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02-013 – The determination of geotechnical properties in soils contaminated with wastewater in the municipality of Tarija, Bolivia – La determinación de las propiedades geotécnicas en suelos contaminados con aguas residuales en el municipio de Tarija, Bolivia

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The stability and durability of civil works depend largely on the quality, capacity and resistance of the soils. The physical and mechanical properties of soils are essential to evaluate their bearing capacity and deformations under applied loads. However, these properties can be altered due to anthropogenic activities, which affects their geotechnical behavior and, therefore, the safety of the structures built on them.

Accelerated growth and poor urban planning not only generate environmental pollution and health risks, but also alter natural resources. Among the most affected are soils, whose physical and mechanical properties can deteriorate due to the discharge of wastewater without adequate treatment. In Tarija, cases have been identified in which wastewater is discharged directly onto the ground, generating uncertainty regarding its impact on the geotechnical characteristics and quality of constructions. Faced with this problem, the Bolivian Catholic University has carried out research to analyze the physical and mechanical properties of soils contaminated with wastewater. This work provides crucial information for decision-making, especially in cases where contamination could compromise land intended for civil works

Keywords: *Domestic wastewater; Industrial wastewater; Geotechnical properties, Contaminated soils*

La estabilidad y durabilidad de las obras civiles dependen en gran medida de la calidad, capacidad y resistencia de los suelos. Las propiedades físicas y mecánicas de los suelos son fundamentales para evaluar su capacidad portante y las deformaciones bajo cargas aplicadas. Sin embargo, estas propiedades pueden alterarse debido a actividades antropogénicas, lo que afecta su comportamiento geotécnico y, por ende, la seguridad de las estructuras construidas sobre ellos. El crecimiento acelerado y la escasa planificación urbana no solo genera contaminación ambiental y riesgos para la salud, sino que también alteran los recursos naturales. Entre los más afectados están los suelos, cuyas propiedades físicas y mecánicas pueden deteriorarse por el vertido de aguas residuales sin tratamiento adecuado.

En Tarija, se han identificado casos en los que aguas residuales son vertidas directamente sobre el suelo, generando incertidumbre respecto a su impacto en las características geotécnicas y la calidad de las construcciones. Frente a esta problemática, la Universidad Católica Boliviana ha realizado una investigación para analizar las propiedades físicas y mecánicas de los suelos contaminados con aguas residuales. Este trabajo aporta información crucial para la toma de decisiones, especialmente en casos donde la contaminación podría comprometer terrenos destinados a obras civiles.

Palabras claves: *Aguas residuales domésticas; Aguas residuales industriales; Propiedades geotécnicas, Suelos contaminados*

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1. Introduction

Understanding and predicting the engineering properties of clayey soils is of vital importance in geotechnical engineering practice. Soil contamination is an issue that must be considered during all construction operations, both to prevent new contamination and to control or clean up existing contamination (Cyrus et al., 2010).

Villena et al. (2019) describe how the geotechnical properties of a soil are affected when the interstitial phase of its structure is contaminated by agents other than water.

Ahmed et al. (2007) establish that any change in the geotechnical properties of the soil or in the behavior of its strata can lead to a loss of bearing capacity and a total or differential increase in settlements, which can lead to possible functional or structural failures.

Several researchers point out that the mechanical properties of soils under the effect of contaminants have important variations that directly affect the foundation system that rests on them, (Al-Adili et al. 2017), (Mahdi & Zaineb, 2017), (Elisha, 2012), (Nazir, 2011), (Ahmed et al. 2007), (Keramatikerman et al. 2017), (Oluremi et al. 2017), (Elahe et al. 2013), (Khodary et al. 2018) and (John et al. 2009).

For example, Rahman et al. (2010), Fine et al. (1997) and Izza et al. (2018) point out that soil pollution causes considerable damage to the environment, affecting not only the quality of the soil, but also its physical properties, and that pollution depends on the chemical composition of the pollutant and the properties of the soil.

In another case, Elisha, A. (2018), in his work on the effect of oil contamination on the geotechnical properties of soft clayey soils, determines that contamination causes an increase in the consistency limits, while porosity and swelling pressure decrease with increasing absorption time and contaminant content, in the case of shear strength this parameter fluctuates.

Nazir (2011) and Mahdi and Zaineb (2017) in their investigations on the effect of oil on the geotechnical properties of clays show that soil strength is significantly reduced in uncontaminated samples. It is noteworthy, for example, that in Al-Jadriah in Baghdad/Iraq, the contaminant has a significant impact on some soil properties and only minor effects on others.

The study of (Meegoda and Ratnaweera, 1994) to investigate the factors that control the compressibility index of contaminated soils, indicates that the compressibility of a soil depends on mechanical and physicochemical factors and that chemical contaminants in the soil change the properties of porosity and viscosity, influencing the compressibility of soils.

According to Khamehchiyan et al. 2007, the effect of contaminants in clay and sandy soils induces a reduction in permeability, however, the effect of contamination on shear strength parameters is not uniform and depends on the soil type but leads to the decrease of maximum shear force in all studied samples.

The process of treating and distributing wastewater in cities has become a problem. Yee-Batista (2013) points out that 70% of wastewater in Latin America is untreated. The water is extracted, used, and returned to rivers completely contaminated, and much of it is dumped directly onto the ground.

Karkush & Abdul Kareem (2015) studied the geotechnical properties of clayey soils contaminated with different percentages of wastewater. The results of the study showed a variation in the Atterberg limits, a decrease in the coefficient of consolidation, and shear strength parameters.

Karkush and Al-Taher (2017) demonstrated that residual water in soil causes an increase in natural moisture content, specific weight, Atterberg limits, maximum dry unit weight, and coefficient of consolidation. In addition, it decreases specific gravity, optimum moisture content, initial void ratio, swelling ratio, permeability coefficient, and cohesion.

El-Kasaby et al. (2023) demonstrate that soil contamination by wastewater causes a decrease in maximum dry density and Atterberg limits and increases optimum moisture content (OMC) and cohesion.

Research shows that domestic wastewater from residential buildings in Tahta city, Egypt that is in contact with soil samples at the depth of the buildings' foundations has significant adverse effects of the contaminated soil on the mineralogical, chemical and physical properties (EASA, A. and Hanamura, T., 2009).

Alo et al. (2021) described the effects of soil contamination with slaughterhouse wastewater at varying ratios of 5, 10, and 20% of the dry weight of lateritic soils. Test results showed a corresponding increase in the liquid limit from 43 to 70% and, consequently, an increase in the plasticity index from 18.27 to 37%.

The addition of the contaminant reduced the maximum dry density (MDD) from 1905 to 1420 kg/m3, while the California bearing ratio (CBR) decreased from 23.42% to 6.14%. However, cohesion and permeability index (k) improved with increasing contaminant dosage. In conclusion, slaughterhouse wastewater negatively affects the geotechnical properties of the soil Alo et al. (2021).

Soil contamination by wastewater generated by the lack of collection systems and/or environmental education in different urban areas of the Municipality of Tarija, Bolivia, has become a recurring problem that not only affects the environment but also the physical and mechanical properties of soils.

This paper aims to study and present the results of an experimental investigation conducted on a series of geotechnical tests on clay samples artificially contaminated with wastewater from oxidation ponds in the municipality of Tarija.

It also analyzes the effect on their geotechnical properties, such as relative density, Atterberg limits, optimum moisture content, maximum dry density, compressibility index, and angle of internal friction, as well as their impact on the structural stability of foundation systems resting on these types of soils.

1.1. Goals

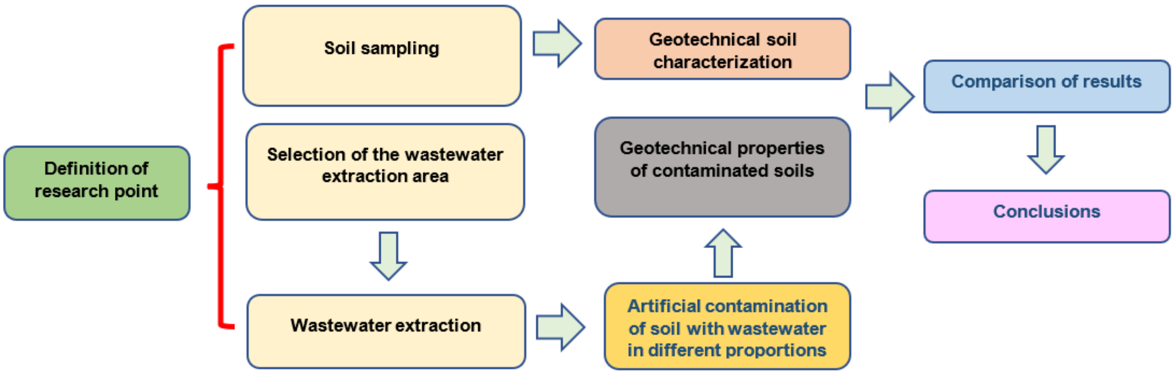
This paper presents the experimental results of a research study on the effect of wastewater on the geotechnical characteristics of fine-grained soils in the urban area of Tarija.

The study includes laboratory tests on soils artificially contaminated with wastewater in different percentages and their comparison with results obtained from an uncontaminated soil sample.

2. Materials and methods

This section describes the methodology used in the process and experimental work. Figure 1 outlines the development phases of the work.

Figure 1: Project development scheme.



2.1. Study area

The research was conducted in the Torrecillas area of the municipality of Tarija, near the Cabeza de Toro stream. This area is one of the most contaminated due to its direct exposure to wastewater discharges from the municipal slaughterhouse and nearby tanneries. Figure 2 shows the location of the soil extraction area and Figure 3 illustrates the water quality of the "Cabeza de Toro" stream.

Figure 2: Location of the study area.

Figure 3: Contaminated water - Cabeza de Toro stream.

Source: Galarza, V. & Herrera, D. (2018)

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. Soil and wastewater

The soil was extracted from the Torrecillas area, near the Cabeza de Toro ravine (see Figure 2).

The contaminated (waste) water was extracted from the Cabeza de Toro river, Figure 3.

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
   - ELE brand standard and modified PROCTOR compaction equipment.

2.3. Methodology

For the experimental process the following methodological process was carried out:

1st. Exploration and Sampling Process: Soil samples were obtained from the Narciso Campero neighborhood, specifically from the Torrecillas area (Cabeza de Toro ravine), using a 3 m excavation.

2nd. Wastewater Sampling: Wastewater samples were extracted from the "Cabeza de Toro" ravine near the soil sampling point.

3rd. Sample Preparation: Soil and wastewater were mixed in proportions of 10%, 20%, and 30%, thus generating artificial soil contamination for geotechnical testing.

4th. Laboratory Tests: Uncontaminated and Contaminated Samples: Various laboratory tests were performed to subsequently generate a comparative analysis of data from natural (uncontaminated) and contaminated soil.

5th. Analysis and interpretation of results: The data obtained is used to analyze the results and the impact of contamination on the structures.

2.3.1. Geotechnical tests

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

For the consolidation and direct shear tests, reshaped samples were extracted from previously compacted soil.

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 performance 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).
- Moisture-Unit Weight Relationship (Compactation Test) (Bowles, J. 1993): ASTM D 698-78 and D 1557-78, (ASTM Standards vol. 4.08).

3. Results and discussion

The results of the investigation are detailed below.

3.1. Physical properties

The results obtained from the different physical properties of the soil are detailed.

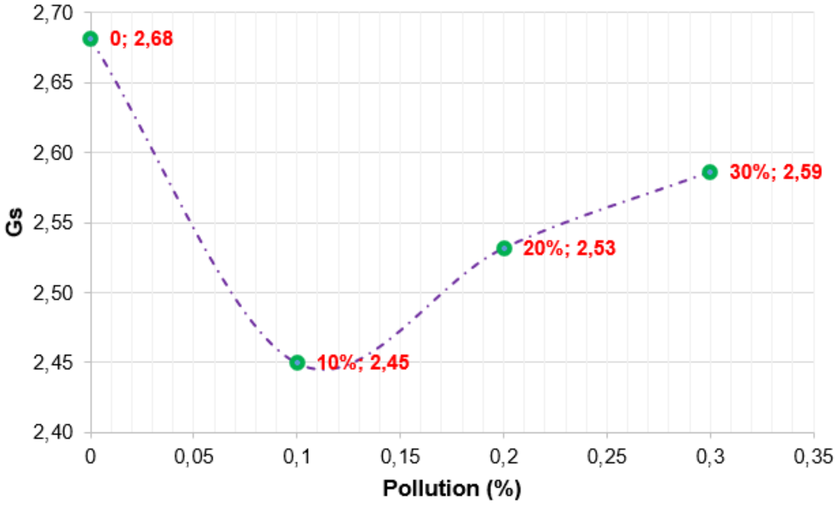
a) Soil characterization: The soil characterization corresponds to a clayey, silty soil with sand and gravel contents CM-GS.

b) Moisture content: The soil in its natural state contains 6.23% moisture, which shows soil in dry conditions.

c) Specific Gravity:

Figure 4 shows the variation in specific gravity of the soil in its natural state and when contaminated with wastewater.

Figure 4: Variation in specific gravity.



It is observed that the specific gravity has a decrease close to 6% when the soil is subjected to a contamination process, although the tendency is increasing in each percentage of contamination, but when the natural soil (without contamination) is compared with the contaminated soils, a considerable decrease is generated.

c) Consistency Limits

Figures 5, 6 and 7 illustrate the results of the Liquid Limit (LL), Plastic Limit (LP) and the Plasticity index of the soil in its natural state and with the 3 levels of contamination.

Figure 5: Liquid Limit (LL) variation.

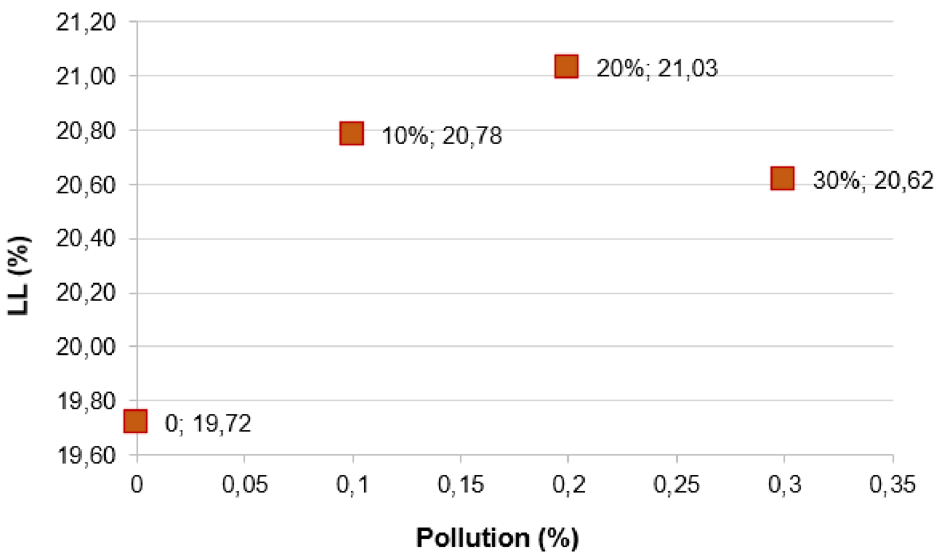
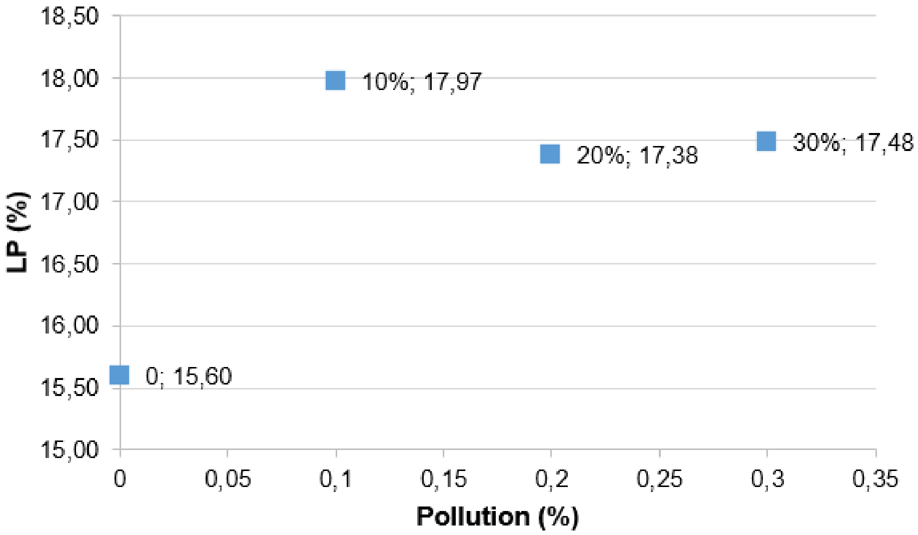


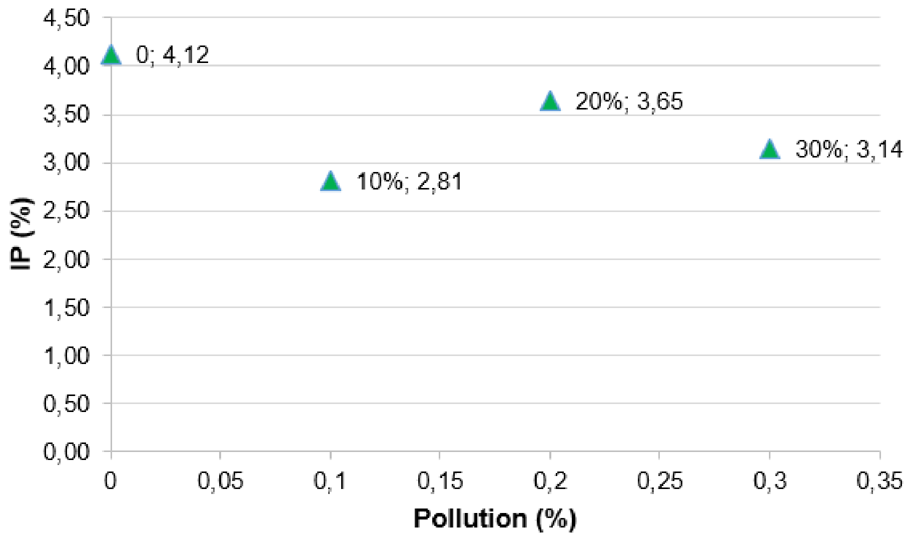
Figure 4 shows a clear variation in LL when the soil is contaminated with wastewater, the variation is in the order of 6% with respect to natural soil.

Figure 6: Plastic Limit (LP) variation.



Similarly, in Figure 6, a variation of 11% of the Plastic Limit of natural soil is observed with respect to soil contamination processes, while the Plasticity Index shows a reduction in Figure 7.

Figure 7: Plasticity Index (IP) variation.



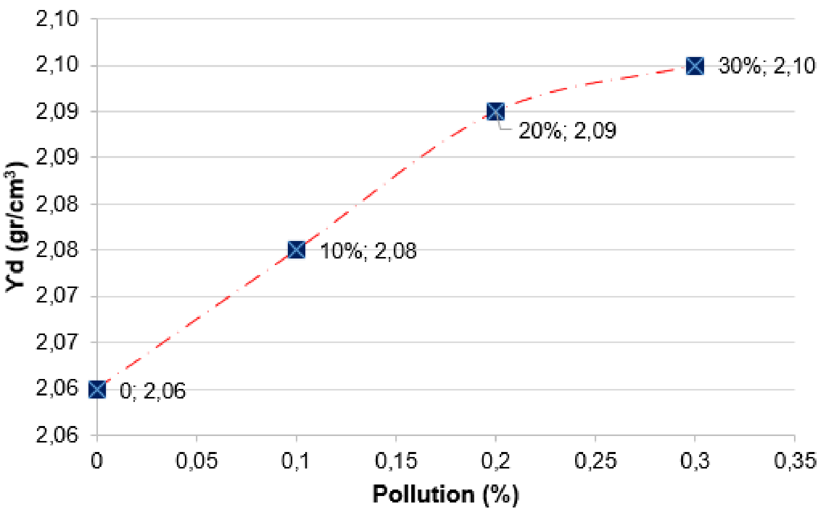
3.2. Mechanical properties

The results of the following mechanical properties investigated are detailed.

a) Proctor T-180 - compaction test.

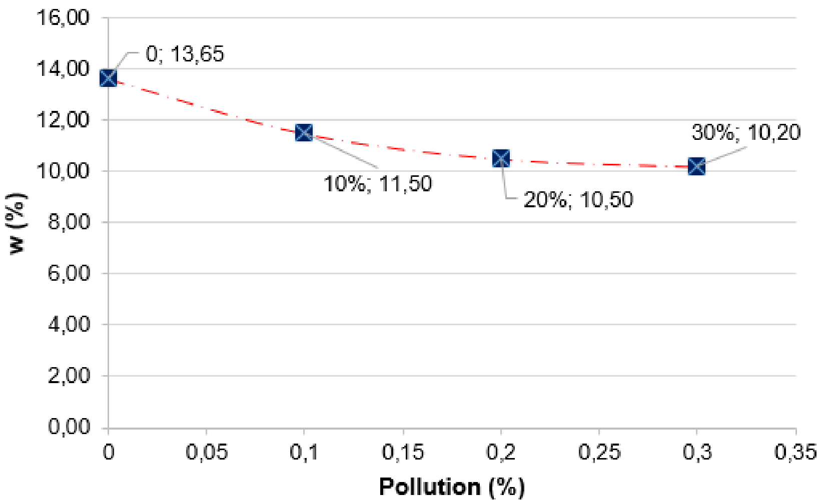
The following figures show the results of the Modified Proctor T-180 compaction test, Figure 8 refers to the maximum dry density and Figure 9 to the optimum moisture content.

Figure 8: Variation of maximum dry density.



It is observed that the maximum dry density achieved by the soil through a T-180 Proctor compaction process increases with increasing wastewater content, figure 8. On the other hand, the optimum moisture content decreases as the wastewater content increases (see Figure 9).

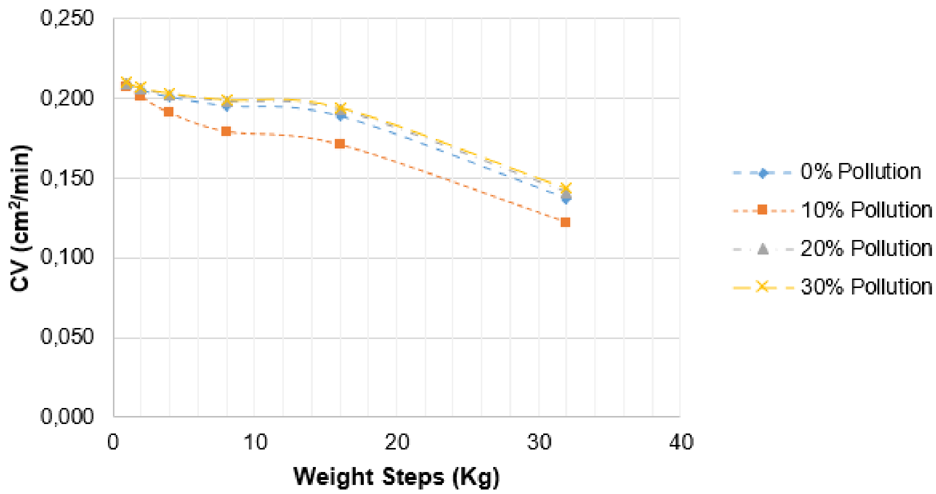
Figure 9: Variation of optimal humidity.



b) One-dimensional soil consolidation.

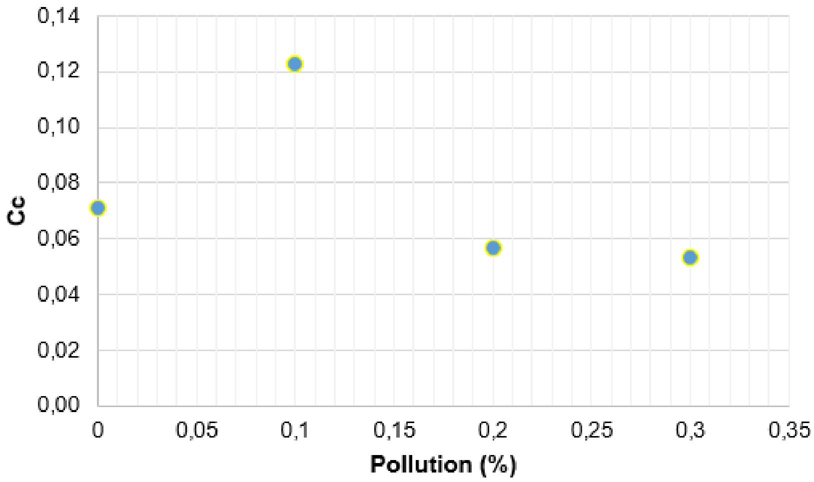
The variation in the consolidation parameters that the soil presents when it is subjected to a process of contamination by wastewater is detailed. Figure 10 details the behavior of the Consolidation Coefficient "Cv" with the different load steps, while Figure 11 illustrates the soil Compressibility index "Cc".

Figure 10: Variation of the consolidation coefficient Cv.



The increase in the Consolidation Coefficient Cv is observed with the increase in the contaminant.

Figure 11: Compressibility index "Cc".



Soil compressibility has an interesting variation, while for 10% residual water, the compressibility index "Cc" tends to improve, however, with 20% and 30% the Cc decreases.

c) Direct shear test.

Direct shear tests were carried out under the Unconsolidated-Undrained model and with three load steps, with 1, 2 and 3 Kg of axial stress, figures 12 and 13 show the results obtained for the internal friction angle Ø´ and cohesion C.

Figure 12: Behavior of the angle of internal friction "Ø´".

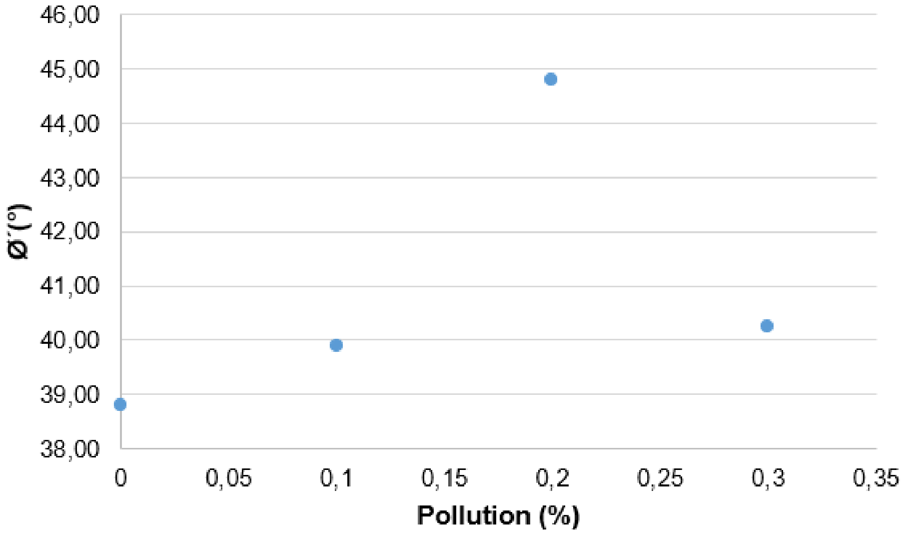
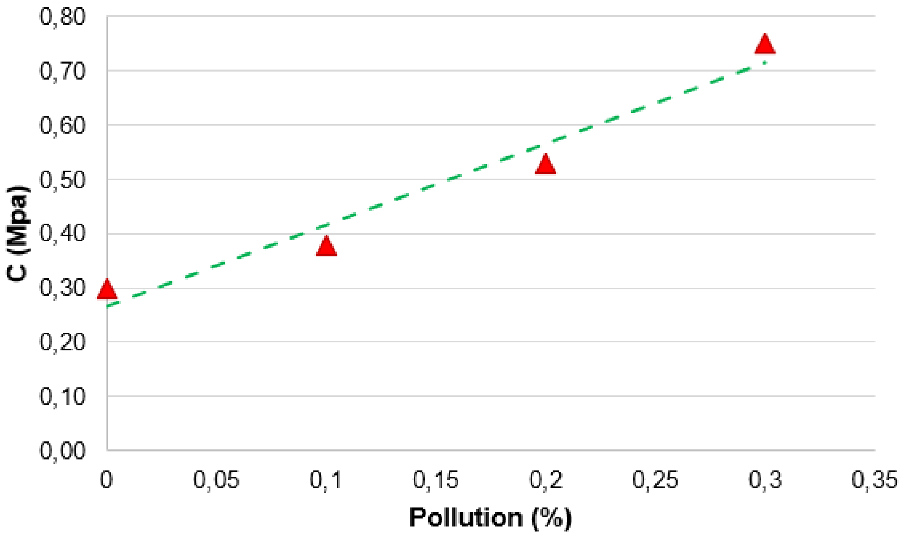


Figure 12 shows the fluctuating behavior of internal soil friction in the face of a contamination process.

Figure 13: Cohesion behavior "C´".



The cohesion behavior shown in Figure 13 is more stable with an increasing trend.

3.3. Discussion of results

The physical properties of the soil obtained from geotechnical tests show that the Specific Gravity "Gs" decreases as contamination increases, while the Liquid Limit "LL" and the Plastic Limit "LP" increase, this is in agreement with what was pointed out by Meegoda and Ratnaweera, 2014 and coincides with the research of Karkush and Abdul Kareem (2015), Karkush and Al-Taher (2017), Alo, et al. (2021) and El-Kasaby, et al. (2023).

Regarding the mechanical and strength properties of the soil, the results show that contamination produces an increase in the maximum dry density obtained from the compaction test and that the optimal humidity decreases, as indicated by Alo, et al. (2021). On the other hand, the soil consolidation coefficient "Cv" increases, while the compressibility index "Cc" fluctuates with a tendency to increase, this coincides with what was expressed by Meegoda and Ratnaweera, 2014 & Karkush and Al-Taher (2017).

The shear strength of the soil is also altered, the results show that the angle of internal friction has fluctuation with increasing tendencies, however, the cohesion shows a clear increase, coinciding with the research of Khamehchiyan et al. 2007, Karkush and Abdul Kareem (2015), Karkush and Al-Taher (2017) & El-Kasaby, et al. (2023).

4. Conclusions

It is demonstrated that wastewater has a direct impact on the physical and mechanical properties of the soil, which tend to increase considerably as the contaminant content increases.

The properties of fine-grained soils in the Torrecillas area of the city of Tarija, Bolivia, were experimentally studied, and an artificial soil contamination process was carried out using wastewater obtained from a stream in the same area.

The contamination process was carried out with wastewater mixed with natural soil in quantities of 10%, 20%, and 30% by soil weight. The following results were obtained:

1. Specific Gravity (Gs) decreases by 8% with 10% residual water content, 6% with a 20% residual water content, and 4% with a 30% residual water content.
2. Liquid Limit (LL) values increase by 6% in the presence of residual water, and the Plastic Limit (PL) increases by up to 11%. The Plasticity Index (PI) decreases by up to 5%.
3. The mechanical properties also show interesting results. Compaction tests demonstrate that the maximum dry density of the soil increases steadily by 0.2% as the residual water content increases. The natural soil has a maximum dry density of 2.06 g/cm^3; 2.08 g/cm3 for 10% contamination with residual water; 2.09 g/cm^3 for 20% and 2.10 g/cm^3 for 30%. This leads to a decrease in the optimum moisture content, from 13.65% for soils without contaminants to 10.2% for soils with 30% residual water.
4. Regarding the consolidation parameters, the behavior of the Consolidation Coefficient "Cv" is fluctuating. It is observed that when the soil has a 10% contaminant load, the Cv decreases up to 6%, however, for 20% and 30% of contaminant, this parameter increases by 1.2% and 2% respectively. The Compressibility Index “Cc” also shows a fluctuation in the results, while for 10% of contaminant, Cc increases up to 72%, for 20 and 30%, Cc decreases 20% and 25% respectively.
5. Direct shear tests show fluctuating results. The internal friction angle "Ø" tends to increase by 2.8% at 10% residual water, 15% at 20%, and 3.7% at 30% contamination. However, cohesion "C" exhibits more stable behavior, with results tending to increase as the contamination load increases.

4.1. Limitations and future work

Since the main limitation is that research is carried out in a single risk zone, it is recommended that analyses and research be conducted in other risk zones and with other types of wastewaters, such as industrial areas.

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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