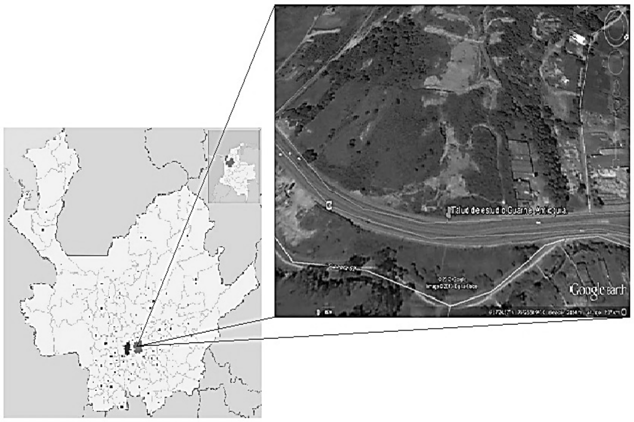


Figure 1. Location of the slope in the study area (Guarne, Antioquia)
Sources: The authors from Mayor of the municipality of Guarne and Google Earth, [1,2]

soil in the Antioquia Batholith. A series of laboratory tests were subsequently carried out. These were tests used in soil mechanics, i.e., natural humidity, specific gravity of solids, granulometry, Atterberg limits, double-edometric, direct shear, pH determination, filter paper suction, pinhole test, X-ray diffraction, scanning electron microscopy and miniature compacted tropical classification, which provide a closer approximation of the corresponding characteristics of the soil in the region.

2. Characteristics of the study area

The study area is located near the town of Guarne, on the west side of the Department of Antioquia, on the right margin of the Medellín-Bogotá Highway, at an elevation of 2,157 m.a.s.l., with coordinates N=1.188.043 and E=847.616 (Datum Bogotá)(Figure 1).

The study site corresponds to a 19-meter slope, which currently exhibits a modified morphology due to excavations carried out at the site. The excavations have produced vertical slopes (escarpments), which are apparently stable, as well as more gradual slopes, on which erosion processes occur. For example, furrows caused by surface runoff can be observed on the gradual slopes.

The municipality is located at approximately 2,150 m.a.s.l. Its average temperature is 17°C, with day to night variations between 27°C and 8°C. The average relative humidity is 80%, and the median annual precipitation is between 1800 and 2800 mm. Two climatic periods are observed in the area, which correspond to the rainy season (April to May and August to November) and the dry season (June to July and December to March) [3]. In terms of the plant life present in the study area, the environment can be classified mainly as a Low Mountain Humid Forest (bh-MB) [4]. The principal drainage from the area is from the La Mosca and Lomeríos creeks.

3. Geological and geomorphological features

Regionally speaking, the study area is made up of the geological units known as Neis de la Ceja (PRlnc), Medellín Amphibolites (PRam), Antioquia Batholith (K2ta), Drainage Basin Deposits (Q2v) and Alluvial Deposits (Q2al) [5].

The slope under study exhibits the Medellín Amphibolites (PRam), which are amphibolite bodies of varying dimensions that extend over the Antioquia Batholith. They display an intrusive relationship; the mineral composition is essentially hornblende and plagioclase. In turn, the predominant facies in the Antioquia Batholith (K2ta) in the study area exhibit a tonalite to granodiorite composition, with more maphic border facies and more felsiclocal facies. The predominant minerals are quartz, potassium feldspar, plagioclase, biotite, hornblende, orthopyroxenes and some accessory minerals.

The Antioquia Batholith rocks and the weathering and erosion processes they undergo generate short, round, semi-hilly geo-formations, in which the forces of material transport shape the landscape and contribute to the formation of short drainage basins in narrow valleys, with dendritic drainage resulting from runoff processes. This makes it possible to uncover the deep saprolitic material exposed on the surface, which is then easily remobilized by erosive processes.

4. Weathering profile

During the visits to the study site, a stratigraphic profile of the slope was defined, and samples were taken within the profile. Based on the (visual) preliminary description of the field of materials found, a brief description of each layer is presented next.

Organic soil: Silty soil, dark brown in color, with medium humidity and low plasticity, of soft consistency and with a high root content. This soil displays a very distinctive color.

Volcanic ash: Clayey-silt with a light brown to gray to beige color, porous, of medium to high humidity and high plasticity, of soft consistency, with some small quartz crystals.

Residual soil contaminated with ash: Clayey-silt soil with some sand, homogeneous, of yellow to orange color, medium to high humidity, medium plasticity and firm consistency, does not exhibit structures inherited from the parent rock, only small quartz crystals can be observed.

Residual soil of the Antioquia Batholith: Clayey-silt soil, with some sand, of orange to reddish color, medium to high humidity and low to null plasticity. This soil does not exhibit a specific structure, but it contains some quartz and mica crystals.

Saprolite of the Antioquia Batholith: Sandy-silt soil, white with black, orange and pink blotches, with low cohesion (it is easily disaggregated in one's hands), medium humidity and low to null plasticity. The granite structure of the parent rock is easily observed, as well as some discontinuities filled with manganese oxides. This soil exhibits a high content of quartz crystals and some mica crystals.

5. Methodology

Soil samples were taken from the study area as both altered (packed into bags) and unaltered (box type) samples. Initially, samples were contaminated with gasoline in the

Geotechnical and Pavement Engineering Laboratory of the National University of Colombia, Medellín Campus. This contamination process consisted of getting both groups of samples, those contaminated and those in their natural state, to exhibit the same humidity level, between 27% and 30%, with the goal of at least having the humidity parameter controlled to the same value for all tests. To that end, a gravimetric analysis was carried out, in which the humidity of the sample was reduced to a value of 15%. Then, enough gasoline was added to reach the desired gravimetric water content of uncontaminated samples. Additionally, upon contamination, the liquid phase was allowed to occupy 60% of the air voids in the soil.

The soil was contaminated with gasoline by drip; the gasoline was allowed to incubate in the soil for 7 days before the tests were started, in order to allow adequate infiltration of the fuel and to allow it to interact with the soil.

Finally, the minimum number of geotechnical characterization tests for the contaminated and uncontaminated soils was two tests to verify repeatability. For the uncontaminated soil, the results of tests developed by students in the Geotechnical Behavior of Tropical Soils course at the National University of Colombia, Medellín Campus, were used, enabling comparison of both states [6].

5.1. Physical characterization

To undertake the physical characterization of contaminated and uncontaminated samples, the following tests were executed:

- Natural water content [7].
- Specific gravity of solids [8].
- Granulometry using sieves and a hydrometer, with and without deflocculant [9].
- Atterberg limits [10].
- MCT rapid Classification, Miniature Compacted Tropical [11].

5.2. Mineralogical characterization

- X-ray diffraction: This test generates a diffractogram that makes it possible to identify the minerals present in the soil [12].
- Scanning Electron Microscopy (SEM): This test enables examination of the microstructure and chemical composition of the soil, and it makes it possible to confirm the presence of specific minerals based on detailed images [12].

5.3. Chemical characterization

- Measurement of the pH in H2O and in KCl: Two solutions are used in this test, and the pH measured in KCl is subtracted from the pH measured in water. If the difference between the pH values is positive (ΔpH), then iron and aluminum oxides and hydroxides are predominant in the soil. If the value is negative, clay minerals are predominant [13-15].

5.4. Mechanical characterization

- Consolidated drained (CD) direct shear test: The purpose of the test is to calculate the friction angle and cohesion parameter [16].
- Double-edometric test: two simultaneous simple edometric tests are performed, one in natural humidity conditions and the other in saturated conditions. Based on the test, two compressibility curves are generated for the soil. The differences between the void ratios are used to calculate the collapse potential [17,18].
- Pinhole test: this test is intended to determine whether the contaminated soil is susceptible to the internal erosion processes [19,20].
- Test of suction through filter paper with mixed trajectory: this test allows for the measurement of both matrix suction and total suction in the soil [21,22].

6. Analysis of results

6.1. Index properties

In order to characterize the material on the site, classification tests were carried out following the Unified Soil Classification System and MCT (Miniature Compacted Tropical classification). These tests were performed on the sample in its natural state and on a sample contaminated with gasoline, both in a humid state and in a dry state.

Figure 2 shows the Atterberg limits, and Table 1 and 2 show the results obtained.

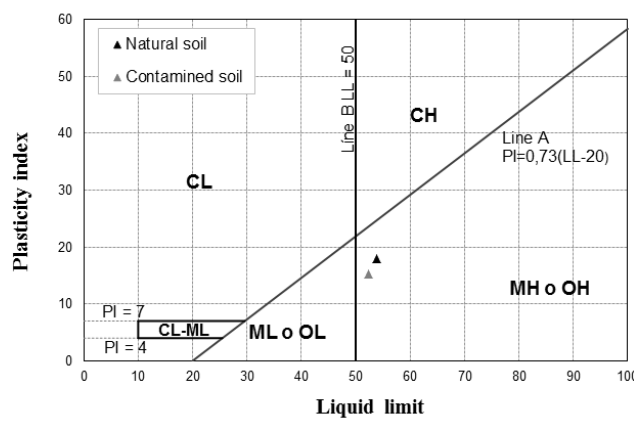


Figure 2. Atterberg limits in Casagrande's plasticity chart
Sources: The authors

Table 1.
Soil Classification

Specimen	% Finer WD	% Finer D	LL(%)	PI(%)	USCS
Natural soil	56	57	54	18	MH
Contaminated soil	61	62	52	15	MH

WD: Without Deflocculant, D: With deflocculant, LL: liquid Limit, PI: Plasticity Index, USCS: Unified Soil Classification System
Sources: The authors

Table 2.
Summary of physical properties

Specimen	Gs	e	S(%)	w_{nat}(%)	MCT
Natural soil	2.8	1.0	71	28	LA'-LG'
Contaminated soil	2.8	1.1	76	29	LA'-LG'

Gs: Specific Gravity, e: Void Ratio, S: Saturation, w_{nat}: natural humidity, MCT: Miniature Compacted Tropical
Sources: The authors

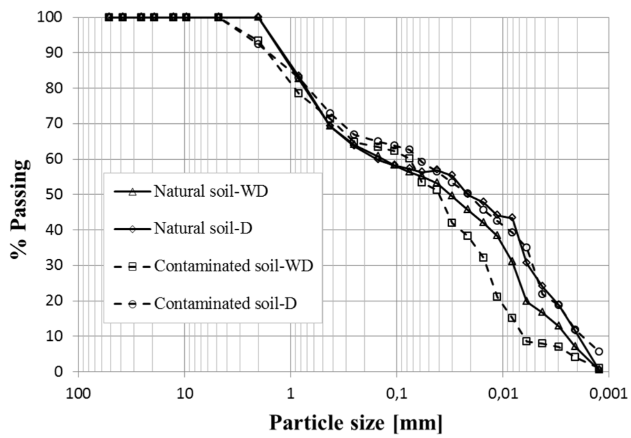


Figure 3. Granulometric curve of the soils
Sources: The authors

It can be seen that for both contaminated and natural samples, the plasticity index is low, which indicates aggregation of particles or presence of clay minerals with low activity. The classification of the material, which corresponds to high-compressibility silt (MH), isn't affected by the contamination.

6.2. Granulometry

To observe the aggregations present in the soil before and after contamination, granulometry was performed by using a hydrometer on both samples with and without a deflocculant. The results for both the natural and contaminated samples are shown in Figure 3. It can be seen in the figure that the fine material percentage is very similar for both cases without deflocculant, which indicates that the contaminant does not affect the size of the particles in the soil. Taking into account Figure 3, the stability of aggregates was determined by calculating the difference between clay percentages with and without deflocculant [12]. The sample contaminated with gasoline exhibits greater aggregation than the natural sample. However, the stability of such aggregations is lower for the contaminated sample than for the natural one, with values of 8% and 4%, respectively. Thus, one can infer that gasoline generates larger aggregations. However, the stability of such aggregations is not very strong.

6.3. MCT Rapid Classification (Miniature, Compacted, Tropical)

The MCT classification is a method developed especially for tropical soils, which allows them to be sorted into two principal groups: lateritic soils (L) and non-lateritic soils (N). These are in turn divided into seven subgroups [12]. The test was performed on 10 samples, 5 in their natural state and 5 contaminated with gasoline, and it was found that the soil in both conditions exhibits the characteristics of a tropical soil belonging to the groups LA' (lateritic clayey sands) and LG' (clays, silty clays and lateritic sandy clays).

For the study area, the classification exhibited by the soil, LA' and LG', is in agreement with the characteristics of the materials in the region. These materials have a high degree of stability despite the steep slopes. Reddish soils are predominant, and there is organic material at a superficial level. There is also a high sesquioxide content. In addition, these materials can be easily collapsed due to water immersion [11].

It is worth clarifying that the MCT classification for the soil studied is not definitive and should be complemented with other tests that corroborate or fail to corroborate its results. Other tests will make it possible to establish the degree of weathering in the soil.

6.4. Mineralogical and structural analyses of the soil

6.4.1. X-Ray Diffraction (XRD)

The results of the XRD test (Figure 4) show that both the natural soil and the soil contaminated with gasoline show a mineralogical predominance of quartz and plagioclases. As a result of the alteration of the latter, clay minerals were generated (mainly kaolinite). The presence of gibbsite, to a lesser degree, can also be observed.

For the contaminated material, gasoline does not alter the mineralogy of the soil. The interaction period of the contaminant in the soil was too short to produce changes in the chemical composition of the minerals. In addition, this test was affected by sampling. Therefore, observing small changes in percentage points is common for the mineralogical components.

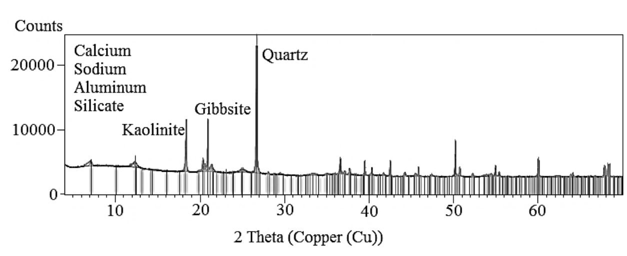


Figure 4a. Natural soil.

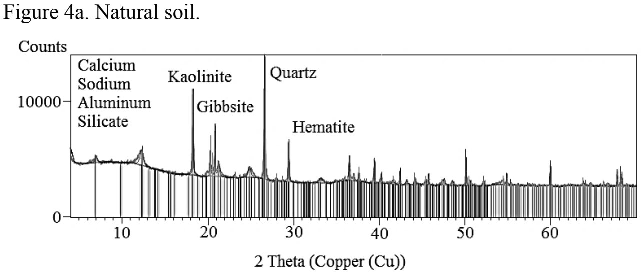
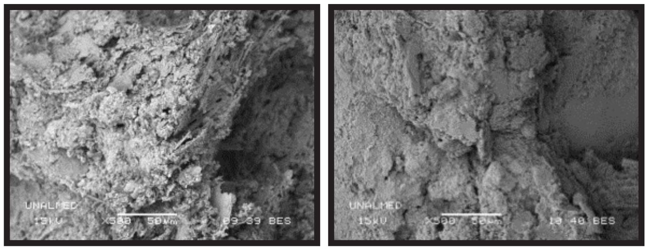


Figure 4b. Contaminated soil.

Figure 4. XRD Results
Sources: The authors



a. SEM of contaminated soil. b. SEM of natural soil.

Figure 5. Scanning Electron Microscopy results
Sources: The authors

Table 3.
Measurement of the hydrogen potential pH

Soil	Specimen	pH (water)	pH (KCl)	ΔpH
Natural	1	6	4.4	-1.6
	2	5.9	4.3	-1.56
	3	5.9	4.3	-1.53
Contaminated	1	7	4.3	-2.77
	2	6.9	4.1	-2.72
	3	6.5	4.1	-2.4

Sources: The authors

6.4.2. Scanning Electron Microscopy (SEM)

Some of the images captured through the scanning electron microscope are shown in Figure 5. Based on these images, one can infer that for the sample contaminated with gasoline, the particles are more aggregated compared to the natural sample. For that reason, more pores are visible than on the natural sample. These observations are of a qualitative character and are directly related with the sample of material analyzed, which is a small fraction of the total sample. However, the results coincide with the granulometry as measured by the hydrometer test, which found that weak aggregations can be observed in the contaminated sample.

6.5. Determination of pH

The results in Table 3 show that the levels of iron and aluminum oxides and hydroxides are very low. Thus, we can state that the soil is in an early stage of weathering (incipient laterization). With respect to the sample contaminated with gasoline, an increase of approximately 13% in the acidity of the soil can be observed compared to the natural soil. The pH of the contaminated soil is within the optimum range for most soil bacteria, which may be optimal for use in bioremediation [23].

On the other hand, the trend toward negative values of ΔpH persists, which is expected given that the time during which the soil was exposed to the contaminant was too short to produce a change in the mineralogy of the soil.

6.6. Consolidated drained (CD) direct shear test

The main objective of this test is to determine the strength parameters of the soil. The shear test performed

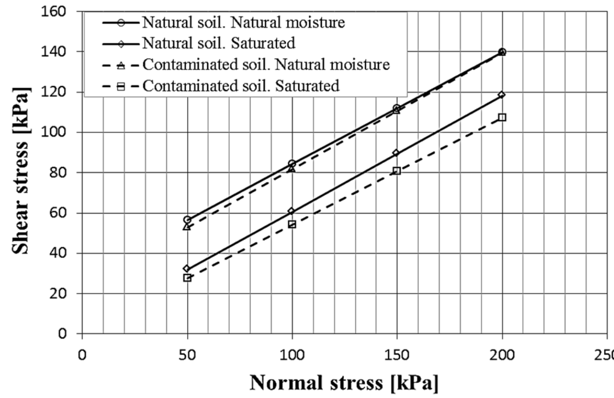


Figure 6. Results of the shear strength test in the natural and contaminated samples
Sources: The authors

Table 4.
Strength parameters

Specimen	C [kPa]		Friction angle	
	Natural moisture	Saturated	Natural moisture	Saturated
Natural soil	29	3	29°	30°
Contaminated soil	24	1	30°	28°

Sources: The authors

The strength parameters corresponding to the failure envelopes represented in Figure 6 are shown in Table 4.

Was of type CD (consolidated and drained), which avoids the development of pore pressures in the samples. The results are shown in Figure 6.

The strength parameters obtained in the shear strength test are similar to the typical values of cohesion (C) and friction angle of soils coming from the Antioquia Batholith [3]. In addition, the data shown in Figure 6 and Table 4 represent the most significant changes in the strength parameters of the soil, which are directly related to its saturation condition.

Based on these results, we can observe that the unsaturated samples have greater strength than the saturated samples. This corresponds to the most critical condition of the soil because water directly affects the mechanical properties of the soil. The influence of the presence of the contaminant is not representative, given that the variation in strength is minimal. In other words, neither the cohesion nor the friction angles are significantly influenced by the interaction with gasoline.

6.7. Double-edometric test

Based on Figure 7 and the estimation of collapse potential, we can state that the gasoline removes the connections that keep the grains of the structure together, which promotes collapse [18]. This phenomenon becomes clear when comparing the values of the collapse potential, which in the case of the natural sample are below 3.0%. These low values correspond to classification of the soil as moderately collapsible. In the case of the contaminated samples, the values are between 10% and 20% for the last

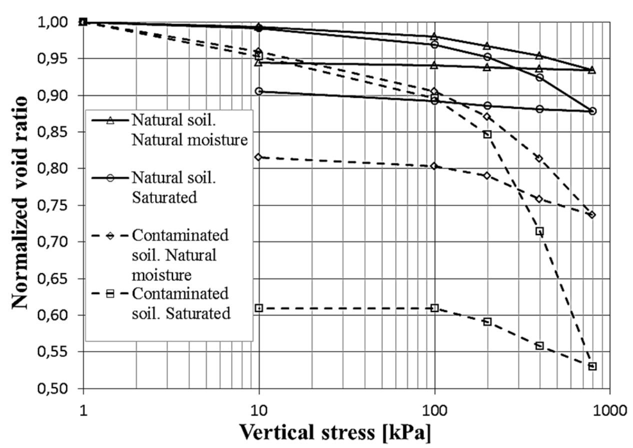


Figure 7. Double-edometric tests, natural and gasoline contaminated soil
Sources: The authors

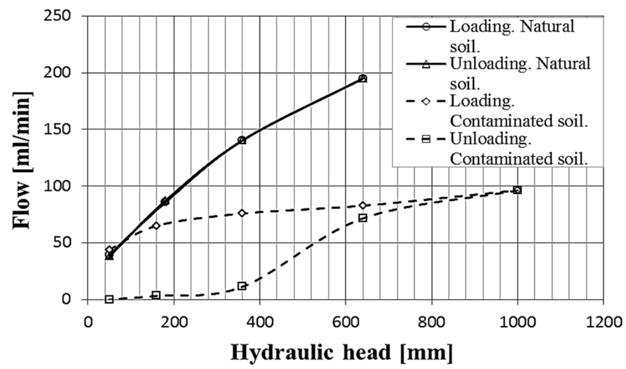


Figure 8. Pinhole test, natural sample and sample with gasoline.
Sources: The authors

load increment, and the problem can be considered serious. In addition, when considering the most unfavorable scenario, comparing the contaminated saturated sample with the natural sample, we obtain a potential of 20.9%, which qualifies the problem as very serious. This is in agreement with what was observed in the SEM. The SEM images showed that the contaminated sample has a more open structure.

6.8. Erodibility tests

A series of erosive processes were observed during the visit to the study area. These erosive processes have affected the soil, and they reveal the degree of erodibility that can be reached. Such processes are superficial (furrows). This means that it is necessary to verify, to a certain degree, the degree of erodibility the soil can exhibit, both in its natural state and when it is contaminated (Pinhole Test) [20].

6.8.1. Pinhole Test

We can observe from Figure 8 that for the natural sample, the stages of loading and unloading overlap. In other words, for a given head, the flow rates in the stage of loading and unloading are the same, which indicates that the natural soil does not show any erodibility. In contrast, the sample altered by gasoline exhibits a high degree of erodibility, given that there is a marked difference between the loading stage and the unloading stage, which is associated with the separation of certain particles due to the flow of water and the subsequent blockage of the hole (stage of unloading below the stage of loading).

6.9. Suction

There was a difference between the matrix suction and total suction, both for the sample in its natural state and for the contaminated sample (Figure 9). This difference is due to the contribution of osmotic suction from each of the samples, which is greater in the sample contaminated with

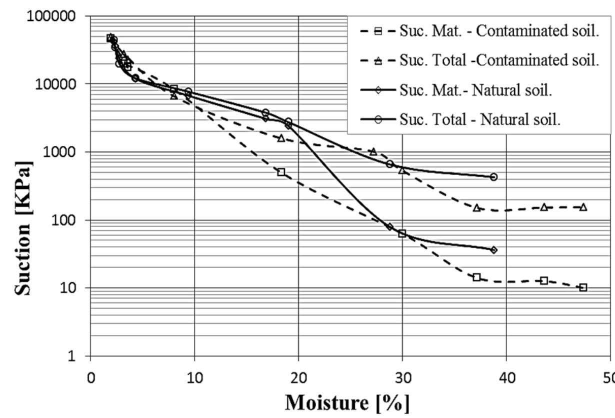


Figure 9.Characteristic curve of the natural soil and soil altered with soap. Matrix and total suction
Sources: The authors

gasoline at humidities below 27%. For greater humidities, the chemical effect is approximately the same as that exhibited by the natural sample. This indicates that the reduction in total suction caused by the contaminant in the soil is mainly observed in the matrix suction component.

Taking this into account, one can say that the reduction in matrix suction observed in the contaminated soil is caused by a change in its structure (see SEM test). It is worth highlighting that the reduction in matrix suction can also occur because of a reduction in surface tension caused by the gasoline. The surface tension of water is approximately 72.3(10^{-3}) N/ml, whereas the surface tension of gasoline is 21.60 (10^{-3}) N/ml [24]. Thus, the surface tension of gasoline is 50% less than that of water, and when these substances are combined, the resulting surface tension of the mixture should be lower.

7. Conclusions

It is important to consider the effects of certain liquid contaminants present in the soil, given that these may alter some of the soil's geotechnical properties. Contaminants may modify the initial stability conditions of the soil. This is demonstrated by using laboratory tests performed on samples contaminated with gasoline.

In terms of the principal volumetric and gravimetric relationships, such as the void ratio, degree of saturation, and specific gravity of solids, one can observe insignificant variations due to the presence of gasoline, which is related to the short period of action of the contaminant in the soil. Similarly, the general characteristics of the soil, such as the predominant size of the particles and the plasticity of the soil, are also not affected considerably.

Regarding the XRD tests, the MCT classification and the pH test, can state that studied soil exhibits a significantly advanced process of laterization. In addition, it can be inferred that gasoline does not influence the mineralogical composition of the soil, given that the results for the natural sample were very similar to those of the contaminated sample.

Considering the hydro-mechanical behavior, no significant changes were observed in the shear strength parameters. On the other hand, gasoline considerably increases the probability of collapse and increases the internal erodibility of the soils. The most notable of these impacts is the increase in the probability of collapse. In the worst-case scenario, the stability problem would change from moderate to very serious, which would indicate that this contaminant is capable of removing the support that holds the grains of the soil structure together.

Finally, it is important to take the contamination scenarios for soils into account during the design and planning of projects that involve the processing, storage and transportation of hydrocarbons. Taking such contamination into consideration will help to prevent possible events that can affect the stability and behavior of soils.

References

[1] Alcaldía de Guarne – Antioquia – Colombia [Online], [date of reference May 11th of 2013]. Available at: http://www.guarne-antioquia.gov.co/index.shtml#3.

[2] Google Earth. Colombia – Antioquia – Guarne, [date of reference: May 11th of 2013].

[3] Escobar, L. and Valencia, Y., Análisis de estabilidad y probabilidad de falla de dos taludes de suelo tropical en la autopista Medellín-Bogotá en el tramo de vía entre Marinilla y Santuario. Boletín de Ciencias de la Tierra, 31, pp. 51-64, 2012.

[4] INSTITUTO GEOGRÁFICO AGUSTÍN CODAZZI, Mapa de Formaciones Vegetales de Colombia 1:500.000, Bogotá, 1977.

[5] INGEOMINAS, Explicación del mapa geológico 1:500.000, Medellín, 2005.

[6] Cano, K. et al., Comportamiento geotécnico de un suelo residual tropical del batolito antioqueño. Informe inédito. 2013.

[7] ASTM. Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. D2216-05. United States of America: ASTM. 2005.

[8] ASTM. Standard test method for specific gravity of soils by water pycnometer. D854-06. United States of America: ASTM. 2006.

[9] ASTM. Standard test method for dispersive characteristics of clay soil by double hydrometer. D4221-11. United States of America: ASTM. 2011.

[10] ASTM. Standard test methods for liquid limit, plastic limit, and plasticity index soils. D4318-05. United States of America: ASTM. 2005.

[11] Nogami, J. and Villibor, D., Pavimentacao de baixo custo com solos lateríticos. Editora Villibor, Brasil, 1995.

[12] Valencia, Y., Influencia da mineralização nas propriedades fisico – mecânicas de um perfil de solo tropical afetado por processos erosivos, PhD Thesis, Universidade de Brasilia, Brasilia, Brasil. 2009.

[13] ASTM. Standard test method for pH of soil. D4972-01. United States of America: ASTM. 2001.

[14] Lima, M.C., Degradacao Fisico – Quimica e Mineralógica de Macicos Junto ás Vocorocas, PhD Thesis, Universidade de Brasilia, Brasilia, Brasil, 2003.

[15] Da Fonseca Cardoso, F.B., Analise química, mineralogica e micromorfológica de solos tropicais colapsíveis e o estudo da dinámica do colapso, MSc Thesis, Universidade de Brasilia, Brasilia, Brasil, 1995.

[16] ASTM. Standard test methods for direct shear test of soils under consolidated drained conditions. D3080-04. United States of America: ASTM. 2004.

[17] ASTM. Standard test methods for one dimensional consolidation properties of soils using incremental loading. D2435-04. United States of America: ASTM. 2004.

[18] Conference for Africa on Soils mechanics and Foundations Engineering (VI, 1975, Durban). A guide to construction on or with materials exhibiting additional settlement due to "Collapse" of grain structure, Durban, Sudáfrica, 1975, pp. 99-105.

[19] Camapun de Carvallo, J., Processos Erosivos no Centro – Oeste Brasileiro, Editora FINATEC, Brasil, 2006.

[20] ABNT. Solos argilosos dispersivos – identificacao e classificacao por meio do ensaio do furo e agulha (Pinhole test). NBR 14114/98. Brasil: ABNT. 1998.

[21] ASTM. Standard test methods for measurement of soil potential (suction) using filter paper. D5298-03. United States of America: ASTM. 2003.

[22] Fredlund, D.G. and Rahadjo, H., Soil mechanics for unsaturated soils, Wiley-Interscience, New York, 1993. http://dx.doi.org/10.1002/9780470172759

[23] Gómez, W., Gaviria, J. and Cardona, S., Evaluación de la bioestimulación frente a la atenuación natural y la bioaumentación en un suelo contaminado con una mezcla de gasoline – diesel. DYNA, 76 (160), pp. 83-93, 2009.

[24] Fengkun, W. et al., Surface tensions of mistures of diesel oil or gasoline and dimethyl carbonate, or ethanol, Energy & Fuels, 20, pp. 2471-2474, 2006.

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