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Update of the geotechnical zoning map of Mexico City

Actualización del mapa de zonificación geotécnica de la Ciudad de México

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ABSTRACT: In this paper, a new geotechnical zoning for the subsoil of the Valley of Mexico is presented. This proposed map is based on a Geographic Information System for geotechnical surveys (SIG-GB), which stores more than 12,000 soil profiles. In addition to the geotechnical information, the topographical and geological data of the studied area were considered. Geostatistical techniques were used to evaluate the spatial distribution of the thickness of the clay deposits in the study area, down to the depth of the so-called Deep Deposits constituted by rigid materials. As a result, a contour map was obtained that was used as a basis to update the geotechnical zoning for the Valley of Mexico. The new geotechnical zoning map, presented in this paper, has been incorporated into the Building Code for Mexico City.

KEYWORDS: borings, subsoil, geotechnical zoning, random field, kriging, geostatistics.

1 INTRODUCTION.

In the Complementary Technical Standard for Design and Construction of Foundations in Mexico City (GOBCDMX, 2017), a geotechnical zoning map is included in which three geotechnical zones are distinguished. As a result of the spatial and temporal variability due to the geological formation of the subsoil and the phenomenon of regional subsidence, it is necessary to periodically update this map.

Considering that the soft soil layers geometrical properties (thickness and depth) tend to change along time due to natural or anthropic phenomena and that knowledge evolves as more information becomes available, it is necessary for geotechnical zoning to be continually updated. This paper describes the methodology that is applied to update this geotechnical zoning map for Mexico City.

In 1959, Marsal and Mazari published the book "The Subsoil of Mexico City" where, based on a considerable number of surveys and tests on more than 10,000 samples extracted from the subsoil, they began to have a general idea about the distribution of materials and their mechanical properties. The first piezometric stations were installed in various points of the city in order to know the alterations in hydrostatic pressures and their links to regional subsidence. In this work, of extraordinary scope and thoroughness, a division of the urban area into three zones was proposed: hills, transition and lake. Likewise, in this same work, the authors made extensive use of statistics to describe the properties of the soils of the different areas.

The Engineering Institute has developed a Geographic Information System for Geotechnical Borings (GIS-GB) that includes an extensive database regarding stratigraphy and subsoil properties in the urban area of the Valley of Mexico. This information is very useful to refine the boundary lines between the existing geotechnical zones and define the basis of a new zoning that will be incorporated into future versions of the Complementary Technical Standard for the Design and Construction of Foundations of the Construction Regulations for Mexico City.

Nowadays, there are new statistical tools with great potential but which, until now, have been little used in Geotechnics. One of these tools is geostatistics, i.e. the application of the theory of random functions (in this case spatial) and the treatment of signals to the description of stratigraphic conditions and the spatial distribution of properties of geological materials. Geostatistics allows it to consider the spatial dependence between properties at nearby points through the concept of autocovariance function or variogram. With these tools, it is possible to rationally solve problems such as estimating strata thicknesses, or property values at a given site or in a given area or volume, based on information from existing surveys based on optimized estimation techniques such as "Kriging" (obtaining linear estimators of minimum variance).

The research work of the Geoinformatics Laboratory of the UNAM Engineering Institute has focused on the following three steps: a) Compilation and processing of recent geotechnical information, b) Incorporation of this information into the II-UNAM database, c) Preparation of soil profiles and local maps and proposal for an updated geotechnical zoning.

2 DESCRIPTION OF THE STUDY AREA

To characterize the geological formations and typical soil deposits of the subsoil of the Valley of Mexico, it was considered necessary to collect different types of information and present it in a simplified form.

2.1 *Location*

The study area considered in this work covers the Álvaro Obregón, Azcapotzalco, Benito Juárez, Cuauhtémoc, Gustavo A. Madero, Iztacalco, Miguel Hidalgo and Venustiano Carranza municipalities of Mexico City, and part of the municipalities of Naucalpan de Juárez, Ecatepec of Morelos, Nezahualcóyotl, Tlalnepantla de Baz in the state of Mexico (Figure 1).

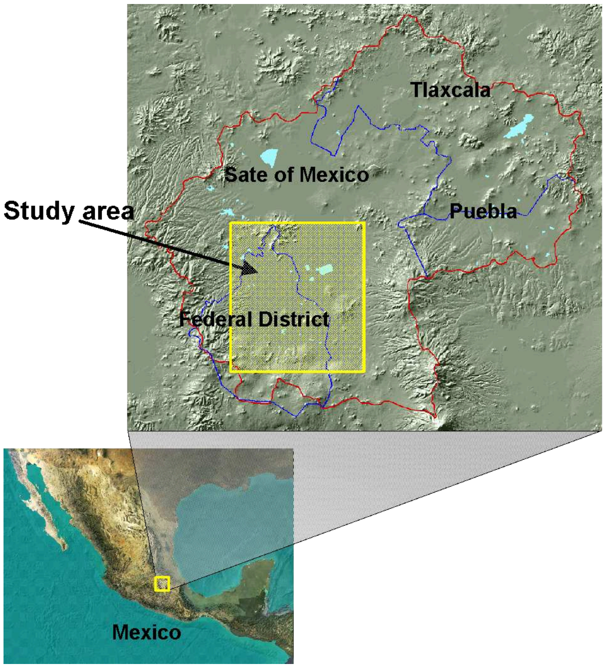


Figure 1. Location of study area.

2.2 *Topography*

From the electronic data of contour lines published by the National Institute of Statistics, Geography and Informatics (INEGI, 2010), a Shaded Relief Model (MRS) was built, which illustrates the topographic configuration of the studied area (Figure 2).

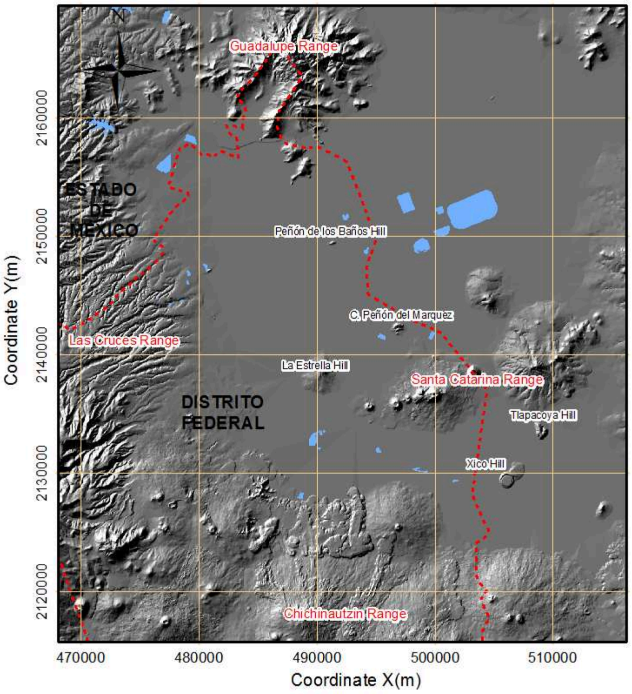


Figure 2. Topographic model for the study area.

Mexico valley consists of a former lacustrine area limited by large topographic elevations: Sierra de Las Cruces, Monte Alto and Monte Bajo to the west reaching an altitude up to 3600 m, Sierra de Guadalupe to the north reaching an elevation of 2960 m, the eastern Sierra Nevada and Sierra de Chichinautzin to the south reaching an altitude of 3800 to 3900 m. Within the valley, some isolated volcanic domes such as Peñón de los Baños (2288 m), Peñón del Marqués (2372 m), Cerro de la Estrella (2443 m), Cerro de Xico (2348 m), Cerro de Tlapacoya (2442 m) and those forming Sierra de Santa Catarina (2482 m) protrude from the lacustrine area.).

2.3 *Geology*

The Geological information represents the fundamental basis for the description of the subsoil characteristics of the Valley of Mexico. This topic has been discussed by several authors, such as Bryan (1948), Arellano (1953), Mooser (1956, 1957, 1975), de Cserna *et al.* (1988), Vázquez and Jaimes (1989), Enciso de la Vega (1992) and Mooser *et al.* (1996). The geological information provided by Mooser has been used in several civil engineering projects and is considered in this work.

Mooser (1975) explains that this territory has had an evolution in seven phases throughout geological times that led to the present configuration of the relief of the current Mexico Basin.

The origin of the plain, on which most of Mexico City is built, is explained by the gradual sedimentation of fine volcanic materials in the large lakes that were formed when the south of the old valley was closed due to the emergence of the Chichinautzin mountain range. (Figure 3).

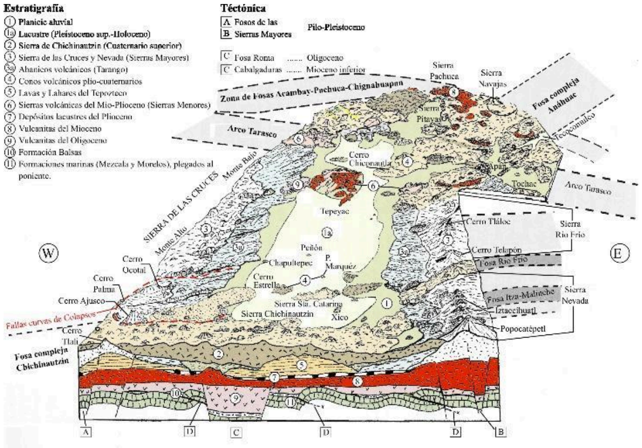


Figure 3. Geology and morphology of the Mexico basin (Mooser, in Santoyo *et al.*, 2005).

The bottom of the basin was filled with intercalations of different types of materials, including proluvial (silt and sand), lacustrine (clay and silt), as well as sand and volcanic ash, which, when weathered, generated highly compressible clays.

The erosion of slopes, river transport and deposits of materials of volcanic origin formed a fill that constantly buried an irregular relief. This determined a variation in the thickness of the sediments, increasing the power of the deposits from north to south. In the vicinity of the city of Pachuca, they are ±30 m thick, in the central portion of the basin they are ±200 m and in the south of the Mexico Basin, near the Sierra del Chichinautzin, they reach approximately 600 m. The ashes produced by volcanic eruptions and deposited in the heart of the lake along with river transport, constituted over time a highly compressible clay soil that is currently known as Valley of Mexico clay.

The geological information used in this work was taken from the "New geological map of the basins of Mexico, Toluca and Puebla" (Mooser *et al*., 1996). The corresponding map adapted for the area considered in this work is shown in Figure 4.

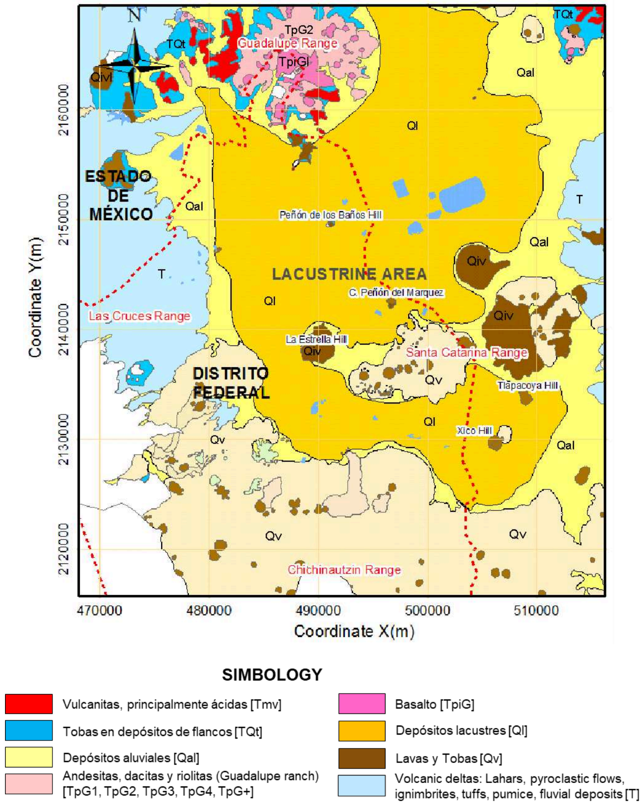


Figure 4. Geology of the study area (adapted from Mooser, 1996).

Within the area occupied by the lake plain, various formations standout such as Cerro de la Estrella, Peñón del Marqués, Pedregal, as well as the chain of volcanic cones of the Sierra de Santa Catarina, Cerro de Xico and Cerro de Tlapacoyán, and, to the south, the Sierra Chichinautzin. These are geological elements that delimit the presence of compressible soil and that on their periphery may present areas of abrupt transition (significant change in the thickness of compressible soil over short distances).

The formation of Lacustrine Deposits (Ql) that belong to the Quaternary period predominates in the study area. This unit is made up mainly of clays and silts with some intercalations of gravel and sand, and with few poorly defined tuff horizons.

The Alluvial Formation (Qal) belongs to the Quaternary period with a smaller extension than the lake surface. It is located between the recently formed slopes of the Sierra de Santa Catarina and Cerro de la Estrella, as well as on the northwest and southwest slopes of Pedregal and at the foot of the Chichinautzin mountain range. This formation represents a cumulative alluvial relief equivalent to the conditions of a fluvial process. These deposits are characterized by the alternation of layers corresponding to phases of accumulation of pyroclasts, rocky waste, sandy material and silt, sometimes interstratified with lava.

2.4 *Alluvial deltas*

The six alluvial deltas that are located at the foot of the slope of the Sierra de las Cruces and that extend from south to north, from Álvaro Obregón municipality to Azcapotzalco municipality, are a source of great heterogeneity in the subsoil and deserve very particular attention from the geotechnical engineers. Currently, its location and characteristics are only approximately known (Fig. 5).

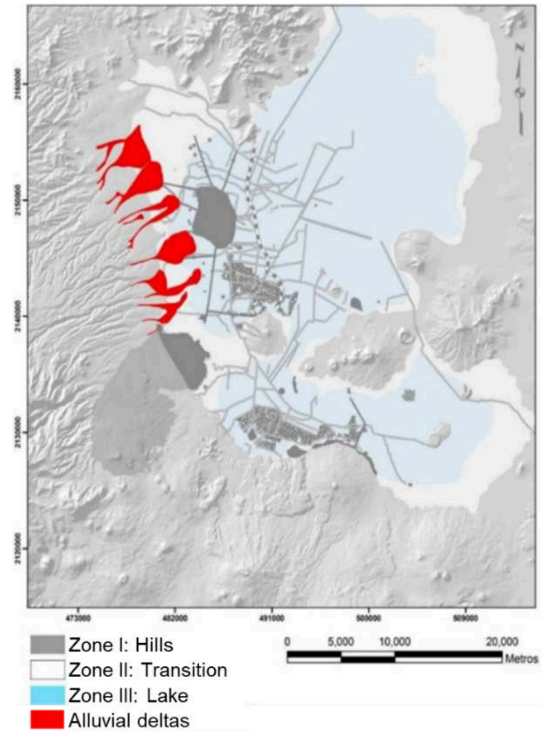


Figure 5. Spatial distribution of alluvial deltas (Mooser *et al*., 1986; Auvinet *et al*., 2017).

2.5 *Geotechnical zoning*

The current geotechnical zoning of Mexico City (Figure 6) is the one proposed by Marsal and Mazarí and adopted in the Construction Regulations of the Federal District (RCDF; GOBCDMX, 2016) and in the Complementary Technical Standard for Design and Construction of Foundations (NTCDCC; GOBCDMX, 2017). In article 170 of the Construction Regulations for the Federal District, three geotechnical zones are defined with the following general characteristics:

Zone I. Hills, formed by rocks or generally firm soils that were deposited outside the lacustrine environment, but in which there may exist, superficially or intercalated, sandy deposits in a loose state or relatively soft cohesive ones. In this Zone, the presence of cavities in rocks and caverns and tunnels excavated in the ground to exploit sand mines is common.

Zone II. Transition, in which the Deep Deposits are found at a depth of 20 m or less, and which are predominantly made up of sandy and silt-sandy strata interspersed with layers of lacustrine clay, the thickness of which varies between tens of centimeters and a few meters.

Zone III. Lacustrine, made up of powerful deposits of highly comprehensible clay, separated by sandy layers with diverse silt or clay content. These sandy layers are firm to very hard in consistency and vary in thickness from centimeters to several meters. Lacustrine deposits are usually superficially covered by alluvial soils and artificial fills; The thickness of this set can be greater than 50 m.

Figure 6 shows the portions of Mexico City whose subsoil is approximately known in terms of previous zoning.

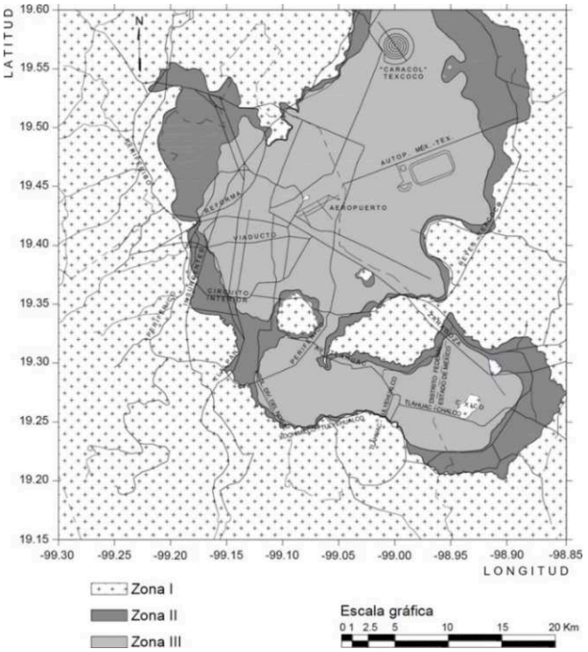


Figure 6. Geotechnical zoning (GOBCDMX, 2017).

2.6 Stratigraphy

The stratigraphic description considered in this work for the lake area is the following:

a) Superficial scab. Composed of clays consolidated by drying, silty sands and clayey silts with an average thickness of 1.5 m. This thickness can reach up to 5 m when approaching the Sierra de Guadalupe. Near Caracol de Texcoco, the presence of cracks is common.

b) Upper Clay Formation. Composed of a package of clays of volcanic-lacustrine origin whose thickness varies from 15 to 30m along the Grand Canal. These clays are highly compressible and are interbedded with sandy, silt-sandy and volcanic glass lenses at various depths.

c) Hard layer. Composed of silt-sandy soils, which have a depth of 2 to 3 m and is located at a variable depth between approximately 27 and 35m. In the surroundings of Cerro Gordo, this layer practically disappears and, eventually, it is interspersed with clay materials.

d) Lower Clay Formation. This formation has lower compressibility than the previous one. In it, the intercalation of lenses and silt-sandy strata, as well as volcanic glass, is common. It has a thickness of approximately 10m in the center of the lake and decreases towards the Northwest, reaching a thickness of approximately 3m.

e) Deep Deposits. Composed of interstratified clay and silt-sandy materials. Due to the short depth of most of the available boreholes, it is not possible to establish their thickness.

2.7 Geotechnical borings

For this work, information from direct and specific geotechnical explorations of the subsoil was used. The geotechnical borings used for this work have been provided by various companies, government agencies, research institutions and from bibliographic sources. The geotechnical borings provide the stratigraphy and the variation of the index properties and mechanical properties; this information constitutes the main basis for the analysis of the spatial distribution of subsoil properties. Currently there is a collection of more than 12,000 borings, their location is shown in Figure 7.

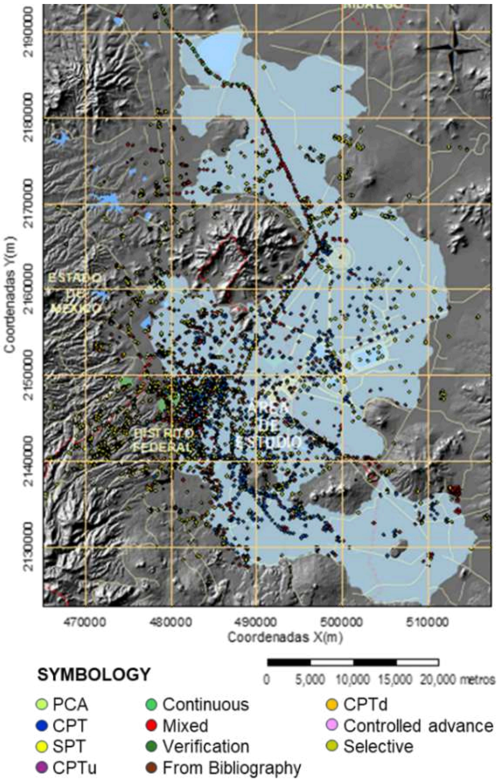


Figure 7. Distribution of borings in the study area.

Recent information comes from:

- Survey campaigns carried out in Tláhuac and Iztapalapa in 2019-2020 for the Commission for Reconstruction.
- Donation of borings form several companies.
- Exploration work carried out in the former lake of Texcoco for the New Mexico City International Airport (NAICM).
- Exploration work made for National Water Commission (CONAGUA) hydraulic works.
- Geophysical information gathered and presented in recent studies (Lermo *et al*., 2019).

These geotechnical borings have been included in figure 7.

The geotechnical information available for this study in some cases presents certain limitations that must be considered, among others:

- Borings with low quality or incomplete information.
- Borings at shallow depths.
- Lack of a location sketch of the borings.
- Lack of explorations in areas of interest.

In addition to the previous limitations, the variation over time of subsoil properties due to the consolidation of soils due to water extraction leading to regional subsidence must be considered, especially considering that this phenomenon is not uniform in the valley of Mexico. Therefore, in this work, it was decided to consider borings no older than 15 years, admitting that the properties have not changed significantly in that period. Trying to rigorously consider the variation in properties induced by regional subsidence would force the number of data to be drastically reduced. This is a limitation that could be reflected in the results of this work.

3. GEOGRAPHIC INFORMATION SYSTEM FOR GEOTECHNICAL BORINGS

To evaluate the configuration of typical layers, geotechnical survey profiles provided by public institutions and private contractors were used. These borings profiles have been incorporated into a Geographic Information System for Geotechnical Borings developed by the Geoinformatics Laboratory of the Instituto de Ingeniería, UNAM (Auvinet *et al*., 1995).

The Geographic Information System for Geotechnical Surveys (GIS-SG) for the study area was built using the ArcMap ver. program. 9.2 (commercial software). Currently, the system includes a Database with information from more than 12,000 geotechnical borings. The data available for each boring are: location, boring type, execution date, reached depth, water table depth and a boring profile image. All these data can be easily consulted (Figure 8).

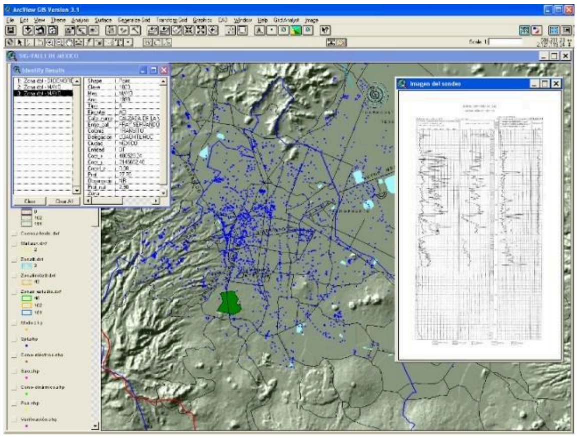


Figure 8. Geographic Information System for Geotechnical Borings (GIS-GB).

The incorporating of the borings information into the system requires prior processing: the information is critically reviewed; Also, geotechnical profiles are converted from analog to digital format, either raster (cell information) or vector (digitized information).

4. FUNDAMENTAL CONCEPTS OF GEOSTATISTICS

To define more accurately the boundary between zones II and III, a contour map of the thicknesses of the soft clay deposits, also corresponding to the depth of the so-called Deep Deposits, was constructed using geostatistical techniques. This section presents the basic concepts used for this type of analysis.

4.1 Random field (Auvinet, 2002 and 2019)

It has been proposed to consider spatial distribution of soil properties and geometrical dimensions of soil strata as realizations of random fields (Matheron, 1965; Auvinet, 2002, 2019). This hypothesis makes it possible to use the mathematical tools of the random function theory for important applications such as estimation of the variables of interest in a specific point, area or volume where no measurement has been performed.

Consider a geotechnical variable $V(X)$, either of physical (i.e. water content), mechanical (i.e. shear strength) or geometrical nature (i.e. depth or thickness of some stratum) defined at points X of a given domain R^p (p = 1, 2, or 3). In each point of the domain, this variable can be considered as random due to the range of possible values that it can take (Figure 9). The set of these random variables constitutes a random field (Vanmarcke, 1983).

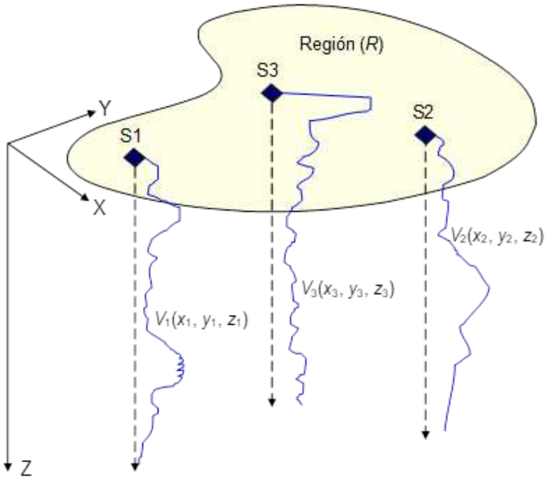


Figure 9. Representation of a random field (Medina, 2000).

4.2 Structural Analysis

To describe this field the following parameters and functions are used:

Expected value:

$$E\{V(X)\} = \mu_V(X) \cong \frac{1}{A}\int_0^A V(x)dx \quad (1)$$

where A is the length of an exploration axis section and x an abscissa defined on this axis.

Variance

$$\sigma^2\{V(X)\} = E\{V(X)^2\} - \mu_V^2 \quad (2)$$

Autocovariance function:

$$C_V(\lambda u) \cong \frac{1}{A}\int_0^A V(x)V(x + \lambda u)dx - \mu_V^2 \quad (3)$$

where λ is constant and $\boldsymbol{u}$ is a unit vector in the considered direction

This function represents the degree of linear dependence between the values of the property of interest in two different points. It can be written in the form of a coefficient of autocorrelation without dimension whose value is always between -1 and +1:

Correlation coefficient:

$$\rho_V(X_1, X_2) = \frac{C_V(X_1, X_2)}{\sigma_V(X_1)\,\sigma_V(X_2)} = \rho_V(h) \quad (4)$$

Variogram:

$$2\gamma(h) = E\{[V(X + h) - V(X)]^2\} \quad (5)$$

The variogram is the second order statistical moment of the increment $V(X+h)$-$V(X)$; in most cases, it can be considered as equivalent to the autocovariance function.

The autocovariance and the correlation coefficient are not intrinsic properties of the two points X_1 and X_2, they also depend on the population, that is to say, on the domain in which the field is defined.

Frequently, it is accepted for simplicity that the expected value is constant in the considered domain and that the correlation coefficient depends only on the vector distance between points X_1 and X_2, that is to say that the random field is wide sense stationary. However, when a drift in the variation of the properties of the soil with depth is detected, it is convenient to remove this trend from the data and to work with the residual random field.

Correlation distance:

To estimate the spatial correlation quantitatively the Correlation distance concept (also known as *Reach, Influence or range*) is introduced. This is the distance from which the regionalized random variables $V\left(X_1\right)$ y $V\left(X_2\right)$ are independent.

The correlation distance, $\delta = 2a$, is estimated from the experimental correlogram, as:

$$a = \int_{0}^{\lambda_c} \rho(\lambda u)\; d\lambda \qquad (6)$$

where: λ_c is the critical value of λ where ρ is null for the first time.

4.3 Estimation

Geostatistics can be used to estimate the value of a property of interest at points of the medium where no measurement has been made. It is then possible to interpolate between available data and to define virtual borings, cross-sections or configurations of a given stratum within the soil. The problem can be generalized to the estimation of the average value of a property in any sub-domain of the studied medium, for example, in a given volume or along a certain potentially critical surface. To reach this objective, linear statistical estimators without bias and with a minimum variance can be used (Best linear Unbiased Estimation or "*BLUE*")

$$V^*(X) = \sum_{i=1}^{n} \lambda_i \cdot V\left(X_i\right) + \left[1 - \sum_{i=1}^{n} \lambda_i\right] \cdot \mu_V \qquad (7)$$

. This technique, also known as Ordinary kriging (Krige, 1962; Matheron, 1965; Vanmarcke, 1983; Deutsch, 1992; Auvinet, 2002) is also widely used in mining engineering.

The value of the (minimized) variance error associated with the estimate, also known as "*estimation variance*" can also be assessed:

$$\sigma_E^2(X) = Var[V(X)] + \nu - \sum_{i=1}^{n} \lambda_i \cdot C\left(X - X_i\right) \qquad (8)$$

5 CONFIGURATION OF DEEP DEPOSITS DEPTH

The so-called Deep Deposits constitute the base on which the layers of soft lacustrine soils were deposited. The methodology used to define the configuration of the Deep Deposits is described below.

5.1 Definition of the random field

The geotechnical zoning map is based on the subsoil models previously described. In the context of the geostatistical analysis, the depth of Deep Deposits (DD) is considered as a random field $V(X)$, distributed within an R^p domain, with p = 2 (area of the former lacustrine zone as defined from topographical and geological information). The set of measured values within the domain (Figure 10) is a random sample of this random field. A structural analysis was performed to obtain experimental correlograms and correlation distances. Theoretical correlograms were fitted to the data set after removing a linear trend.

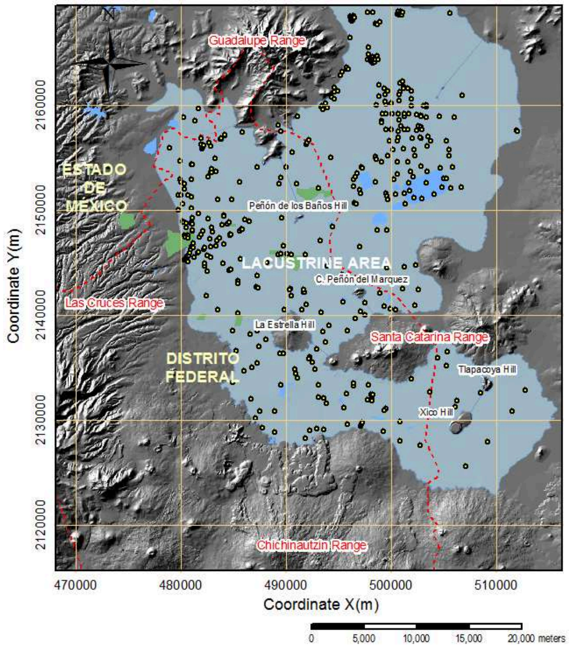


Figure 10. Study area and location of the Deep Deposits depth data.

5.2 Statistical description

Accepting the ergodic hypothesis for the random field in study, the main statistical parameters of the depth of the Deep Deposits were estimated (Table 1). In Figure 11 the variability of the data is described graphically by means of a histogram.

Table 1. Statistical parameters of the Deep Deposits depth.

Parameter	Value
No. data	544
Mean, *m*(m)	32.78
Variance, s^2(m^2)	319.28
Standard deviation, *s*(m)	17.87
Coefficient of variation	0.5451

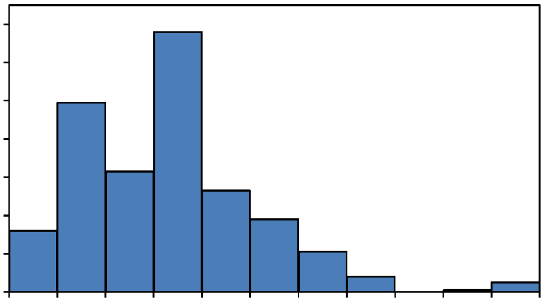


Figure 11. Histogram of the Deep Deposits depth.

5.3 Structural analysis

Trend analysis

The general trend of the *Deep Deposits* depth was assessed by means of a linear regression analysis, fitting an equation of the form $V(X) = ax+by+c$ to the data. The coefficients that describe this trend are: a = -0.00096398, b = 0.00064913 and c = -955.997663.

The corresponding linear regression surface (Figure 12) helps to identify the preferential direction of variation of the random field. The figure shows that the values of the *Deep Deposits* depth decrease from northwest toward the southeast. The presence of this trend is considered to calculate the experimental correlograms and in the estimations.

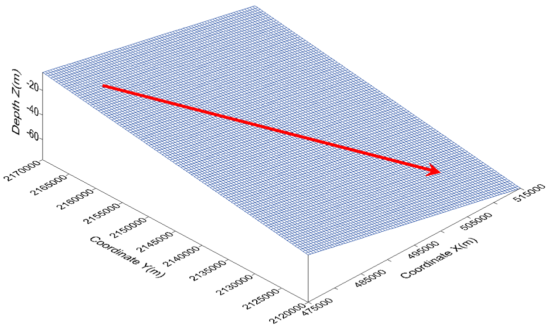
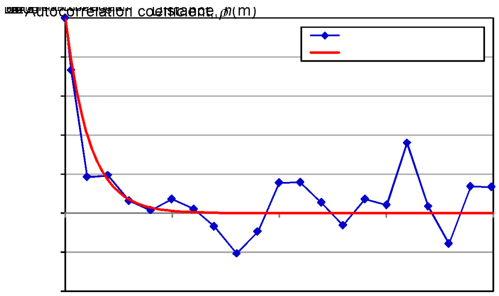


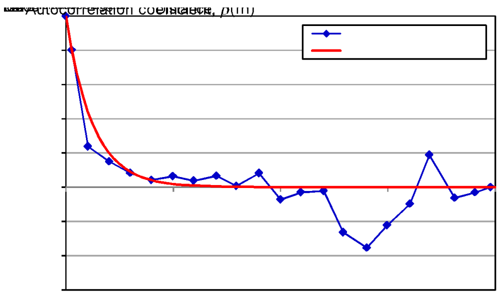
Figure 12. Linear regression surface of the Deep Deposits depth.

Estimation of the autocorrelation coefficient function

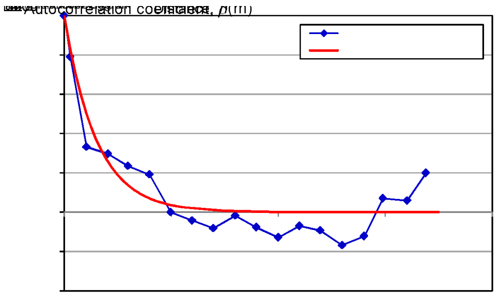
After removing the trend from the original data, a residual field was obtained. The autocorrelation coefficient function was calculated along four preferential directions with azimuth Az = 0°, 45°, 90° and 135°, and steps (Δh) of 250m (Figure 13).



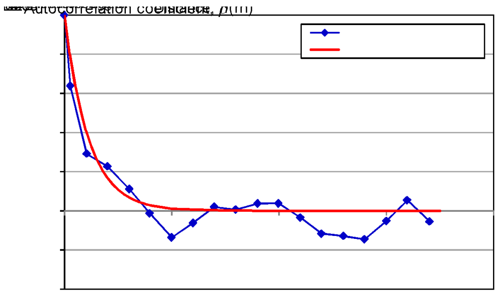
a) Direction Az = 0°



b) Direction Az = 45°



c) Direction Az = 90°



d) Direction Az = 135°

Figure 13. Directional correlograms for Deep Deposits depth.

These functions describing the correlation structure are shown in Figure 13. The correlation distances (δ) obtained for each preferential direction are shown in Table 2.

Table 2. Autocorrelation distances of *Deep Deposits* depth.

Direction, Az(°)	δ(m)
0	4500
45	5000
90	6000
135	4500

It can be seen that influence distances are of the order of several hundred meters. Some anisotropy is detected. The Figure13 shows that the shortest correlation distance of 4500m corresponds to directions Az=0° and 135° and the highest correlation distance of 600m to direction Az=90°.

The experimental correlograms were fitted to a single exponential function to obtain the spatial correlation model.

$$\rho = e\text{-}(2h/\delta) \qquad (9)$$

5.4 Estimation

The expected value and standard deviation of the depth of the *Deep Deposits* were obtained at all nodes of a regular grid conveniently defined, using the technique of Ordinary Kriging (Journel & Deutch, 1992).

Conservatively, a correlation distance of δ=5000m was considered in direction Az=45° and δ=4500m in direction Az=135°. The final estimate of the field was obtained reinstating the linear trend into the results. Additionally, the estimation variance was obtained.

5.5 Visualization

From the results a contour map was then built showing the spatial distribution of the depth of this layer within the studied area (fig. 14).

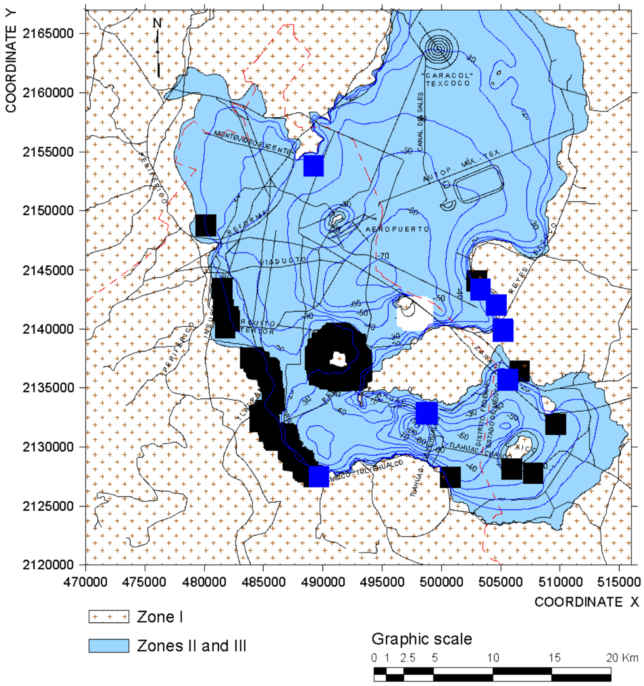


Figure 14. Contour map of the *Deep Deposits* depth.

The results of the estimation can also be represented by a surface map, assigning the value of the depth to the vertical coordinate (elevation) of each point (Figure. 15).

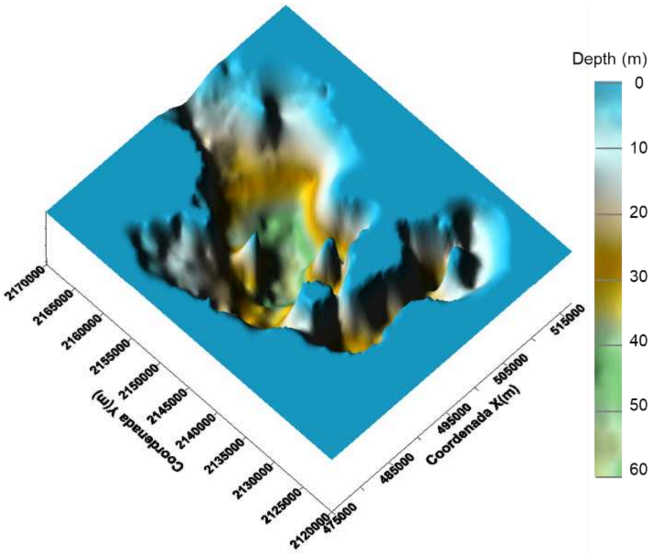


Figure 15. Representative surface of estimated depth of *Deep Deposits*.

Figs. 14 and 15 show that the greatest depths of the *Deep Deposits* are located in the area of the former Chalco Lake, in the south part of the lacustrine area. In this area the *Deep Deposits* depth varies between 90 and 100m.

6 GEOTECHNICAL ZONING MAP

The map of Figure 14 has immediate practical implications, and is useful to update the geotechnical zoning map of Federal District. The curves of equal depth of *Deep Deposits* are also useful in earthquake engineering to evaluate the site effects expected at some specific place.

Considering the definition of the transition zone previously indicated (GDFa, 2017) and using the map of figure 14, it was possible to define more accurately the boundary lines between zones II and III. After defining this boundary line and making the appropriate settings, the new geotechnical zoning map, shown in figure 16, was build. This map has been integrated into the recently updated Technical Standards (NTC-DCCDF) of the Building Code of Mexico City (2023).

It should be taken into account that the proposed zoning map (Figure 16) will have to be updated periodically as more information becomes available. Also, it should be observed that the geotechnical zoning map only provides a general orientation and should not be used for, avoiding the traditional geotechnical explorations that must be performed for each project as stressed by the building code.

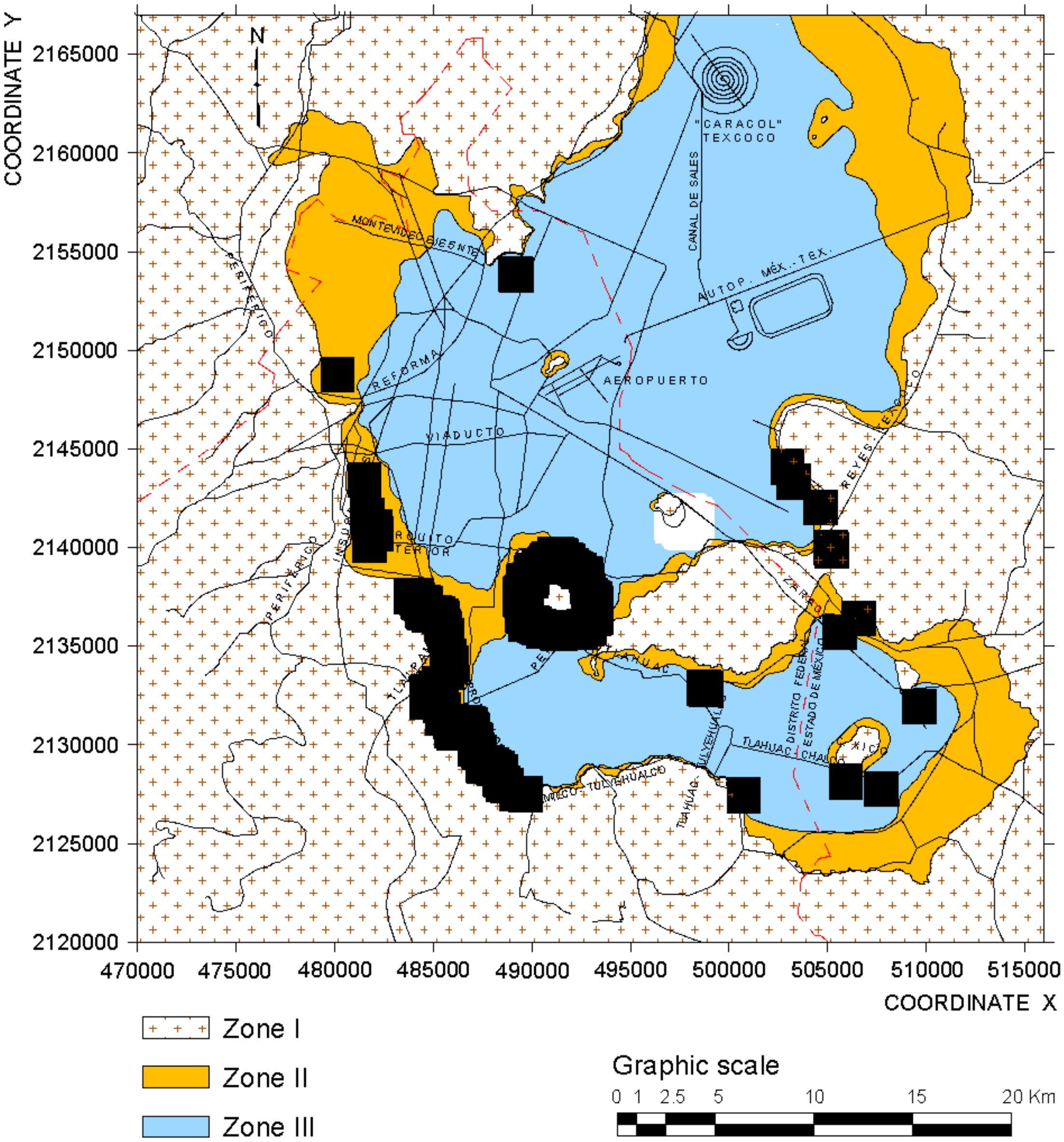


Figure 16. Geotechnical zoning map (NTC-DCCDF, Mexico City Building Code, 2023).

7 CONCLUSIONS

The updating of geotechnical zoning is a continuous task in large cities such as Mexico City; so, based on the information and results presented in this work, the limits of the current geotechnical zoning map for Mexico City were refined and incorporated in the new version of the NTC-DCCDF (2023).

The purpose of this map is improving the current geotechnical zoning by establishing more precise borders that help better define the location of the different types of soil in the Valley of Mexico. However, it is necessary to emphasize that the map must continue to be updated periodically as new information is collected, in order to increase accuracy on the location of the limits between the geotechnical zones.

It must be kept in mind that the zoning map (Figure 16) only provides general guidance and, in no case, does it allow to substitute the traditional geotechnical exploration studies that must be carried out for each project as established by current regulations.

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