DEEP EXCAVATION AND IMPROVEMENT OF PASSIVE EARTH REACTION IN WEATHERED CHALK: DESIGN WITH DEEP SOIL MIXING OR CONCRETE CROSS WALL SOLUTIONS

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ABSTRACT

As part of the Grand Paris Express project, the Pont de Sèvres station required the use of retaining structures in the form of diaphragm walls. Forty-five meters long, they are anchored in the underlying Campanian chalk. Base slab level, thirty-five meters below ground level, was reached using top-down construction. Even with this method, control over the deformations of the diaphragm wall required reinforcing the weathered chalk to improve passive soil pressure during both construction and final stages. Two processes were implemented in different sectors of the structure: localized unreinforced concrete cross walls (using diaphragm wall excavation technology); or wide-reaching soil reinforcement through Deep Soil Mixing.
The article explains how to model retaining structures and these passive soil pressure reinforcement methods. Results of calculations using subgrade reaction coefficients are compared to those obtained by finite-element modelling. Issues related to the verticality tolerances of Soil Mixing columns being accounted for are also addressed: a computational approach enabling to consider possible gaps in soil treatment generated by column deviation is put forward.

Keywords: passive pressure improvement, deep soil mixing, diaphragm walls, cross wall supports, weathered chalk

INTRODUCTION

Pont de Sèvres is one of the new metro stations being built for the Grand Paris Express railway project. It is located on the shores of the river Seine, in the west of Paris.
The diaphragm wall is anchored in the mediocre weathered chalk and was under strict limitation of displacements to prevent damages on surrounding structures. To improve passive pressure, two systems were combined:

- Unreinforced concrete cross walls
- Deep soil mixing

Cross walls have a more reliable and stronger modulus. But they are discontinuous and might slow down and damage the TBM when it enters the station (the tunnel must be constructed before the station is excavated). DSM columns are better for the TBM but its parameters must be confirmed with a trial before construction, as described in Mathieu (2021).

This article describes the modelling of these solutions by the design office, using computational methods that needed to take into consideration uncertainties on the verticality of the soil improvement method. It also compares results between calculations using finite elements and subgrade reaction coefficients.

PROJECT CONTEXT

Location and geology

The main excavation is 109 m long, 23 m wide and 35 m deep. It is supported by diaphragm walls, anchored in weathered chalk 45 m below ground level. Close to the station are sensitive buildings and mains that require a strict limitation of ground displacement around the structure.

Fig. 1 – Aerial view of the station's location and surroundings

The geology comprises alluvium deposits covering layers of Campanian chalk. At the levels considered for the project the chalk is weathered and its geo-mechanical characteristics are quite mediocre with pressure meter modulus ranging from 15 MPa to 30 MPa, and limit pressures ranging from 1 MPa to 2.2 MPa.

Therefore, ground improvement solutions were required below the bottom of the excavation to limit maximum displacements.

Below are the geology and a representative cross-section view of the project (Fig. 2):

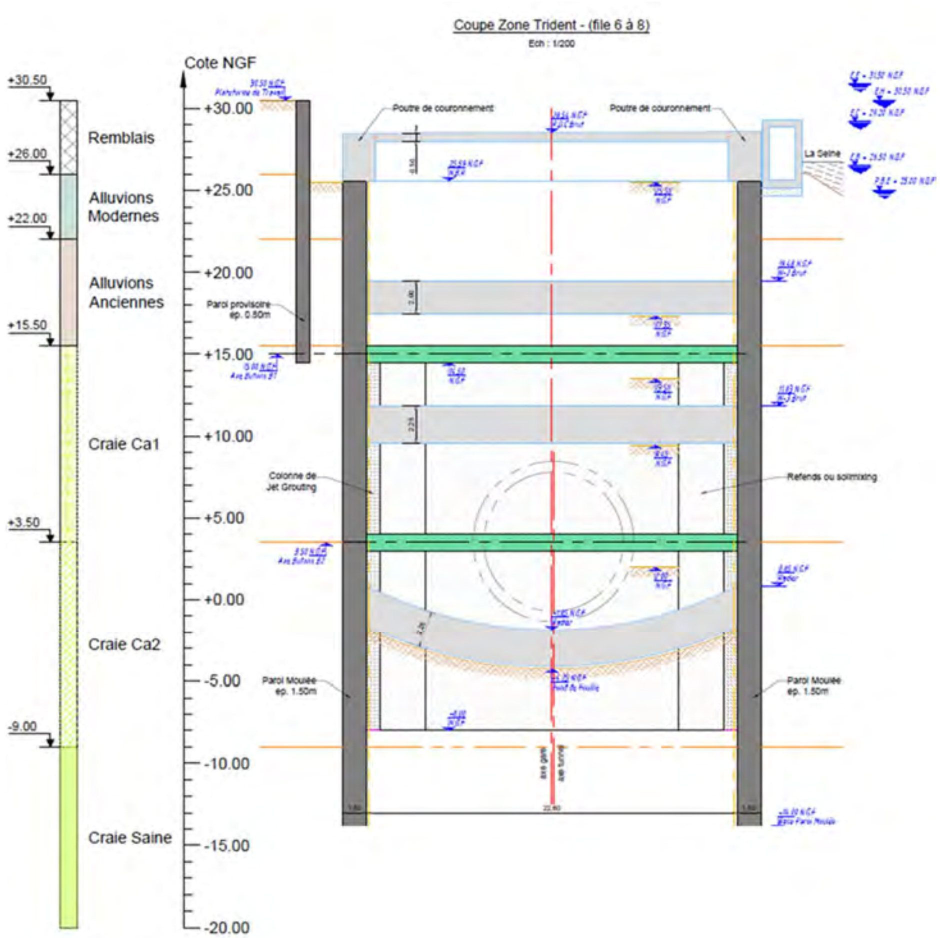

Fig. 2 – Geology and cross-section

Proposed solution

For this project, displacements were limited as follows:

	Sensitive buildings	Other buildings
Max deformation at the top of the d-wall	1,5 cm	2,0 cm
Max deformation at mid-level	3,0 cm	4,0 cm

The chosen solution is composed of two elements (see fig. 4 below):

- Deep soil mixing below excavation level, covering most of the station's footprint
- Five cross walls, made of unreinforced concrete, located just in front of a sensitive building

DEEP SOIL MIXING – COMPUTATIONAL ANALYSIS OF DEVIATIONS

For the Colmix® process (deep soil mixing), a pile boring machine is used to create columns of mixed soil and binder (cement). The junction with the surrounding diaphragm walls is achieved with jet-grouting. DSM columns are supposed to completely overlap within each line, and partially between separate lines.

Fig. 3 – Pile boring machine making deep soil mixing columns ©C.Helsly

The expected characteristics for the improved mixed soil are as follows:

- Ey = 1000 MPa
- C'= 0.4 MPa
- $\varphi' = \varphi_{soil} + 10° = 37°$ for Ca1 and 45° for Ca2

But, given the depth of the project, the design office had to take into consideration possible uncertainties in the verticality of the columns, that could potentially create gaps of untreated soil in between them and weaken the structure.

To reach this target value of 1000 MPa for the soil mass, the construction team decided to aim for a Young modulus of 3000 MPa. This value was confirmed by the outcomes of the trial described in Mathieu (2021).

Then, a model to assess the effect of these deviations on the Young modulus was constructed.

First, a CAD drawing of the columns actual layout was created (see Fig. 4 below).

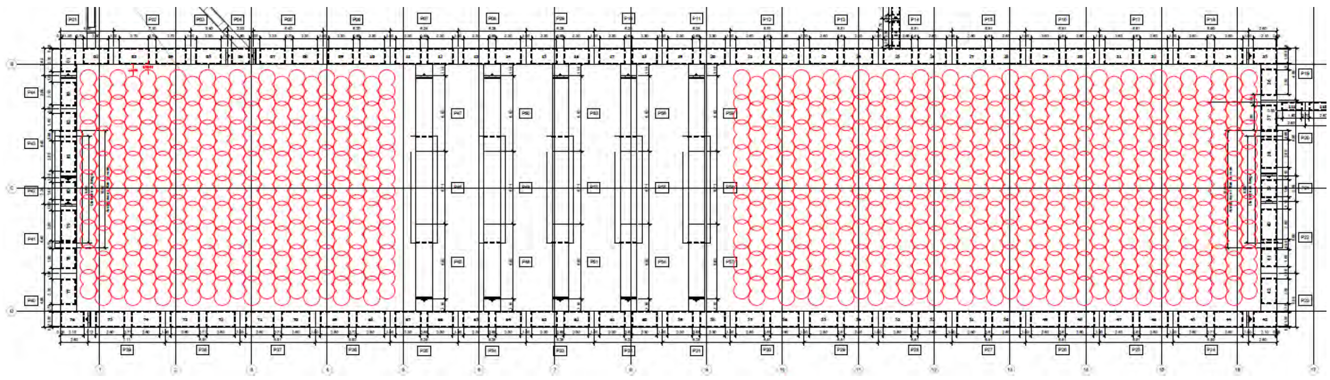

Fig. 4 – Theoretical layout of the DSM columns

The first step in this modelling is estimating the possible deviations during the construction of the columns. Column deviations follow a normal distribution. Deviation values were assessed using past experiences and the on-site trial.
The design office created an Excel program that could - when given parameters like the depth of the columns, average theoretical deviation, 95% confidence interval deviation or standard deviation - randomly generate statistically realistic columns layouts.

The average deviation was put at 1%, which is rather conservative when compared to previous experiences.

An example of a generated layout:

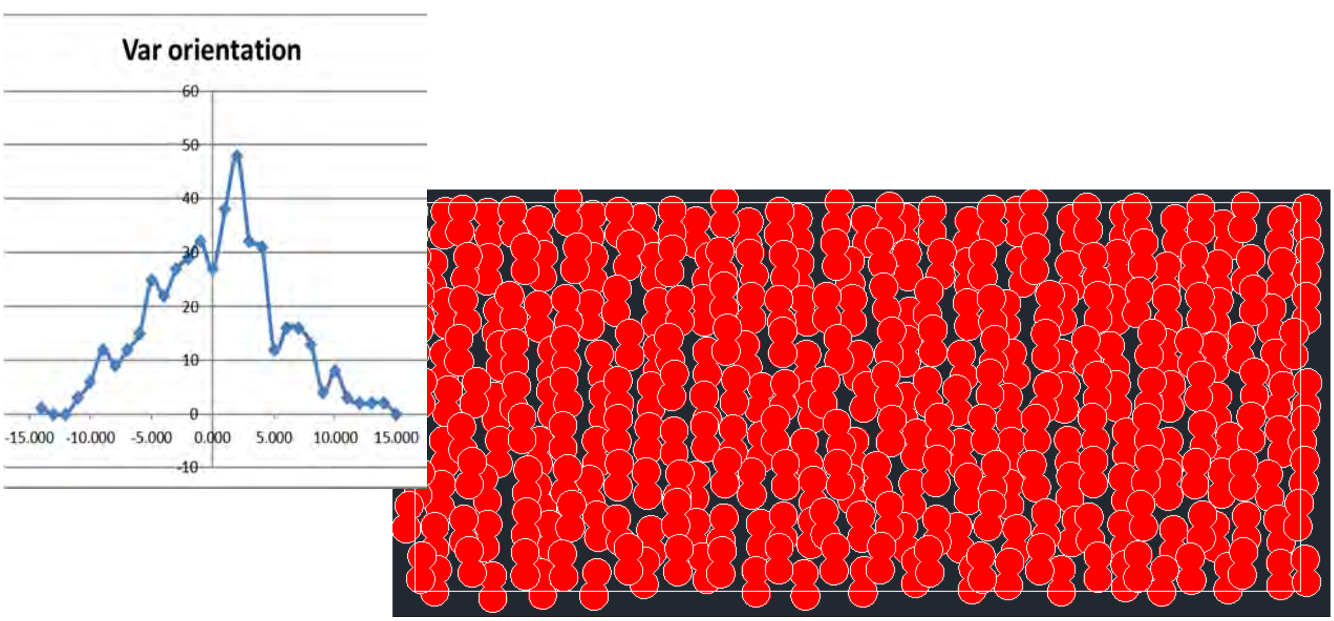

Fig. 5 – Randomly generated DSM layout

This layout is then imported in the program Robot Structural Analysis as a slab, where it is given the characteristics of the treated soil (for the columns) and the characteristics of the weathered chalk (for the gaps in between columns).

The weathered chalk geo-mechanical parameters are as follows:

- Ey0 = 45 MPa
- Poisson coefficient = 0.3
- γ = 19.5 kN/m3

A 1 MN/m effort is then applied on this slab and the displacement induced calculated to estimate its stiffness (as shown in Fig. 6 below).

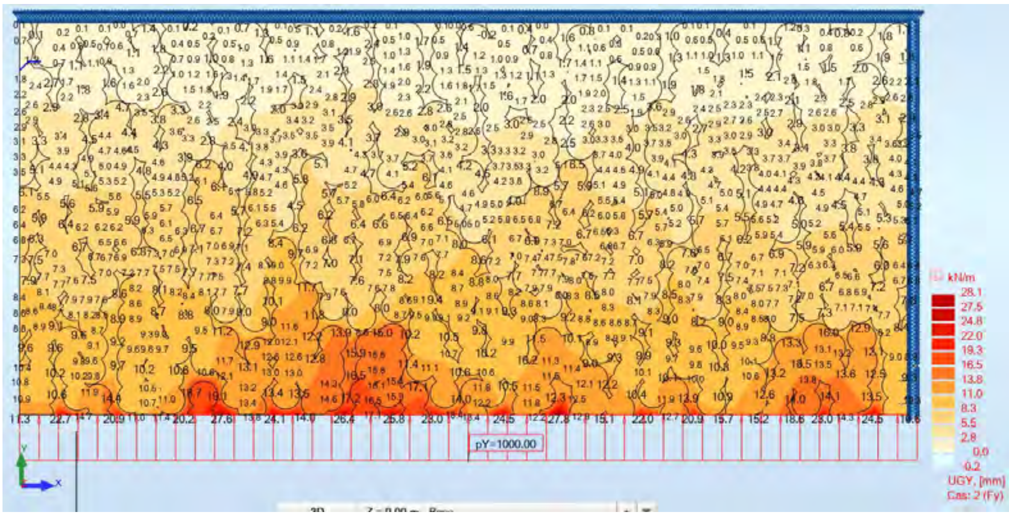

Fig. 6 – Displacement calculation – Input and results

The stiffness and Young Modulus of the structure can be calculated:

1. $k = F/\Delta y$ (Δy the output of the Robot calculation)
2. With the stiffness k comes the Young modulus E: $k = ((E \times S))/L_{el}$

With:

- S = section = 1 m^2
- L_{el} = elastic length = 20.5 m, the width of the station.

The results obtained with this model were as follows:

- Filling rate = 85 % (of the treated zone)
- Δy = 12.8 mm
- k = 78 MN/m
- E = 1402 MPa

This confirms that the final Young modulus for the slab of mixed soil would be higher than the expected 1 GPa, even when considering possible deviations during the construction of the columns.

For safety, more than one layout can be generated, and the same calculations run to estimate Young's moduli with different configurations.

CONCRETE CROSS WALLS – COMPARISON OF FINITE ELEMENTS AND SUBGRADE COEFFICIENTS MODELS

In addition to deep soil mixing, five cross walls are placed in front of a sensitive building located across the street from the future station.

These walls run from one side of the excavation to the other, are 1.5 m wide and made of unreinforced concrete. Each cross wall supports one 6.3 m long diaphragm wall panel. They act as ground improvement and, as such, are modelled as soils in the calculation models. This means that the required verification is the safety factor on passive pressure, following Eurocode 7 regulations.
Two calculations were run, one using subgrade reaction coefficients and one using finite elements.

Subgrade reaction coefficients model

The cross walls are made of C40/50 concrete. Their mechanical characteristics are:

- Compressive strength = Rc = Fck* = 25.6 MPa
- Tensile strength = Rt = Fctk* = 1.8 MPa

Using the Mohr-Coulomb criterion, we can extrapolate geo-mechanical parameters that can be used to integrate these cross walls as soil clusters in the subgrade reaction coefficients models:

- $\sin \varphi = (Rc-Rt)/(Rc+Rt)$
- $Rc = 2.c.\tan(\pi/4+ \varphi/2)$

Hence:

- Cohesion c’ = 3.400 MPa
- Internal friction angle φ’ = 60°

In the models, passive earth pressure is calculated using Caquot & Kerisel (1948) tables and the formula:

- $\sigma_p = K_{p\gamma}.\sigma'_v + K_{pc}.c'$

The tables provide us with :

- $K_{p\gamma} = 17.3$
- Kpc = 14

N.B.: the Caquot-Kerisel tables don’t provide values for friction angles superior to 45°. The values were chosen for 45°.

The parameters calculated here are for the cross walls alone. But their width (1,5 m) doesn’t cover the full length of each diaphragm wall panel (6,3 m). The values for Kpγ and Kpc must be reduced by a factor 1.5/6.3. We end up with the following parameters:

- $K_{p\gamma} = 4.1$
- $K_{pc} = 3.3$

The final geo-mechanic parameters used in the subgrade reaction coefficients models for the cross walls are as follows:

- $\gamma = 20$ kN/m^3
- c’ = 3.4 MPa
- Kh = 460000 kN/m^3
- Kpγ = 4.1

- Kpc = 3.3

The other soil clusters were modelled using Schmitt (1995) for stiffness calculations. The model also accounts for asymmetrical active pressure by introducing a berm on the river's side (it automatically considers lines of minimum passive pressure, as described in Schmitt & Dodel (2002)).

The model is shown below in Fig. 7:

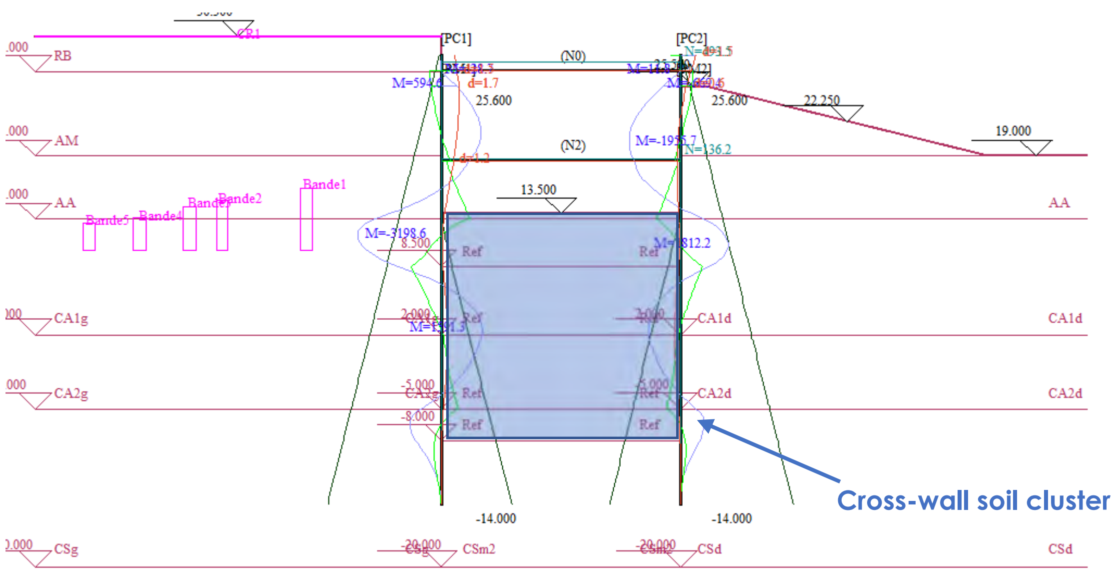

Fig. 7 – Subgrade reaction coefficients model

Finite Elements model

The finite elements model was conducted using the program Plaxis 2D. It is not possible to use the same method as previously described, as one cannot manually enter passive pressure parameters (Kpγ and Kpc). The soil improved with cross walls had to be described using the shear strain parameters: c' and φ'.

Passive earth pressure must be the same in both models. Starting with the parameters found above:

- Kpγ = 4.1
- Kpc = 3.3
- C' = 3.4 MPa

This value of Kpγ is found for an internal friction angle of φ' = 27°. We can keep this value and work out a value for the soil's cohesion to use in the Plaxis model, c'_{Plaxis}.

We need: Kpc(27°) x c'_{Plaxis} = Kpc x c'

Hence: c'_{Plaxis} = 3.3 x 3400 / 5.6 = 2 MPa

Eventually, the cross walls cluster can be defined with shear strain parameters:

- E = 5200 MPa
- C' = 2 MPa
- φ' = 27°
- γ = 20 kN/m^3

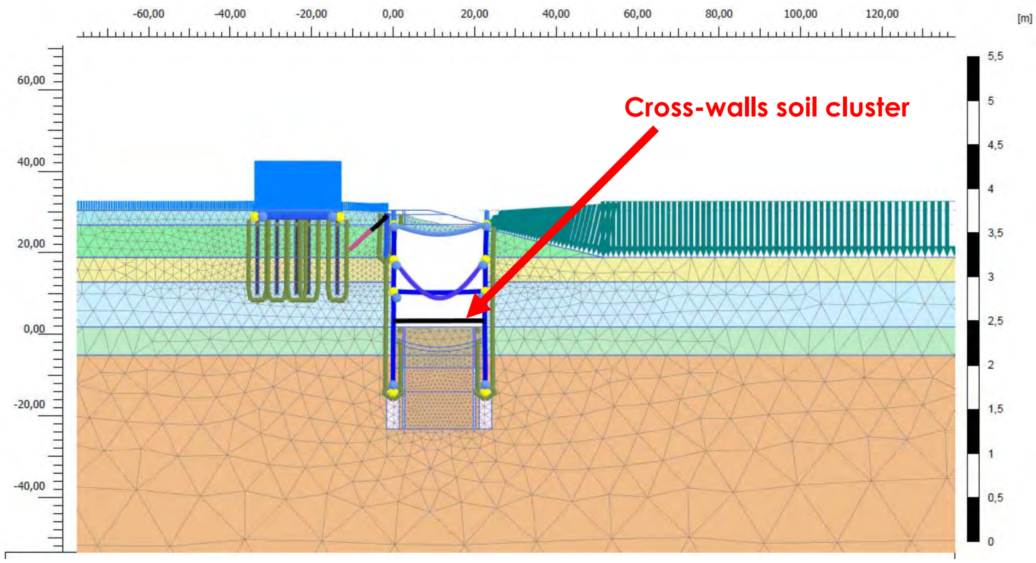

Fig. 8 – Finite elements model

Results analysis

Both models showed that adding cross walls to support the excavation was enough to limit deformations within contractual limits (1.5 cm at the top, 3 cm near excavation bottom).

In addition, the design office compared results between subgrade reaction coefficient models and finite elements models. The graph below shows bending moments versus depth for finite elements (in dotted yellow) and subgrade reaction coefficients (in blue) for both diaphragm walls.

Fig. 9 below shows very similar behaviour of the diaphragm walls for both models.

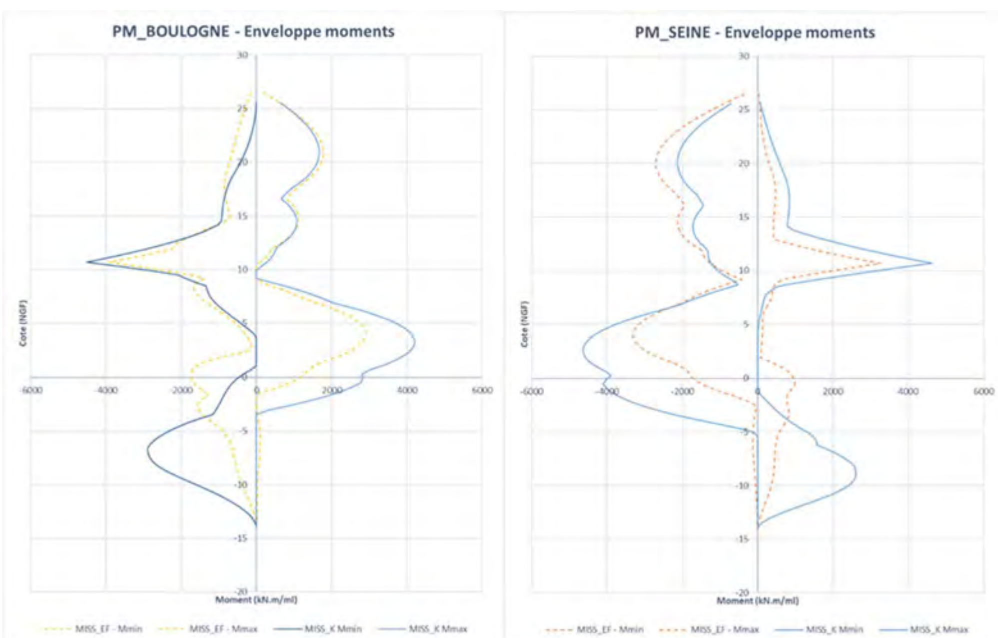

Fig. 9 – Diaphragm walls bending moments vs depth

CONCLUSION

This project was quite complex as it combined two different methods for improving passive earth pressure inside the excavation. Both these methods carry different challenges when it comes to integrating them in the calculation models.

Deep soil mixing comes with clear geo-mechanical parameters but need to be computationally assessed to consider the effects of vertical deviations that occur in the making of the columns. The model had to incorporate probabilistic elements to anticipate possible gaps and ensure they did not affect the overall added resistance too severely.

Cross walls came with a different challenge, as soil parameters had to be extrapolated from the concrete's compression and tensile strengths. Calculations had to be conducted using both subgrade reaction coefficients and finite elements. These methods require different input, hence different extrapolations were used to determine the soil parameters. Eventually, both models were compared to ensure that the results showed a similar and realistic behaviour of the diaphragm walls.

The station's construction is currently in the early stages of excavation. Deformations of the diaphragm walls will be monitored using inclinometers. The results will be compared to the deformations anticipated in the calculation models.

ACKNOLEDGMENTS

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