Engineering characterization of lacustrine soil deposits at the inner bay of Puno around Titicaca Lake

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ABSTRACT

The inner bay of the city of Puno has been the subject of various investigations that seek to recover and enable flood-prone areas, through strategic urban development projects (urban infrastructure) and protection works. On the other hand, the characteristics of soft soil deposits, such as those in the inner bay of Puno, represent a risk of problems with excessive settlement of the infrastructure. This study presents an engineering characterization of the lacustrine soil deposits in the inner bay of the city of Puno, around Lake Titicaca. The site lies around the Pier of Puno city at Lake Titicaca, the highest navigable lake in the world, approximately a few hundred meters in front of the National University of the Altiplano of Puno (UNAP) and a few hundred meters to the southward of the Pier of Puno city. Physical, strength, and deformation properties were determined from standard laboratory tests. The material studied corresponds to the shallow layers of the study area, corresponding to sedimentary soils of the lacustrine units and fluvial-alluvial deposits of the inner bay of Puno. These lacustrine soils are classified as highly plastic silts and organic clays (MH and OH). The results show the significant influence of the quality of soil samples, due to the sampling method and storage time, on consolidation and resistance parameters. Finally, this study provides valuable insights into the influence of sample quality on consolidation parameters and shear strength of the lacustrine soils in the inner bay of Puno city around Titicaca Lake.

Keywords: engineering characterization, lacustrine soil, shear strength, soil consolidation, Titicaca Lake.

1. Introduction

The field of engineering, particularly in civil and geotechnical aspects, involves making decisions amidst numerous uncertainties. It primarily reflects the application of engineering judgment, which is closely tied to the factual aspects of engineering projects. (Brandl 2004; DiBiagio and Flaate 2000; Nagaraj 1993; De Mello 1975). Effective soil investigation, employing suitable sampling techniques and laboratory tests, is essential for the accurate development of calculations and designs for structures in contact with the ground (Burland et al. 2012; Lanzky and Palmquist 2015; Long 2006; Brandl 2004; Terzaghi, Peck, and Mesri 1996). Despite improvements in methods and current methodological advancements currently used in the design and execution of works; of foundations, retaining structures, slope stability, etc. challenges persist with issues of failures and errors that become apparent during their operational phases (Alonso, Pinyol, and Puzrin 2010; Puzrin, Alonso, and Pinyol 2010; Atkinson 2007; Brandl 2004; De Mello 1975).

The importance of undisturbed samples' mechanical properties of soils has long been recognized (Lim 2018; Carter and Bentley 2016; Lanzky and Palmquist 2015; Bohlin 2014; Rahman and Siddique 2010; Long 2006; DeGroot, Poirier, and Landon 2005; Hvorslev 1949). Most cases of structural failure or damage are mainly due to the bad behaviour, or unforeseen behaviour, of the soils in contact with them (Alonso, Pinyol, and Puzrin 2010; Puzrin, Alonso, and Pinyol 2010; Logeais 1984; Széchy 1961) and this is due to ignorance of the mechanical behaviour properties of soils in real construction conditions.

When determining soil properties, through the sampling procedure and laboratory tests, the sample quality, or degree of disturbance, of soils obtained from the site must be taken into account (Lim 2018; Lanzky and Palmquist 2015). Depending on the sampling method and how the samples are handled; during transportation, storage, and laboratory preparation; the alteration will be different and this will affect the soil parameters. The consequences may be, among other things, economic and greater risks of structural damage to the project and its surroundings.

The inner bay of the city of Puno has been the subject of various investigations that seek to recover and enable flood-prone areas, through strategic urban development projects (urban infrastructure) and protection works (Municipalidad Provincial de Puno 2020). Currently, in this area, local authorities are planning the development of various engineering projects, intending to provide the area with greater value for the development of economic activities, mainly oriented to the tourism sector and various public facilities. On the other hand, the characteristics of soft soil deposits, such as those in the inner bay of Puno, represent a risk of problems with excessive settlement of the infrastructure (Pineda et al. 2019).

Because even the best soil sampling techniques cause some alteration of the natural soil conditions, it is necessary to take into account the degree of alteration they cause. The evaluation of the level of alteration, or quality, of soil samples has been widely investigated and reported in the available technical literature, producing various methods for the evaluation of the quality of soil samples onit (Lunne et al. 2006; Lunne, Berre, and Strandvik 1997; Onitsuka and Hong 1995; Okumura 1971; Nagaraj 1993; Nelson et al. 1971; Hvorslev 1949).

The main indicators used to indicate the quality of the samples are the volumetric strain, ε_{v0}, during laboratory reconsolidation for the initial effective stress (in situ) (Andresen and Kolstad 1979; Terzaghi, Peck, and Mesri 1996) and the variation of the void ratio related to the initial (natural, field) void ratio, $\Delta e/e_0$, for reconsolidation at the initial effective stress (Amundsen, Thakur, and Emdal 2016; 2015; Lunne et al. 2006; Lunne, Berre, and Strandvik 1997). To determine $\Delta e/e_0$ was considered the field water content, w_{field}, and the specific gravity of the particles, G_s, of soils.

The basis for the criterion of Lunne et al. (2006; 1997) was the influence of sample disturbance on laboratory measurements such as volumetric deformation during reconsolidation, preconsolidation stress, oedometric modulus (confined or compressibility modulus) (M_0, where $M = d\sigma'_v / d\varepsilon_v$) and consolidation coefficient from the results of the oedometric test.

This study presents an engineering characterization of the lacustrine soil deposits in the inner bay of Puno city, around Titicaca Lake, with special attention to soil sample quality.

2. Materials and methods

2.1. Field sites

The study area includes a large part of the lake coastline, at the inner bay of Puno City, from the land located in front of the National University of the Altiplano (North) to the land in front of the C.P. Jayllihuaya and C.P. Salcedo as shown in Fig. 1 on the shores of Titicaca Lake, the highest navigable lake in the world.

Puno, also known as the "Silver City" or the "Capital of Peruvian Folklore", was founded with the name "City of our Lady of Concepción and San Carlos de Puno" and is located in the southeast Peru. It is currently the capital of the Puno region and is the main city on the border with Bolivia. It occupies 67000 km² of territory made up of the western half of the Collao Plateau, west of Lake Titicaca, and the Amazonian Yungas to the north. It borders to the east with Bolivia, to the southwest with the departments of Tacna, Moquegua and Arequipa, to the west with Cuzco and the north with Madre de Dios. Its average altitude is 3820 meters above sea level.

Most of the study area has free access, reaching the sampling points through stretches of road on foot of between 50 m to 200 m from the urban roads near each exploration point. In some cases, access on foot is difficult due to the presence of water, that is, due to the rise in the water table, mainly on the southern side of the study area.

Figure 1. Exploration sites: from National University of the Altiplano (North) to C.P. Jayllihuaya (South).

2.2. Basic soil sample properties

The soil samples correspond to the study area's superficial layers (< 5.0 m depth) and correspond to sedimentary soils of the lacustrine units and fluvial-alluvial deposits of the inner bay of Puno, on the shores of Lake Titicaca. However, previous studies, from previous works carried out, indicate those soils extend to depths from 20 m to 50 m.

In this research, lacustrine soils were used, characteristic of the interior bay of Puno, obtained from twelve (12) exploration points, distributed in the study area as shown in Fig. 1. The study area covers areas of the interior bay. from the city of Puno; included between the area aligned with the National University of the Altiplano (Northside); passing through the area of the second section of the Bahía de los Inca's boardwalk, the Interprovincial Land Terminal, Wastewater Treatment Plant (Espinar Zone), in front of the Chejoña Neighborhood; until you reach the exit towards Desaguadero (Southside) in front of the town center of Jayllihuaya.

The soil samples, necessary to carry out the laboratory tests, correspond to the lower layers of the pits excavated at the exploration points and correspond to fine soils characteristic of the study area, lacustrine deposits of sedimentary soil.

Based on the provided classification in "Table 1", the soils scheduled for testing are predominantly high-plasticity silts and organic clays (MH and OH categories), except for the sample from C9, identified as low-plasticity organic clay (CL). Notably, a discernible decomposing organic odor was detected during the sampling and laboratory testing process.

Table 1. Soil classification for the site of research.

Pit	w	w_P	w_L	I_P	I_F	SUCS
C1	59.8	52.7	83.9	31.2	0.23	OH
C2	62.8	56.1	80.2	24.1	0.28	OH
C3	63.0	53.2	78.6	25.4	0.39	OH
C4	62.6	47.8	74.8	27.0	0.55	OH
C5	61.3	44.4	67.3	22.9	0.74	OH
C6	63.2	44.1	69.3	25.2	0.76	OH
C7	59.2	38.9	66.3	27.4	0.74	OH
C8	55.2	36.8	62.2	25.4	0.72	OH
C9	41.2	22.8	46.2	23.4	0.79	OL
C10	76.3	68.3	83.9	15.6	0.51	OH
C11	90.2	69.8	94.2	24.4	0.84	OH
C12	88.1	64.4	90.7	26.3	0.90	OH

Examining exploration points C1 to C8, the organic clays exhibit average liquid limits (w_L) of 72.8%, ranging within 21.7%, and plastic limits (w_P) averaging 46.8%, within a range of 19.3%. For the last three exploration points (C10 to C12), the liquid limits average 89.6%, within a range of 10.3%, and plastic limits average 67.5%, within a range of 5.4%. The plasticity indices (I_P) for C1 to C8 organic clays average 26.1%, within a range of 8.3%, while those for C10 to C12 average 22.1%, within a range of 10.7%. The generally small dispersion of the data affirms these results as typical for high-plasticity organic clays in the study area (see "Table 1").

Additionally, the flow indices (I_F) for C1 to C8 clays average 0.55, indicating soft to very soft plastic consistency, while those for C10 to C12 average 0.75, suggesting very plastic to semi-liquid consistency. This observation aligns with the visual inspection during sampling, confirming a soft to very soft plastic consistency. Moreover, the natural water contents (w) at each exploration point indicate that the soils, in their naturally saturated state, maintain a reasonable distance from their liquid limit, suggesting enhanced resistance and reduced deformability.

The "Table 2" shows that characteristic values of the natural unit weights of the soils, which correspond to the first nine pits, are relatively uniform and greater than those obtained for the rest of the exploration points. The soils, found at the bottom of the pits, from exploration points C1 to C8 have an average unit weight of 15.4 kN/m^3, with a standard deviation of 0.4 kN/m^3. While for exploration points C10 to C12 they have an average unit weight of 14.5 kN/m^3, with a standard deviation of 0.4 kN/m^3. All of this indicates the influence of the interventions carried out in the first points, due to filling and movements by nearby constructions, which contributed to the densification of the superficial layers of the soil, which does not occur in the last three exploration points, following what was observed during the visits and fieldwork carried out in the study area.

Table 2. Physical properties of soils at the research site.

Pit	Depth *m*	z_w *m*	γ_{sat} *kN/m³*	G_s -	e_{field} -	σ'_{v0} *kPa*
C1	3.36	1.12	14.9	2.520	1.887	35.4
C2	2.87	0.70	15.1	2.560	1.863	26.5
C3	2.85	0.67	15.2	2.541	1.800	25.2
C4	2.54	0.35	15.6	2.565	-	20.1
C5	2.72	0.78	15.3	2.502	-	24.0
C6	2.88	0.82	15.5	2.540	1.625	25.7
C7	3.02	1.04	15.7	2.485	-	30.5
C8	2.72	0.68	16.2	2.541	-	16.3
C9	2.84	0.54	16.8	2.536	-	25.1
C10	2.94	0.43	14.9	2.539	-	19.4
C11	2.88	0.38	14.4	2.538	2.289	17.4
C12	2.82	0.36	14.2	2.520	-	16.3

On the other hand, "Table 1" shows the natural water content values of soils at the study area present three differentiated groups of natural water content: organic soils that are found in the exploration points C1 to C8, which have an average water content of 60.9%, with a standard deviation of 5.8%, the organic soil of the exploration point C9 has a humidity of 41.2%, and the soils corresponding to the Exploration points C10 to C12 present average water content of 84.9%, with a standard deviation of 7.5%.

2.3. Soil sampling

Two sampling methods were employed, including block samples (MB: approximately 0.40 m × 0.30 m × 0.30 m) and the Shelby tube samplers of 75 mm diameter (TS75). The block samples, obtained from pits (< 5.0 m depth), were preserved following standards and stored in the laboratory. The tube samplers, used at the bottom of the pits, also provided samples that were subjected to simple extrusion for analysis.

Preliminary results indicate that all samples could be considered high quality, although more detailed analysis of laboratory data will be required to confirm this. The preliminary quality of the samples was evaluated through dimensional measurements of the tube samplers used, such as the TS75. From these measurements, it was preliminarily concluded that all samples could be described as unaltered or of high quality, depending on the determined area ratio.

On the other hand, knowing preliminarily of the poor quality of the disturbed soil samples, the remoulding of the samples of the residues of the soil samples was carried out using the kneading technique in the oedometer ring.

a)

b)

Figura 1. Soil sampling by a) block, and b) Shelby tube.

3. Results and discussion

This section shows the results related to the evaluation of the quality of the samples obtained from the analyzed exploration points (C1, C2, C3, C6, and C11) in the research area, as well as the results on their influence on the consolidation parameters and the shear resistance characteristics of the silt and organic clay deposits of the interior bay of Puno, around Titicaca Lake.

3.1. Sample quality

This research is aimed at determining the influence of soil sample quality, based on the results of field measurements and laboratory tests, on the values of mechanical behaviour parameters (shear strength and consolidation) of the typical plastic silts and lacustrine clays in the study area.

Sampling and laboratory tests were used to verify the influence of the quality of the soil samples, depending on their state after sampling and after a certain period of storage in the laboratory, on the results of the consolidation through oedometric tests, following the ASTM D 2435 standard.

In this section, sample quality assessment will be presented, due to sampling from block sample (MB), Shelby tube sampler (TS75), remolded (R), and storage of sample for about 7 days (MB7d) and 30 days (MB30d). Samples used for laboratory tests were obtained from five pits in the research area (C1, C2, C3, C6, and C11), with field void ratio shown in "Table 2" (see "Table 3").

Table 3. Soil samples quality assessment.

Pit	Sample	$\Delta e/e_o$	σ'_p *kPa*	OCR	M_0/M_L	Quality
C1	MB	0.032	45.6	1.29	2.63	Very good
	TS75	0.054	47.7	1.35	1.56	Good
	R	-	-	-	-	-
	MB7d	0.054	48.2	1.36	1.27	Good
	MB30d	0.108	50.0	1.41	< 1	Poor
C2	MB	0.027	42.4	1.60	2.70	Very good
	TS75	0.061	36.5	1.38	1.29	Good
	R	-	-	-	-	-
	MB7d	0.049	39.6	1.49	1.31	Good
	MB30d	0.093	44.9	1.69	<1	Poor
C3	MB	0.028	43.3	1.72	3.52	Very good
	TS75	0.059	42.0	1.67	1.75	Good
	R	0.154	29.3	1.16	<1	Very poor
	MB7d	0.052	38.7	1.54	1.25	Good
	MB30d	0.098	40.4	1.60	<1	Poor
C6	MB	0.036	42.1	1.64	2.88	Very good
	TS75	0.063	40.3	1.57	1.66	Good
	R	0.177	32.7	1.27	<1	Very poor
	MB7d	0.062	42.7	1.66	1.60	Good
	MB30d	0.127	44.3	1.72	1.24	Poor
C11	MB	0.031	21.8	1.25	5.71	Very good
	TS75	0.056	20.8	1.20	1.55	Good
	R	0.163	20.7	1.19	<1	Very poor
	MB7d	0.058	23.2	1.33	1.87	Good
	MB30d	0.076	23.9	1.37	1.43	Poor

In general, for the soil at all exploration points, "Table 3" shows that the block sample (MB) has very good to excellent quality, which indicates that the sample has undergone minimal alteration during the process, from sampling to laboratory testing. In the case of samples obtained with Shelby tube (TS75) reduces its quality from good to acceptable, mainly caused by the shape of the tube, which does not allow comfortable handling for sample extraction, and the driving procedure carried out during sampling. The remolded samples were results of very poor quality.

On the other hand, samples storage about 7 days (MB7d) have good to an acceptable quality, and those storage about 30 days (MB30d) have poor quality.

3.2. Consolidation parameters

The analysis of soil consolidation parameters, particularly compression and recompression indices, which are crucial for calculating settlements in fine-grained soils are presented below (see Fig. 2). The study follows traditional practices and incorporates corrections suggested by Schmertmann (Schmertmann 1955).

Compression indices relate to the novel part of the compression curve, indicating the soil's response during a one-dimensional consolidation test. Recompression indices estimate the slope of the discharge stage in the absence of recharges, providing qualitative insights into parameter variations across different tested samples.

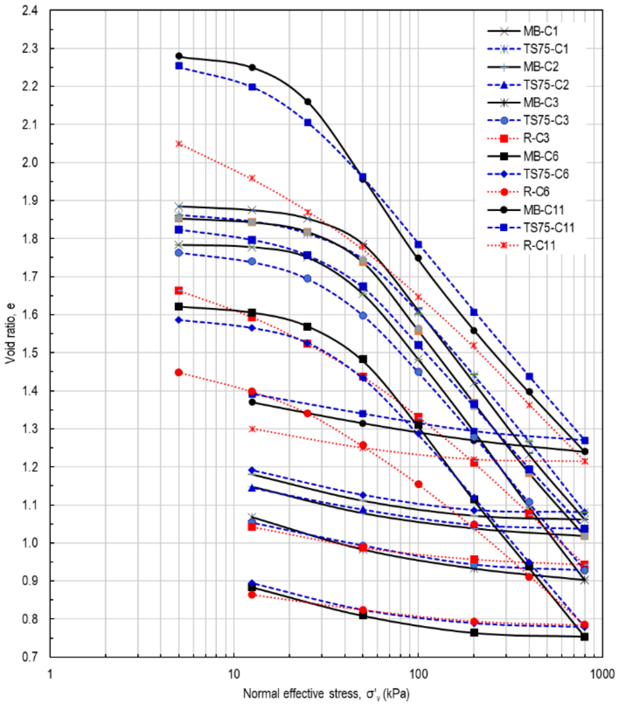

Figure 2. Typical compression curves of Titicaca's lacustrine soils from different sampling methods.

The results, shown in "Table 3" and Fig. 3, highlight trends in compression indices (C_c) obtained from different sampling methods. A clear reduction in values is observed as the sample quality decreases or sample alteration increases. Quality limits, based on Lunne et al.'s (Lunne, Berre, and Strandvik 1997; Lunne et al. 2006) criteria, are also presented. A correlation equation (R^2 = 0.65) between the laboratory compression index (C_c) and sample quality ($\Delta e/e_0$) according to Lunne et al.'s criteria (Lunne, Berre, and Strandvik 1997; Lunne et al. 2006) are approximately following.

$$C_c = 0.4311 - 0.064\ln\left(\frac{\Delta e}{e_0}\right) \qquad (1)$$

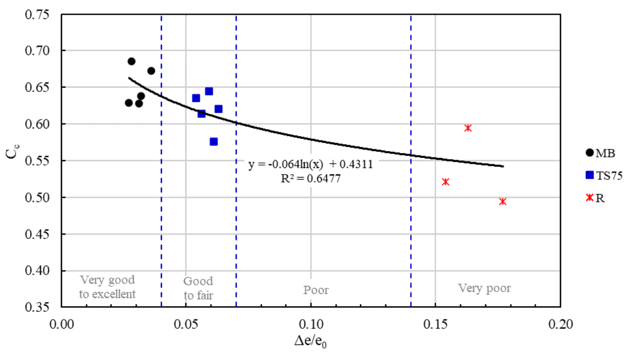

Figure 3. Sampler influence on compression index (C_c).

Fig. 4 shows, as "Table 3", the values of the compression indices (C_c), obtained with the samples stored in the laboratory for different periods (0 days, 7 days, and 30 days). A clear trend is observed towards a reduction in its value as the quality of the samples stored for a longer period decreases or the alteration of samples due to changes in the water content of the corresponding samples increases. Note, in the Fig. 3, the quality limits, according to the ranges of values established by Lunne et al. (Lunne, Berre, and Strandvik 1997; Lunne et al. 2006).

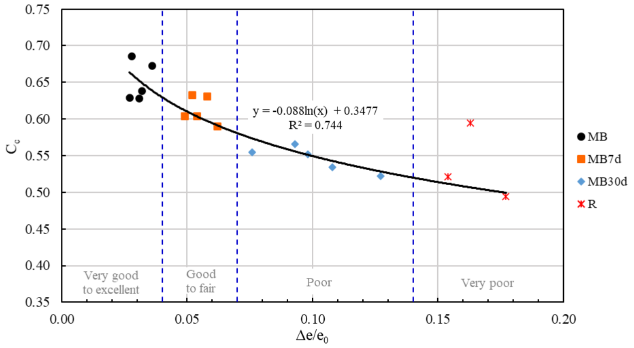

Figure 4. Sample storage influence on compression index (C_c).

On the other hand, a regression equation ($R^2 = 0.74$) was obtained between the laboratory compression index (C_c) and the quality of the sample, represented by the value of $\Delta e/e_0$ according to the criteria of Lunne et al. (Lunne, Berre, and Strandvik 1997; Lunne et al. 2006), whose expression is the following:

$$C_c = 0.3477 - 0.088\ln\left(\frac{\Delta e}{e_0}\right) \qquad (2)$$

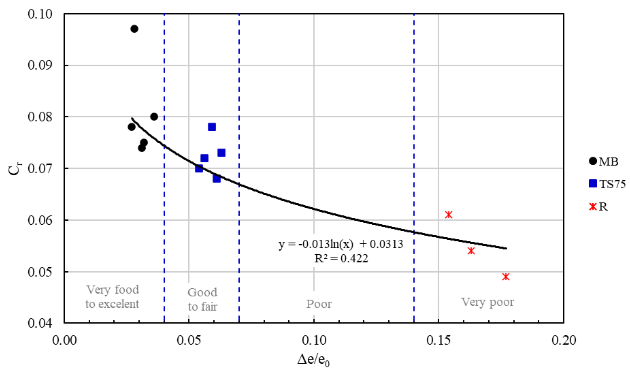

Figure 5. Sampler influence on recompression index (C_r).

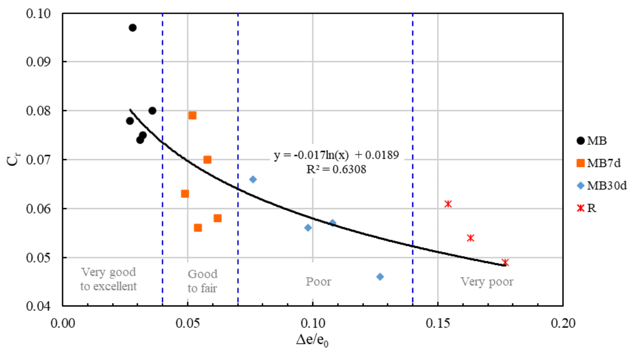

Figure 6. Sample storage influence on recompression index (C_r).

Similarly, the effect of the different sampling methods on the values of the laboratory discharge-recharge indices (C_r), presented in Fig. 5 and 6, are shown, also indicating the limits between the quality levels of samples according to the proposal of Lunne et al. (Lunne, Berre, and Strandvik 1997; Lunne et al. 2006), showing the same trend of reduction in the value of the discharge-recharge index with the decrease in the quality of the samples, obtained through the different methods considered in this research.

3.3. Shear strength response and parameters

Typical drained, obtained from direct shear tests (DS test) and undrained, obtained from unconsolidated and undrained triaxial test (TRX test), strength results are presented below (Fig. 7). Strength laboratory tests are carried out with block samples, with very good quality samples.

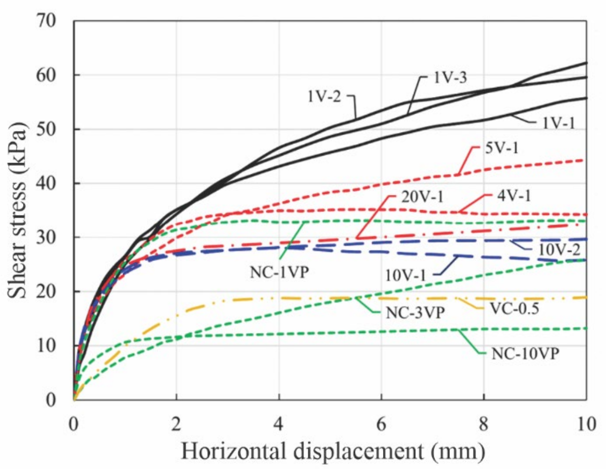

Figure 7. Typical drained lacustrine soil response in direct shear testing.

Fig. 7 shows typical soil responses against direct shear stresses in various laboratory direct shear tests, carried out according to ASTM D3080 with 81.4 kPa of vertical stress, with samples of lacustrine soft clay deposits at the inner bay of Puno city around Titicaca Lake. On the other hand, Fig. 8 shows a typical undrained response against triaxial compression stresses in various laboratory triaxial tests. All of the tests were carried out with block samples of good to very good quality, according to the previous assessments.

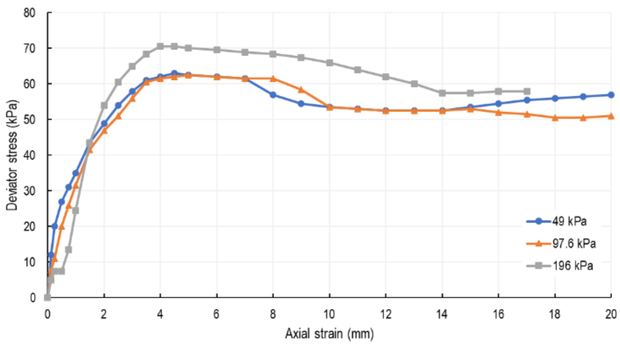

Figure 8. Typical undrained soil response in triaxial compression testing.

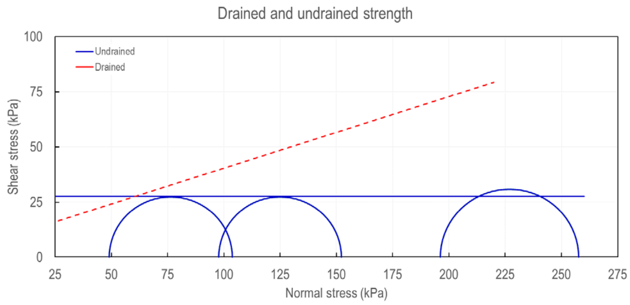

Figure 9. Typical drained (DS test) and undrained (TRX test) strength of lacustrine deposit samples.

Typical values of undrained strength (s_u) of lacustrine soft soils, at inner bay of Puno around Titicaca Lake, are 27.5 ± 3 kPa. On the other hand, the drained strength parameters are an effective cohesion of 7.8 ± 0.15 kPa and an effective friction angle of 18.3° ± 0.6° (see Fig. 9). These values are between typical values reported by another researcher (Look 2014; Bol and İspıroğlu 2016; Ladd and Lambe 1963).

4. Conclusions

The study presents the engineering characteristics of the lacustrine soil deposits in the inner bay of the city of Puno, around Titicaca Lake, emphasizing the quality of soil samples collected from exploration points in the research area, specifically focusing on the consolidation parameters and shear resistance characteristics of the silt and organic clay deposits. The quality assessment considers different sampling methods and storage durations for laboratory testing.

Samples from block sampling (MB) generally show excellent quality, with minimal alteration. In contrast, Shelby tube samples (TS75) have slightly reduced quality due to their shape and sampling method. Remolded samples are of very poor quality. Samples stored for about 7 days (MB7d) maintain good to acceptable quality, while those stored for 30 days (MB30d) degrade in quality.

Compression indices (C_c) decrease as sample quality worsens, with a clear correlation established between C_c and sample quality ($\Delta e/e_0$). Longer storage periods or increased alteration lead to lower compression indices, as indicated by a regression equation.

Strength tests on block samples with very good quality reveal typical undrained strength of lacustrine soft soils around Lake Titicaca as 27.5 ± 3 kPa. Drained strength parameters include an effective cohesion of 7.8 ± 0.15 kPa and an effective friction angle of 18.3° ± 0.6°, consistent with prior research.

In conclusion, the study provides valuable insights into the influence of sample quality on consolidation parameters and shear strength characteristics, contributing to a better understanding of the geotechnical behaviour of the studied soils in the inner bay of Puno City around Titicaca Lake.

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