02-012 – A comparative analysis of the results of the mechanical properties of clay soils determined with SPTregarding direct-hear test – Un análisis comparativo de los resultados de las propiedades mecánicas de suelos arcillosos determinados con SPTrespecto a corte directo

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Geotechnical studies are essential to evaluate the quality of the land in civil construction projects. The omission of these studies or their replacement by simpler or cheaper tests can introduce a high degree of uncertainty in the design and in the capacity of the soil to support structures. Frequently, the design of buildings and other works is based on data from the SPT (Standard Penetration Test) test. However, the complexity of certain soils, such as clays, demands more specific and rigorous methods to obtain precise geotechnical information. Among these tests, the triaxial test and the direct shear test stand out as key alternatives.

In the urban area and the expansion zones of Tarija, clay soils predominate, including expansive or collapsible clays in some areas. This study compares the results of SPT and direct shear tests carried out at the same analysis points, highlighting how these differences can influence the quality of the works and their costs. The findings of this project provide valuable scientific information to define the most appropriate type of geotechnical prospecting and investigation in the structural design phase, thus promoting safety and efficiency in future constructions

Keywords: *Geotechnical properties; SPT; Direct-shear test; Clay soils*

Los estudios geotécnicos son esenciales para evaluar la calidad del terreno en proyectos de construcción civil. La omisión de estos estudios o su sustitución por ensayos más simples o económicos puede introducir un alto grado de incertidumbre en el diseño y en la capacidad del suelo para soportar estructuras. Con frecuencia, el diseño de edificaciones y otras obras se basan en datos del ensayo SPT (Standard Penetration Test). Sin embargo, la complejidad de ciertos suelos, como las arcillas, demanda métodos más específicos y rigurosos para obtener información geotécnica precisa. Entre estos ensayos destacan el ensayo triaxial y el ensayo de corte directo como alternativas clave.

En el casco urbano y las zonas de expansión de Tarija predominan los suelos arcillosos, incluyendo arcillas expansivas o colapsables en algunas áreas. Este estudio compara los resultados de ensayos SPT y de corte directo realizados en los mismos puntos de análisis, resaltando cómo estas diferencias pueden influir en la calidad de las obras y en sus costos. Los hallazgos de este proyecto aportan información científica valiosa para definir el tipo de prospección e investigación geotécnica más adecuada en la fase de diseño estructural, promoviendo así la seguridad y eficiencia en futuras construcciones.

Palabras claves: *Propiedades geotécnicas; SPT; Corte directo; Suelos arcillosos*

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1. Introduction

One of the critical design parameters for evaluating soil structure is the friction angle, derived from the Mohr's Circle failure criterion. The friction angle is a laboratory-estimated engineering parameter used to quantify soil shear strength in geotechnical applications (Skuodis et al., 2016).

In foundation test borings, retrieving soil samples with a 2-inch OD split-sample bucket driven with a 140-pound weight dropped 30 inches has been used for over 30 years. Recording the number of blows required to drive the bucket 12 inches has been termed the Standard Penetration Test (SPT). It provides an approximation of in-situ soil densities. It adds little to the cost of drilling operations but adds considerably to the evaluation of results when performed correctly and its limitations are recognized. However, using the SPT test requires an understanding of the modifications that have been introduced, the variables inherent to the test, and the factors affecting the results (Fletcher, G. 2021).

The importance of in situ testing in geotechnical engineering, such as SPT, is increasing, as most laboratory tests are laborious, time-consuming, and expensive (Nair, R. and Wood, D., 1987). However, the results are sometimes inaccurate due to poor laboratory conditions (Venkatasubramanian, C. & Dhinakaran, G., 2011).

The standard penetration test is widely used due to its simplicity and low cost. The test is performed to measure soil strength and predict some properties, such as Atterberg limits and shear strength parameters. (Yusof, N. and Zabidi, H. 2018).

Sermalai, S. et al. (2021) indicate that a standard penetration test (SPT) is one of the most performed in situ tests for soil investigation projects. SPT test data are widely used for the estimation of soil design parameters required for geotechnical analysis. However, the quality and reliability of SPT results are very often unsatisfactory due to various reasons such as variable hammer drop height, inclination of drive rods, improper hammer release resulting in partial energy transfer.

Mahmoud, M. (2013) points out that determining the actual geotechnical values of soils requires special, standardized techniques and procedures, which are often costly. Therefore, the prediction of some properties, such as shear strength parameters like cohesion and angle of internal friction (C & Ø), among others, is difficult. He also indicates that tests (SPT) provide an approximate measure of soil strength.

The Standard Penetration Test (SPT) is widely used to estimate in situ soil properties. However, the determination of the angle of internal friction or other soil parameters is usually done by SPT - $N_{(60)}$ correlations proposed by different researchers (Gibbs and Holtz (1957), Meyerhof (1956), Yoshida & Ikemi (1988) and Kibria & Masood (1998).

The shear strength of soils is essential for any type of stability analysis. Therefore, it is important to determine reliable values. For this purpose, triaxial tests are the most appropriate. However, direct shear tests are primarily performed to determine the shear strength of soils as a more economical alternative to triaxial tests (Thermann, K. et al. 2006).

The direct shear test is very popular for laboratory soil analysis due to its simplicity. The conventional direct shear test apparatus consists of an upper and lower shear box, and the sample is sheared along the plane between them by pushing the lower shear box horizontally with a normal (vertical) load applied. The shear force is measured with a support ring or load cell fixed to the upper shear box (Liu et al., 2005, Taylor, DW. 1948 & Skempton, AW. & Bishop, AW., 1950).

On the other hand, Nam, S. et al. (2011) points out that determining the shear strength of unsaturated soils is generally more complicated, time-consuming, and expensive compared to determining the shear strength of saturated soils. They also point out that the direct shear test is a rapid and practical method for determining the shear strength of unsaturated soils.

Llori et al. (2017), Feligha et al. (2016), Zhu et al. (2011) and Peng et al. (2010), say that soil shear strength is fundamental in the design of various structures in direct contact with the ground and, although designers use empirical values for their designs, it is essential to obtain more accurate values for soil shear strength with solid materials. They further point out that the direct shear test represents a suitable way to analyze the interface between soil and concrete foundation and is more suitable for studying displacement and deformation properties.

Research conducted by Fernández, W. (2015); Rodríguez, I. & Soto, C. (2016); Mamani, R. (2019) and Castrejón, A. (2019) shows that the results of the internal friction angle or cohesion obtained with SPT and Direct Shear tests can vary between 2% and 20% between both tests.

Publications by Shibuya et al., (1997), Stoewahse, C. (2001), Goldscheider, 2003 & Lindemann, 2003, have shown that various aspects, such as the top box assembly and the associated wall friction effects, influence the results of direct shear tests.

Shibuya et al., 1997; Lindemann, 2003, recommend lubrication of the soil-steel interface as an effective method to reduce errors in the results. Jewell, R. A., & Wroth, C. P. (1987), on the other hand, demonstrate that the direct shear friction angle derived from conventional analysis underestimates the frictional shear strength of sand by approximately 20%.

In Tarija, it is very common to design buildings using the SPT test and its correlations to obtain design parameters, leaving doubt as to whether design parameters such as the angle of internal friction and cohesion are representative of the soil. Considering that the urban area is dominated by plastic soils, often with the presence of expansive and collapsible clays, this work presents the results of geotechnical tests conducted at various locations in the city of Tarija and compares the parameters found using the SPT and the direct shear test. A case study is also presented illustrating the impact of these differences on the design of isolated shallow foundations.

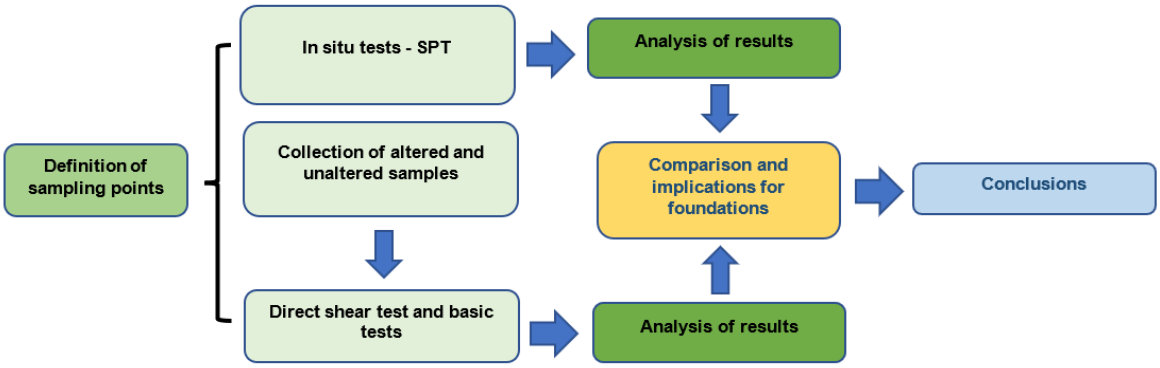
1.1. Goals

This paper presents the results of laboratory tests on soil samples from the urban area of Tarija city using the SPT test and the Direct Shear test. It also analyzes the differences between the two tests and their implications for the design of shallow foundations.

2. Materials and methods

This section describes the materials and methods used in the study's experimental process. Figure 1 describes the development phases of the work.

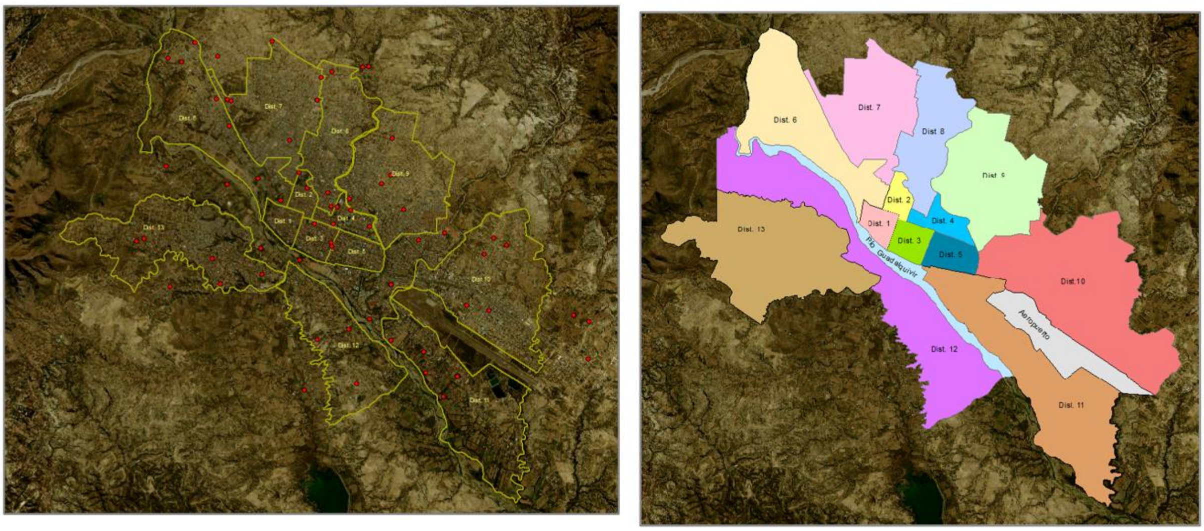
Figure 1: Project development scheme.



2.1. Study area

The study was carried out in the city center, covering 13 districts of the Municipality of Tarija. The geotechnical results of 60 sampling points are presented, and the results of the SPT analysis versus the ten-point direct cut analysis are analyzed. The collection points were distributed among the different districts and urban expansion areas. Figures 2a and 2b show the location of the analysis points and the zoning by district of the city.

Figure 2: Location of the analysis points.



(2a) Sampling points (2b) city districts

Source: Tolaba, S. (2019)

2.2. Materials

The material used for laboratory tests and the equipment necessary to carry out the different geotechnical tests are described.

2.2.1. Soils

The predominant soils in the city of Tarija are fine-grained soils with significant plasticity characteristics. Fine-grained soils are analyzed due to their impact on foundation behavior.

2.2.2. Laboratory equipment

The equipment and supplies used for the characterization and determination of soil resistance parameters are described and detailed.

a) **For basic parameters:** The following equipment was used to determine the basic parameters:
   - Temperature-controlled oven for determining moisture content.
   - ELE brand H-152 sieve and hydrometer set for soil classification.
   - ELE brand Casagrande scoop for determining the Plastic Limit.

b) **Resistance parameters:** The following equipment was used for the mechanical analysis of the soil:
   - ELE brand oedometer for consolidation testing.
   - SPT equipment.
   - MATEST brand “direct shear” equipment for determining the angle of internal friction and soil cohesion.

2.3. Methods

The laboratory methods and techniques used to determine the different soil parameters are described.

2.3.1. Technical prospecting

In situ tests such as the SPT, soil sampling, and geotechnical prospecting at each sampling point were conducted by excavating pits up to 3 m deep, with soil analysis performed every meter.

For the test’s, disturbed samples were extracted, allowing characterization, plasticity, and physical properties such as moisture content and density to be determined.

For the consolidation and direct shear tests, undisturbed samples were performed.

All tests were performed in compliance with the international standard "The American Society for Testing and Materials," Series D, which corresponds to soil tests (ASTM D, 2017), and the laboratory manual by J. Bowles (1980). The tests performed and their execution standards are detailed below:

- Water-Content Determination (Bowles, J. 1993): ASTM D 2216-90 (ASTM Standards vol. 4.08).
- Liquid and Plastic Limits (Bowles, J. 1993): ASTM D 4318 (ASTM Standards vol. 4.08).
- Particle-Size Analysis – Mechanical Method (Bowles, J. 1993): ASTM D 421 and 422, (ASTM Standards vol. 4.08).
- Particle-Size Analysis – Hydrometer Method (Bowles, J. 1993): ASTM D 421 and 422, (ASTM Standards vol. 4.08).
- Specific Gravity of Soli Solids (Bowles, J. 1993): ASTM D 854, (ASTM Standards vol. 4.08).
- Classification of Soli (Bowles, J. 1993): ASTM D 2487-85, (ASTM Standards vol. 4.08).
- Direct – Shear Test (Bowles, J. 1993): ASTM D 3080-90, (ASTM Standards vol. 4.08).

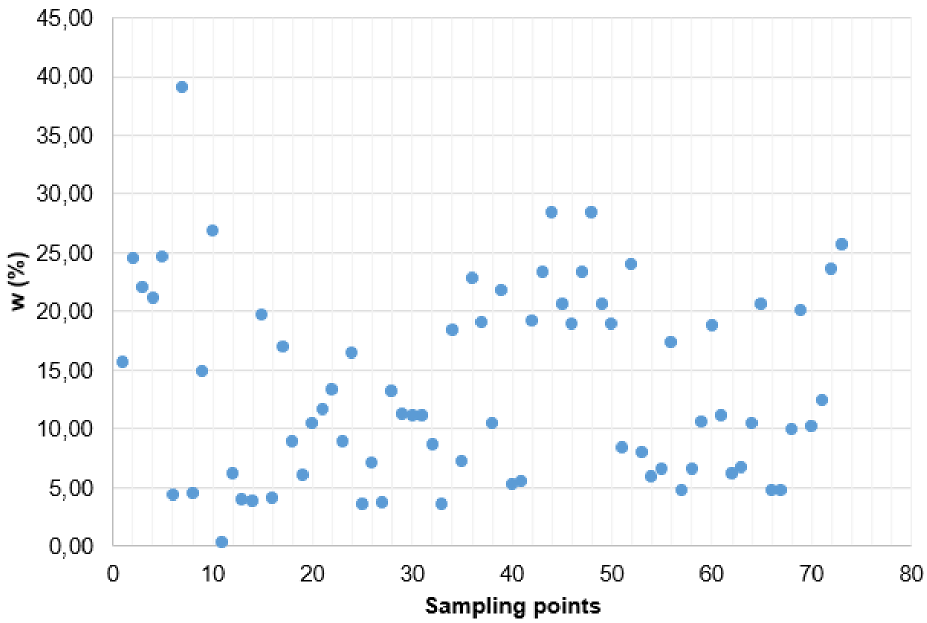
3. Results and discussion

The results of the investigation are detailed below.

3.1. Physical and mechanical properties of soils

Graphs 3, 4, 5 and 6 detail the moisture content, Liquid Limit, Plasticity Index and SPT of the 74 survey points at 3 meters of analysis.

Figure 3: Moisture content – w.



A clear disparity in soil moisture content is observed throughout the urban area. Data show that soil moisture ranges from 5% to 40%, the latter due to the proximity to a body of water.

Figure 4: Liquid Limit – LL.

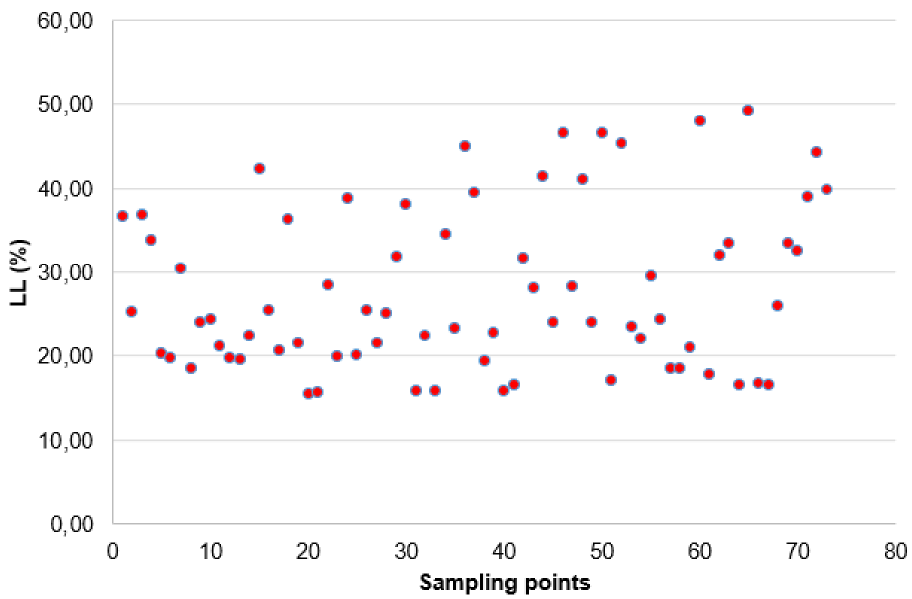
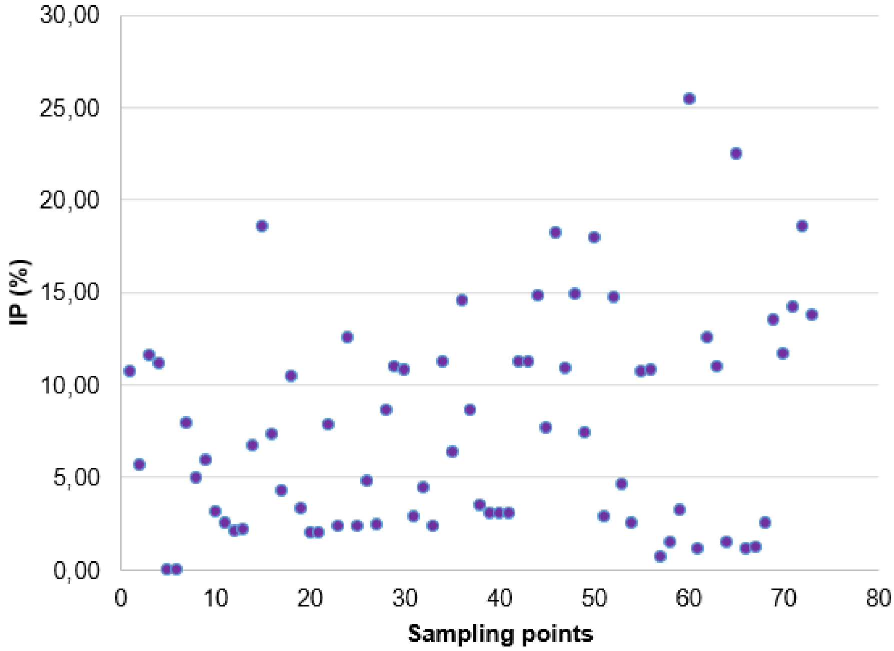
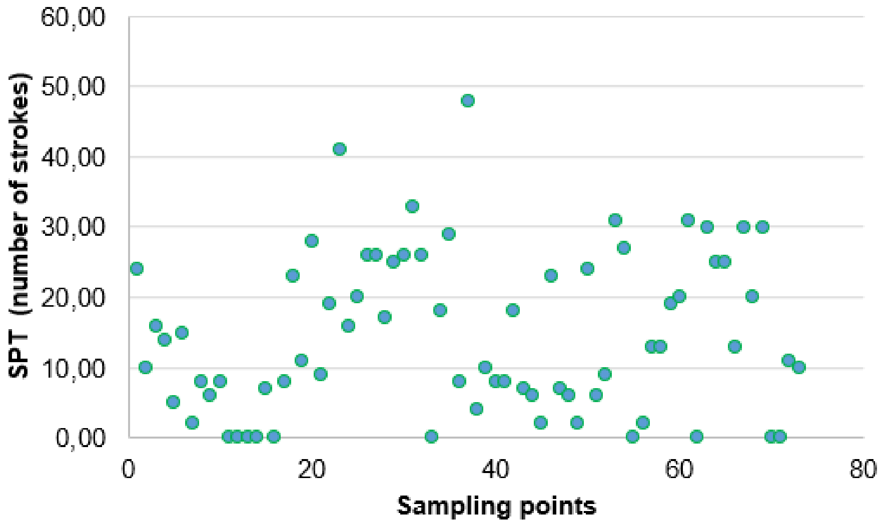


Figure 5: Plasticity Index – IP.



The Liquid Limit (LL) and the Plasticity Index (PI) are data that allow defining the plasticity of soils. The data obtained and shown in Figures 4 and 5 indicate a tendency toward soils with a significant content of fine soils. The LL of the urban area of the city of Tarija ranges from 15% (low plasticity soils) to around 50% (high plasticity soils).

Figure 6: SPT.

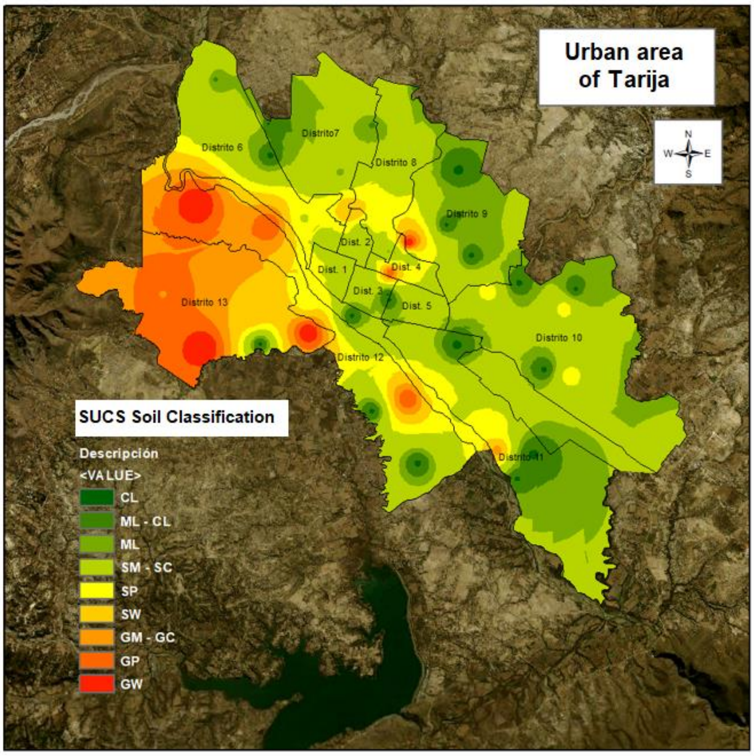


Source: Tolaba, S. (2019), Palacios and Montaño (2015), Choque and Segovia, (2016), Ticona, N. (2018), Duran, W. (2019) and Consulters Unión (2017)

SPT tests were performed at all sampling points, where a clear diversity of soil hardness can be observed.

Figure 7 illustrates a soil classification map in the city's urban area.

Figure 7: Location of the analysis points.



Source: Tolaba, S. (2019)

The map shows a clear trend of fine soils that are between CL and ML, medium clay and silts with high plasticity.

3.2. Evaluation of soil strength between SPT and direct shear

The comparative analysis of soil strength properties such as the angle of internal friction **Ø** and cohesion **C** obtained from SPT tests versus direct shear tests is performed for 10 sampling points. Figure 8 shows the location of the analysis points.

While the SPT (Number of Blows) data was obtained in situ, the Direct Shear tests were performed with undisturbed samples taken at each sampling location. Sampling points were located at a depth of 3 meters.

Table 1 shows the internal friction angles obtained with the SPT correlations and those obtained with the direct shear test.

Figure 8: Analysis points: Direct shear vs. SPT.

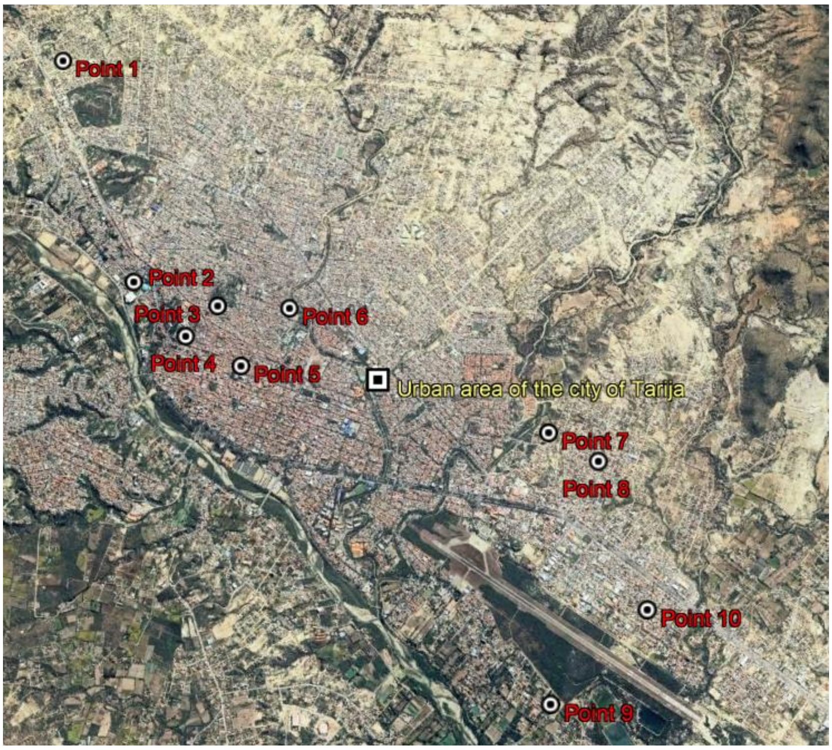


Table 1: Internal friction angle "Ø": Direct shear Vs. SPT.

Internal Friction Angle "Ø"			Ø (°)	Ø (°)
N.	**Point**	**Neighborhood**	**SPT**	**Direct Shear**
1	P4	San Mateo	35,5	34,3
2	P5	U.C.B San Pablo	31,7	30,3
3	P1	San José	30,6	27,2
4	P9	San Luis	34,0	28,8
5	P6	Hornos	35,1	27,3
6	P3	La Loma	36,3	33,2
7	P8	Aeropuerto	37,3	31,5
8	P10	Morros Blancos	35,3	33,1
9	P2	Ballivian	31,2	29,2
10	P7	Guadalquivir	32,3	29,3

Source: Duran, W. (2018)

Table 2 shows the cohesion obtained with the SPT correlations and those obtained with the direct shear test.

Table 2: Cohesion "C": Direct shear Vs. SPT.

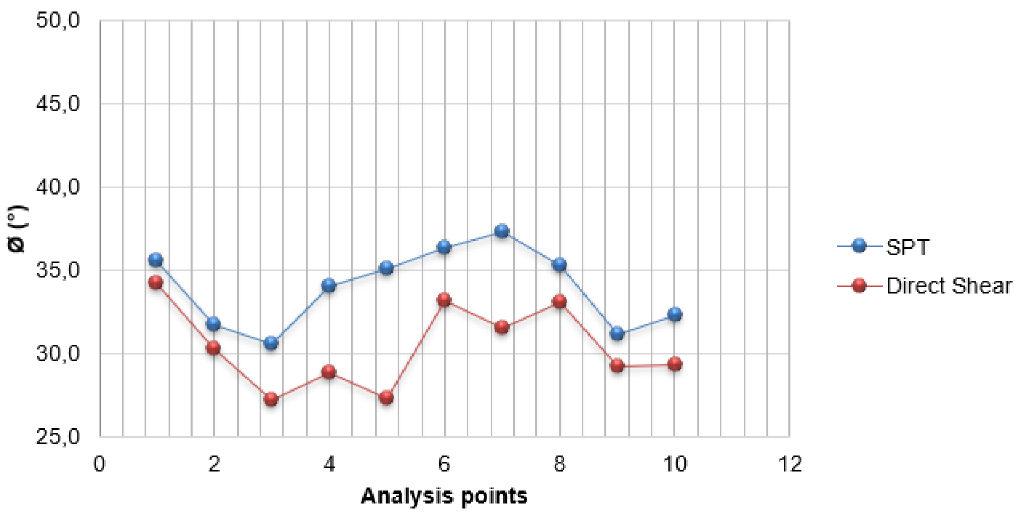
Cohesion MPa			C (Kg/cm^2)	C (Kg/cm^2)
N.	**Point**	**Neighborhood**	**SPT**	**Direct Shear**
1	P4	San Mateo	0,286	0,623
2	P5	U.C.B San Pablo	0,118	0,438

N.	Point	Cohesion MPa Neighborhood	C (Kg/cm²) SPT	C (Kg/cm²) Direct Shear
3	P1	San José	0,105	0,420
4	P9	San Luis	0,141	0,358
5	P6	Hornos	0,152	0,878
6	P3	La Loma	0,294	0,805
7	P8	Aeropuerto	0,344	0,925
8	P10	Morros Blancos	0,311	0,716
9	P2	Ballivian	0,105	0,480
10	P7	Guadalquivir	0,048	0,326

Source: Duran, W. (2018)

Figure 9 shows the behavior of the internal friction angle and the differences between those obtained with the SPT test vs. Direct Shear.

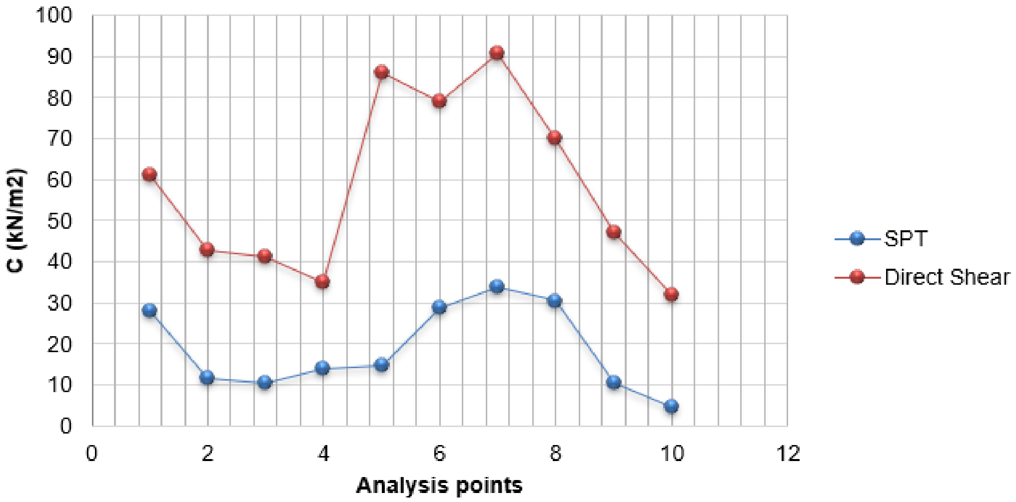
Figure 9: Behavior of "Ø": Direct Shear vs. SPT.



Source: Duran, W. (2018)

Figure 10 shows the behavior of soil cohesion and the differences between those obtained with the SPT test vs. Direct Shear.

Figure 10: Cohesion: Direct Shear vs. SPT.



The differences between the results obtained with the SPT test and the direct shear test are clear. On the one hand, internal friction, represented by the angle of internal friction of the soils obtained through correlations with the SPT's number of blows, is 14% higher than that obtained with the direct shear test. This undoubtedly has a significant impact on the design of structures, especially foundations.

Although the cohesion data is low for the soils analyzed, there are still significant differences between the two results.

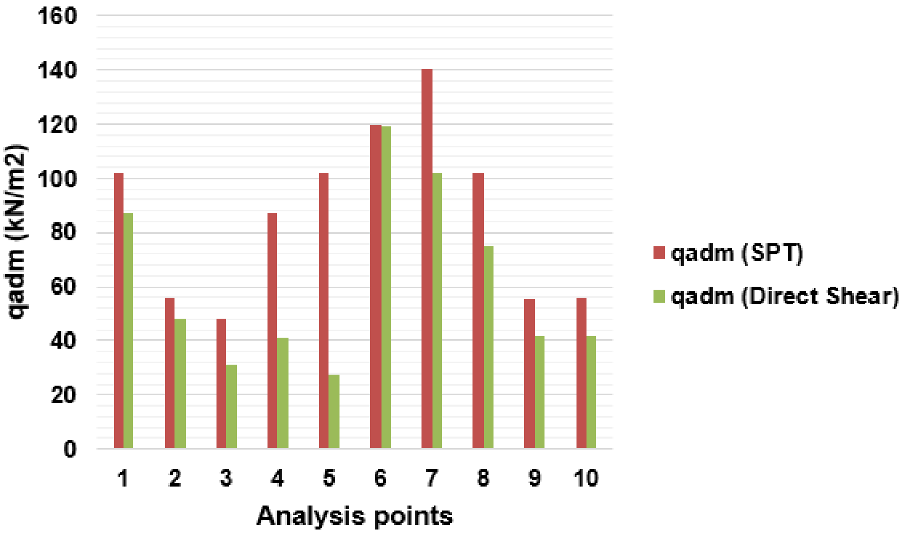
3.3. Implication in the design of works

The results show differences in the angle of internal friction obtained between the two methods. This, when applied to foundation design, will result in significant differences in sizing; that is, foundations designed solely with SPT correlations will have smaller dimensions than those designed with direct shear tests. This has a direct impact on foundation economics, its behavior, and soil-foundation interaction.

The differences in load parameters obtained with different geotechnical methods have not only economic but also functional implications. Footing sized with greater capacity tend to have smaller cross-sections, which means that, in the presence of plastic soils, they may exhibit adverse structural behavior.

Figure 11 shows the difference in the ultimate allowable load capacity “qadm” calculated with the angle of internal friction obtained with SPT vs. Direct Shear. The load capacity of foundations was calculated using the general Meyerhoff formula, indicated by Braja. D. (2006).

Figure 11: Allowable Soil Bearing Capacity (qadm) SPT vs. Direct Shear.



It is observed that the differences in soil load-bearing capacity are 25% on average, between those obtained using data with SPT compared to direct shear.

3.4. Discussion

It is observed that the angle of internal friction obtained with the direct shear test is lower than that obtained with the SPT test, this agrees with what was expressed by Jewell, R. A. and Wroth (1987) who indicated that the angle of internal friction obtained with the direct shear test is underestimated compared to that obtained with SPT.

The difference in loading parameters such as the angle of internal friction has an impact on the ultimate load-bearing capacity of foundations. These findings agree with those indicated by Niels, T. (2018) and Duran, W. (2019) who indicate that foundations designed with an angle of internal friction obtained by SPT against a direct shear force generate differences in the ultimate load-bearing capacity.

The results for the angle of internal friction obtained through correlations with the number of blows of the SPT differ by 14% compared to the results obtained with the direct shear test. Similarly, cohesion varies by approximately 20% between the two methods. These results are consistent with research conducted by Fernández, W. (2015); Rodríguez, I. and Soto, C. (2016); Mamani, R. (2019); and Castrejón, A. (2019), which show that the results for the angle of internal friction or cohesion obtained with the SPT, and direct shear tests can vary between 2% and 20% between the two tests.

This is also in agreement with Jewell, R. A. and Wroth, C. P. (1987), who showed that the angle of internal friction derived from conventional SPT analysis underestimates the friction shear strength by approximately 20% when performed using more accurate methods such as direct shear.

4. Conclusions

The geotechnical zoning carried out from the study of different soil parameters in the urban area of the city of Tarija shows a heterogeneity of soil types; however, it is observed that there is a predominance of CL plastic soils.

The prevailing humidity in the study areas ranges from 5% in dry areas to 40% in areas near rivers and streams.

The Liquid Limit (LL) ranges from 15% to 50%, and the plasticity index is between 3% and 25%.

SPT tests show that N is between 5 and 40 blows, demonstrating the range of soil strengths that the soil in this study area can have.

The SPT tests performed at the 10 control points in Table 1 indicate that the average internal friction angle in these areas is around 34°, while the internal friction angles obtained from the direct shear test average 31°. This corroborates what was indicated by Jewell, R. A., & Wroth, where it was shown that the internal friction angle obtained with direct shear is underestimated by 10% compared to the SPT.

Cohesion is a variable, with significant differences observed across the 10 analysis zones.

Foundation design varies significantly when using only SPT data. The differences between SPT and Direct Shear show that the allowable capacity of foundations can vary by up to 29%.

4.1. Future work and lines of research

The city of Tarija has several areas of real estate expansion and diverse geotechnical zoning in terms of soil classification. There are highly plastic soils, as well as low-plasticity soils and soils of mixed composition. This has allowed for future research to be planned to measure soil strength parameters for different soils and different areas.

Future lines of research include:

- Geotechnical zoning based on strength parameters between SPT and Direct Shear
- Zoning at different depths

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Use of generative artificial intelligence

Generative artificial intelligence was not used in the preparation of this work.

Communication aligned with the Sustainable Development Goals