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Uncertainty analysis in the assessment of settlements caused by urban work

M. El Gonnouni, Y. Riou, P. Y. Hicher
Laboratoire de Génie Civil Nantes Saint Nazaire, Ecole Centrale de Nantes, France

ABSTRACT: The aim of this study is to assess the influence of the uncertainties related to the soil variability in the numerical modelling of settlements caused by underground work. Based on a great number of in situ tests, a geostatistical method (kriging) applied to the subsurface is justified and applied in order to determine the mean position of the soil layers and their estimation variances. This uncertainty is then interpreted in terms of calculated surface settlements.

1. INTRODUCTION

The construction of underground engineering projects (tunnels, opened trenches, subways, underground passages) in urban sites causes settlements which can affect existing buildings and provoke environmental harm. Disorders of this kind can be estimated by deterministic geotechnical analysis, especially numerical methods based on discretization. But in spite of their complexity, such modelling contains some serious deficiencies : lack of information on the physical and mechanical characteristics of the soil and its initial state, limited control of actions caused at different stages of construction, etc.

The aim of this study is a sensitivity analysis on the error caused by the natural variability of the subsurface in urban sites, and caused by the linear regression technique used to define a set a cross sections in the numerical modelling. With this in mind, it was decided to resort to a geostatistical method in order to characterise statistically the composition of the soil (estimation of the mean position and estimation variance of elevation of interfaces). This uncertainty is then applied to the surface settlement calculation taking into account the boring of the underground work. So this uncertainty is expressed in terms of variation of settlement trough, a typical concern for geotechnical engineers.

The aim of this study is to supply engineers in charge of a underground work in urban sites with some information on the number of tests required for geometrical characterisation, and on the error in settlement calculations. This study has a practical interest, so, it refers to a particular site and tunnel project likely to cause surface settlement. This is the D line extension subway in the city of Lyon, a site subject to a important geotechnical investigation program, leading to numerical modelling and an initial statistical approach (Riou et al., 2000)

2. INPUT DATA FOR GEOSTATISTICAL ANALYSIS

This study concerns a 1000 meter long and 200 meter wide section located on the extension D line of the subway of Lyon between Gorge-de-Loup and gare de Vaise. The geotechnical report contains data from in situ and laboratory tests. All over this section, the geotechnical study includes 90 drillings, destructive and non-destructive testing, in-situ tests in boreholes, Standard Penetration Tests, conventional pressuremeter tests and scissometers (Bernat, 1998). In this study, the measurements are supposed to be reliable and the geotechnical analysis proposed by the Centre d'Etude des TUnnels (CETU) relevant. So, the subsurface provided by this analysis for each drilling point should be in agreement with some reality.

The three-dimensional representation of the drilling points with their subsurface elevation is shown on figure 1. This figure provides a qualitative information of the sampling density.

square:	fill
up triangle:	ochre silt
down triangle:	grey silt
right triangle:	sandy silt
left triangle:	gravel sand 1
diamond:	clay
circle:	gravel sand 2

X, Y:	Lambert co-ordinates.
Z:	NGF elevation

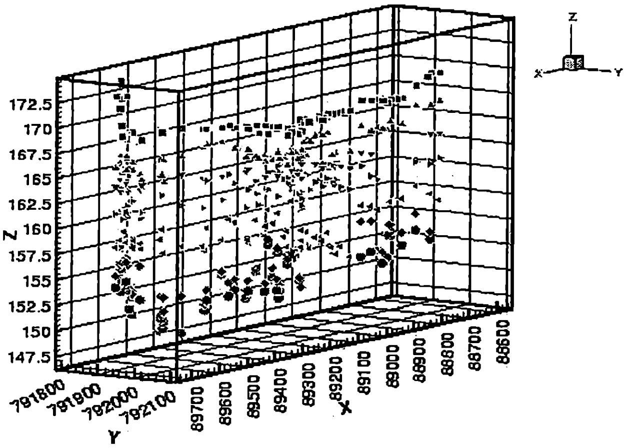
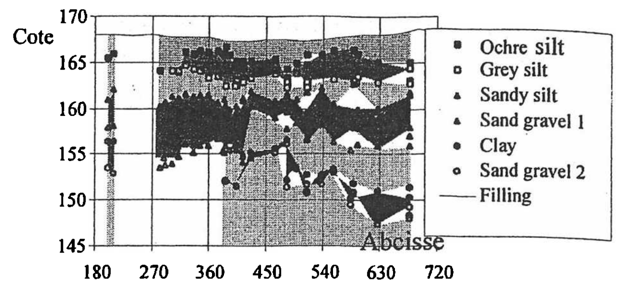


Figure 1: Drillings and subsurface provided by the geotechnical analysis

3. STATISTICAL CHARACTERISATION OF THE INTERFACES

The kriging was used in this study to obtain at any point of the soil an estimate of the position of the soil layer roof, in particular in an unsampled zone, and to define a variance of this estimate. The estimate is established by a weighting of the measurements taken in the vicinity of the studied point. Optimal weighting, namely the one that proves to be most realistic to estimate the elevation, is based on the variogram. This basic statistical tool gives a structural interpretation of the phenomenon, i.e. in the present case, the similarity of the elevation of two points according to the distance which separates them.

The method used in this document is the ordinary kriging. This method is based on a hypothesis of stationarity of the random function that gathers a set of random variables representing the natural variability at any point. Considering the site section following the axis of the tunnel, this hypothesis seems to be justified in the whole support (900m), at least with regard to the four first layers (ochre silt, grey silt, sandy silt and sand gravel 1 : figure 2). We note in particular here that the fluctuations are more important than the drift. One the other hand, the two deepest layers (clay and sand gravel 2), along the support, display a «carrier», not uniform but likely to call into question the technique of estimate and the evaluation of the variance. The geostatistical study was also applied to the two zones (0-600m) and (600-900m) in order not to integrate the whole depression (500m-800m) in natural variability.



Figures 2 : Subsurface profile of the site in the studied zone Projection on the vertical plane passing by the axis of the tunnel

3.1 *Variogram models*

All the data concern the elevations of each layer at different points, so it seemed natural to use this rough information in order to characterise the subsurface. However, the profile provided by the kriging of these data is not realistic. Due to the drift of the clay and sand gravel 2 layers, the estimate variance exceeds the thickness of clay layer. So the geostastical analysis leads to extreme lies with no clay layers. An overlapping of layers occurs in some areas. In order to avoid this pattern, a variogram model dealing with mean positions and thickness of soil is proposed here. These data provide a more realistic representation of subsurface profile.

The representation of the experimental variogram depends on the lag distance. A sensitivity study was achieved in order to obtain a variogram associating precision and regularity smoothing the disturbance due to a lack of data. A 25m step fit the best compromise (figure 3).

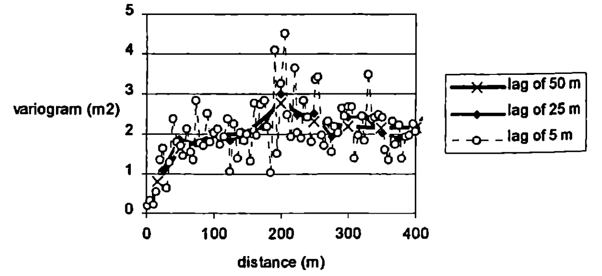
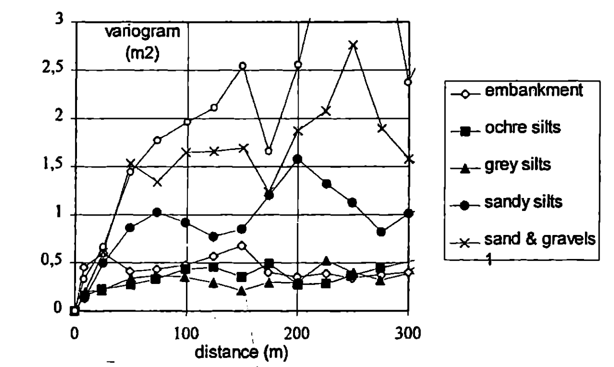


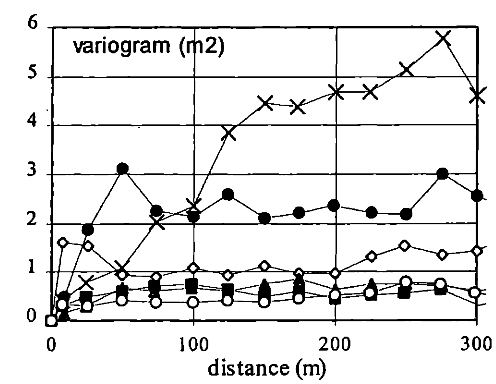
Figure 3 : Variogram from sand gravel 1 layer

The variograms related to the first four layers are bounded (figure 4). This confirms, for these layers, the stationary hypothesis expressed previously. The clay and sand gravel 2 variograms show the typical profile of a signal with a drift. Nevertheless, it was decided to use these variogram structures and to validate them on the kriging results in comparison with the observations.

These variograms show some variations (hole effect), due to the lack of information, recurrent problem in geotechnical study. But these variations are smaller in cohesive material layers (embankment, ochre silt and grey silt) than in sandy material layers, except for the clay layer located between the two sand-gravel layers. So, when the interfaces is related to a cohesionless material layer or a layer with a sandy part, the elevation variogram indicates a sharp profile, a smaller range and a higher sill. The two silt layers have a mean position range varying from 70 to 130m and a sill varying from 0.4 to 0.5 m^2. A smaller range (approximately 60-70m) and an important variability (maximal sill of 1 to $2m^2$) characterize the sandy layers. These ranges justify here the method to assess the subsurface profile and its variance. So, it seems there are two different spatial structures, depending on the nature of soil.



a : mean position



b : thickness

Figure 4: Variogram of mean position and thickness of the layers

No geological interpretation of this phenomenon is proposed here. That concerns a particular site. It would be useful to compare these results with similar analyses carried out on other urban sites.

3.2 *Kriging*

For the purpose of kriging, correlation structures are determined by fitting typical variogram shapes : mathematical models assuming a positive estimation. Spherical and exponential models were applied in this study : tables 1. From cross validation tests, the spherical model is preferred to the other one for all soil layers : table 2.

Table 1.a: Sets of models tested for mean position variograms

Soil layer	diagram	range (m)	sill (m^2)
embankment			
ochre silts	S + E	70 -130	0.4
grey silts	S + E	70 -130	0.3
sandy silts	S + E	60 -70	0.85
sand gravels 1	S + E	60 -70	1.65
clay	S + E	60 -70	2.00

S = Spherical model, E = Exponential model

Table 1.b: Sets of models tested for thickness variograms

Soil layer	diagram	Range (m)	sill (m^2)
embankment			
ochre silts	S + E	30 – 50	0.5
grey silts	S + E	30 - 50	0.5
sandy silt	S + E	50 - 60	2.3
sand gravels 1	S + E	100 - 120	4.2
clay	S + E	30 - 50	0.40

S = Spherical model, E = Exponential model

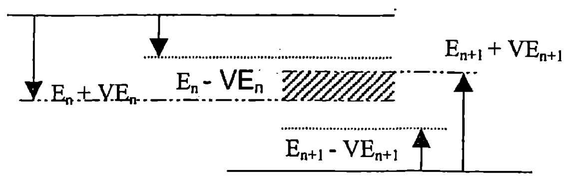
Table 2: Results of the cross validation

soil layer	Select models		Errors estimate m	Error Variance m^2
	model	range (m)		
Ochre silts	S	90	0.021	0.164
Grey silts	S	80	0.036	0.13
Sandy silts	S	60	0.0215	0.41
Sand gravels 1	S	60	0.006	0.88
Clay	S	70	0.027	1
Sand gravels 2	S			

3.3 *Elevations and estimation variance of layers in a 600m zone*

On the basis of the previous results, a "likely interface zone" is then defined as the intersection of zones indicated in figure 5.

This process does not take into account the mean position variance that would lead to a greatest interface zone and to some subsurface without clay layer. On basis of the geotechnical analysis (figure 2), this possibility cannot be justified.



P_n : estimate of the "n" layer mean position
E_n : estimate of the "n" layer half thickness
VE_n : variance of the "n" layer half thickness

Figure 5 : Assessment of "likely interface zone"

Other convenient processes likely to propose a subsurface profile and its variability, can be probably applied. However, this process has been selected on account of the results in conformity with the observations (figure 7). Contrary to the process dealing with interface data, all the observed layers are represented.

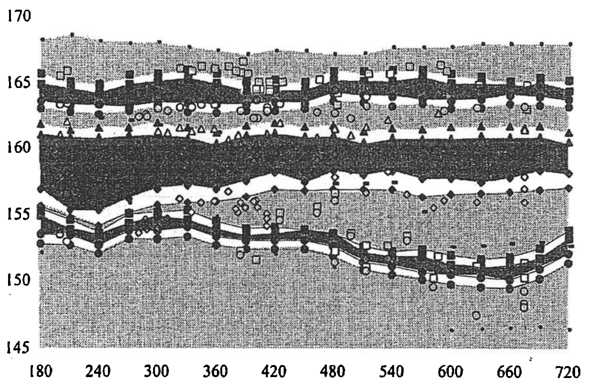


Figure 7 : Measures and geostatistical subsurface

Some measurements are located outside the "likely interface zone". This is due to the process and the kriging that, as for most interpolators, smooths the profiles resulting from measurements. So, this zone has to be considered as a 'likely' zone. We notice here that the elevation variability is probably underestimated because of the extent of measured area exceeding the tunnel zone. A weighting of measurements located in this zone would be probably more realistic.

4. VARIANCE OF SURFACE SETTLEMENTS

From the previous geostatistical subsurface, 19 cross sections have been defined in a 540m long profile, each section including the tunnel position, as indicated in figure 7. So, a two-dimensional numerical modelling of the boring can be carried out every 30m, a distance corresponding to the third of the smallest range. In this study, only three numerical results related to the sections located respectively at the 240m, 480m and 720m are presented. In each cross section, the interface is supposed to be horizontal. This hypothesis can be justified by the diameter of the tunnel (6m) representing only one tenth of the weakest range.

For each of these cross sections, and for all extreme positions (lower and upper limits) of the interface, a numerical calculation of surface settlement has been carried out. The numerical modelling is defined as follows :

- FEM resolution — code : Cesar-LCPC ;
- 2D plane strain — depth : 8m under the tunnel invert [1]; half width : 38 m
- mesh — 3500 nodes — 1700 quadratic elements
- constitutive relationship for soil: Mohr Coulomb model: elastic perfectly plastic, non-associated model

Tableau 3: mechanical parameters of subsurface materials

Layers	E MN/m^2	γ kN/m^3	ν	c kPa	φ °	ψ °
filling	11,2	18,0	1/3	30	38	18
ochre silts	15,0	20,3	1/3	15	36	16
grey silts	15,0	16,3	1/3	50	22	2
sand gravels 1	47,7	21,0	1/3	5	35	15
clay	16,9	18,4	1/3	14	20	1
sand gravels 2	47,7	21,0	1/3	5	35	15

water level: 166,5 NGF.

tunnel lining — linear elastic behaviour
thickness : 0.35m,
mean radius : 2.825m,
Young's modulus : 13500 MPa

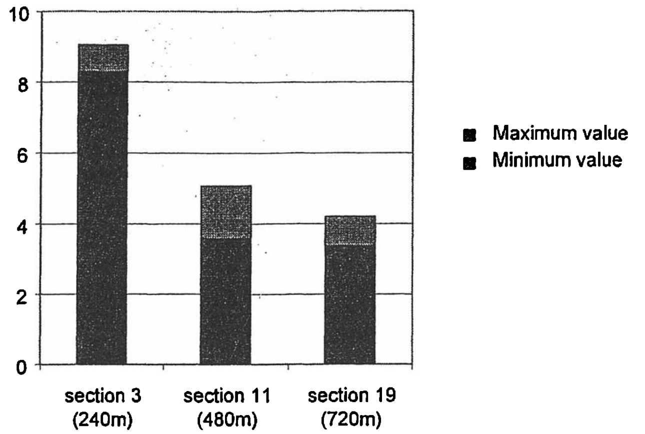
- boring modelling :
  3 stages
  - stage 0 :
    assessment of the initial stress state
    $k_0 = 0.5$
  - stage 1 :
    partial force release at the outside line of the tunnel up to λ rate (no lining)
    3 steps
  - stage 2 :
    complete force release with lining
    application of tunnel weight ($-3{,}2\ kN/m^3$)
    7 steps

The assessment of the λ rate is based on a comparison of the numerical results with the measurements in a reference section[2]. λ was calculted here to be 32.5%.

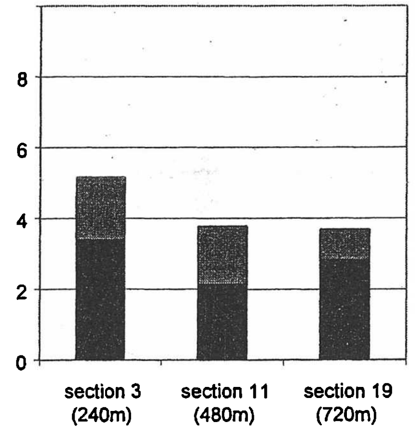
[1] The heave at the tunnel invert depends on this distance when the Mohr Coulomb model is used with a constant Young'modulus,. So this distance is fixed.

[2] As mentionned in the introduction, the aim of this study is a sensitivity analysis on the error caused by the natural variability of the subsurface in urban sites. With this in mind, λ is fixed

The lower and the upper limits of the surface settlement in the three sections are shown in figure 8.



a : end of stage 1



b. end of stage 2

Figure 8 : Variation of surface settlement in the three sections

The sensitivity analysis based on the calculated surface settlements gives a maximum discrepancy of 55% (34%, if stage 1 is only taken into consideration). Concerning the stage 1, this discrepancy is in relation with the number of soil layers crossed by the tunnel. This result seems consistent as the unloading acts mainly on these layers. The discrepancy of the complete surface settlements (end of stage 2) cannot be simply analysed because of the tunnel upheaval due to hydrostatic pressure acting on the lining and accordingly on upper layers.

The variation of the three calculated surface settlements along the 480 m zone combines unnatural variability, tunnel position governed by practical requirements, and subsurface considerations. This first variability has been introduced in this study because the subsurface structure generally controls the tunnel design.

These calculated values are to be compared with the recorded surface settlements ranging from 2 to 11 mm. But it should be noted that this range encompasses more than subsurface uncertainties: mechanical parameters and the implicit uncertainty in the construction of the tunnel were also included.

5. CONCLUSION

A method based on a geostatistical process and FEM software is presented and applied to an urban tunnel project in order to evaluate the reliability of the calculated surface settlement. This method dealing with the interface locations, provides a subsurface variability consistent with the recorded measurements. The FEM code provides a surface settlement variability from this previous variability.

For the case history in Lyon, and for the total settlement, at the end of the stage 2, the calculated discrepancy ranges from 26 to 55 %. It ranges from 9 to 34 % for the stage 1 prior to the lining laying.

These values depend on the position of tunnel in regard to the subsurface and especially on the number of layers crossing the tunnel. These values provide some useful information to geotechnical engineers involved in a tunnel project. But we suggest applying this method on other urban sites in order to validate it.

Further calculations are now intended every 30m, along the studied zone. These calculations aim at the assessment of a spatial correlation structure of the calculated settlement. This result will be then analysed to direct exploration at the position of greatest estimation variance.

A similar study dealing with mechanical parameters of each soil layers and Stochastic Finite Element Method, remains to be investigated.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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