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Geostatistical analysis of geotechnical uncertainty: risk assessment in engineering projects

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RÉSUMÉ
Le Port de Trois-Rivières est un acteur important dans le développement économique sur le plan régional, national et international pour des secteurs industriels tels que l'aluminium, la foresterie et l'agroalimentaire. Avec les projets de développement prévus, des analyses géotechniques sont jugées essentielles pour évaluer les incidences sur les structures. La variabilité est attribuable à la nature des dépôts meubles, aux interventions de remblaiement, d'amélioration des sols, dans les matériaux de construction des quais allant des pieux en bois, des tirants métalliques ancrés à des murs en béton jusqu'à l'utilisation des pieux métalliques avec des palplanches. Des méthodes basées sur la géostatistique sont considérées pour analyser les incertitudes des paramètres géotechniques critique, d'établir des plages de valeur représentative d'un niveau de confiance jugé acceptable et de gérer les risques d'intégrité sur des structures existantes. Ces plages de valeur sont utilisées pour la modélisation numérique du tassement des sols.

ABSTRACT
The Port of Trois-Rivières plays a significant role in the economic development at the regional, national, and international levels for industrial sectors such as aluminum, forestry, and agri-food. With the proposed developments, geotechnical analyses are judged essential to assess the impacts on structures. The spatial variability is attributed to the nature of soil deposits, the historical backfilling, soil improvement interventions, the materials used in the quay walls construction from wood piles with tie rods anchored to concrete walls, and the more recent use of sheetpile anchored walls. Geostatistical methods are used to analyze uncertainties in critical geotechnical parameters. These methods help establish a representative range for each parameter within an acceptable confidence level. In addition, they quantify risks to existing structures and identify suitable prevention solutions ensuring their integrity. These representative range values are then used in numerical modelling to assess soil deformation.

1 INTRODUCTION

The Port of Trois-Rivières was established in 1882 at a strategic location between Montreal and Quebec cities. The Port of Trois-Rivières is a key contributor to economic growth at local, national, and global levels, particularly in vital industries like aluminum, forestry, and agri-food. To meet evolving demands of maritime and economic sectors, it is necessary to continuously develop the Port of Trois-Rivières, including construction of new facilities and enlargement of existing docks. Conducting geotechnical analysis is considered crucial for assessing effects on current and proposed potential structures, infrastructures, and facilities within the Port's anticipated expansion zone.

Geotechnical evaluation is a fundamental pillar in project design that ensures stability. Data are gathered from a variety of sources, including historical records, geological maps, on-site investigations, laboratory results, over a specific period. On the other hand, the deposit of overburden soils is often heterogeneous due to its association with sedimentary deposition. Soil improvement interventions are designed to enhance geotechnical properties of a specific area of overburden soil and must be taken into consideration. Backfilling activities carried out in certain areas should also be incorporated. Hence, foundations of proposed and existing structures within the same location could potentially be established on different soil types and thickness. In terms of modelling, constructing a 3D stratigraphic model and quantifying spatial properties can often present challenges.

It is essential in the geotechnical modelling phase of a project to build a representative stratigraphic model with precise geotechnical properties. Achieving this objective can sometimes be challenging due to the uncertainties inherent in the available data. The predictive model should incorporate those uncertainties, and their quantification should be carried out using robust methods tailored to the specific site conditions (Schorpp et al. 2022). Geostatistical methods are employed to quantify uncertainties in geotechnical parameters, establishing confidence intervals that reflect an acceptable level of certainty (Chilès and Delfiner 2012). The geotechnical properties are spatially determined using these intervals, which are based on empirical relationships tied to soil units within the stratigraphic model. These analyses lead to

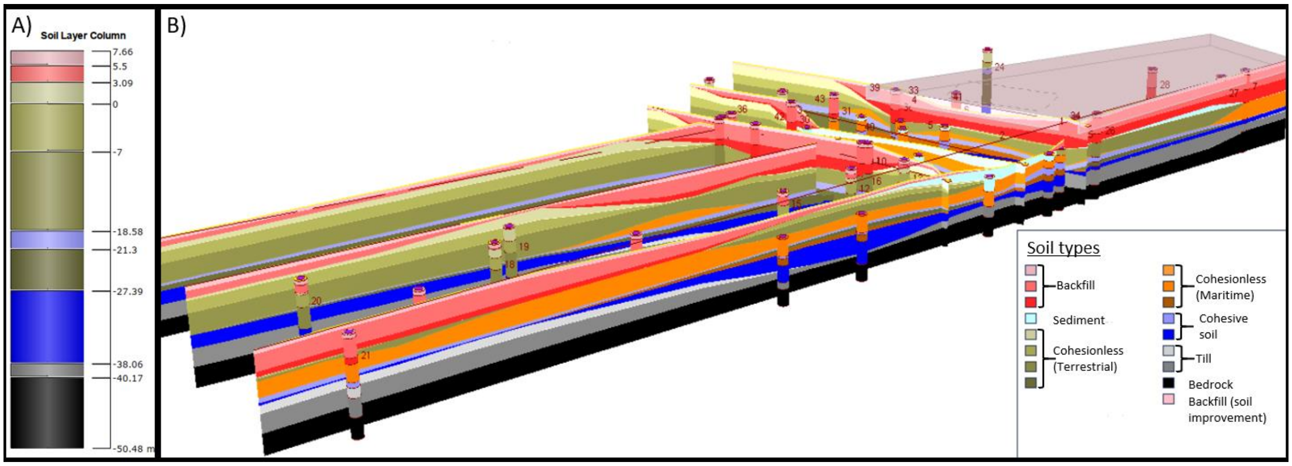

Figure 1. Stratigraphic model conditioned to borehole data. A) Example of a borehole data. B) Stratigraphic model

creation of multiple scenarios for numerical modelling.

This paper will utilize geostatistical techniques to investigate uncertainties in key geotechnical parameters and to define a representative spectrum for each parameter within a satisfactory level of confidence. These representative range values are then considered in numerical modelling by spatially outlining geotechnical properties and subsequently attributing them to the soil units of the stratigraphic model. Representative scenarios of soil settlements are considered in the assessment of the projected development's impact on structures, infrastructure, and facilities stability.

2 REGIONAL GEOLOGY

There have been four glacial periods in North America during the Quaternary period. These glacial cycles have significantly shaped the landscape. Trois-Rivières area is approximately 90% covered by surficial deposits, which consist of several sediment types. These include till, fluvioglacial sediments, marine clays, regressive sands, and organic deposits (Occhietti 1989, Leblanc et al. 2013).

3 FIELD INVESTIGATIONS

In the context of geotechnical risk analysis, an essential starting point entails creating a stratigraphic model. This model encompasses defining stratigraphic units as captured by geotechnical investigations. Over 130 geotechnical boreholes were considered in this analysis. In the second phase, the model is populated with essential geotechnical and hydraulic properties. These properties include density, internal friction angle, cohesion, elastic modulus, consolidation properties, and hydraulic conductivity. These parameters play a crucial role in understanding and analyzing the behaviour of the overburden soil, especially in geotechnical and environmental engineering contexts. Correlation between field and laboratory data will lead to drive best fitting curves to consider it in the numerical model.

Over the past 90 years, on-site geotechnical investigations have been conducted. Evaluating all gathered information and assessing its reliability is a crucial step in the geostatistical evaluation process. To prevent misleading conclusions, outlier data has been excluded.

3.1 Stratigraphic model

In Figure 1, the overburden stratigraphy and bedrock roof are presented at a borehole scale (left) and at the site level (right). The stratigraphy model was built considering data from geotechnical boreholes judged reliable and using Settle 3. The study classifies the soil into eight types, each represented by a distinct colour. From top to bottom, the soil types are classified as backfilling (pink), sediment (light blue), cohesionless terrestrial (beige), cohesionless maritime (orange), cohesive (blue), till (gray), and bedrock (black).

3.2 Geotechnical properties

The primary measured data for cohesionless native soil comes from the Standard Penetration Test (SPT) N_{SPT} values. The site coverage area had an abundance of (thousands) N_{spt} values. Also, ground improvement using dynamic compaction technique has been implemented in some areas of the quay apron to improve mechanical properties of the infill. Figure 2 illustrates the initial and final young modulus from pressuremeter tests, measured on site and the depth of soil improvement using dynamic compaction (Baguelin 1978, Briaud 1992).

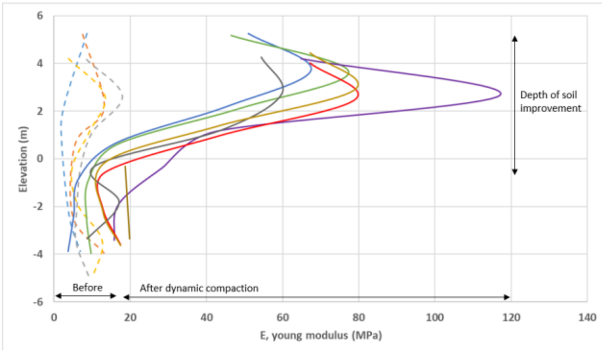

Figure 2. Young modulus from pressuremeter test (E in MPa), before and after dynamic compaction ground improvement

In the case of cohesive soil, various measurements were obtained from the site, including undrained shear strength under both intact and remoulded conditions (S_U and S_R in kPa), as well as piezocone penetrometer profiles (various parameters). In the laboratory, data from tests such as odometer consolidations, Atterberg limits, and Swedish resistance tests were accessible.

Due to the natural variability of properties in both cohesionless and cohesive soil, as well as project strategic significance, traditional statistical approaches are not deemed robust enough to capture on-site statistical variability (i.e., differences observed in parameters or phenomena across various locations within a given geographic area). Mean and standard deviation calculation over the whole dataset lacks robustness, mainly due to spatial correlations observed within specific areas, for example, those with or without soil improvement, extending over different depths. Consequently, the adoption of a geostatistical approach for estimation and uncertainty assessment was implemented to understand the consistency of available geotechnical data.

4 UNCERTAINTY ASSESSMENT USING GEOSTATISTICAL METHOD

4.1 Regression-Kriging

Without loss of generality, a soil property can be represented by a variable denoted as $Y(\mathbf{X})$ as a function of a coordinate vector **X**=(x, y, z). Variable $Y(\mathbf{X})$ is assumed to be the sum of a fitted deterministic part, denoted as $\widehat{m}(\mathbf{X})$, and an interpolated residual $\hat{e}(\mathbf{X})$, such as $Y(\mathbf{X}) = \widehat{m}(\mathbf{X}) + \hat{e}(\mathbf{X})$. Spatial variation can be modelled independently for both deterministic and stochastic components. By integrating these two approaches, we obtain at a given sampling coordinate x_0 :

$$Y(x_0) = \widehat{m}(x_0) + \hat{e}(x_0) = \sum_{k=0}^{m} \hat{\beta}_k q_k(x_0) + \sum_{i=1}^{n} \lambda_i e(x_i) \quad [1]$$

where $\hat{\beta}_k$ are estimated deterministic model coefficients, q_k is the k[th] predictor at the estimated location x_0, λ_i is the kriging weight associated with the sampling location x_i, and $e(x_i)$ is the residual at the sampling location x_i. The coefficients $\hat{\beta}_k$ are estimated from the sample using the generalized least squares method (GLS):

$$\widehat{\boldsymbol{\beta}} = (\boldsymbol{q}^T \boldsymbol{C}^{-1} \boldsymbol{q})^{-1} \boldsymbol{q}^T \boldsymbol{C}^{-1} \boldsymbol{y} \quad [2]$$

where $\widehat{\boldsymbol{\beta}}$ is the vector of estimated regression coefficients, $\boldsymbol{C}$ is the covariance matrix of the residuals, $\boldsymbol{q}$ is the matrix of predictors at the sampling locations and, $\boldsymbol{y}$ is the vector of measured values of the target variable. Using the generalized least squares method, the coefficients are objectively determined to accurately incorporate spatial autocorrelation among the residuals.

To estimate the covariance function, we need to compute the residuals. The Regression-Kriging with GLS is a multi-step process: we 1) derived the coefficient by using the ordinary least squares method, 2) calculated the residuals as $e(x_i) = Y(x_i) - \sum_{k=0}^{m} \hat{\beta}_k q_k(x_i)$, 3) estimated the covariance function of the residuals, 4) estimated the regression coefficients by GLS. We repeated these steps until a convergence was reached. Typically, fewer than 10 iterations are acceptable.

4.2 Estimation and Confidence Intervals

When regression coefficients and covariance function are established, one can compute a predicted value, $\hat{y}_{RK}(x_0)$, and a variance, $\hat{\sigma}^2_{RK}(x_0)$, at a given unvisited location using Regression-Kriging by:

$$\hat{y}_{RK}(x_0) = \boldsymbol{q}_0^T \widehat{\boldsymbol{\beta}} + \boldsymbol{\lambda}_0^T (\boldsymbol{y} - \boldsymbol{q}\widehat{\boldsymbol{\beta}}) \quad [3]$$

$$\hat{\sigma}^2_{RK}(x_0) = (C_0 + C_1) - \boldsymbol{c}_0^T \boldsymbol{C}^{-1} \boldsymbol{c}_0 + (\boldsymbol{q}_0 - \boldsymbol{q}^T \boldsymbol{C}^{-1} \boldsymbol{c}_0)^T (\boldsymbol{q}^T \boldsymbol{C}^{-1} \boldsymbol{q})^{-1} (\boldsymbol{q}_0 - \boldsymbol{q}^T \boldsymbol{C}^{-1} \boldsymbol{c}_0) \quad [4]$$

where $\boldsymbol{q}_0$ is the vector of predictors at location x_0, $\boldsymbol{\lambda}_0$is the vector of *n* kriging weights used to interpolate the residuals, and $\boldsymbol{c}_0$ is the vector of covariances of residuals between the unvisited location x_0 and the sample location x_i.

By assuming that the kriging prediction error was normally distributed, we can obtain the lower and upper limits of the prediction interval for soil properties at location x_0 by subtracting and adding the critical z-score values, z^*, times the kriging standard deviation to the kriging prediction:

$$CI(x_0) = \hat{y}_{RK}(x_0) \pm z^* \sqrt{\hat{\sigma}^2_{RK}(x_0)} \quad [5]$$

For a 90% CI, z^* equals 1.645. For a 75% CI, z^* equals 1.15.

We utilized Regression-Kriging to predict the uncertainty associated with geotechnical parameters.

Our model is 1-D, focusing solely on spatial correlation along borehole data, that is, vertical plane. We assume that the parameters are constant along the horizontal plane. We choose $\hat{m}(x_0)$ to be a *m*th degree polynomial regression and the predictors is, therefore, the z-coordinate (i.e., $q(x_i) = (1, z_i, z_i^2, \ldots, z_i^m)$).

Note that if there is no spatial autocorrelation in the residuals, indicating a pure nugget effect, regression rigging converges to a pure multiple linear regression. This occurs because the covariance matrix of the residuals becomes an identity matrix. Similarly, when the target variable demonstrates no correlation with the predictors, the regression-kriging model simplifies to an ordinary kriging model, as the deterministic part equals the global mean value.

4.3 Gaussian Anamorphosis

A Gaussian anamorphosis is conducted to transform the original data space into a Gaussian space. The graphical anamorphosis involves associating Gaussian quantiles with the corresponding experimental quantiles of the data, ensuring only a marginal Gaussian distribution. The Regression-Kriging is then performed in the Gaussian space, and a pre-processing step back transforms the estimates of the original space.

5 GEOSTATISTICAL ANALYSIS

A methodical procedure has been formulated for the evaluation of geotechnical applications. This procedure encompasses six unique steps as follows:

- Data Screening and Outlier Exclusion: Recognize and eliminate any data points that significantly deviate without a clear rationale.
- Histogram Evaluation: Examine histograms of both the original and transformed data to evaluate their adherence to a normal or log-normal distribution.
- Probabilistic Law Assessment: Explore various probabilistic laws to identify the best regression fit curves for the data.
- Confidence Interval Evaluation: Compute confidence intervals for the mean regression best fit curve to comprehend its uncertainty.
- Representative Geotechnical Properties: Determine a representative spectrum of geotechnical properties for subsequent analysis.
- Uncertainty Range Determination: Employ sensitivity analyses to ascertain the range of uncertainty in your results.

The geostatistical analysis ties the gap between available data and spatial patterns, providing valuable information on large scale and helping understand their spatial variability. Exploring sensitivity analyses in geostatistical workflows helps reveal the influence of input parameters and allows for the definition of a pragmatic range of uncertainty. Ultimately, identifying potential risks for a specific project or application allows for the proper definition of a suitable mitigation action plan.

Figure 3 illustrates analysis of particle size distribution for backfill materials. By understanding particle size distribution, theoretical correlations can be defined for soil behaviour. Figure 4 presents the histogram of raw and transformed data for N_{spt} of backfill materials. In Figure 5, the diagram on the left illustrates the best-fitting regression means curves along with a range of variability, considering one or two standard deviations. The diagram on the right side of Figure 5 shows the confidence level of mean regression curves.

A correlation exists between geotechnical properties and elevation. However, the horizontal spacing between boreholes is sometimes too vast to include X and Y coordinates in the analysis. The variograms examined do not reveal any discernible structure in the horizontal plane; only the variance can be estimated. As a result, for geotechnical properties with low density of information at the site observation scale, the decision taken was to focus exclusively on the vertical plane and assume that the horizontal plane remains consistent.

At 3D observation scale, geostatistical equiprobable simulation was done for N_{SPT} values due to the significant information collected at site observation scale. Figure 6 visually depicts the populated model for this property, generated through geostatistical workflow and geotechnical borehole data. The 3D geostatistical workflow is possible only once the density of properties is sufficient to estimate the spatial structure. Otherwise, 1D or 2D geostatistical approach will be considered.

Considering soil particles distribution and probabilistic best-fitting curves for the Standard Penetration Test (Nspt), soil's elastic modulus is obtained using various theoretical correlations proposed by Bowles. Figure 7 depicts the results of the soil's Young modulus obtained through this workflow and compares them to existing boundary values from literature (Bowles 1997, AASHTO 2017, Holtz 2010, Look 2007, MCIF 2013).

The same process was applied for all geotechnical properties. Figure 8 illustrates analysis of particle size distribution for cohesive native soils used in the process of estimating preconsolidation pressure. Probabilistic approach for fitting curves of preconsolidation pressure for cohesive soil has required two additional steps (Figure 9). The first one for plasticity index and the second one for undrained shear strength. Leroueil correlation is then used to evaluate preconsolidation best fitting curves (Leroueil et al. 1993, Demers et al. 2002).

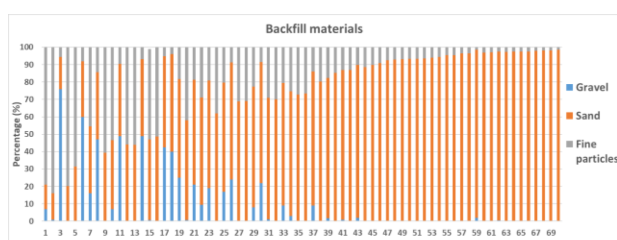

Figure 3. Backfill material particle size percentage (blue: gravel – orange: sand – grey: fine particles)

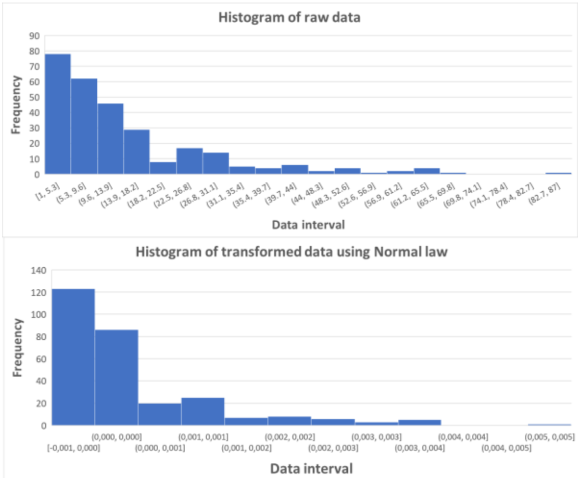

Figure 4. Histogram of Backfill N_{SPT} values for raw data and in transformed normal law

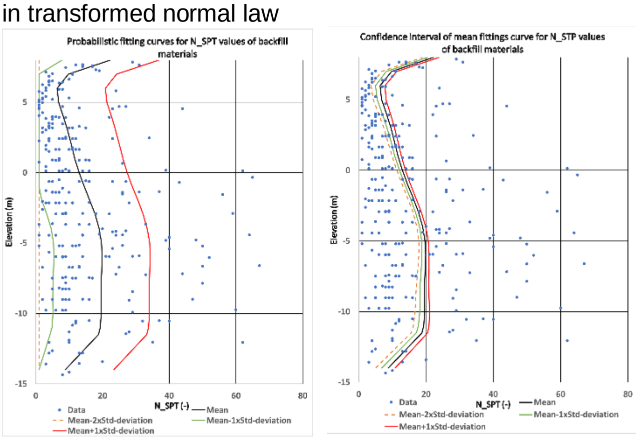

Figure 5. Probabilistic approach for fitting curves of N_{SPT} and confidence interval of mean fitting curve

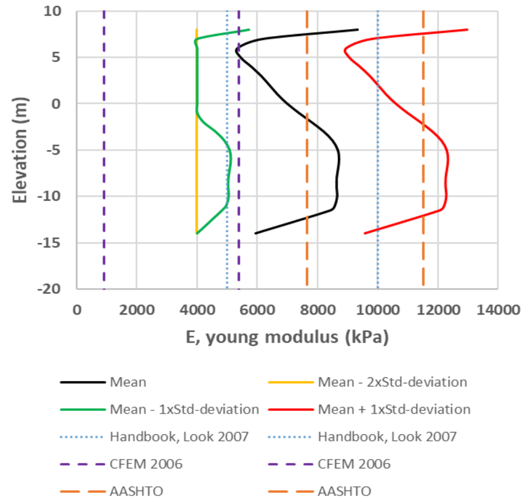

Figure 7. Young modulus from geostatistical approach using Nspt and comparison with literature values

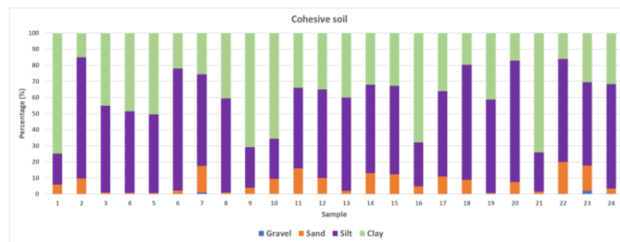

Figure 8. Cohesive soil particle size percentage (blue: gravel – orange: sand – purple: silt – green: clay)

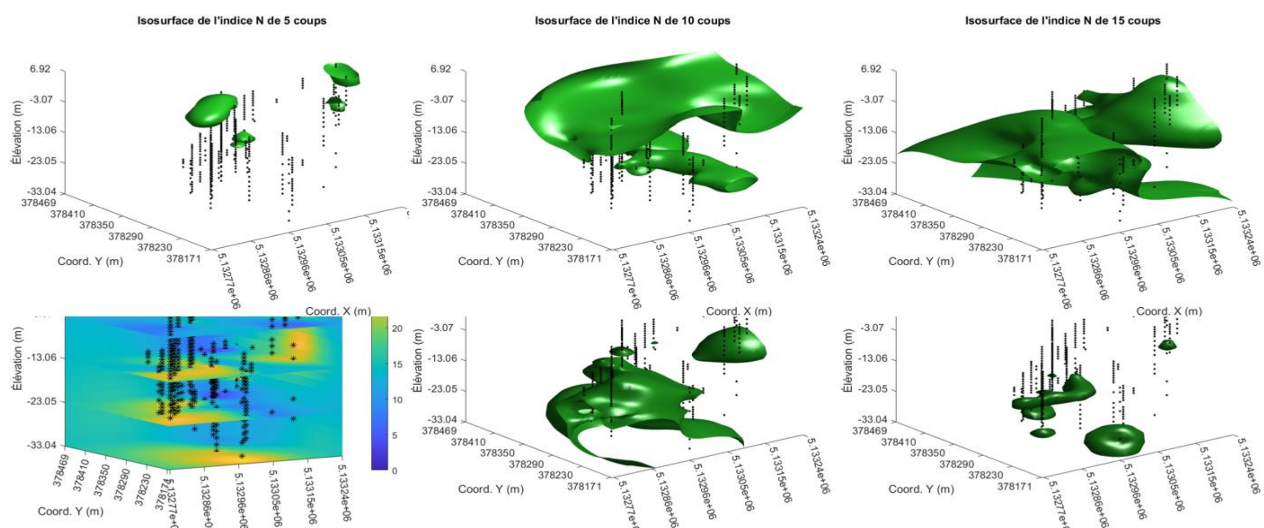

Figure 6. 3D modelling of N_{SPT} values using geostatistical approaches based on boreholes data

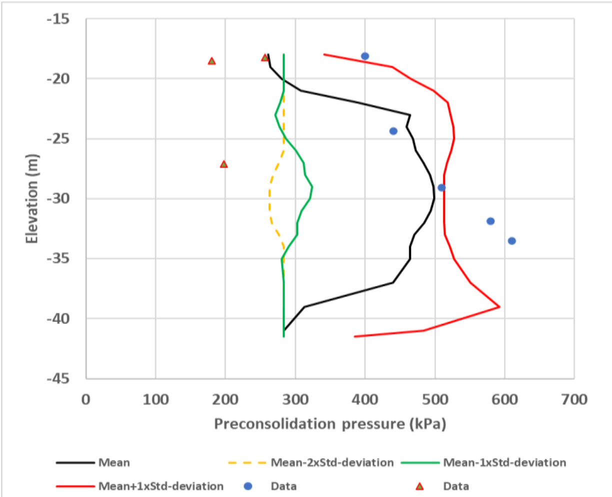

Figure 9. Probabilistic approach for fitting curves of preconsolidation pressure for cohesive soil.

6 GEOTECHNICAL PROPERTIES TO NUMERICAL MODELLING

Accurate representation of geotechnical properties in numerical models enhances their reliability and applicability. Properties must be continually refined using laboratory testing, field investigations, empirical correlations combined to a geostatistical workflow to improve the accuracy of geotechnical simulations.

Geostatistical methods described above are then considered to analyze uncertainties in critical geotechnical parameters and to establish a representative range for each parameter within an acceptable confidence level. These representative range values are then used in the numerical modelling to assess soil deformation under existing and proposed structures, as well as their structural tolerances.

Figure 10 illustrates the workflow used to evaluate the impact of variations in geotechnical properties on soil deformation through numerical modelling. The results of the parametric analysis, which consider both conventional and geostatistical approaches for establishing geotechnical properties in modelling, are compared against project requirements and structural tolerances. As a result, an appropriate mitigation plan is formulated to address deformation challenges in specific areas.

Furthermore, the workflow also takes into account the consolidation duration, which is the time span during which soil, usually clay, experiences compression due to a change in pressure, leading to the expulsion of water and a decrease in volume (Sivaram et al. 1977, Taylor 1948, Casagrande 1938).

7 MITIGATION MEASURES AND RECOMMENDATIONS

The application of geostatistical analysis in geotechnics has proven to be effective in evaluating soil deformation, comparing it with the tolerances of structures, quantifying the levels of risk on existing structures, and then identifying appropriate preventive solutions to ensure their integrity. Subsequently, several recommendations are put forward to enhance the assessment of soil deformation and to ensure the structural integrity as follows:

- Additional geotechnical investigation to assess more crucial geotechnical properties both on the site and in the laboratory.
- Development and execution of an instrumentation monitoring plan. This includes creating a plan to monitor soil deformations, anchor tensions, and the structural integrity at the study site using specific instruments. A reference level (zero level) is established before starting the planned work. Continuous monitoring of these instruments is required throughout the construction phase and

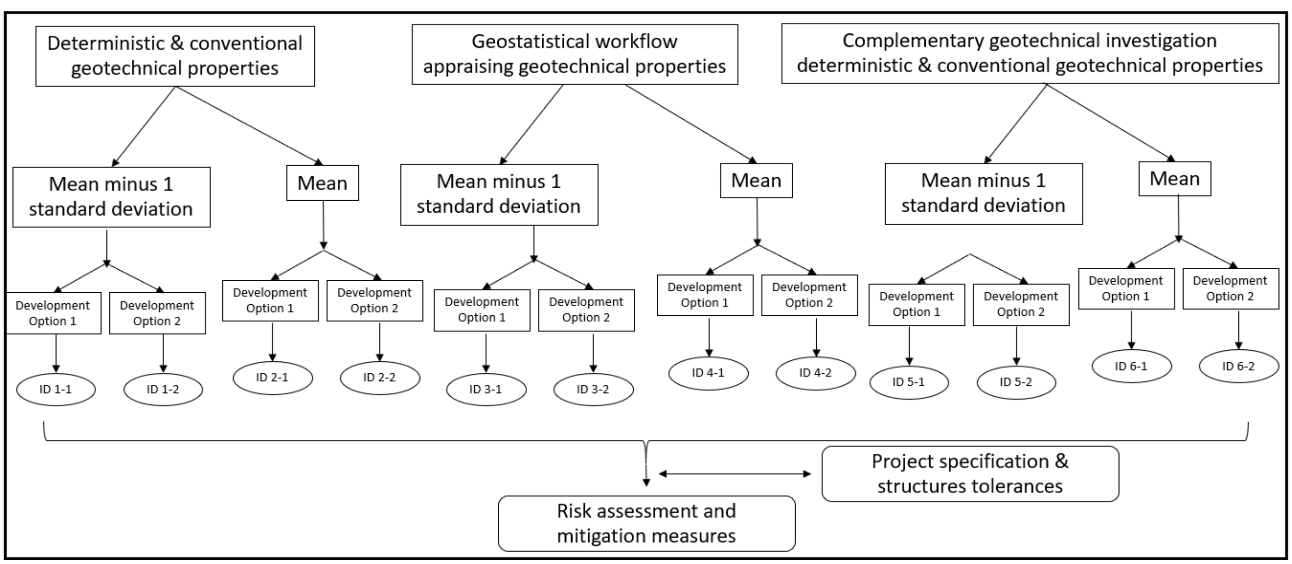

Figure 10. Numerical simulation workflow using both conventional and geostatistical approaches to establish specific mitigation actions for the need of a project

occasionally post-completion for a specified duration.

- Alert level plan considering structural tolerances of the existing infrastructure. These levels dictate suitable actions depending on the severity of the deviations.
- Rehabilitation plan for older infrastructures that are unable to withstand soil deformation.

8 DISCUSSION AND CONCLUSION

This publication acts as a start-up project that develops a sturdy method for detecting and reducing risks in geotechnical applications using geostatistical tools. Focus was placed on the development of a comprehensive, structured, and geostatistically adapted database. Stratigraphical model, which is based on a geostatistical approach, enables more detailed geological modelling. The geostatistical process improves risk evaluation by accounting for model variability and offering targeted mitigation measures.

Future advancements include the creation of a geotechnical database to facilitate automated geostatistical analyses and optimization. This endeavour aims to pinpoint the location for future geotechnical boreholes drilling, estimate the required depth to reach significant geological structures, and accomplish the design of stratigraphical model. Most procedures will be stochastic, allowing for the quantification of uncertainty and thorough geotechnical analysis. The input data will comprise a borehole dataset and the associated stratigraphic context. The significance of a well-structured database is underscored, as geostatistical analyses can be challenging when parameters are inadequately represented or inaccessible due to privacy policies. Open-source databases are vital for evaluating uncertainty parameters on a regional scale, particularly on a local scale where data may be limited, outdated, or only available in paper format. The final anticipated development is a machine learning workflow capable of processing available data in a specific format and integrating them into a regional geotechnical model using a geostatistical approach.

9 ACKNOWLEDGEMENT

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