical centres

100% accessible
for people with reduced mobility

90%
of network underground

100% automatic
Guarantee of regular service, stability, comfort and safety

Close to 3 million
passengers per day

1 train
every 2 to 3 minutes

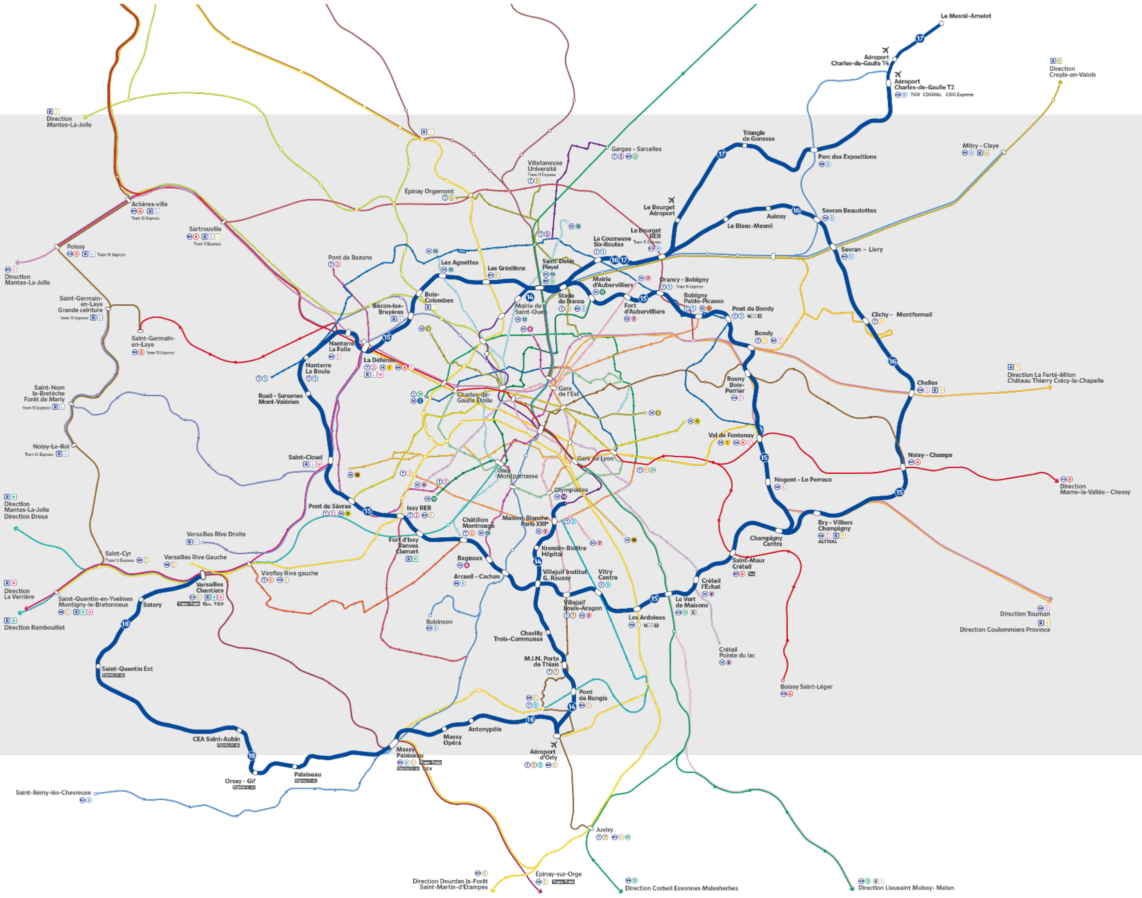
200 KM of lines
added to the existing 200 km in Île-de-France (metro and RER)

Travelling at a speed between
55 and 65 km/h
on average

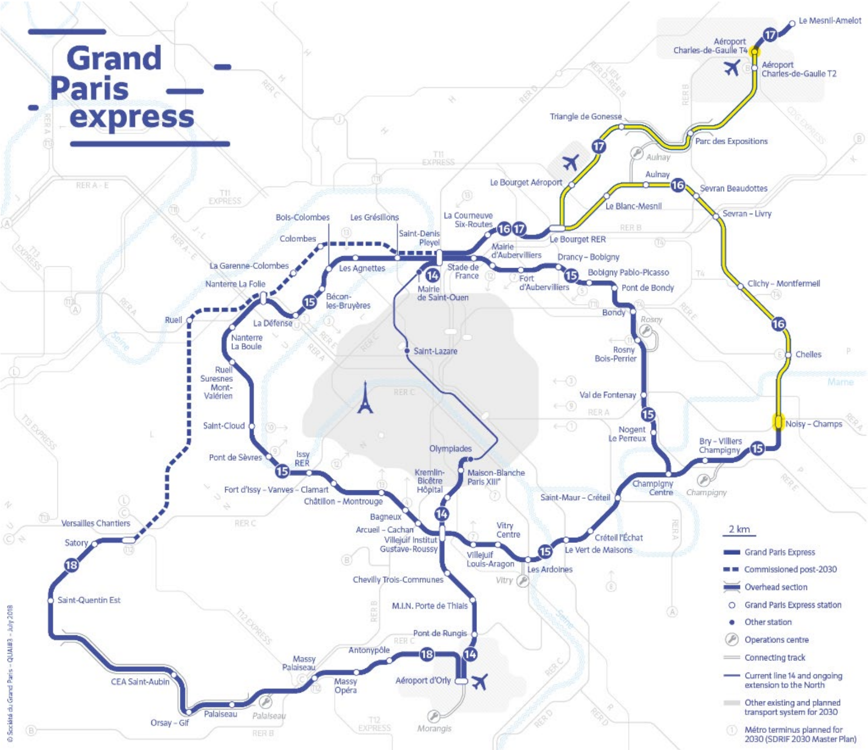
80 % des gares interconnectées

au réseau de transport

Réseaux
de transport
projeté à 2030
(Sdrif)



A revolution for residential and economic mobility



AÉROPORT CHARLES-DE-GAULLE T2 › NOISY CHAMPS

Today

1 h 27

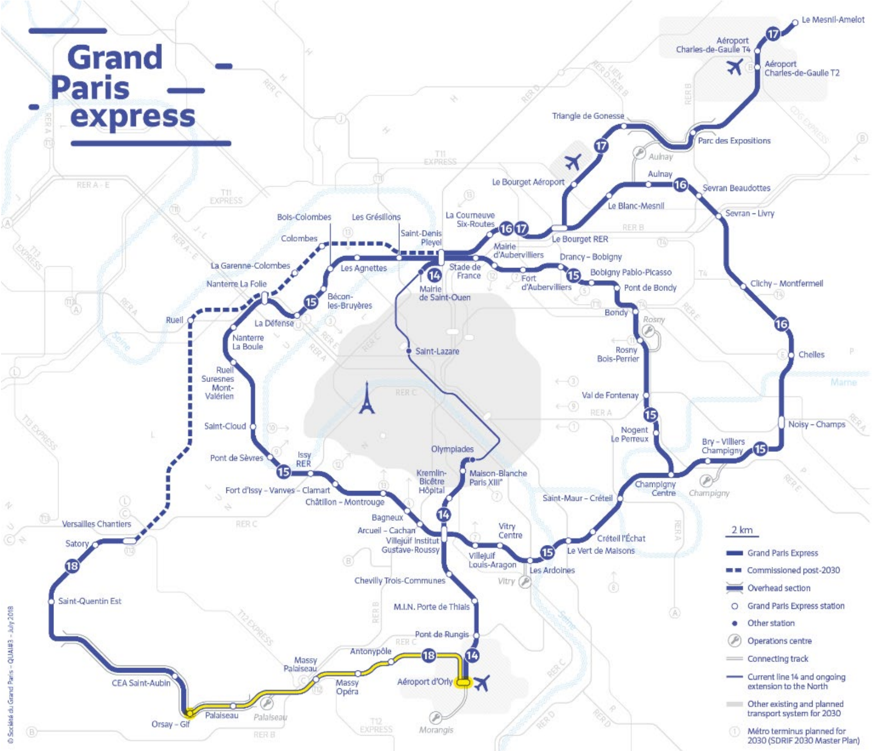
Tomorrow

31 min

Gain

56 min

A revolution for residential and economic mobility



AÉROPORT D'ORLY 〉 ORSAY GIF

Today

41 min

—

Tomorrow

15 min

Gain

26 min

On board the future metro

Automated trains

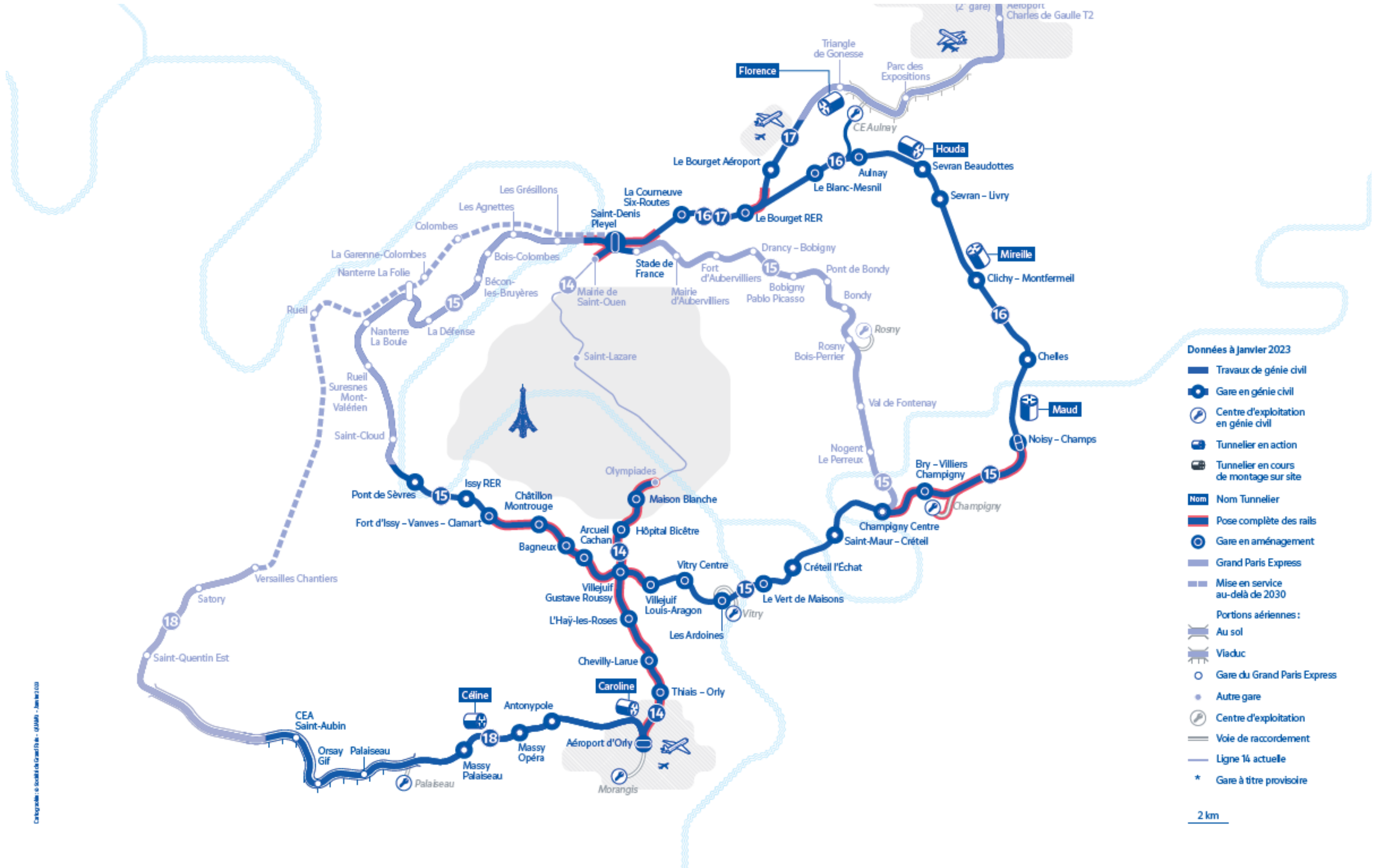
Fully accessible

Internet access
5G and Wi-fi

Secured
cars and passenger areas

Project progress

Work has started



Work has started

100 km dug

46 km
of double-track railways completed

In july 2023

Work has started

15,000 to 20,000 jobs

Per year needed to build the Grand Paris Express

Over

7,769 employees

mobilised in civil engineering

Work has started

5,443 companies

working on the construction sites

Including

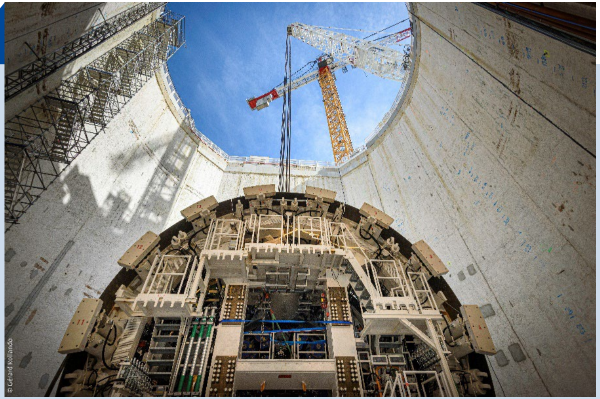
4,473 SMEs

Economic footprint as of December 1st 2022

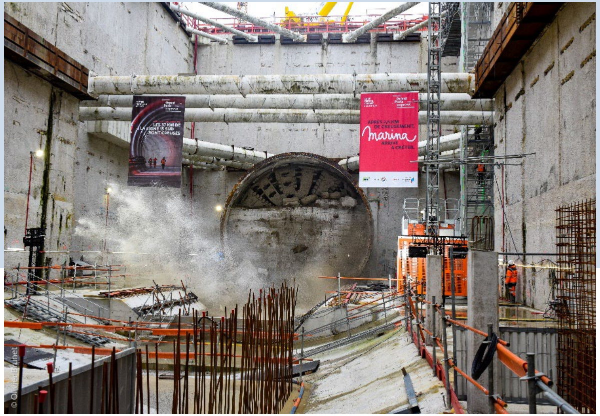
An unprecedented underground adventure

24 **tunnel boring machines (TBMs)**
christened in January 2023

Breakthrough of the Mireille TBM in Clichy-Montfermeil



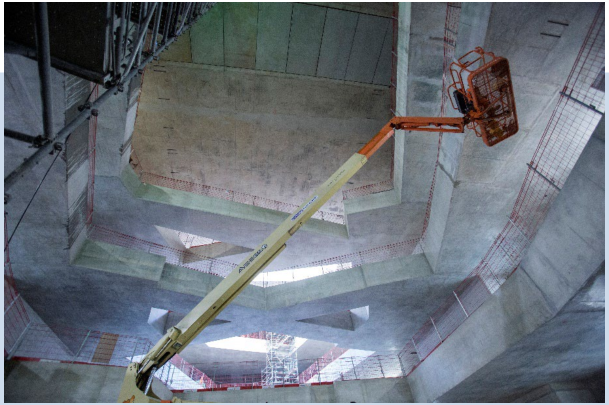
Lowering of the Caroline TBM’s cutter head in Massy



Breakthrough of the Marina TBM in Créteil l’Echat

Line 15

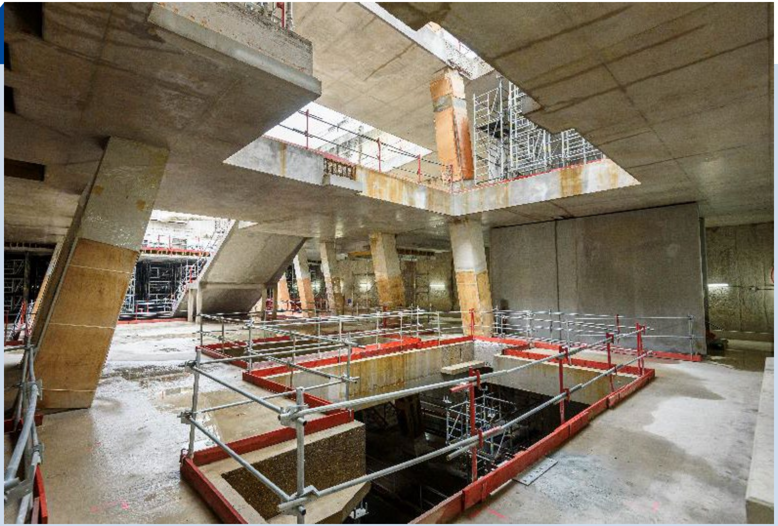
Villejuif Institut-Gustave Roussy station



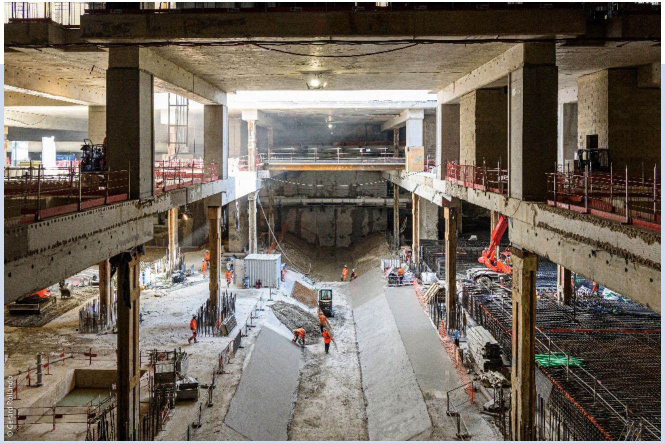
Chatillon-Montrouge station

Saint-Maur-Créteil station

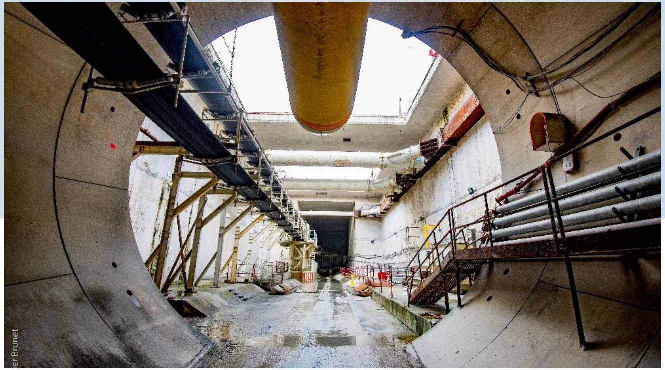
Line 16



Le Blanc-Mesnil station



Saint-Denis Pleyel station



Aulnay station

Line 17

La Courneuve Six-Routes station

Le Bourget RER station

Line 18

Antonypole station

Viaduct Palaiseau

A major project to drive environmental progress

A project to advance the ecological and energy transition

-14 million
of CO_2
equivalent tonnes by 2050

36% thanks to reduced car use

64% by renovating neighbourhoods around stations

CO_2 emissions reduction **3 to 5 time greater** than the emissions generated by the Grand Paris Express project

2018-2019CarbOptimum Stratec study

Massively reduce the carbon footprint of tunnels

-25% CO_2 emissions on construction sites

i.e. 1.1 million teq CO2 saved

Annual publication of a carbon footprint

The replacement of conventional concrete segments with Ultra Low Carbon (UBC) segments based on cement-free alkali-activated slag has a significant impact on the environmental impact of the site, with a reduction of around 70% in carbon emissions. CO2 compared to traditional concrete and 50% compared to low carbon concrete, i.e. respectively 90 kg CO2/m3 for UBC concrete, 170 fg CO2/m3 for very low carbon concrete and 330 kg CO2/m3 for concrete traditional.

The first feedback from construction sites experiences; Concret, Supports,…

Line 16 - Lot 1 St Denis Pleyel/Aulnay

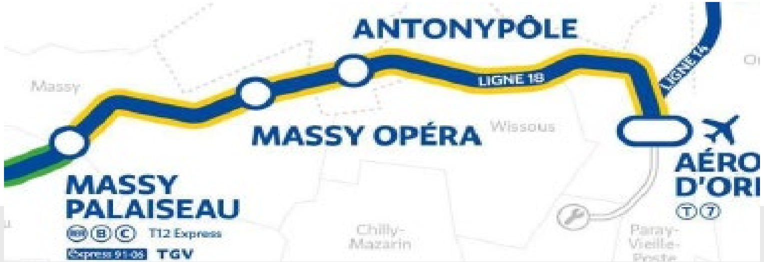
Tunnel in fibers segments

REX:

- Conclusive experience because 80% of the 12km of tunnel are 100% fiber-reinforced concrete
- Facilitated transition between reinforced concrete and fiber-reinforced concrete
- Maintenance of all the productivity gains of the reinforced concrete segment in terms of; number of segments/ring, length of the segment, power of the tunnel boring machine (shoe forces).
- Same level of cracking in percentage as reinforced concrete; comparable crack size, the cracks close.
- This results in better resistance to corrosion (size of the fibers/diameter of the reinforcements) and therefore greater durability of the fiber covering.
- Environmental gain (lower consumption of raw materials, manufacturing of fibers less polluting than that of reinforcements, gain in transport of fibers is equal to 300% compared to reinforcements).

Groupement Eiffage et Maitre d'Œuvre EGIS

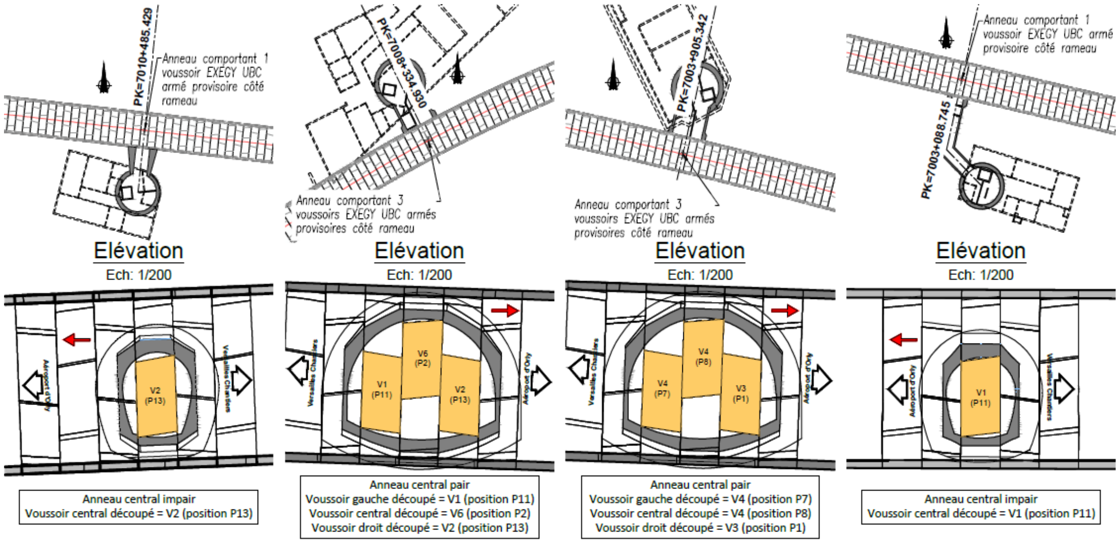
Line 18 – Lot 1 Massy/Orly



« ultra-low-carbon concrete » experiment- Location of the segments

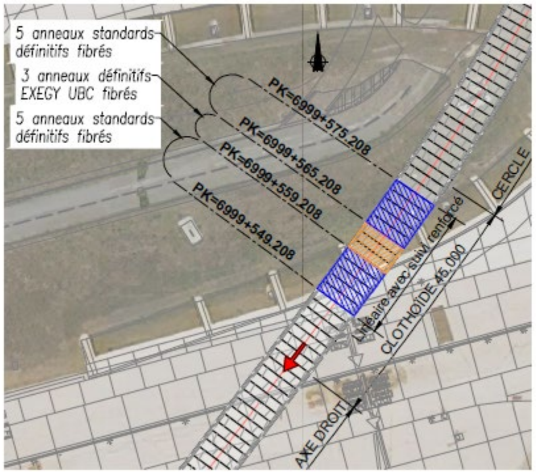
Groupement VINCI et Maitre d'Œuvre ICARE

8 temporary reinforced segments



21 final fiber reinforced segments (3 rings)

Behind the station, after the terminus of the line



Conclusion for experiment

8 reinforced + 21 fiber reinforced ULC segments for a 6,050m long tunnel

(HK EPB TBM, Ø = 9,15m, 7 reinforced or FR segments per ring- 40cm thickness - 2,00m wide)

Exegy Ultra Low Carbon (ULC) Concrete:

- Nearly 100% of the clincker replaced by acrtivated Ground Granulated Blast Furnace Slag (GGBS)
- 70% less of CO2 emmission

Activated GGBS:

- Chemical composition close to clincker
- Environnementale footprint :16kg eq.CO2/t

Line 15 Sud – Gare Fort d'Issy Vanves Clamart

Performance and modelling of a deep excavation in the context of the Grand Paris project

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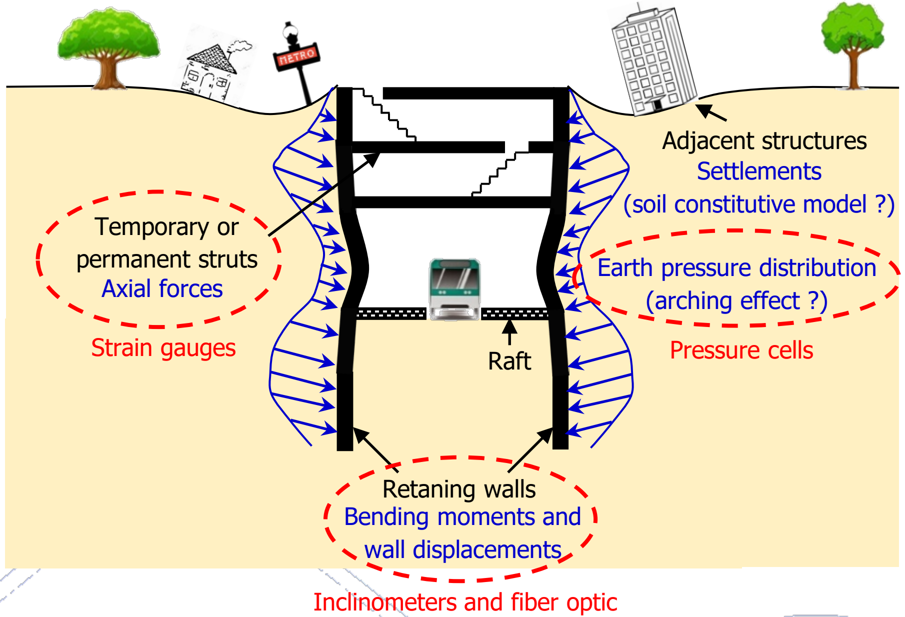
[1] *Terrasol, Paris, France*

[2] *Soletanche-bachy, Paris, France*

[3] *3SR Laboratory Grenoble Alpes University, Grenoble, France*

Main topics

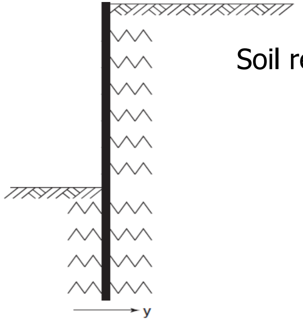


Assessment of FIVC metro station performance with advanced monitoring system

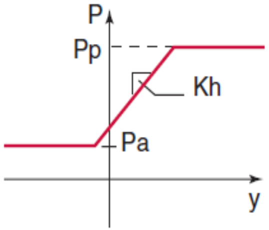
Comparison with modelling using two approaches: Subgrade Reaction Method (SRM) and Finite Element Method (FEM)

Modelling approaches

Subgrade reaction method
(SRM)



Soil reaction modeled with independent springs

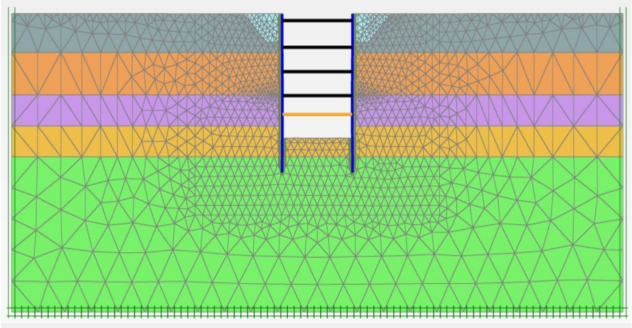


<u>French standard NF P 94-282 :</u>

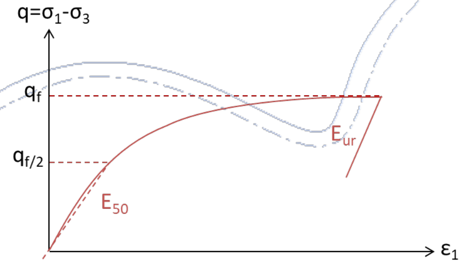
$Kh=2\ (E_M/\alpha)^{4/3}/(EI)^{1/3}$

Active and passive earth pressure Pa and Pb from Caquot-Kerisel Theory

Finite element method
(FEM)



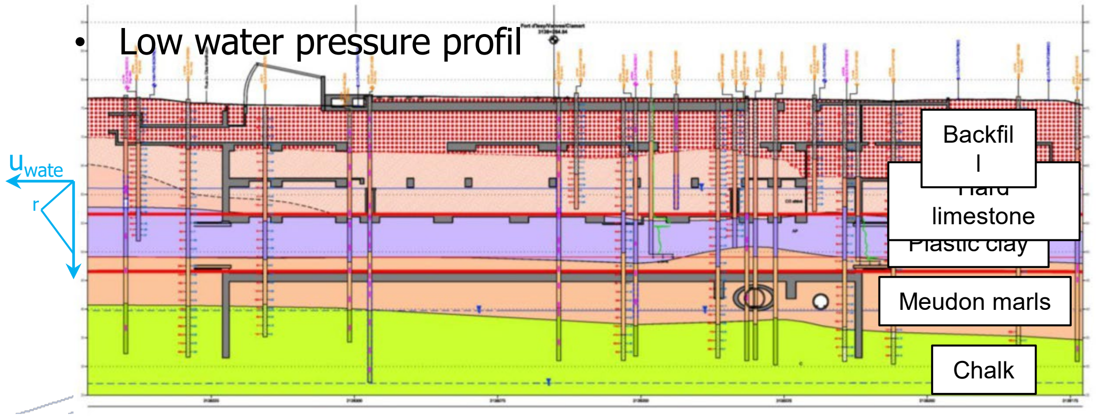
Soil modeled as continuum medium with HSM constitutive model

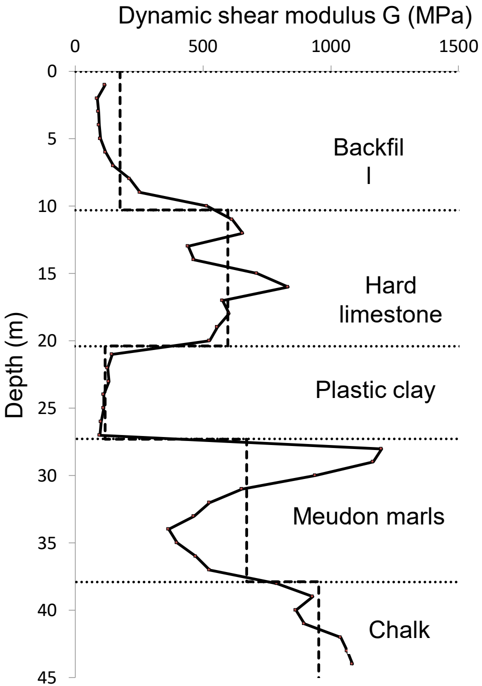


FIVC metro station performance

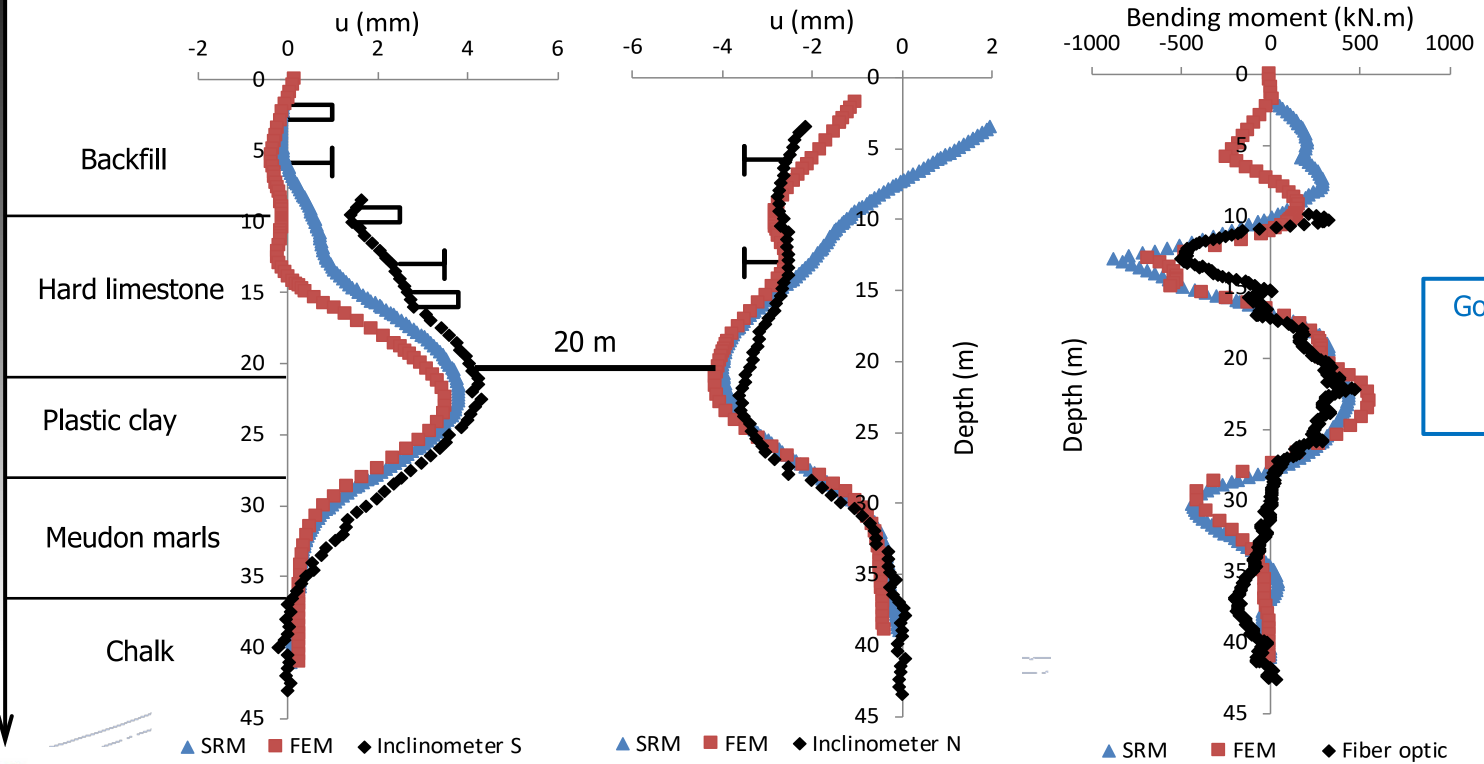
Geological context

- Stiffness contrast between Hard limestone and Plastic clay
- Plastic clay (8m): stiff (C_u = 120 kPa) overconsolidated (OCR=2.2), water content 30%, plasticity index 55%
- Retaining wall (1.2 m) bottom in Chalk at 40 m deep
- Low water pressure profil



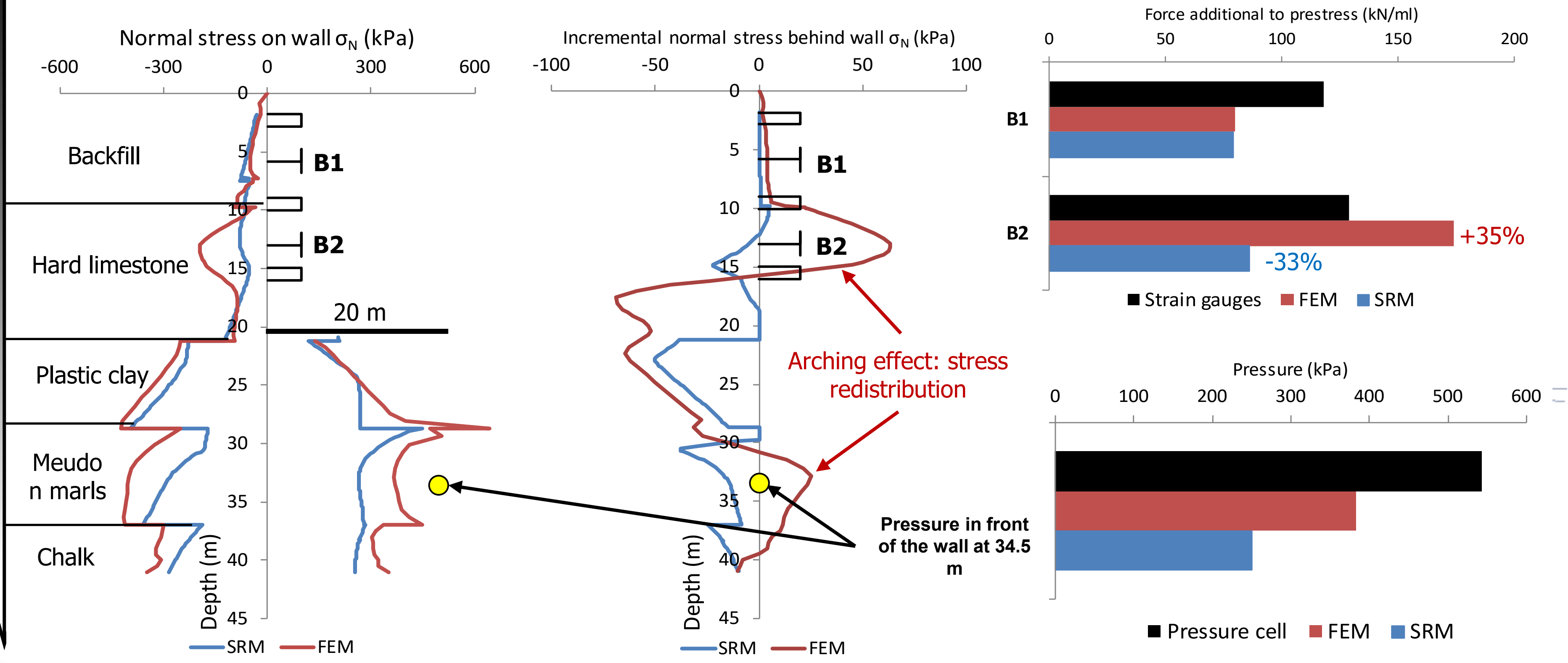


FIVC metro station performance



Good agreement of predicted wall displacements and bending moment with measurements

FIVC metro station performance



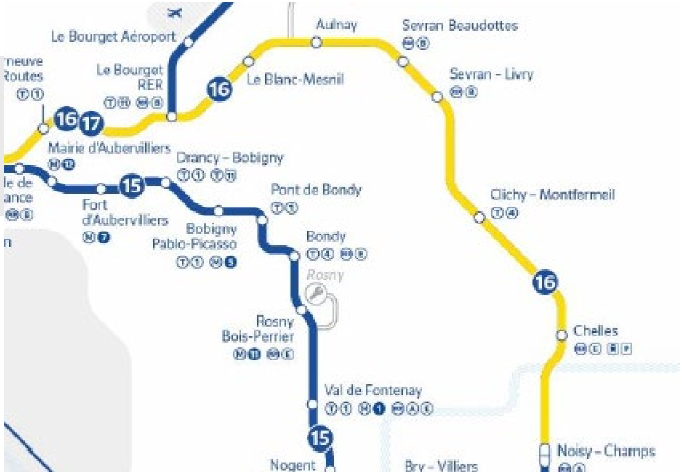
Conclusions

- Rich case studied with advanced monitoring system allowing to assess modelling results with different mesurements : wall displacement, bending moment, strut force and earth pressure
- SRM is largely sufficient to predict wall displacement and bending moment of retaining walls
- FEM may be needed to assess the impact of arching on stress redistribution for deep excavations in particular where the pore pressure is low
- Hybrid method seems ideal to improve the classical subgrad reaction method with considering springs interaction

Thank you for your attention

FIVC metro station worksite 2018

Line 16 – Gare Clichy Montfermeil



Conception d'un radier sur sol gonflant – Cas pratique de Clichy- Montfermeil

Missom OUEDRAOGO

Ingénieur-Doctorant

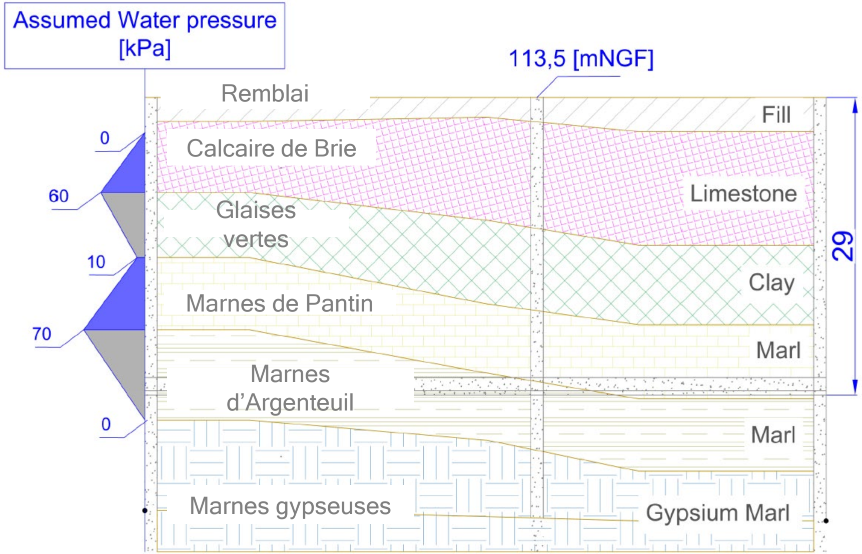
egis

General context

Clichy Montfermeil, Paris, 2021

Diameter 1 : 33 m ; Diameter 2 : 39m ; Excavation : 30m.

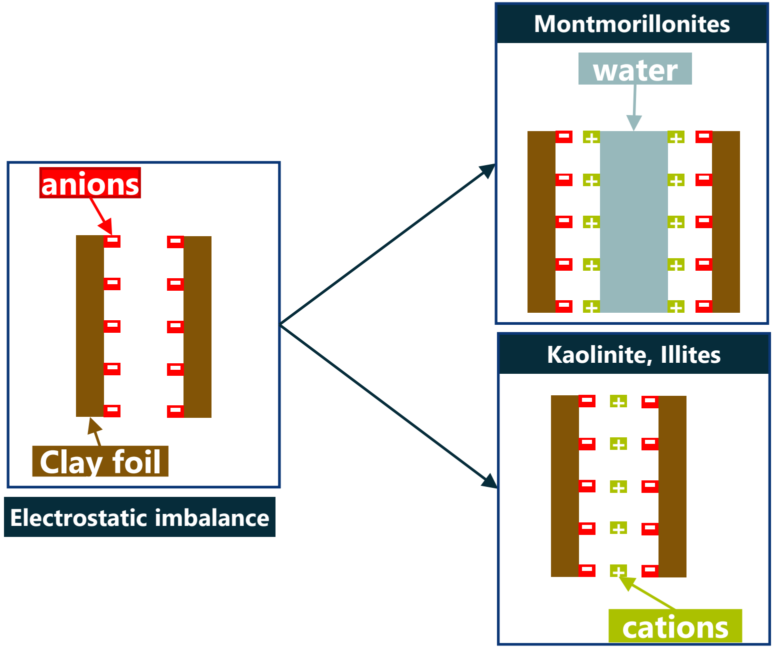
- Complex geometry of the structure
- Raft laying on expansive marls
- Expansive behavior of the soil assessed after the first conception step ➔ Optimization of the design



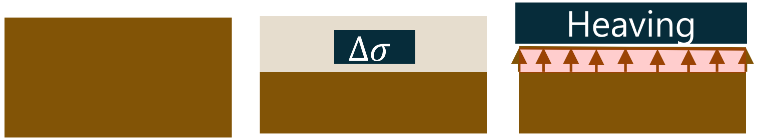
Vertical slice - Stratigraphy and pressure profile

What is swelling ?

Swelling due to hydratation

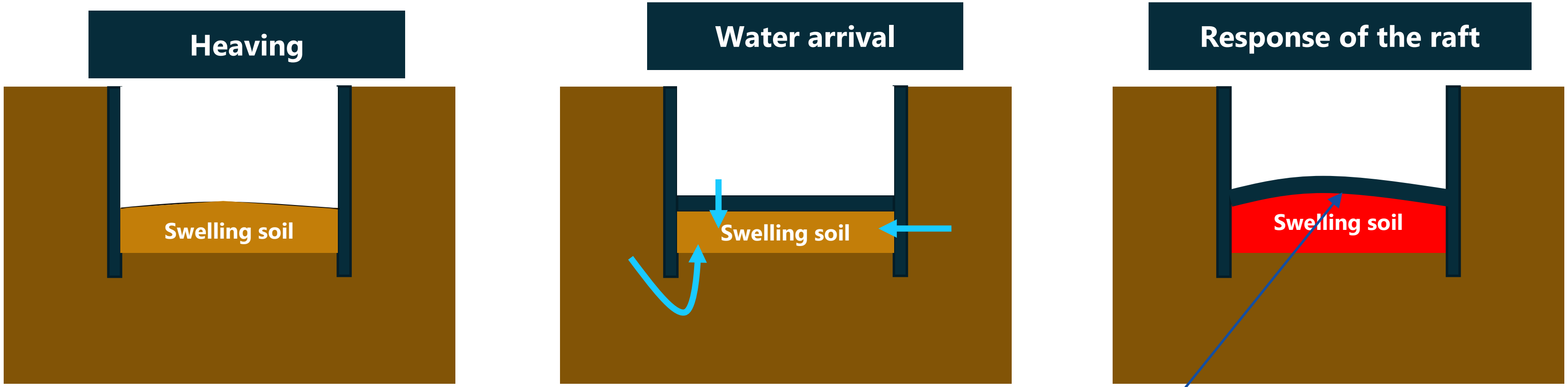


Swelling due to mechanical unloading



- For more details about swelling due to hydratation: (Delage et Cui, 2000).
- The term **heaving** is more appropriate for the response to mechanical unloading
- The order of magnitude of 'mechanical swelling' is small compared to the hydratation swelling

Impact of the swelling

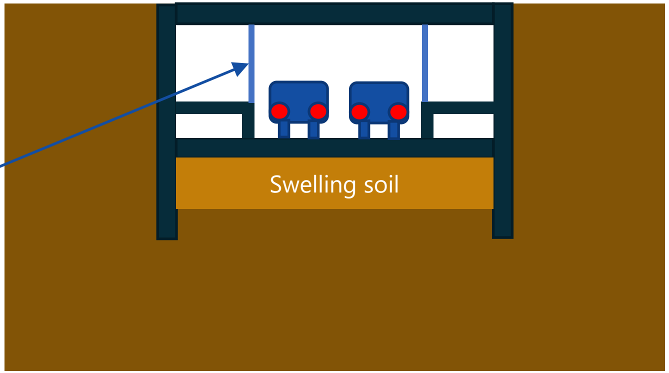


May lead to safety or serviceability issues

Impact of the swelling

Specific case of Clichy-Montfermeil

<u>Serviceability issue:</u> The future subway's barriers are very sensitive to vertical displacements



Possible solutions

- Substitute the swelling soil,
- Prevent the soil from hydratation,
- Reinforce the structures in contact with the swelling soil,
- Intercalate a very soft material between the soil and the structure.

Conception process
Solution 1 : Reinforcement

<u>Designing principle</u> : Thicker = Stiffer + heavier

<u>In our situation :</u>

- Required thickness 3,5 m;
- Large amount of concrete.

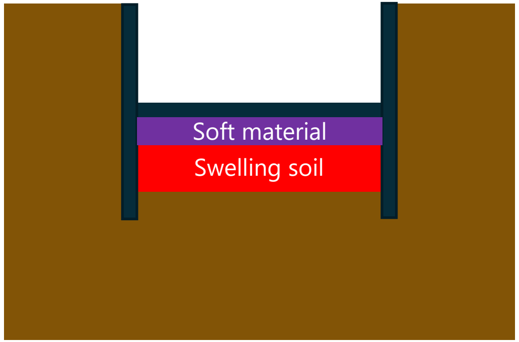
Conception process

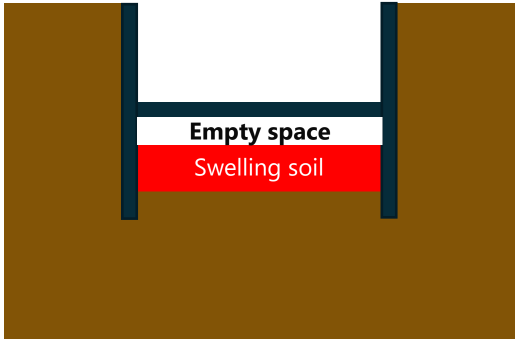
Solution 2 : Soft layer of connection

<u>Designing principle</u> : Free swelling = no swelling pressure applied to the raft

<u>In our situation</u> :

- Considered Material: Polystyrene
- Local punching of the compressible soil due to the structure
- Requires extra excavation and installation of a material ➔ consequences on planning and costs.



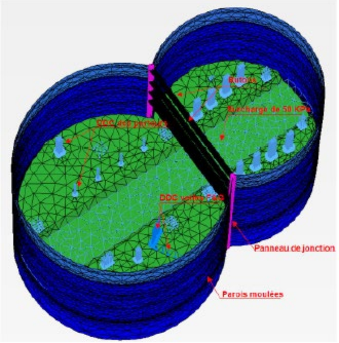


Conception process
Solution 3 : Accurate evaluation

Designing principle : Two methods

1. 3D MEF : Simulation of swelling by applying volumetric deformation on the soil,
2. 3D MEF : Simulation of imbibition by decreasing soil's suction.

$$\varepsilon_G = -K.\log\left(\frac{\sigma'_a}{\sigma'_{G\ Ref}}\right)$$

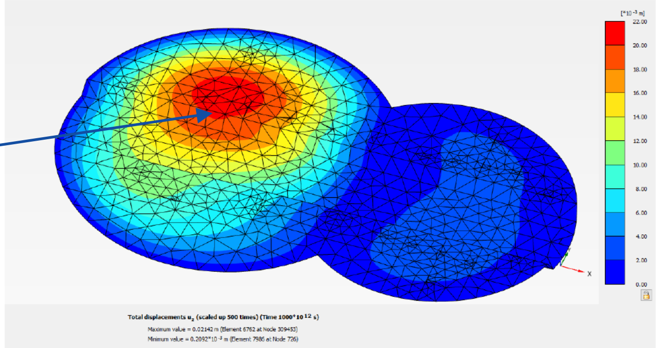


Conclusion:

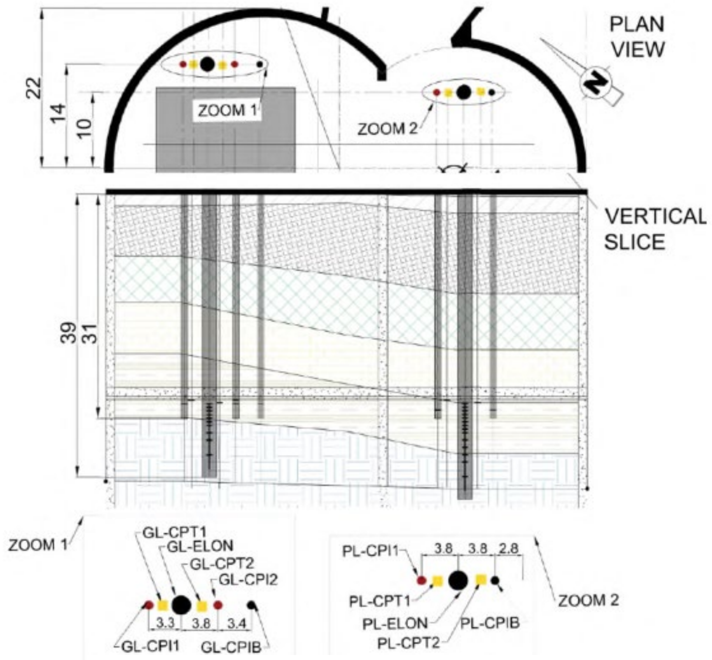
1. Some agreements in the results of the 2 methods,
2. Thickness of the raft adjusted to 1.3m ,
3. Highlighting of a limited zone where the swelling is higher than the serviceability treashold of the barriers,

Additionnal actions

1. Substitution of the swelling soil in the red zone,
2. Implementation of a system in order to monitor pore pressure, vertical displacements, and total stress under the raft. The monitoring system have been conceived and installed by egis.



Conception process
Monitoring system



Overview of the monitoring system

Different steps of the installation of the monitoring system

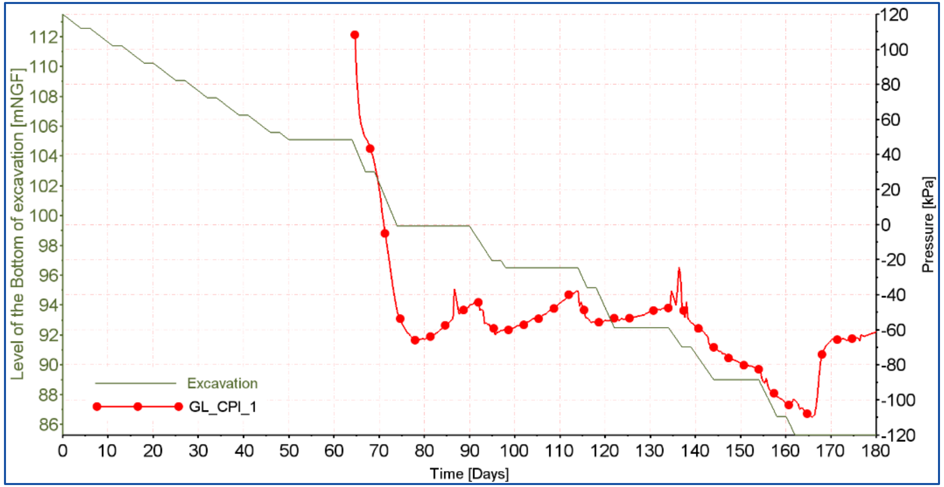
Conception process

Monitoring system

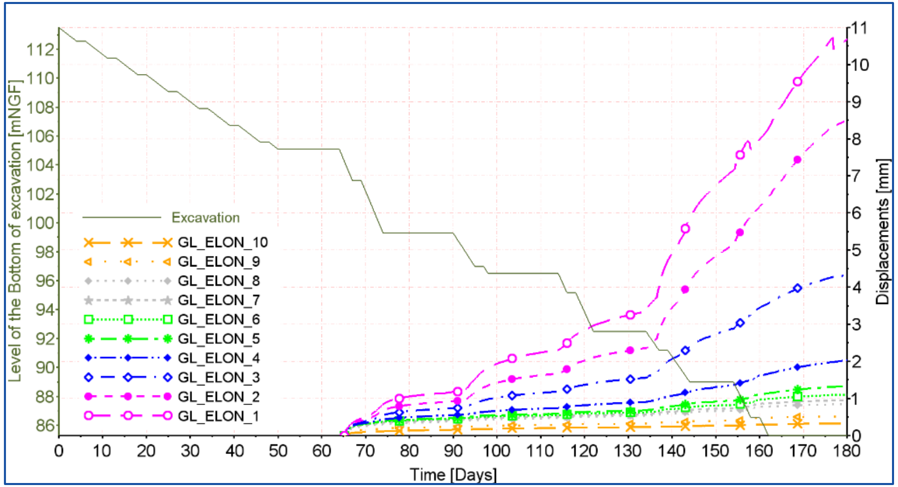
Substitution of the soil in the swelling zone

Monitoring system during excavation

Conception process
Results



Evolution of pore pressure with time



Evolution of vertical displacement with time

(Ouedraogo et al., 2023)
https://doi.org/10.1051/e3sconf/202338224006

CONCLUSION

- In today's context, issues linked with swelling are taking more and more importance,
- Yet there is no standardized methods to deal with this process. A technical comittee of 'CFMS' is now working on that,
- In the case of Clichy-Montfermeil, MEF method have been applied in order to accurately estimate the impact of the soil's swelling on the raft. Two methods have been used to evaluate this impact and an appropriate solution have been implemented.
- In addition, a monitoring system has been installed by egis before the start of the excavation and may help improve the comprehension of this process.

Thank you for your attention

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