What to remember from 10 years of Grand Paris Express?

Thierry Huyghues-Beaufond, Hervé Le Bissonnais, Missom Ouedraogo
Summary

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

<table>
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<tr>
<th>68 stations</th>
<th>90% of network underground</th>
<th>Close to 3 million passengers per day</th>
<th>200 KM of lines added to the existing 200 km in Île-de-France (metro and RER)</th>
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<td>and 6 technical centres</td>
<td>100% automatic Guarantee of regular service, stability, comfort and safety</td>
<td>1 train every 2 to 3 minutes</td>
<td>Travelling at a speed between 55 and 65 km/h on average</td>
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<td>100% accessible for people with reduced mobility</td>
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80 % des gares interconnectées au réseau de transport

Réseaux de transport projeté à 2030 (Sdrif)
A revolution for residential and economic mobility

Today 1h 27
Tomorrow 31 min
Gain 56 min
A revolution for residential and economic mobility

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

Economic footprint as of December 1st 2022

5,443 companies
working on the construction sites

Including
4,473 SMEs
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
La Courneuve Six-Routes station

Le Bourget RER station
Antonypole station

Viaduct Palaiseau
A major project to drive environmental progress
A project to advance the ecological and energy transition

-14 million of CO₂ equivalent tonnes by 2050

36% thanks to reduced car use
64% by renovating neighbourhoods around stations

CO₂ emissions reduction 3 to 5 time greater than the emissions generated by the Grand Paris Express project

2018-2019 CarbOptimum Stratec study
Massively reduce the carbon footprint of tunnels

-25% CO2 emissions on construction sites
  i.e. 1.1 million teq CO2 saved

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,...
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).
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 emission

Activated GGBS:
- Chemical composition close to clincker
- Environmental footprint : 16kg eq.CO2/t
Performance and modelling of a deep excavation in the context of the Grand Paris project

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Main topics

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

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

Finite element method (FEM)

Soil modeled as continuum medium with HSM constitutive model

French standard NF P 94-282:

\[ Kh = 2 \left( \frac{E_0}{\alpha} \frac{1}{3} \right) \frac{1}{3} (EI)^{1/3} \]

Active and passive earth pressure Pa and Pb from Caquot-Kerisel Theory
FIVC metro station performance

Geological context:

- Stiffness contrast between Hard limestone and Plastic clay
- Plastic clay (8m): stiff ($C_u = 120$ kPa) over consolidated (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

Dynamic shear modulus $G$ (MPa)

Depth (m)

0 500 1000 1500

0 5 10 15 20 25 30 35 40

Chalk Meudon marls Plastic clay Hard limestone Backfill
Performance and modelling of a deep excavation in the context of the Grand Paris project

FIVC metro station performance

Good agreement of predicted wall displacements and bending moment with measurements
Performance and modelling of a deep excavation in the context of the Grand Paris project

FIVC metro station performance

Normal stress on wall $\sigma_N$ (kPa)

Incremental normal stress behind wall $\sigma_N$ (kPa)

Arching effect: stress redistribution

Pressure in front of the wall at 34.5 m

Force additional to prestress (kN/ml)

Backfill

Hard limestone

Plastic clay

Meudon marls

Chalk

0 5 10 15 20 25 30 35 40 45
0 100 200 300 400 500 600

0 50 100 150 200

0 50 100 150 200

B1

B2

FIVC metro station performance

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Conclusions

- Rich case studied with advanced monitoring system allowing to assess modelling results with different measurements: 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
Conception d’un radier sur sol gonflant - Cas pratique de Clichy- Montfermeil

Missom OUEDRAOGO
Ingénieur-Doctorant

ega
General context

- 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

Clichy Montfermeil, Paris, 2021

Diameter 1 : 33 m ; Diameter 2 : 39m ; Excavation : 30m.
What is swelling?

Swelling due to hydration:
- Montmorillonites
  - Water
  - Anions (Clay foil)
  - Electrastic imbalance
- Kaolinite, Illites
  - Cations

Swelling due to mechanical unloading:
- Heaving
- Δσ

- For more details about swelling due to hydration: (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 hydration swelling.
Impact of the swelling

Swelling soil

Heaving

Swelling soil

Water arrival

Response of the raft

Swelling soil

May lead to safety or serviceability issues
Impact of the swelling
Specific case of Clichy-Montfermeil

**Serviceability issue:** 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

**Designing principle**: Thicker = Stiffer + heavier

**In our situation**:
- Required thickness 3,5 m;
- Large amount of concrete.
Conception process
Solution 2: Soft layer of connection

**Designing principle**: Free swelling = no swelling pressure applied to the raft

**In our situation**:

- 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.

\[ \varepsilon_G = -K \log \left( \frac{\sigma'}{\sigma_{G\ Ref}} \right) \]

**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 threshold of the barriers,

**Additional 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

(Ourdeago et al., 2023)
https://doi.org/10.1051/e3sconf/20233822400
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 committee 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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