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Characterization of soil permeability in the former Lake Texcoco, Mexico

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Abstract: The geotechnical subsoil conditions of the former Lake Texcoco represent a complex sequence of highly compressible lacustrine clays interbedded with layers and seams of harder and more permeable materials. Although the mechanical properties of these deposits have been extensively studied in the past, the information about their hydraulic properties is scarce. Currently, a comprehensive characterization of the hydraulic conductivity of this site has become necessary because of the construction of the New Mexico International Airport (NAIM). The present study describes a systematic evaluation of the hydraulic conductivity in the former Lake Texcoco through three different *in-situ* methods (well permeameter, LEFRANC and piezocone dissipation test). The measurements, taken from 155 locations, show a high spatial variability, with ranges spanning more than two orders of magnitude. The results also reveal that the estimated permeabilities vary significantly among methods. These discrepancies reflect the scale dependency of the hydraulic conductivity in the area caused by soil heterogeneities. A comparison of the presented results with previous studies demonstrates that piezocone tests provide representative results for the clayey formations, while LEFRANC tests better estimate the hydraulic conductivity of the permeable strata. Besides, CPTu tests yield more consistent values of hydraulic conductivity, with smaller dispersion than well permeameter and LEFRANC tests.

Keywords: Hydraulic conductivity, Lake Texcoco, LEFRANC test, USBR test, CPTu test, Piezocone

1 Introduction

The construction of the New Mexico International Airport (NAIM) has drawn renewed attention to the subsoil conditions of the former Lake Texcoco. This area overlies a series of soft clay and clayey silts, widely known for their high water content and large compressibility, interlayered by units of cemented clastic material [1]. In the past, several authors have studied the mechanical characteristics of the clayey deposits [1–6]. However little research has been conducted to evaluate their hydraulic properties. In particular, the available information about the permeability of the deeper strata is scarce.

A comprehensive hydraulic characterization of the area is important for the design of airport and hydraulic structures under construction. Hydraulic conductivity k affects geotechnical analyses that involve water flow within the ground or earth structures, such as uplift pressure in excavations, regional subsidence and the effects of rain infiltrations on slope stability of lagoons and canals. It also exerts a strong influence on the design of pumping systems and soft ground improvement methods. Despite its great importance, the accurate evaluation of this parameter remains a complex task because of soil's inherent heterogeneity. Many authors have documented the great spatial variability of k , finding coefficients of variation up to several orders of magnitude [7–9]. Furthermore, soil permeability can vary with the measurement scale. Some field features (e.g., fractures, cracks and pervious seams) create preferred flow paths that increase the value of k as the volume of tested material augments [10].

The methods to determine soil hydraulic properties include laboratory and *in-situ* tests. Although the former are economical, relatively quick and allow controlling different boundary conditions, they require an appropriate sample handling and provide just local k values. *In-situ* methods, instead, evaluate a more representative volume of soil under actual field conditions. However, most of them are costly, laborious and time-consuming. These drawbacks complicate the obtainment of large datasets required for studying the spatial variability of the hydraulic conductivity.

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ity. As an alternative, soil permeability can be estimated indirectly from direct-push probings carried out to determine other geotechnical properties (e.g., piezocone and flat dilatometer tests). The simplicity, inexpensiveness and speed of these indirect *in-situ* methods enable the acquisition of a greater number of measurements. Nevertheless, most of the proposed interpretation theories are empirical and their applicability is restricted to specific soil types and field conditions.

This paper presents a systematic evaluation of soil permeability in the former Lake Texcoco through three different *in-situ* methods: well permeameter, LEFRANC and piezocone dissipation test. The characterization provides the permeability values of previously unexplored strata and applies univariate statistics to evaluate the influence of the various measurement techniques. Accordingly, the specific objectives of this study are: (a) to determine the hydraulic conductivity of clayey and permeable strata of the former Lake Texcoco using different *in-situ* methods; (b) to evaluate the ability of indirect *in-situ* methods to estimate accurate and reliable values of k ; and (c) to quantify the scale effects in the determination of soil permeability in the study zone.

2 Methods

2.1 Geological and geotechnical context of the study area

The study area (bounded by latitude $19^{\circ}28'12''$ – $19^{\circ}33'36''$ N and longitude $98^{\circ}56'24''$ – $99^{\circ}01'12''$ W) lies at the lowest portion of the Basin of Mexico, formerly occupied by Lake Texcoco (State of Mexico, Mexico). The Basin of Mexico is a compound graben of 9600 km^2 elongated in the NNE-SSW direction (about 125-km length and 75-km width). It is bounded on the north by the Pachuca Range, east by the Río Frío and the Nevadas Ranges, south by Chichinautzin Range and west by the Ajusco Volcano and Las Cruces Range [11]. The basin is an extensive plain with an average elevation of 2240 m above sea level and a subtropical climate [12]. It was originally open until 700,000 years ago when volcanic activity blocked its drainage resulting in the development of an extensive system of lakes: Zumpango, Xaltocan, Texcoco, Xochimilco and Chalco. During this period, lacustrine sediments, volcanic ash and other pyroclastic materials were deposited overlaying previous alluvial-fluvial sediments [13]. The basin remained closed until the completion of the Nochistongo cut in 1789. The construction of new drainage systems and land

reclamation for urban expansion during the 20th century caused the gradual shrinking of the lakes, which today have practically disappeared [14]. Fig. 1 shows a geologic map of the Basin of Mexico.

The site stratigraphy corresponds to a typical Lacustrine Zone according to Mexico City Geotechnical Zoning [16]. Soil strata consist of soft clays and clayey silts interspersed with seams and layers of harder clayey silts with sands. As seen in Table 1, the soil strata are: a) *Surface Crust* (SC) of light brown fat clay of soft consistency with the presence of cracks; b) *Upper Clay Formation* (UCF), a thick layer of very soft lacustrine clay interspersed with relatively thin seams of volcanic origin and sandy silt; c) *Hard Layer* (HL) composed of thin layers of hard sandy silt with variable cementation; d) *Lower Clay Formation* (LCF), a green brown clay interspersed with gray fat clay of the same origin of the UCF; e) *Deep Deposits* (DD) formed by silts and sand interspersed with hard clays; f) *Deep Clay Formation* (DCF), a soft to very firm clay layer with similar characteristics to the others; and g) *Deep Stratified Formation* (DSF) composed of stratified deposits of clay, sand and silty sand.

The thickness of the strata remains relatively constant, with exception of the UCF that increases from northeast to southwest (Table 1). Clayey formations are characterized by their extremely high water content (varying from 300 to 400 %, but in some areas of the UCF values of up to 600 % have been registered) and void ratios (between 2–4 in the DCF, 3–6 in the LCF and above 6 in the UCF), high plasticity index and extraordinary compressibility [1, 2, 4]. Anisotropy is an important factor in Texcoco's soils due to the presence of permeable seams and their intrinsic geological formation process. Generally, clays have greater horizontal permeability k_h than vertical permeability k_v , with ratios of k_h/k_v ranging from 1.1 to 10.0 [17–23]. Field or laboratory estimates of the anisotropy of the former Lake Texcoco clays have not been obtained yet, however, considering their layering, a value of k_h/k_v between 2 and 5 may be assumed [4, 18, 20].

The groundwater table is close to the surface. Previous pumping wells for brine extraction have caused a significant depletion of the hydrostatic pressure influencing the stress condition at the site (Fig. 2). *In-situ* piezometric measurements show that the drawdown is gradual in the study area, beginning at a lower depth in the north (between 5 and 10 m) and deepening to the south (between 20 and 24 m). In addition, the subsoil of the site has a high salt content, even the presence of gas has been detected (mainly methane).

Figure 1: Geologic map of the Basin of Mexico (adapted from [15]).

Table 1: Stratigraphic description of the study site.

Stratum	ID	USCS Classification	Thickness (m)	Unit weight, γ (kN/m ³)
Surface Crust	SC	CH	0 – 1.6	15
Upper Clay Formation	UCF	CH	18 – 35	12
Hard Layer	HL	ML	2 – 3	16
Lower Clay Formation	LCF	CH	5 – 12	13
Deep Deposits	DD	-	8 – 10	18
Deep Clay Formation	DCF	CH	9 – 11	15
Deep Stratified Formation	DSF	-	16 – 19	17

Figure 2: Initial stress conditions at the study site: a) pore pressure, b) effective stress.

2.2 Previous studies of hydraulic conductivity

Most prior research at the former Texcoco Lake has focused on evaluating the hydraulic conductivity of the uppermost

strata, i.e. up to the DD. In 1974, [24] proposed a mathematical model to predict the settlement that would occur in the construction of four artificial lakes for the *Lake Texcoco project*. The authors estimated the permeability of the UCF and LCF from consolidation tests, whereas they obtained the permeability of the HL and DD from field pumping tests performed in the area between 1967 and 1968. In 1989, [13] investigated the hydraulic behavior of the Texcoco saline aquifer system by evaluating historical data, field studies, and numerical analyses of underground flow and solute transport. For the hydrogeological model, they determined the permeabilities of the HL and DD from a series of pumping tests and the hydraulic conductivity of the UCF and LCF from standard consolidation tests performed by [1, 2]. More recently, [4] estimated the horizontal hydraulic conductivity of the UCF and LCF from excess pore pressure dissipation records of a piezocone test (CPTu) done in 2000, while [25] performed a series of flexible wall permeameter tests. Table 2 presents a summary of hydraulic conductivities determined in the area according to the aforementioned studies.

2.3 Current measurement of saturated hydraulic conductivity k of soils

Three different *in-situ* measuring techniques were used to estimate the hydraulic conductivity in the study area: Well Permeameter Method (USBR 7300-89), LEFRANC (NF P94-132) and Piezocone (CPTu) test. The test campaign was part of the geotechnical survey performed for the construction of the New Mexico International Airport (NAIM) and included for the first time an extended study of the lower formations (DCF and DSF). Fig. 3 provides information about the location of the 155 test completed (21 USBR, 15 LEFRANC and 119 CPTu), including a location map of the study site.

2.3.1 Well Permeameter Method (USBR 7300-89)

The well permeameter method, also known as USBR test, is an *in-situ* test originally developed for assessing the hydraulic conductivity of semipervious and pervious soils ($k \geq 1 \times 10^{-7}$ m/s) along canal alignments and reservoir sites [26]. In general, it consists of injecting water into an uncased well and measuring the flow rate under a constant gravity head (Fig. 4a). Data analysis depends on the location of the groundwater table and impervious soil layers. For high groundwater tables, the hydraulic conductivity k

can be estimated as:

$$k = \frac{qV}{2\pi h^2} \left[\frac{\ln(h/r)}{(h/T_u)^{-1} + \frac{1}{2}(h/T_u)^{-2}} \right] \quad (1)$$

where h is the height of water in the well, r is the radius of the well, q is the discharge rate under steady-state condition, V is the ratio of water viscosity at the temperature of the test to water viscosity at 20 °C, and T_u the unsaturated distance between the water surface in the well and the groundwater table.

2.3.2 LEFRANC test

The LEFRANC test is a variable-head method developed to estimate the hydraulic conductivity of coarse and fine soils located below the groundwater table. The test consists of injecting water by gravity into a cavity of known dimensions and measuring the subsequent water level decline over time (Fig. 4b) [27]. Percolation takes place through an infiltration chamber (usually 1 m long) filled with clean gravel located at the bottom of a casing. By evaluating the mass-balance equilibrium, the hydraulic conductivity k can be calculated as:

$$k = A_i C \frac{\ln \left(\frac{h_1}{h_2} \right)}{t_2 - t_1} \quad (2)$$

where A_i is the internal cross-section of the borehole, h_1 and h_2 are the differences in the total head at times t_1 and t_2 , and C is a shape factor that depends on the ratio of the injection chamber length L to its diameter D . For ratios between 1.2 and 10, [28] suggests using the ellipsoid formula:

$$C = \frac{2\pi \left(\frac{L}{D} \right)}{\ln \left(\frac{L}{D} + \sqrt{\left(\frac{L}{D} \right)^2 + 1} \right)} \quad (3)$$

2.3.3 Piezocone dissipation test (CPTu)

In the piezocone (CPTu) test an instrumented steel probe is driven into the ground at a constant speed (2 cm/s) to obtain a continuous record of tip resistance, sleeve friction and pore water pressure induced during cone penetration (Fig. 4c). These measurements provide valuable information for soil profiling and estimation of its mechanical and hydraulic properties [29]. As an alternative to continuous penetration, the dissipation of the interstitial water pressure at a certain depth can be studied [4]. A dissipation test involves interrupting the steady penetration of the cone and measuring over time the decay of induced excess pore

Table 2: Summary of permeabilities previously estimated in the former Lake Texcoco.

Soil stratum	Hydraulic conductivity, k (m/s)			
	Herrera <i>et al.</i> (1974) [24]	Rudolph <i>et al.</i> (1989) [13]	Alanís-González (2003)* [4]	Lucero-Rivera (2018) [25]
SC	-	-	-	1.31×10^{-08}
UCF	5.44×10^{-09}	5.00×10^{-09}	2.13×10^{-09}	1.61×10^{-09}
HL	9.26×10^{-05}	8.00×10^{-05}	-	-
LCF	1.67×10^{-10}	5.00×10^{-09}	4.39×10^{-10}	6.98×10^{-10}
DD	8.68×10^{-05}	1.00×10^{-04}	-	5.58×10^{-10}
DCF	-	-	-	4.46×10^{-09}

Note: SC = Surface Crust; UCF = Upper Clay Formation; HL = Hard Layer; LCF = Lower Clay Formation; DD = Deep Deposits; and DCF = Deep Clay Formation. *Value of horizontal hydraulic conductivity.

Figure 3: Overview of the study area and location of the field tests.

Note: R-# = Runway; C# = CPTu test; L# = LEFRANC test; U# = USBR test.

water pressure until reaching the equilibrium pressure or some percentage of it. Fig. 5 presents typical dissipation records for different clayey formations of the former Lake Texcoco.

The dissipation process is mainly radial, and it is controlled by the horizontal coefficient of consolidation C_h , which in turn is a function of the soil horizontal permeability k_h [30]. There are many methods to estimate the value of k_h using dissipation test data [18, 31–34]. The selection of a specific interpretation theory depends on the amount of information available about the equipment, stratigraphy and initial stress conditions at the site. [35] studied the applicability of four different methods in the former Lake Texcoco and concluded that both the [18] and [34] proposals provide sufficiently representative results of the soil strata. Accordingly, the theory of [18] was chosen for the present article.

The solution proposed by [18] gives a rational interpretation method based on linear uncoupled consolidation analyses (i.e., C_h does not change during consolidation). It assumes that the soil behaves as a homogeneous, isotropic, linear-elastic material. Thus, C_h can be calculated as:

$$C_h = \frac{R^2 T_x}{t_x} \quad (4)$$

where R is the radius of the cone shaft, t_x is the measured time to reach a degree of consolidation x and T_x is its corresponding time factor.

Eq. (4) implicitly considers that the dissipation is mainly controlled by the soil properties within a cylindrical cavity of radius R , though the failure zone caused by cone penetration extends a distance at least four to six times R [36]. In linear analysis, C_h is proportional to the ratio of permeability to compressibility, therefore [18] proposed the following equation to determine k_h :

$$k_h = \frac{\gamma_w}{2.3 p'_{v0}} \cdot RR \cdot C_h \quad (5)$$

where p'_{v0} is the initial vertical effective stress, γ_w is the unit weight of water, RR is the recompression ratio controlling dissipation around the piezocone.

It is important to note that the piezocone provides only parameters in the horizontal direction. Parameters in the vertical direction can be estimated from empirical correlations that consider the anisotropy and stratification of soils, as discussed in Section 2.1.

3 Results

The hypothesis of linear consolidation is not valid for all soils. According to [30], linear solutions are reasonably applicable to normally consolidated clays, however [18] recommends checking the validity of this assumption when dissipation tests are first conducted at a new site. For this, they suggest calculating C_h with Eq. (4) at different degrees of consolidation. Large discrepancies between the estimated values of C_h indicate that coupling effects are significant and this methodology is not applicable. Table 3 shows the horizontal coefficient of consolidation C_h and hydraulic conductivity k_h calculated at different degrees of consolidation for the dissipation data of the study site presented in Fig. 5. Discussion of results is given in Section 4.

Table 4 presents summary statistics of the hydraulic conductivity k for each *in-situ* test. Several authors have suggested that the variability of the hydraulic conductivity can be described using the lognormal distribution [37–42], thus Table 4 includes the geometric mean and the standard deviation of the decimal logarithms of k as a more reliable measure of central tendency and dispersion of the dataset, respectively.

4 Discussion

4.1 Applicability of piezocone dissipation test (CPTu) to estimate hydraulic conductivity in the former Lake Texcoco

The values presented in Table 3 show that C_h remains approximately constant during the consolidation process for the different clayey strata. Furthermore, the maximum difference between k_h estimated with Eq. (5) is less than half order of magnitude. As stated in Section 2.1, anisotropy is an important factor of Texcoco's clays, therefore a direct comparison of the estimated hydraulic conductivity with CPTu and previous studies [4, 13, 24, 25] is not possible. Assuming a ratio $k_h/k_v=3$ [4, 18, 20], the geometric means of k_v of the UCF, LCF, DCF and DSF are 1.29×10^{-9} , 1.61×10^{-9} , 7.86×10^{-10} and 9.75×10^{-10} m/s, respectively. These values are similar to those reported in Table 4 and show that the selected interpretation method provide representative results for the clayey formations in the former Lake Texcoco. This confirms the applicability of linear uncoupled consolidation theory for the analysis of dissipation curves and suggests that indirect *in-situ* methods, such as CPTu, con-

Figure 4: *In-situ* tests: a) Well permeameter (USBR), b) LEFRANC, c) Piezocone dissipation test (CPTu) (photos courtesy of Federal Electricity Commission and GEOSOL).

Table 3: Horizontal coefficient of consolidation C_h and hydraulic conductivity k_h calculated at different degrees of consolidation.

Depth (m)	Soil stratum	Parameter	Unit	Degree of consolidation (%)				
				30	40	50	60	70
24.38	UCF	C_h	m^2/s	1.74×10^{-05}	2.19×10^{-05}	2.51×10^{-05}	2.88×10^{-05}	3.15×10^{-05}
		k_h	m/s	5.46×10^{-09}	6.88×10^{-09}	7.89×10^{-09}	9.07×10^{-09}	9.91×10^{-09}
29.73	LCF	C_h	m^2/s	8.00×10^{-05}	8.26×10^{-05}	8.94×10^{-05}	8.49×10^{-05}	9.35×10^{-05}
		k_h	m/s	1.59×10^{-08}	1.64×10^{-08}	1.78×10^{-08}	1.69×10^{-08}	1.86×10^{-08}
45.3	DCF	C_h	m^2/s	6.12×10^{-06}	6.74×10^{-06}	7.91×10^{-06}	8.69×10^{-06}	1.02×10^{-05}
		k_h	m/s	6.83×10^{-10}	7.52×10^{-10}	8.84×10^{-10}	9.71×10^{-10}	1.13×10^{-09}
50.06	DCF	C_h	m^2/s	2.49×10^{-05}	2.74×10^{-05}	2.79×10^{-05}	3.11×10^{-05}	3.53×10^{-05}
		k_h	m/s	2.56×10^{-09}	2.82×10^{-09}	2.87×10^{-09}	3.20×10^{-09}	3.63×10^{-09}
67.59	DSF	C_h	m^2/s	1.33×10^{-05}	1.74×10^{-05}	2.08×10^{-05}	2.41×10^{-05}	2.95×10^{-05}
		k_h	m/s	8.16×10^{-10}	1.07×10^{-09}	1.28×10^{-09}	1.48×10^{-09}	1.82×10^{-09}

Note: UCF = Upper Clay Formation; LCF = Lower Clay Formation; DCF = Deep Clay Formation; and DSF = Deep Stratified Formation.

stitute a valid alternative to traditional field tests for determining k values in the study area. The application of such indirect techniques can help to reduce costs and time, optimizing the geotechnical site characterization process. It should be noted that the values of the estimated k_v are practically in the same order of magnitude of k_h . However, a comprehensive study of the *in-situ* anisotropy of Texcoco clayey formations is still necessary to provide reliable estimates of the vertical hydraulic conductivity.

4.2 Influence of the measurement technique

The results presented in Table 4 also suggest that the estimated hydraulic conductivity vary significantly among methods. The different locations of the tests hinder a point-to-point comparison of the measurement techniques. However, an analysis of the global summary statistics shows that both the USBR and the LEFRANC tests provide consistently higher permeabilities and exhibit greater dispersion than CPTu. In general, the values estimated with the CPTu are consistent with those reported in the literature for the clayey formations (UCF, LCF and DCF) (Table 4), but lower for the DD. Conversely, LEFRANC tests

Table 4: Summary of hydraulic conductivity statistics currently estimated in the former Lake Texcoco.

Test		Soil stratum					
		UCF	HL	LCF	DD	DCF	DSF
USBR	<i>n</i>	40	-	-	-	-	-
	Min (m/s)	4.60×10^{-06}	-	-	-	-	-
	Max (m/s)	1.14×10^{-04}	-	-	-	-	-
	m_k (m/s)	2.08×10^{-06}	-	-	-	-	-
	s_k	1.18	-	-	-	-	-
LEFRANC	<i>n</i>	6	12	-	14	-	13
	Min (m/s)	1.07×10^{-09}	8.46×10^{-07}	-	8.38×10^{-10}	-	5.42×10^{-06}
	Max (m/s)	2.55×10^{-08}	3.51×10^{-04}	-	6.95×10^{-04}	-	1.41×10^{-03}
	m_k (m/s)	6.69×10^{-09}	2.39×10^{-05}	-	5.57×10^{-06}	-	9.11×10^{-05}
	s_k	0.46	0.88	-	1.84	-	0.76
CPTu*	<i>n</i>	46	-	30	57	46	50
	Min (m/s)	4.21×10^{-10}	-	5.60×10^{-10}	5.84×10^{-10}	4.32×10^{-10}	2.43×10^{-10}
	Max (m/s)	2.40×10^{-08}	-	3.42×10^{-08}	3.41×10^{-08}	8.18×10^{-09}	4.17×10^{-08}
	m_k (m/s)	3.88×10^{-09}	-	4.84×10^{-09}	5.19×10^{-09}	2.36×10^{-09}	2.93×10^{-09}
	s_k	0.36	-	0.41	0.48	0.32	0.49

Note: UCF = Upper Clay Formation; HL = Hard Layer; LCF = Lower Clay Formation; DD = Deep Deposits; DCF = Deep Clay Formation; DSF = Deep Stratified Formation; *n* = sample size; Min = minimum; Max = maximum; m_k = geometric mean of *k*; s_k = standard deviation of log (*k*).

*Value of horizontal hydraulic conductivity.

Figure 5: Pore pressure dissipation curves of the CPTu tests at different depths in the study site.

provide similar results to those reported for the more permeable and heterogeneous strata (HL and DD). Fig. 6 contrasts the distribution of the estimated *k* values in three strata (UCF, DD and DSF) and shows that this difference can be as many as four orders of magnitude.

Several authors have reported similar behaviors, which have been attributed to differences in flow geometry, measurement scales and inherent disturbances during testing [10, 42–45]. Although an exhaustive analysis of the causes of these discrepancies is beyond the scope of the present article, scale effects are likely the most signif-

icant factors. Compared to CPTu, USBR and LEFRANC affect a larger volume of soil, which increases the influence of material heterogeneity. Fractures, cracks and pervious seams in the soil matrix create preferred pathways that allow faster flow and increase the measured value of *k* [10]. The presence of preferred flow paths explain the higher hydraulic conductivities estimated with the USBR test. These measurements were performed at shallow depths of the UCF (Fig. 7) which are characterized by the existence of extensive fracture networks [13]. Scale effects may also clarify the discrepancies obtained in the hydraulic conductivity of the DD and the DSF. Pumping tests used by [13, 24] have a large area of influence, slightly greater than the evaluated with the LEFRANC test. By contrast, CPTu and flexible well permeameter tests evaluate a considerably lower volume of soil, which limits the effects of the strata heterogeneities. Consequently, the permeabilities reported by the former authors are almost four orders of magnitude higher.

4.3 Spatial variability of the hydraulic conductivity

Fig. 7 evidences the variability of the hydraulic conductivity across the study area. The *k* values span more than two orders of magnitude regardless of the stratum or the mea-

Figure 6: Boxplot comparison of hydraulic conductivity obtained using CPTu, LEFRANC and USBR methods: a) UCF, b) DD, c) DSF.

Figure 7: Profiles of the hydraulic conductivity variability for each stratum.

surement technique. This variability is typical of natural and compacted soils, which can have a coefficient of variation CV up to 500 % [7-9]. Despite their great dispersion, the data also suggest that all clayey formations (UCF, LCF, DCF and DSF) have similar hydraulic characteristics. According to CPTu results, the horizontal permeabilities of these strata range from 10^{-10} to 10^{-8} m/s with a standard deviation between 0.3 and 0.5 (Fig. 8).

Figure 8: Boxplot comparison of hydraulic conductivity estimated with CPTu test for different clayey formations.

The results show the limitations of traditional univariate statistics to describe the hydraulic conductivity variability in the area. In this context, geostatistical analysis represents a suitable alternative to study the spatial correlation of the sample data and obtain a better characterization of this soil property.

5 Conclusions

The hydraulic conductivity is an important parameter for different geotechnical and geohydrological analyses that involve the movement of water within the soil or earth structures. This paper described an extensive geotechnical survey performed to characterize the subsoil hydraulic conductivity k at the former Lake Texcoco. This test campaign was part of the preliminary studies for the construction of the New Mexico International Airport (NAIM) and included for the first time an extended evaluation of unexplored strata (the deepest formations DCF and DSF). The study used three different *in-situ* methods: well permeameter (USBR), LEFRANC and piezocone dissipation test. The assessment of the results showed that the estimated

permeabilities vary significantly among methods with differences up to four orders of magnitude. Piezocone dissipation tests gave consistently lower values of k than the well permeameter (USBR) and LEFRANC methods. CPTu tests yielded more consistent values of the horizontal hydraulic conductivity of the clayey formations, with smaller dispersion than well permeameter and LEFRANC tests, and therefore, they are more reliable. The possible reasons for these discrepancies were mainly related to scale effects. In effect, compared to CPTu, USBR and LEFRANC affect a larger volume of soil, which increases the influence of material heterogeneity. Fractures, cracks and pervious seams in the soil matrix create preferred pathways that increase the measured value and dispersion of k . On the other hand, LEFRANC tests provided better estimates of the hydraulic conductivity of the permeable strata. Finally, the results also demonstrated that more work is necessary to assess the great variability of the hydraulic conductivity in the study zone, whose values span more than two orders of magnitude regardless of the stratum or the measurement technique. Further research should focus on implementing geostatistical analyses to investigate its spatial distribution and in the evaluation of *in-situ* anisotropy.

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