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Geostatistical analysis of the spatial variation of geotechnical properties in Mexico Valley subsoil in presence of soil cracking

Analyse géostatistique de la variation spatiale des propriétés géotechniques dans le sous-sol de la vallée du Mexique en présence de fracturation

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ABSTRACT: This work presents the geotechnical characterization of the lacustrine subsoil of a southeastern zone of Mexico City affected by fractures. The purpose was to identify the stratigraphic configuration of the soil through a detailed analysis of the distribution of the water content (w) and the tip resistance (q_c) in CPT tests by means of the geostatistical methodology, based on the information from an exploration campaign performed on the site.

RÉSUMÉ : Cette communication présente la caractérisation géotechnique du sol lacustre d´une zone située au sud-est de Mexico qui a été touchée par une importante fracturation. L´objectif était de déterminer les conditions stratigraphiques en réalisant une étude détaillée de la distribution des teneurs en eau (w) et de la résistance de pointe (q_c) en essai CPT en se basant sur les résultats d´une campagne de reconnaissance profonde réalisée sur le site.

KEYWORDS: soil cracking, geotechnical properties, geotechnical characterization, geostatistics.

1 INTRODUCTION.

In several zones of Mexico City, soil fracturing constitutes an important risk factor that must be evaluated to define protectives and coexistence measures. The actual or potential presence of cracks must be taken into account in the design of structures and facilities to avoid or at least reduce the damage they may cause.

Subsoil cracking can appear in any condition that generates significant tensile or shear stresses in the ground (Auvinet, 2010; Auvinet *et al*., 2013; Auvinet *et al*., 2015). However, the most important and destructive cracks in the soil are a direct consequence of the regional subsidence that occurs in the Valley of Mexico due to the pumping of water in deep aquifers. These types of cracks have been extensively studied in recent decades (Auvinet *et al*., 2017). On the other hand, it has been observed that earthquakes can alter the geometry of existing cracks and generate some additional discontinuities.

To understand the propagation and generation of cracks in the subsoil, it was considered necessary to know in detail the stratigraphic characteristics and the distribution of the geotechnical properties of the different materials encountered in the area. With this objective, a detailed geotechnical exploration and instrumentation campaign was carried out at several sites considered as representative of the abrupt transition zone between soft and rigid soils or volcanic rocks in the southeastern part of Mexico City (Auvinet *et al*., 2019).

To interpret the results of the geotechnical investigations of the subsoil carried out to evaluate the cracking zones, the geostatistical methodology was used to define the stratigraphy of the subsoil. This theory has been applied before and good results have been obtained in the modeling of the distribution of the geotechnical and geometric properties of the subsoil, since it allows describing the spatial variation of the soil properties by means of a predictive technique (Kriging or some of its variants) and estimating values of these properties at points where exploration was not carried out (Krige, 1962, Matheron, 1965, Auvinet, 2002).

2 STUDY AREA

The study area is located south-east of Mexico City specifically in four sites of Iztapalapa (Cananea park, La Planta and Molino Tezonco suburbs) and Tláhuac (Del Mar suburb) municipalities. (Figure 1).

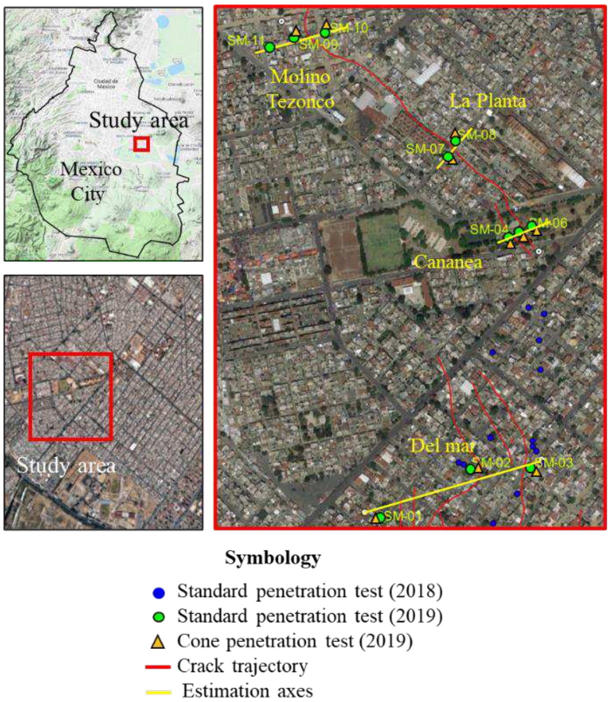


Figure 1. Location of the study area and boreholes distribution.

According to the city geotechnical zoning (NTCDCC-2017), the study area is located within zone III or lake zone, where the stratigraphy is generally made up of powerful highly compressible clay deposits, interbedded with sandy layers with diverse content of silt or clay.

Evidences of the cracking phenomenon of the ground at four sites: a) La Planta, b) El Molino-Tezonco, c) Cananea and d) Del Mar, can be seen in Figure 2, where the path of the crack is indicated.

Figure 2. Step-shaped cracks in the study sites

2 GEOSTATISTICS THEORY

Geostatistics can be broadly defined, as the application of the principles of probability theory and statistics to earth sciences, to describe more realistically the spatial variations of the geotechnical properties at a site of interest or within an earth structure.

The geostatistics methodology assumes that the values or a variable of interest (such as mechanical, dynamical, or geometrical properties) at different points X of a geological medium of interest constitute a field of random variables $V(X)$. These variables distributed inside a space R (length, area, or volume) can be referred to as a regional random variable. Regional random variables are also known as random fields (Auvinet; 2002; Auvinet *et al*., 2017). Figure 3 depicts a 3D random field.

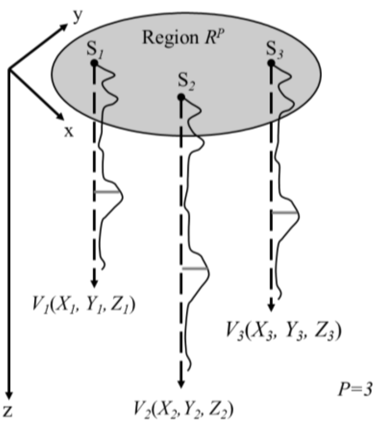


Figure 3. Random field

With geostatistics it is possible to solve rationally problems such as the estimation of the spatial distribution of geotechnical properties in the subsoil of a given site based on the information from existing borings, taking in account the spatial dependency between properties at nearby points through the autocovariance function and by using optimized estimation techniques such as Kriging and/or Cokriging (Krige, 1962, Matheron, 1965; Journel, 1977, Auvinet, 2002).

The kriging estimation technique, also known as BLUE (best linear unbiased estimator, for its acronym in English) consists in using an estimator defined by (Deutsch and Journel, 1992):

$$V^*(X) = \sum_{i=1}^{n} \lambda_i V(X_i) + [1 - \sum_{i=1}^{n} \lambda_i]\mu_v \tag{1}$$

where λ_i are the influence weights and μ_v is the expected value of the random field.

One of the variants of the kriging estimation is the ordinary kriging (OK), where imposing the condition $\sum\lambda_i=1$ in the Eq. (1), makes it unnecessary to know the mean value μ_v of the random field (Deutsch and Journel, 1992). The estimation of ordinary kriging is then defined as:

$$V^*(X) = \sum_{i=1}^{n} \lambda_i V(X_i) \tag{2}$$

The value of the minimized error variance associated to the estimation ($\sigma^2_{EK}(X)$), is obtained with the following expression:

$$\sigma^2{}_{EK}(X) = Var[V(X)] + \mu - \sum_{i=1}^{n} \lambda_i C(X_n - X_i) \tag{3}$$

where $Var[V(X)]$ is the variance of the random field, and μ is the Lagrange multiplier

4 METHODOLOGY FOR APPLICATION .

In general, the geostatistics methodology is integrated by three stages: i) exploratory analysis, ii) structural analysis and iii) prediction. To analyze and interpret the spatial distribution of the geotechnical properties, the basic theoretical foundation of the geostatistical analysis is adapted and follows a series of stages as indicated in the Figure 4.

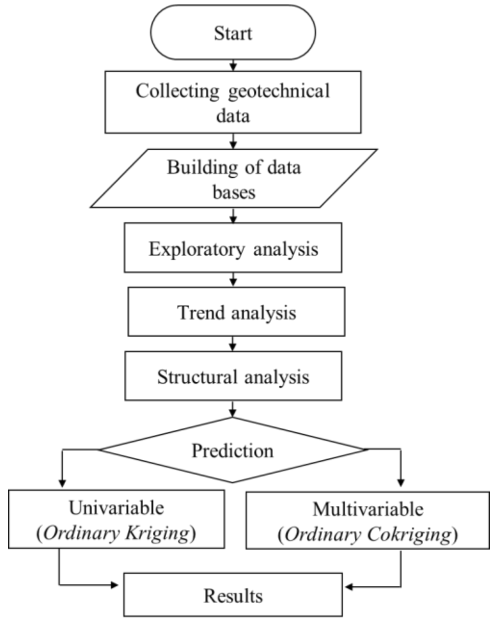


Figure 4. Stages of the geostatistical analysis (Delgado, 2017).

5 ANALYSIS OF THE SPATIAL DISTRIBUTION OF WATER CONTENT AND CPT TIP RESISTANCE.

5.1 *Definition of the random field*

Water content values (w) and CPT tip resistance (q_c) are considered to be random fields $V(X)$ and $U(X)$ respectively, distributed within R^P, with P=3 (3D case). The w and q_c data sets measured within domain R^3, from standard penetration and electric cone penetration tests, constitute a sample from that random field. To perform the univariable and independent geostatistical analysis of these geotechnical properties, eleven profiles of water content (w) and ten profiles of tip resistance (q_c) of electric cone were used. Their distribution in the study area is shown in Figure 1.

The same Figure 1 shows the field tests (SPT and CPT) are distributed along directions perpendicular to the trajectory of the cracks.

5.2 *Statistical analysis*

With the experimental data (water content and tip resistance) and assuming ergodicity of the random fields, the main statistical parameters were obtained and synthetized in Table1.

Table 1. Statistical description of geotechnical properties.

Parameter	Water content, w (%)	Tip resistance, q_c (kPa)
Mean	14.0	1444.8
Median	146.6	1197.7
Mode	150.0	750.0
Standard deviation	82.4	928.5
Minimum value	0.3	206.4
Maximum value	417.8	5000.0

The values from the previous table were plotted in the histograms of Figures 5 and 6. The w values with magnitude larger than 200 % are linked to the clay formations, while the lower values correspond to rigid strata. On the other hand, the tip resistance (q_c) values below 1000 kPa are linked to clay formations, while upper values correspond to stiff soils (sand and silt).

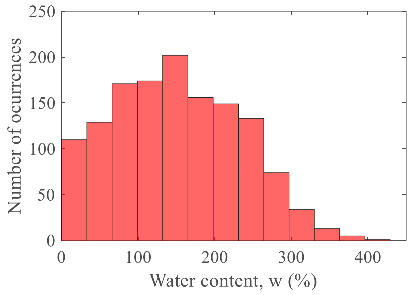


Figure 5. Histogram of water content data.

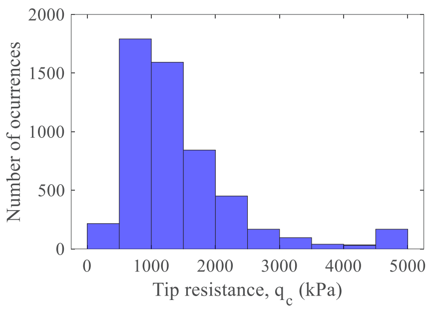


Figure 6. Histogram of CPT tip resistance data.

5.3 *Trend analysis*

Figure 7 shows the set of profiles of the experimental data of the w and tip resistance q_c, where the values of water content tend (discontinuous line) to decrease with depth, while the resistance data q_c presents a tendency to increase with depth.

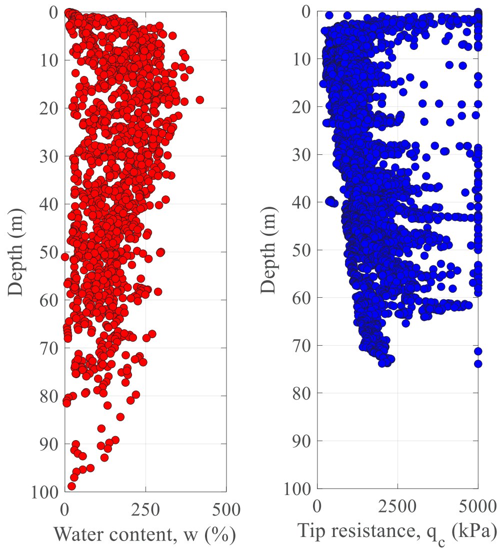


Figure 7. Experimental fields of the water content and tip resistance data.

The trends of the random fields can be represented by hyperplanes with lineal equation $V(X)=ax+by+cz+d$ where "a, b, c and d" are linear regression coefficients. The resultant coefficients for w and q_c are shown in Table 2. It is convenient to remove the trend from the water content and tip resistance data to work with simpler stationary residual fields.

Table 2. Linear regression coefficients of the water content (w) and tip resistance (q_c).

Property	a	b	c	d
w	0.003	-0.009	-0.7631	1070.5490
q_c	0.944	0.726	11.3895	-2010330.004

5.4 *Structural or correlation analysis*

Considering the data of the residual fields of the water content and tip resistance, correlograms in the horizontal and vertical direction were obtained; the correlation distances are presented in Table 3.

Table 3. Directional correlation distances of the geotechnical properties w and q_c

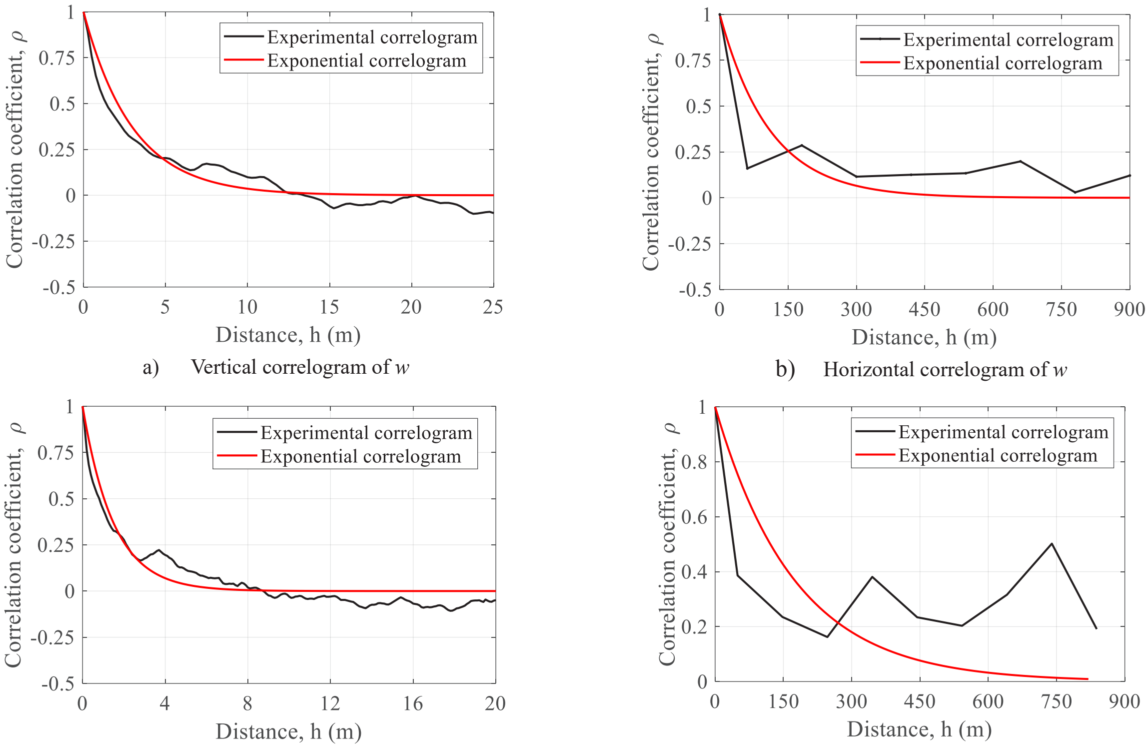
Property	Vertical, δv *(m)*	Horizontal, δh *(m)*
Water content	1.5	1450.0
Tip resistance	3.0	350.0

With these correlation distances and adopting a simple exponential correlation model, the vertical and horizontal correlograms of Figure 8 were determined.

5.5 *Prediction*

Applying the kriging estimation technique, cross-sections of estimated water content w and tip resistance q_c were obtained along the different preferential axes in the perpendicular direction to the cracks, with a horizontal calculation step of 20 m and vertical calculation step of 0.25 m for the water content w an 0.1 m for q_c. The final predictions were obtained reincorporating the trend to the residual estimations.

In addition, in this stage, the topography of the site was considered, therefore the predictions were obtained in terms of elevation.



a) Vertical correlogram of w b) Horizontal correlogram of w

c) Vertical correlogram of q_c d) Horizontal correlogram of q_c

Figure 8 Directional correlograms of the water content and tip resistance.

5.6 *Visualization and interpretation*

To simplify the interpretation of the tabular values of w and q_c obtained in the prediction stage, advanced graphics techniques can be used to allow the elaboration of cross-sections (Figures 9 to 12) that facilitate the visualization of the spatial distribution of the water content and tip resistance in the sites of the study area. The position of the cracks is shown in the upper part of the cross-sections.

The spatial distributions in the study area are presented in the following order: I) Cananea, II) La Planta, III) Molino Tezonco and IV) Del Mar.

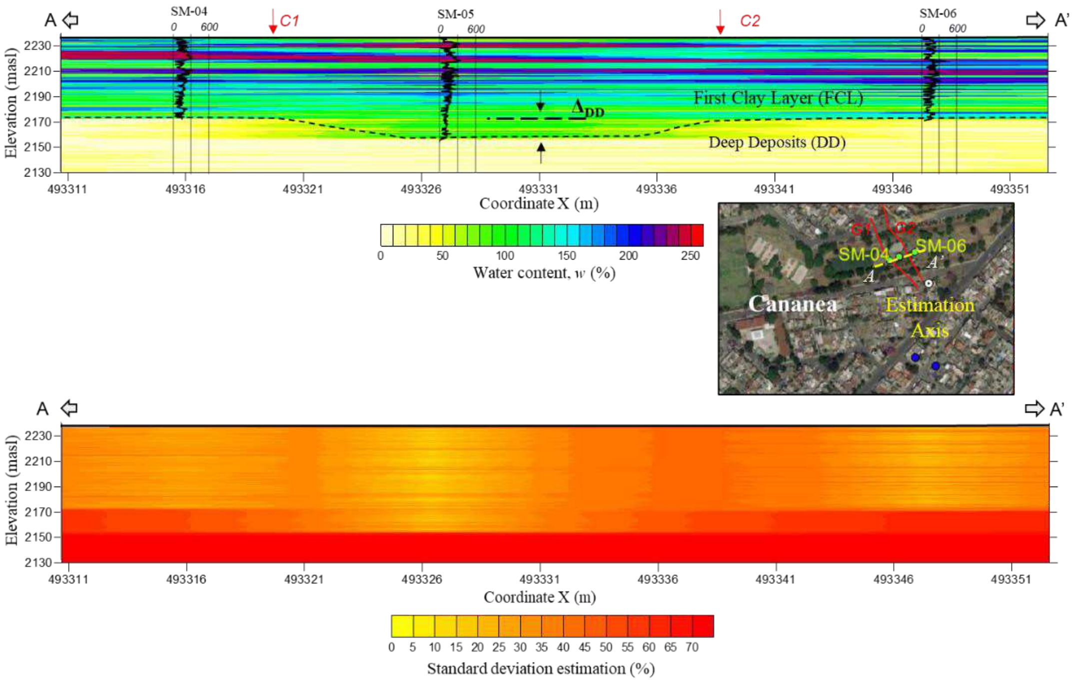


Figure 9. Cross section of water content estimated along the axis in Cananea suburb.

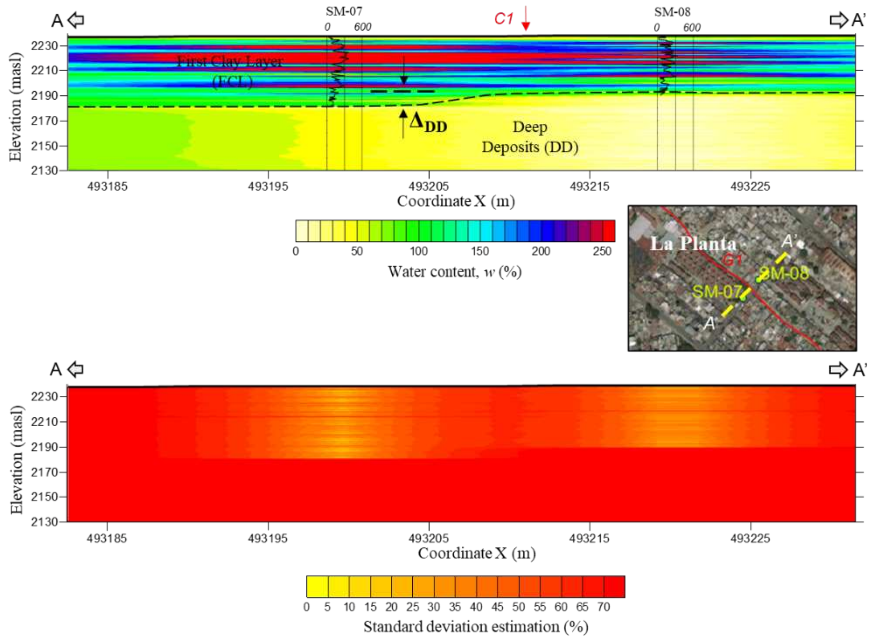


Figure 10. Cross section of water content estimated along the axis in La Planta suburb.

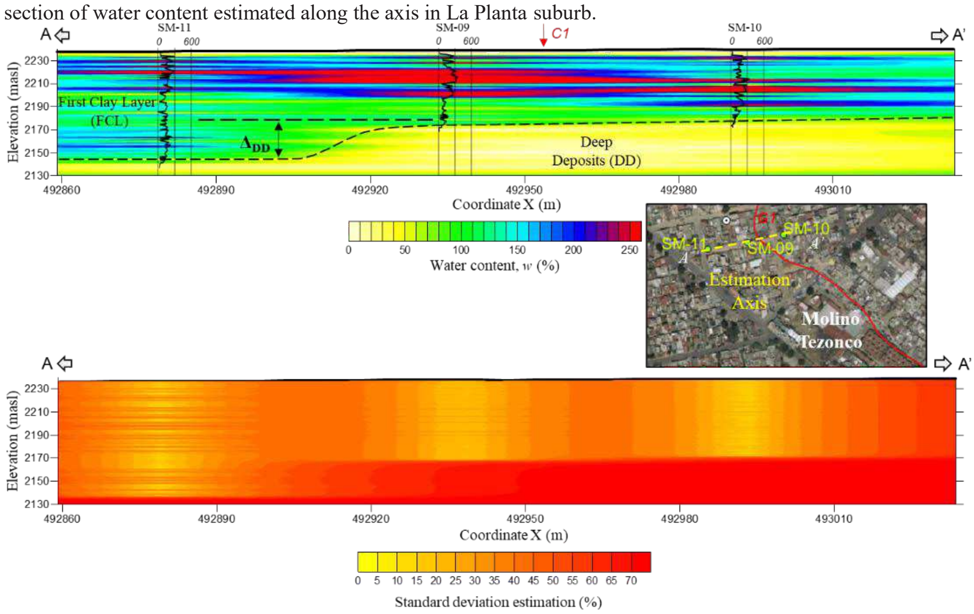


Figure 11. Cross section of water content estimated along the axis in Molino-Tezonco suburb.

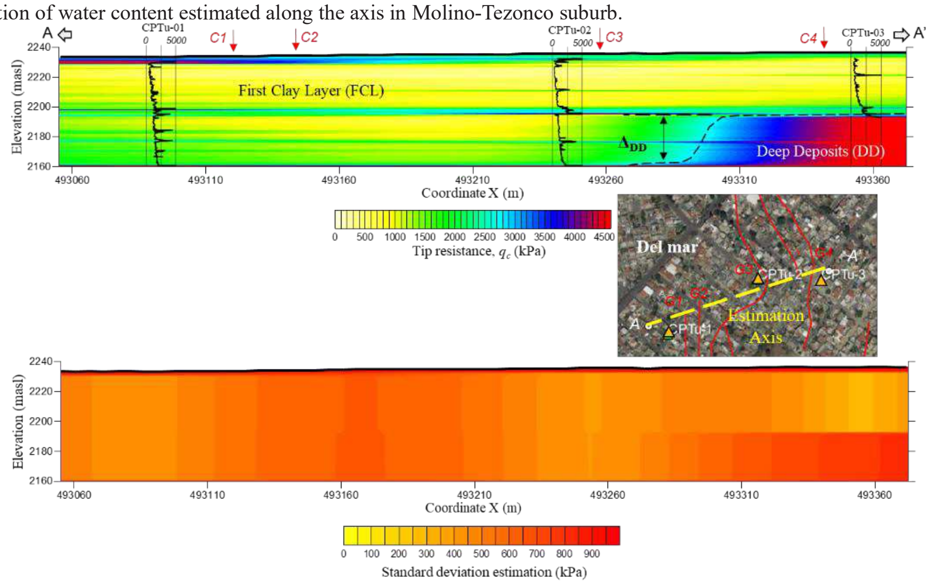


Figure 12. Cross section of tip resistance estimated along the axis in Del Mar suburb.

5.6.1 *Cananea suburb*

In the upper part of the cross-section of Figure 9, a thin layer can be observed, with greater thickness in the central part, composed of materials with low water content values that correspond to the so called Dry Crust (DC). Below this material is the First Clay Layer (FCL) made by materials with *w* values as high as 400% that correspond to a highly compressible stratum with some intercalations of silty sandy lenses. Finally, in the deepest part of the section, the lowest values of *w* correspond to Deep Deposits (DD); as can be seen in the central part of the section, these deposits present a difference in level (Δ_{DD}) of the order of 15 m in a convex shape.

5.6.2 *La Planta suburb*

In the water content cross-section of Figure 10, a thin layer of variable thickness with low values of water content can be seen in the upper part, which makes up the DC. Below this material First Clay Layer is found, with high water content values and some interbedded silty-sandy lenses; this formation presents a greater thickness in the northeast direction (A') and a smaller one in the southwest (A). Below this material, the Deep Deposits present a step (Δ_{DD}) of the order of 10 m in the central part of the section.

5.6.3 *Molino Tezonco suburb*

According to the results obtained and based on the color scale of *w*, in Figure 11, a layer of thin thickness with low values of water content is observed in the upper part of the cross-section; these materials correspond to the Dry Crust (DC). Below the DC, the First Clay Layer (FCL) is found with water content values of the order of 400%. In the deepest part of the section, the lowest values of water content correspond to the Deep Deposits (DD); this formation presents a step of approximately 25 m (Δ_{DD}).

5.6.4 *Del Mar suburb*

The q_c tip resistance spatial distribution (Figure 12) allows identifying in the upper part of the section, a layer of variable thickness with resistance values of approximately 2000 kPa corresponding to the DC. Below the DC, the First Clay Layer is appreciated, with an approximately homogeneous distribution of q_c values that do not exceed 1000 kPa. Finally, under the soft material it is possible to appreciate in blue the highest values of the tip resistance q_c that can be associated with the Deep Deposits (DD). The DD distribution presents a step-shaped (Δ_{DD}) unevenness of the order of 35 m.

6 CONCLUSIONS

Geostatistical methodology is a useful and powerful tool for the interpretation of the distribution of the geotechnical properties in the subsoil, based on geotechnical data coming from exploration campaigns including standard penetration tests (water content profiles) and cone electric tests (tip resistance profiles).

On the other hand, these models (profiles and cross-sections) that describe de spatial distribution of the water content and the tip resistance allows obtaining a better stratigraphic characterization of the subsoil reducing part of the subjectivity introduced in the traditional interpretations. In addition, these cross-sections help identifying anomalies in the subsoil as in the case of the studied sites affected by the cracking phenomenon.

7. ACKNOWLEDGMENTS

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