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Geostatistical modelling of geotechnical properties in the context of a tunneling project: Application to the Grand Paris Express project (France)

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ABSTRACT: In the context of underground construction projects, the knowledge of the urban subsoil is of major importance. This article focuses on the development of a 3D geostatistical modelling of the pressuremeter tests applied on a section of the Grand Paris Express. The spatial variability of the geotechnical behavior is studied through a comparison between deterministic geostatistical methods: ordinary kriging and collocated cokriging. They both give quite similar results but collocated cokriging is definitely more accurate. This study also shows that large-scale underground projects are an ideal setting for the application of such 3D modelling.

1 INTRODUCTION

Knowledge of the urban subsoil is one of the major current and future challenges in the context of underground development projects. In order to better characterize these subsoils and to minimize the major risks that may arise during the construction phase of the works, large-scale investigation campaigns are being carried out. They give a large amount of geological, geotechnical and hydrogeological data. Despite this, inaccuracies and uncertainties remain, which can have an impact on the time and cost of the works.

The development of geostatistical methods over the last few decades offers the possibility of responding to some of the problems raised. Indeed, through the production of geological and/or geotechnical models in 2D or 3D, they provide a continuous imaging and a detailed analysis of the spatial variability of the subsoil properties. However, the use of geostatistical models in their is still insufficiently developed in the field of tunneling projects.

Thus, the study presented in this article aims to show that large linear projects are an ideal setting for the construction of geostatistical model. To demonstrate this, a 3D geological-geotechnical modelling of pressuremeter tests parameters (limit pressure and pressuremeter modulus) is applied to a section of the Grand Paris Express.

After introducing the study site and the data of interest, the methodological process leading to the creation of a 3D geostatistical model will be described. The process is conducted on one of the geological units of interest: the *Coarse Limestone*. The resulting 3D model will be discussed through a comparative analysis between two deterministic geostatistical methods. The performance and relevance of the methods are evaluated through the statistical analysis of their respective results and the accuracy of predictions.

2 STUDY SITE AND AVAILABLE DATA

2.1 Study site

This study focuses on a specific sector of the Grand Paris Express (Figure 1). This research project is made possible thanks to the Société du Grand Paris, which provides access to their geological/geotechnical database (SONGE) compiling all the drillings and tests carried out along the line of interest. At this stage, for confidentiality reasons, the work and results presented here cannot be linked to a precise location.

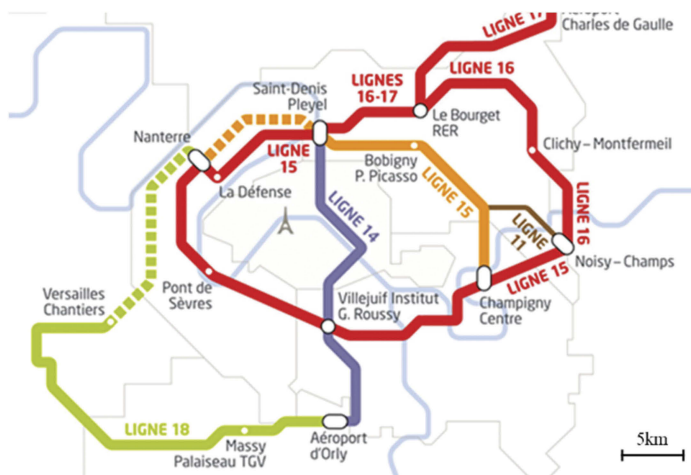


Figure 1. Map of the Grand Paris Express (Société du Grand Paris).

2.2 Available data

Within the framework of this tunneling project, extensive investigation campaigns were carried out and a wide variety of geotechnical tests were performed. In this work, it was chosen to develop the method from the pressuremeter tests because of their regular distribution and high density along the studied sector: more than 6,000 tests distributed with an average of one pressuremeter borehole every hundred linear meters.

The pressuremeter test is an *in situ*, geotechnical test which gives three soil parameters: the pressuremeter modulus E_m , the creep pressure P_f and the limit pressure P_l . Here, the modulus E_m and net limit pressure P_l^* ($P_l^* = P_l - \sigma_{h0}$ with σ_{h0} which is the total horizontal stress at test depth) will be studied.

3 DATA PROCESSING AND SECTORISATION OF THE LINE

3.1 Data processing

The methodology of geotechnical modelling by geostatistics presented here is divided in four main stages. Firstly, the processing of the database and therefore of the pressuremeter tests is an essential step to be carried out before any modelling attempt. This step identifies, process and eventually discard outliers that may have a negative influence on the final model. In our case, 4% of the total data are dismissed during the pre-processing of the database, which is not negligible.

When analysing the pressuremeter data, a number of tests were found for which the limit pressure was not reached or calculated according to the european rules of NF EN 22476-4. This is explained by two factors relating to the limitations of the pressuremeter test: either early bursting of the probe during the test or the limit pressure of the soil exceeding the capacity of the pressuremeter probe, limited to 5MPa in the case of a conventional probe and 8MPa for a high-pressure probe (standard NF EN 22476-4). For coarse limestones, these cases concern 75% of all tests. For these tests, an estimation of the net pressure limit, where this is not reached, has been made in order to improve the resolution of the analysis in the high values. This estimation of the net limit pressure is based on the existing correlation between net limit pressure and pressure modulus, the methodology followed is detailed in Lacherade et al. (2022). The geostatistical modelling is conducted on the new dataset consisting of the original PI* tests plus the re-evaluated ones.

3.2 Sectorisation

In this methodology, it was not chosen to make a single global geotechnical model of the whole *Coarse Limestone*. The originality here is to proceed with several local models thanks to the implementation of a sectorisation process. The aim of sectorisation is to divide the *Coarse Limestone* into several sectors with homogeneous geotechnical characteristics, validated from statistical criteria, and to model each sector individually. A hierarchical ascendant classification (*HAC*) (Ward 1963) method is first applied on pressuremeter parameters to create clusters within which the individuals are similar. Then an analysis of variances (*ANOVA*) (Fisher 1918) is used to validate the sectorisation. The sectorisation methodology is detailed in Lacherade et al. (2022).

In a second step, a concatenation of the sectors is carried out, this results in a global model of the *Coarse Limestone* on the whole line. This local approach give a better representation of the spatial variability of the geological unit and thus improves the accuracy of the interpolation with respect to a global model.

The sectorisation of the *Coarse Limestone* has identified for the PI*, four sectors with homogeneous geotechnical characteristics (Figure 2). This subdivision is justified by the

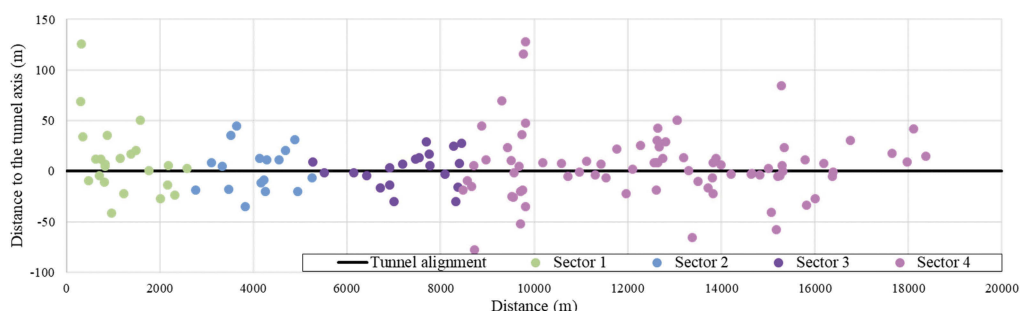


Figure 2. Sectorisation of the Coarse Limestone along the tunnel alignment.

Table 1. Results of normality, homoscedasticity and *ANOVA* tests.

Variable	Normality p-value	Homoscedasticity p-value	<i>ANOVA</i> p-value
Em	7.97E-08	1.4E-06	3.09E-15
PI*	9.62E-04	0.03	1.07E-15
Em/PI*	4.5E-06	0.57	2.62E-13

results of the *ANOVAs*. The p-values obtained for *ANOVAs* performed on Em, PI* and Em/PI* considering the 4 sectors are extremely low (Table 1, last column). This means that the 4 sectors do not belong to the same population and thus justifies the sectorisation made on the line. It should be noted that the *ANOVAs* carried out are non-parametric (Kruskal-Wallis tests) because the prior hypotheses to be verified simultaneously (normality and homoscedasticity hypotheses) are not (Table 1, columns 2 and 3).

4 3D GEOSTATISTICAL MODELLING

4.1 Methodology and variographical analysis

The geostatistical modelling is conducted on each sector independently with the use of two deterministic methods: Ordinary Kriging (OK) and Collocated CoKriging (CoCK). After a brief description of the principles of these deterministic methods, the interpolation results are analysed and a comparison between both is made.

Deterministic geostatistical methods are weighted linear estimators that use the spatial correlation studied by the variogram or covariogram to estimate a variable of interest. Here, ordinary kriging (Matheron 1963) and collocated cokriging (Xu et al. 1992) are used. Cokriging involves taking into account auxiliary variables correlated to the parameter of interest (PI*). Here, the auxiliary variable used for the collocated cokriging, is the pressuremeter modulus (Em) previously interpolated by ordinary kriging.

Because the collocated cokriging is based on the linear correlation between principal and auxiliary variable, the correlation diagram between Em and PI* is studied. Here, the linear correlation coefficients between Em and PI* are respectively 0.93, 0.92, 0.91 and 0.94 for the four sectors. These correlations are statistically significant for the application of cokriging.

The 3D geostatistical modelling per sector is undertaken through the use of Isatis Neo[®] software. Classical stages of a geostatistical modelling are applied: variogram map (identification of possible anisotropy directions in the spatial structure of the data), calculation of experimental variograms in the principal anisotropy directions (horizontal and vertical in our case) to analyse the spatial variability and fitting of the variogram model, cross validation to validate the variogram model. Finally, geostatistical interpolation is applied on a grid 5 x 5 x 1.5 m³, from the variogram models defined above. Note that the grid extends laterally over a length of 75m, giving a constant total width of 150m. Also, in order to compare OK and CoCK with same calculation parameters, the neighborhoods (experimental points used to estimate a point without measurement) used during the interpolations are the same for each method.

The variogram models used for the interpolation are displayed on Figure 3 (with $\gamma(h)$ corresponding to the experimental semivariance of the variable, calculated according to the distance step considered), three main types of structures are found in the model: nugget effect, spherical and linear. On each case the nugget effect is present, it shows the variability of the parameter at a very short distance. The ranges are also identified which shows that there are spatial correlations. Moreover, the variograms of the 4 sectors clearly differ, which justifies working with a sectorisation.

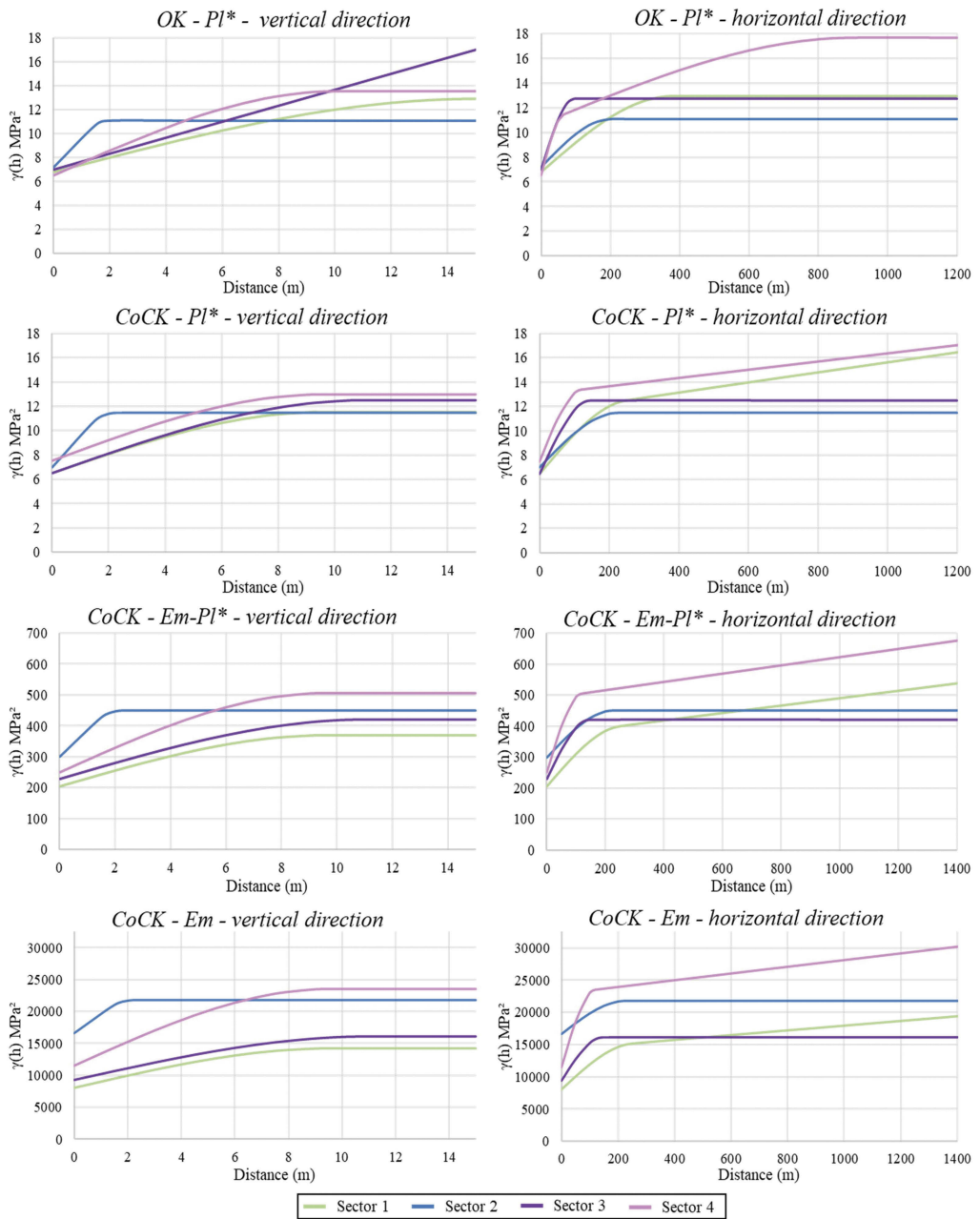


Figure 3. Variogram models used for ordinary kriging (OK) and collocated cokriging (CoCK) for each sector in the vertical and horizontal direction (with $\gamma(h)$ the experimental semivariance of the variable).

4.2 Results

The interpolation results by ordinary kriging (OK) and collocated cokriging (CoCK) are shown together in Figure 4 (a. and b.).

The errors of prediction are given by the kriging standard deviation: S_k (Figure 4, c. and d.). This parameter provides an indication of the accuracy of the interpolation and the local variability of the parameter studied (Cardenas and Malherbe 2003). The interpolation error is

useful to highlight regions where lack of data makes the modeling less reliable. A statistical review for both methods is presented in Table 2 with the minimum, maximum, average, median values and the coefficient of variation (CV) exposed.

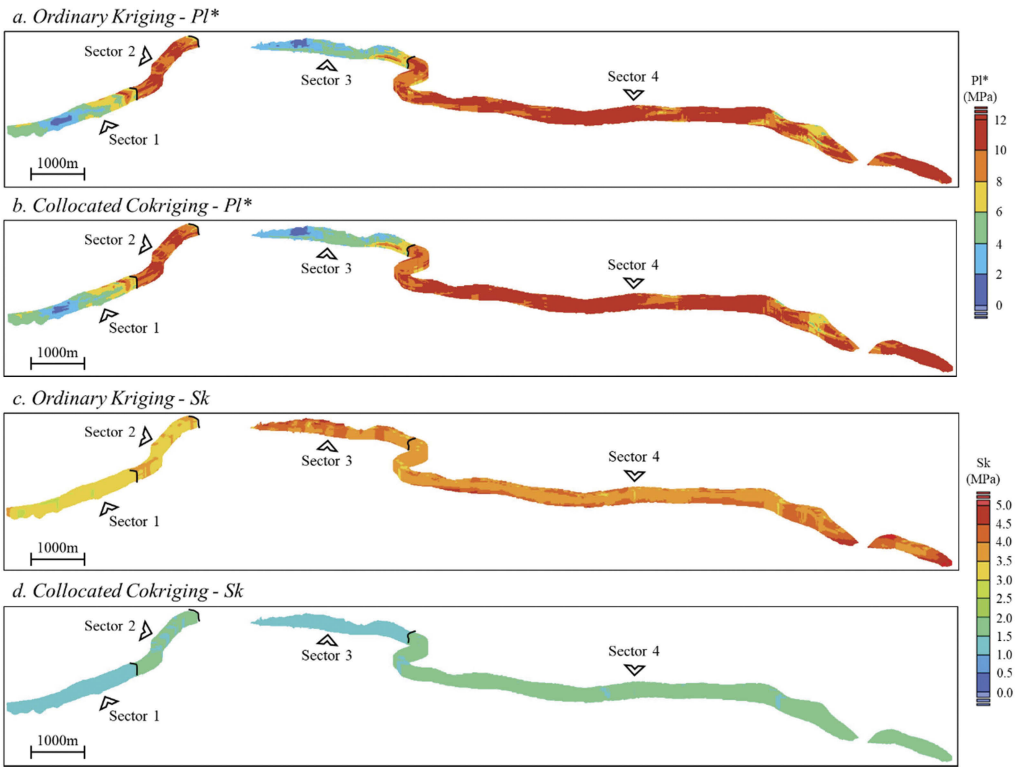


Figure 4. Results of the estimation of the PI^* in the Coarse Limestone by a) Ordinary Kriging and b) Collocated Cokriging and of the standard deviation (Sk) of the estimation by c) Ordinary Kriging and d) Collocated Cokriging.

Table 2. Statistical review of results – PI^* and Sk in the Coarse Limestone.

Parameter	Minimum	Maximum	Average	Median	CV
Unit	MPa	MPa	MPa	MPa	%
OK – PI^*	0.7	15.5	9.3	9.9	30
CoCK – PI^*	0.7	15	9.3	10	29
OK – Sk	2.8	5.4	3.7	3.8	8
CoCK – Sk	1	1.7	1.5	1.5	7

4.3 Discussion

The interpolation results of the PI^* between the ordinary kriging (OK) and collocated cokriging (CoCK) models are substantially identical (Figure 4 a. and b.) the statistical analysis confirm this (Table 2). The average difference of 0.5MPa (median of 0.3MPa) between both grids exposes this strong similarity. In addition, for both methods, the analysis of the model (Figure 4) for the *Coarse Limestone* shows that the net limit pressure varies significantly along the line. These important variations, expose contrasts between areas with low and high PI^*

values and allows to identify four regions (black arrows on Figure 4) within which the behaviour of the pressuremeter characteristics seems to be quite homogeneous. These four sectors overlap almost perfectly with those resulting from the division of the line by *HAC*, which confirms the choice of the sectorisation made upstream.

Regarding the kriging standard deviation (Figure 4 c. and d.), it is very homogeneous for both methods (CV of 8% for OK and 7% for CoCK) despite some local variations. However, the Sk is significantly weaker on the model produced by CoCK than by OK: median values of 1.5MPa and 3.8MPa respectively (average of 1.5MPa and 3.7MPa also). This reflects a more accurate model for the CoCK and it is related to the use of Em as an auxiliary variable. Moreover, this accuracy gap is also found on the comparative graph of predictions with error bars *vs.* observations (from the cross-validations) conducted for example in Sector 1 (Figure 5). The CoCK provides higher accuracy when comparing the best estimates and the observations, and higher reliability of the confidence intervals (CI), either at 68 and 95%, which contain the observations for most of them. Moreover, this is very noticeable for tests with low values ($PI^* < 2.5\text{MPa}$) or high extreme ($PI^* > 10\text{MPa}$) where OK accuracy is very poor as well as the coverage of the confidence intervals, due to the smoothing effect of kriging.

As mentioned in the section 4.1, the Em variable is highly correlated with the PI^* data. This correlation is taken into account in the construction of the model in the cross variograms (between Em and PI^*) during the interpolation stage where Em is taken as the auxiliary variable all over the field. Thus, due to the very high correlation between

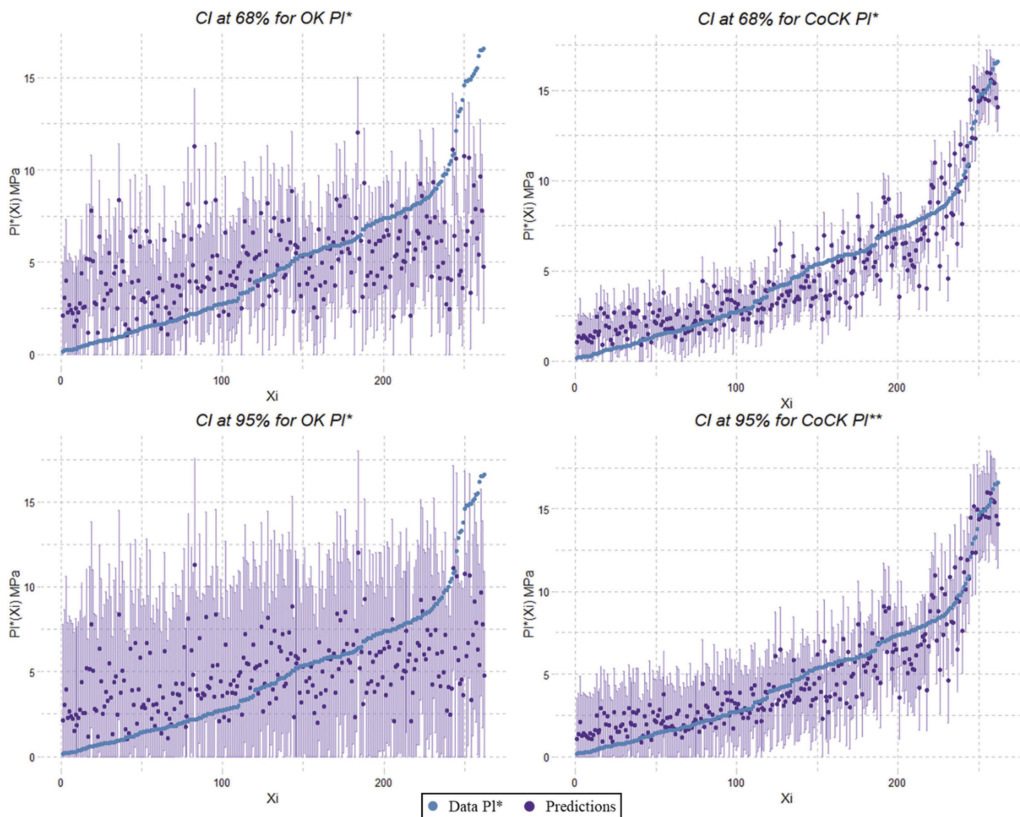


Figure 5. Comparative graphs of predictions with confidence intervals (68% and 95% CI) and observations for OK and CoCK of sector 1 with the values in ascending order on the x-axis.

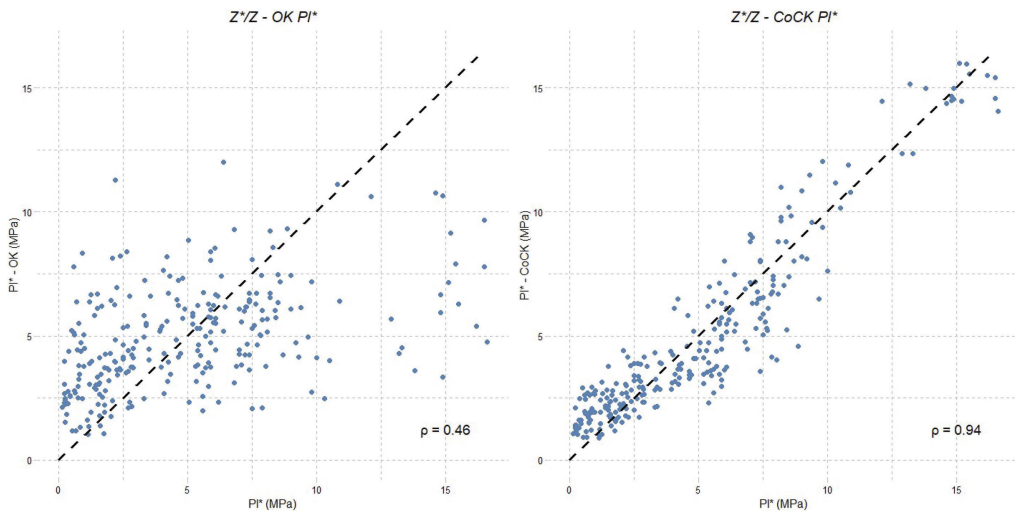


Figure 6. Correlation coefficients Z^*/Z of cross-validations OK and CoCK of sector 1 (Z^* = estimated value, Z = data PI^*).

both variables, it is logical that the Sk is low. This is reflected in the correlation Z^* (estimated value) and Z (initial value) resulting from the cross-validations process: results are better for CoCK (respectively 0.94, 0.91, 0.91, 0.94 for the four sectors) than OK (0.46, 0.15, 0.36, 0.52). Figure 6 outline this aspect with cross-validation result for the sector 1.

Despite globally similar PI^* grids, due to better accuracy (lower Sk) and higher confidence on interpolated values (error bars), collocated cokriging seems in this context more suitable than ordinary kriging, which is consistent with Isaaks and Srivastava (1989) or Giraldo et al. (2020). This is especially true for extreme values, which is interesting from an engineering point of view.

5 CONCLUSION

The aim of this study was to show that due to the amount of data provided by large linear projects as tunnels, they are an ideal setting for the construction of geostatistical models and there is a real interest for decision-makers to democratize their use. This was done by presenting a 3D geostatistical modelling approach of geotechnical parameters at the scale of a subway line. This approach extends from data processing to the graphic production of the 3D geotechnical model with the related errors of predictions, including the division into homogeneous sectors using statistical methods.

In this work, the methodology was applied to a lithological formation of interest: the *Coarse Limestone* found on one of the sections of the Grand Paris Express. The data processing and sectorisation of the tunnel line were first briefly described in order to show these stages are very important phase in the modelling process. The spatial variability of the PI^* exhibited by the 3D modelling allowed to identify four contrasted regions with similar pressuremeter characteristics inside. The comparative study between ordinary kriging and collocated cokriging showed that collocated cokriging has better predictive accuracy and higher confidence on interpolated values than ordinary kriging. Collocated cokriging reproduces also better low and high extreme values which are of a great interest for risk analysis.

Beyond the comparison, the study reveal that geostatistical methods are fitted for tunneling projects thanks to the large amount of information they provide (here, more than 6000

pressuremeter tests along the 20km of tunnel). They efficiently describe and expose the spatial variability of geotechnical parameters, and allow to consider boreholes that are off-centre from the tunnel alignment in order to build a 3D band around (here 150m wide band).

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