Geotechnical and geophysical characteristics of soils in Mahotiere area (Kenscoff-Haiti)

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
A geological study based on bibliographic data found on Kenscoff-Mahotiere area revealed that this region is part of "Massif de la Selle System" and is constituted mainly of two sedimentary dating from the Eocene (ei - limestone) and Paleocene (ep - clay). The geotechnical analysis (physical, mineralogical and chemical identification tests) carried out in the laboratory has allowed to classify the soil samples collected in Mahotiere as calcareous sand and plastic clay, especially in the presence of smectite, chlorite and kaolinite. The geophysical survey carried out in situ (electrical sounding, electrical tomography and refraction seismic) confirms the geological nature of the soil and also describes its geophysical behavior. We made a comparative study between these two approaches to obtain the final characterization of the soil and to determine in the study area the different soils profiles such as: plastic swelling clay and limestones.

RÉSUMÉ
Une étude géologique sur base des données bibliographiques retrouvées sur la zone de Kenscoff-Mahotiere a montré que cette région fait partie du "Système Massif de la Selle" et est constituée principalement de deux ensembles sédimentaires datés de l'Eocène (ei - calcaire) et du Paléocène (ep - argile). L'analyse géotechnique (essais d'identifications physique, minéralogique et chimique) réalisée au laboratoire a permis de classer les échantillons de sol pélevés dans Mahotière en sable calcaire et argile plastique, spécialement avec la présence de smectite, chlorite et kaolinite. Les sondages géophysiques effectués in situ (sondage électrique, tomographie électrique et sismique réfraction) confirme la nature géologique des sols présents sur le site et décrit également le comportement géophysique de ces sols. Une étude comparative est faite entre ces deux approches pour caractériser le sol et a permis de trouver exactement dans la zone les différents profils de sols avec argile gonflante plastique et calcaire pure.

1 INTRODUCTION

Much of what is known on the Mahotiere region is outline in the geological reconnaissance of Prepetit et al. (2006). They examined the geological environment together with recent landslide to determine the geological and structural terrain conditions and the argillaceous soil behavior during the rainy season.

Our objective here is to use geotechnical analysis and geophysical surveys in order to constrain the soil conditions and geometry in the Mahotiere region. We performed conventional geotechnical tests to obtain more accurate characterization of the soil types. In parallel, geophysical surveys, are used to constrain the geological geometry. Combining these two approaches, we evaluated the feasibility and the reliability of such methods in the studied region. The expected results are a key step in order to later assess the behavior of the Mahotiere slope.

2 GEOGRAPHICAL AND GEOLOGICAL CONTEXT

2.1 Location, topography and morphology of the Mahotiere region

The Mahotiere region is located in the fourth section of the commune of Kenscoff. It is approximately situated southeast of Kenscoff with the following UTM: X = 07-91-000 and Y = 20-39-750 (figure 1).

Mahotiere is part of the "Massif de la Selle System" in the eastern part of the Southem Peninsula of Haiti. The "Massif de la Selle System" has two types of morphology, (Prepetit et al., 2006):

- A karstic topography constituted of crystalline limestone.
- A morphology characterized by volcanic rocks with narrow ridges, eroded slopes, hilly relief and deeply chiseled V-shaped valleys.

Mahotiere is part of the southem slopes, ranging at 1495 m in altitude. This slope can be divided into three distinct zones according to the inclination: (1) 15% from the summit to the altitude of 1400 m, (2) 40% to 45% with a more rugged terrain between altitudes 1400 m and 1200 m and finally, (3) 34% from the elevations 1200 m to 1000 m (figure 2). The first zone, inclined at 15%, is similar to a platform inclined towards the south, constituted of small sinkholes and ponds that have moved during rainy periods. The second zone (figure 2) corresponds to a rounded morphology slope less important than the slope, (Jean, 2013).

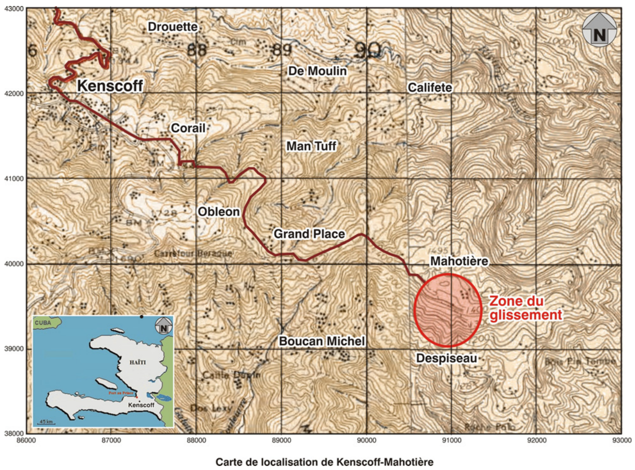


Figure 1. View of Kenscoff and Mahotiere

2.2 Geological context

From a geological point of view, the “Massif de la Selle System” is dominated by calcareous sedimentary rocks and basaltic volcanic rocks.

The sedimentary sequences form the major part of the Massif and correspond from the bottom to the top, (Prepetit et al., 2006) to:

- a basic detrital set constituted of conglomerated, sandstone, clay and limestone. This set is dated from Paleocene to Eocene.
- a thick limestone and chalk series, incorporating flints, showing alternatively regular and thin beddings massive and crystalline beddings, and crushed zones deformed by tectonic movements.

The magmatic series are represented only by basaltic volcanic rocks covering 20% of the overall Massif. They represent an important outcrop area in the axis of the Massif and are dated from the Cretaceous.

The geological map of Mahotiere-Kenscoff shows the presence of these two sets of sedimentary and basaltic volcanic series (figure 2). The studied area is located between the two basaltic and sedimentary complexes. The succession of these geological complexes suggests that this region is located on an anticlinal.

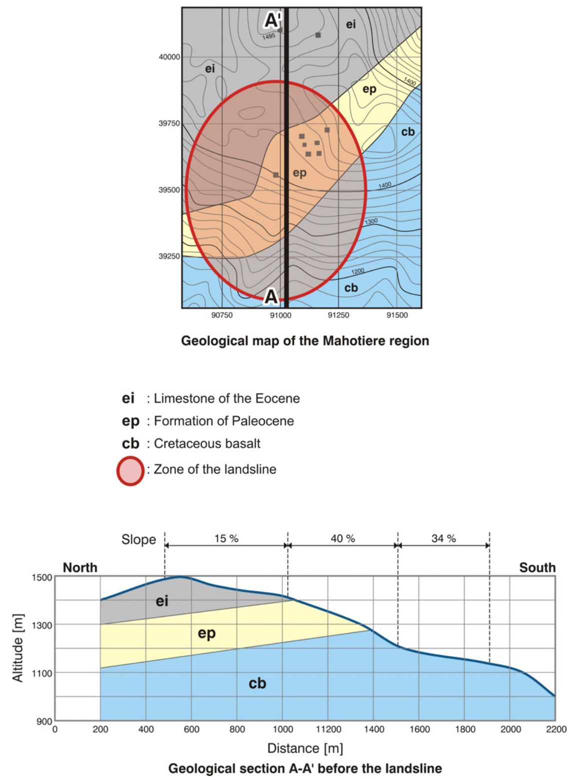


Figure 2. Geological map and profile (AA’) of Mahotiere, based on the synthetic geological Jacmel - Cap-Haitien section (Boisson et al., 1993)

3 GEOTECHNICAL CHARACTERISTICS

3.1 Localization of samples

Three soil samples (E-01, E-02 and E-03) were collected at depths varying from 2 to 15 m on the site:

- Sample E-01 was collected at 10 m depth and is located on the most eastern site.
- Sample E-02 was collected at 2 m depth and is located on the most western site of the landslide.
- Sample E-03 was collected at 15 m depth and is located on the top part of the landslide.

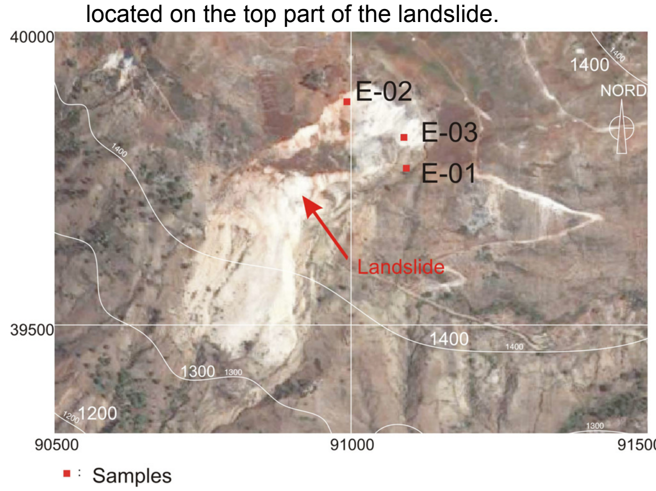


Figure 3. Localization of samples E-01, E-02 and E-03, (Jean, 2013)

3.2 Mineralogical, chemical and physical identification

A set of 320 kg of soil samples (E-01, E-02 and E-03) were transported to “Université catholique de Louvain” in Belgium for mineralogical, chemical and physical identification. Our focus were mainly on geotechnical parameters such as: natural water contents (w), organic matter contents (MO), carbonate contents ($CaCO_3$), X-ray diffraction, cation exchange capacity, specific weight (γ_s), permeability coefficient (k), size analysis and sedimentation, Atterberg limits (liquid limit W_L, plastic limit W_P, and plastic index I_P), Standard and Modified Proctor tests (water content w and dry unit weight γ_d).

3.2.1 Mineralogical identification

The mineralogical analysis of the samples is based on four tests: the organic matter contents (MO), the carbonate contents ($CaCO_3$), the X-ray diffraction and the cation exchange capacity. This analysis shows the different minerals composing the samples. Sample E-03 consists solely of calcium carbonate $CaCO_3$ (close to 100%). The very high value obtained for this sample shows the presence of a pure white limestone. Sample E-02 is formed of hematite Fe_2O_3 and clay minerals. This is mainly an assembly halloysite $Al_2Si_2O_5(OH)_4.2H_2O$, chlorite $(Fe,Mg,Al)_6(Si,Al)_4O_{10}(OH)_8$ and kaolinite $Al_2Si_2O_5(OH)_4$. Sample E-01 is dominated by impurities of calcium carbonate $CaCO_3$ and clay minerals. These clay minerals are in majority of the smectite $(Na,Ca)_{0,3}(Al,Mg)_2Si_4O_{10}(OH)_2.nH_2O$, pyroxene $XY(SiO_3)_2$ and trydimite, a polymorphic of SiO_2. This majority of smectite in E-01, estimated from the X-ray diffraction spectra performed on the entirety sample, indicates that its sensitivity to water can lead to swelling or large withdrawals. We also observed through X-ray diffraction, the presence of calcite in E-01 sample and the absence of calcite in E-02. The results of the mineralogical analysis are shown in table 1 and figures 4 and 5.

Table 1. Mineralogical characteristics of the sample E-01, E-02 and E-03, (Jean, 2013)

Samples	E-01	E-02	E-03
Designation	Greenish clay	Laterite	Limestone
Minerals	Carbonates Smectite Pyroxene Trydimite	Hematite Halloysite Chlorite Kaolinite	Carbonates
Organic matter contents (%)	0.83	0.67	0.035
Carbonate contents (%)	27.70	22.65	99.765

3.2.2 Chemical identification

The chemical analysis is also based on the four tests. The analysis of the samples show the presence of a small amount of organic matter (MO extremely low 0.035% to 0.83%, non organic soils). These low values of organic matter content reflects the depth of sampling. In contrast, samples E-01 and E-02 show high percentage of calcare-

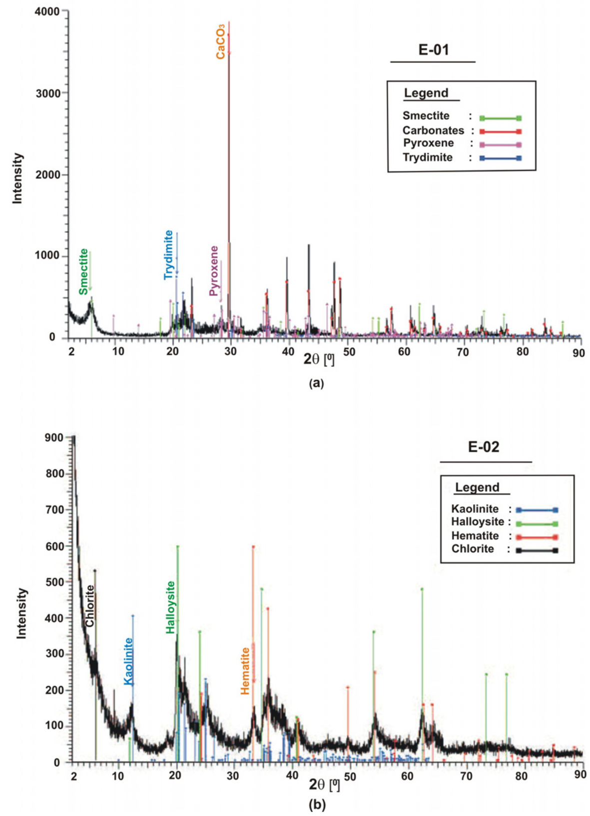


Figure 4. (a) Spectrum for sample E-01 and (b) Spectrum for sample E-02, (Jean, 2013)

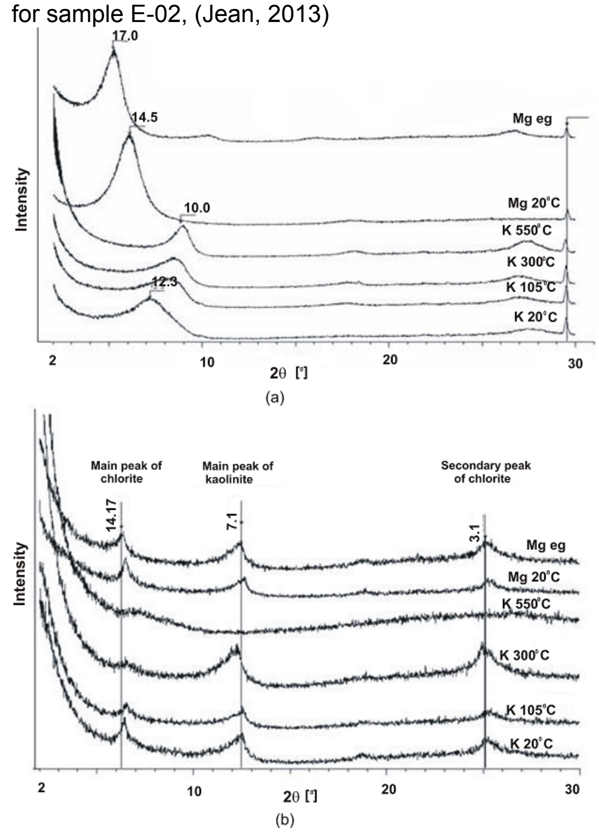


Figure 5. (a) Spectrum for clay fraction of E-01 and (b) Spectrum for clay fraction of E-02, (Jean, 2013)

ous materials (carbonate contents of 27.7% to E-01 and 99.77% to E-03). This significant presence of limestone has also been confirmed by X-ray diffraction. This significant value in E-01 justifies the relatively chalky texture and the very pale color at dry conditions. A significant percentage of $CaCO_3$ is also obtained in E-02 (22.65%). This high percentage is due to the dissolution in HCl, a portion of the hematite present in the sample. Because, this sample is not contaminated by the limestone, as shown by X-ray diffraction. These results are confirmed by the yellowish color of the washing solution obtained during the organic matter contents tests, reflecting the disappearance of red color characteristic of lateritic soils.

3.2.3 Physical identification

The physical identification is based on six tests: natural water contents (w), specific weight (γ_s), size analysis and sedimentation, Atterberg limits (liquid limit W_L, plastic limit W_P, and plastic index I_P), standard and Modified Proctor tests (water content w and dry unit weight γ_d) and permeability coefficient (k). The results of these tests are listed in table 2.

Table 2. Physical properties of three soil samples used (E-01, E-02 and E-03), (Jean, 2013)

Samples		E-01	E-02	E-03
Natural water contents	*w* (%)	35.51	42.88	5.27
Specific weight	γ_s (kN/m^3)	25.884	27.689	26.491
Atterberg limits	W_L (%)	67.3	85.8	-
	W_P (%)	35.3	45.7	-
	I_P (%)	32	40.1	-
	W_S (%)	24.73	24.19	-
	I_S (%)	42.57	61.61	-
Size analysis and sedimentation	sand (%)	5	-	70
	silt (%)	50	6	23
	clay (%)	45	94	7
Caracteristics of particule size distribution curves	D_{10} (μm)	-	-	3
	D_{30} (μm)	-	-	60
	D_{50} (μm)	3	-	300
	D_{60} (μm)	4.5	-	500
	g (-)	-	-	0.006
	C_c (-)	-	-	2.4
Physical classification		highly plastic silt	highly plastic silt	silty sand
Optimum water content	w_{opt} (%)	24	34	10
Maximum dry unit weight	γ_{dmax} (kN/m^3)	15.7	14.1	20.1
Permeability coefficient	k (cm/s)	8.20×10^{-9}	1.16×10^{-8}	1.31×10^{-1}

The sample E-01 consists of approximately 45% of clay, 50% of silt and a small amount of sand 5%. The sample E-02 consists of approximately 94% clay and 6% silt. For sample E-03, the dominant size classes are 70% sand, 23% silt and 7% clay (table 2). The proportion of clay is highly variable. The highest proportions are found samples E-01 and E-02. In contrast, this presence of clay content is low for E-03.

The values of I_P (I_P = 32% for E-01 and I_P = 40.1% for E-02) show that these samples, by absorbing water, have the capacity to become highly deformable. Based of their plastic indexes sample E-01 can be classified as a plastic soil while sample E-02 is a highly plastic soil. There is small variation of their withdrawal limits (24-25%). These high values (withdrawal) indicate the amount of water necessary to fill the voids to a minimum volume and reflect the ability of these soils to shrink significantly during the dry season (table 2).

Sample E-03 behaves like a sandy soil with low optimum water content and high maximum dry unit weight (w_{opt} = 10% and γ_{dmax} = 20.1 kN/m^3). This sample is located at significant distance from E-01 and E-02 (figure 6). The compaction curve for sample E-03 is very similar to the type curves B1 and C1, according to Holtz and Kovacs (1991). However, samples E-01 and E-02 are more sensitive to water. The optimum water content is the highest and the maximum dry unit weight is lowest for those samples. This high water content can be explained by the fact that these samples have a certain adsorption capacity for water and have the same characteristics as clay. Their behavior in the presence of water is regulated by the resultant swelling. The diagram also shows a compaction curve for sample E-01 above the E-02 one. This observation proves that sample E-01 is more sensitive to water and its swelling capacity is important. This is due to the presence of the smectite found in this sample (table 1). These two samples E-01 and E-02 are close respectively typical curves A3 and B3, according to Holtz and Kovacs (1991).

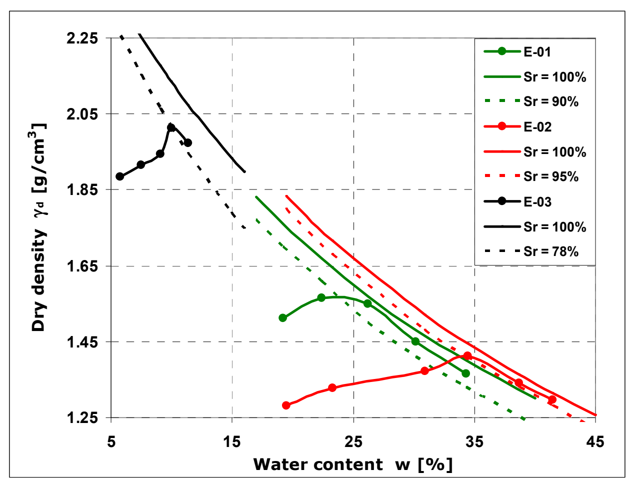


Figure 6. Results Proctor on samples E-01, E-02 and E-03, (Jean, 2013)

4 GEOPHYSICAL CHARACTERISTICS

4.1 Geophysical investigations

Two conventional geophysical methods have been deployed in the Mahotiere region: electrical resistivity method and seismic method. These methods were used to constraint the soil geometry in the “Massif de la Selle System”, and also the spatial representativity of the collected samples. In this context, the geophysical tests have been conducted in the sampling area. Three geophysical profiles were defined: East side (P-01), West (P-02) and North (P-03) of the landslide located at the experimental area (figure 7). Profiles P-01 and P-02, generally oriented N-S, crossed respectively the location of specimens E-01 and E-02. Profile P-03, oriented E-W, pass through E-03 sampling location.

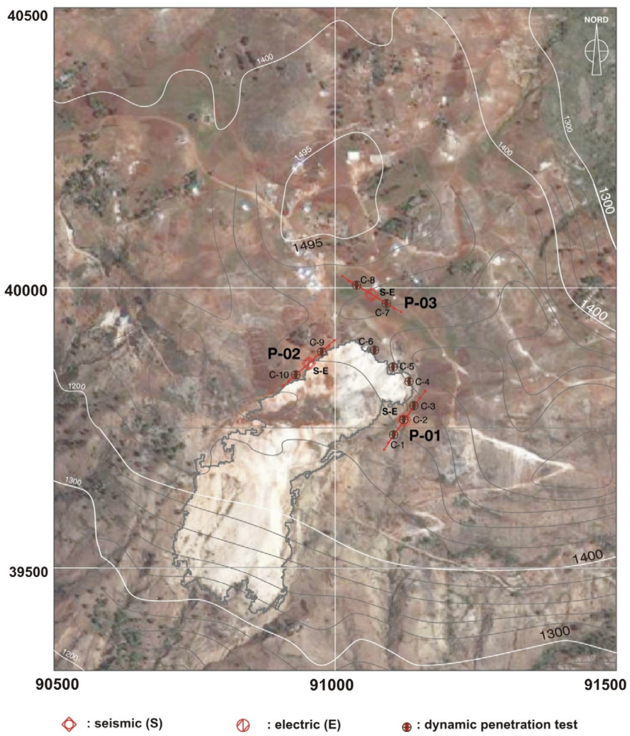


Figure 7. Location of geophysical profiles P-01, P-02 and P-03, (Jean, 2013)

4.2 Geophysical results

4.2.1 Electrical sounding

Three electrical soundings ($C_1C_2/2$ = 50 m) were acquired transversely (P-03) and longitudinally (P-01 and P-02) through the landsliding zone in the Mahotiere area. The measurements were conducted according to the Schlumberger configuration and using a sequence of about 20 quadripoles. We used the software “Elec” developed at the “Université de Liège” by Schittekat and Schroeder (1978) to process the collected data. The apparent resistivities and the calculated depths are shown in table 3.

Table 3. Results of electrical soundings: Hypothesis P-01, P-02 and P-03

	Resistivities (Ω.m)	
Hypothesis P-01	Hypothesis P-02	Hypothesis P-03
(0 - 2 m) → 5	(0 - 0.75 m) → 570	(0 - 4 m)→12
(2 - 3 m) → 10	(0.75 - 3 m) → 5000	(4 - 6 m) → 350
(3 - X m) → 30	(3 - 3.75 m) → 1000	(6 - X m) → 1600
	(3.75 - X m) → 13000	

However, it is necessary to be prudent about the precision on the thickness of layers and the measures of apparent resistivities. A comparison with the following results based on electrical tomography will be a first step in order to address this uncertainly.

4.2.2 Electrical tomography

Three electrical tomography profiles were performed at the same location as the vertical electrical soundings. 64 electrodes were used along three profiles of 126 m each. The distance between 2 electrodes is fixed to with a 2 m. Each sequence contains 472 measurement points, following a Wenner 64 acquisition protocol. We use this protocol in order to decrease the sensitivity to noise and to increase the horizontal structures. Data was processed using “Res2Dinv” by Loke and Barker (1996). The pseudo-sections obtained for electrical tomography P-01, P-02 and P-03 are shown in figure 8.

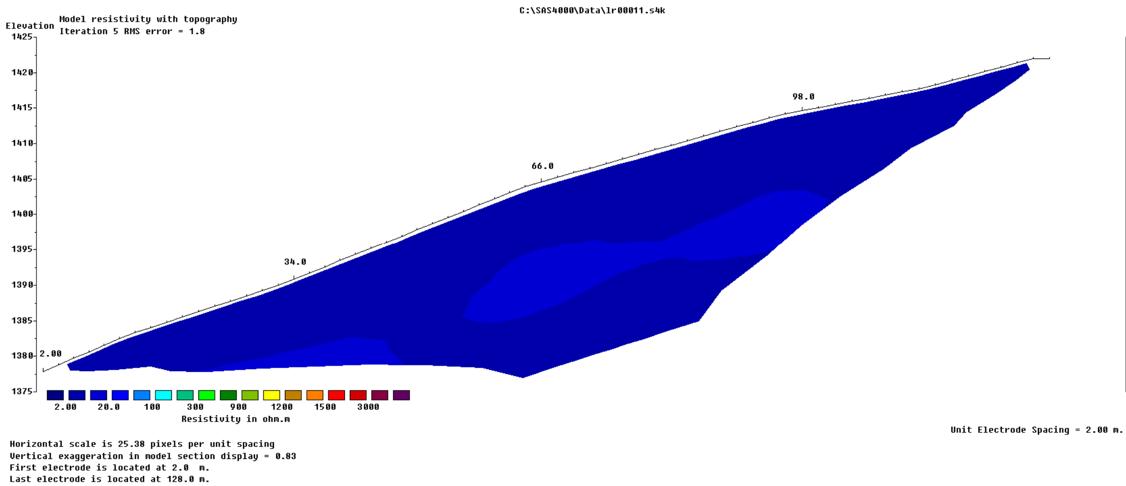
The pseudo-section P-01 (figure 8a) shows good homogeneity of the resistivity. The observed resistivities range all from 3.66 to 11.4 Ω.m. These measurements may indicate the presence of clay as suggested previously from vertical electrical acquisitions. This assumption is also confirmed by the study of soil samples taken at P-01 that show the presence of a layer of greenish clay.

The electrical tomography for the two other profiles P-02 and P-03 are represented respectively in figures 8b and 8c. Profile P-03 shows an overall good homogeneity of apparent resistivity. The resistivity along profile P-03 is increasing with depth (> 1500 Ω.m). These high resistivities may indicate the presence of limestone as it was observed near the profile through shafts performed in the corresponding area. This profile also shows the presence of water on the surface (low resistivity), which was noticed by small ponds on the site. Profile P-02 shows homogeneity of the high resistivity values throughout the depth of the profile. However, pockets of low resistivities were observed, near the surface on the upper portions of P-02. These low resistivity values at the surface indicate the presence of the lateritic clay that is directly observed on the site. After, we come across the highly resistive limestone, present on all along the profile.

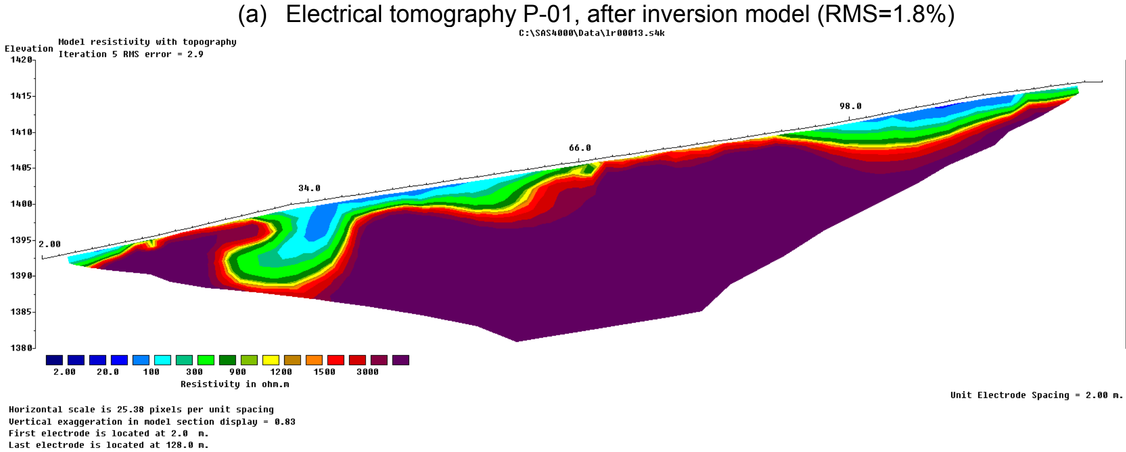
These electrical tomography profiles (P-01, P-02 and P-03: figure 8), compared to simple electrical soundings (table 3), show subsurface models that approximate the best lithological structures sought to highlight in Kenscoff-Mahotiere.

4.2.3 Seismic refraction

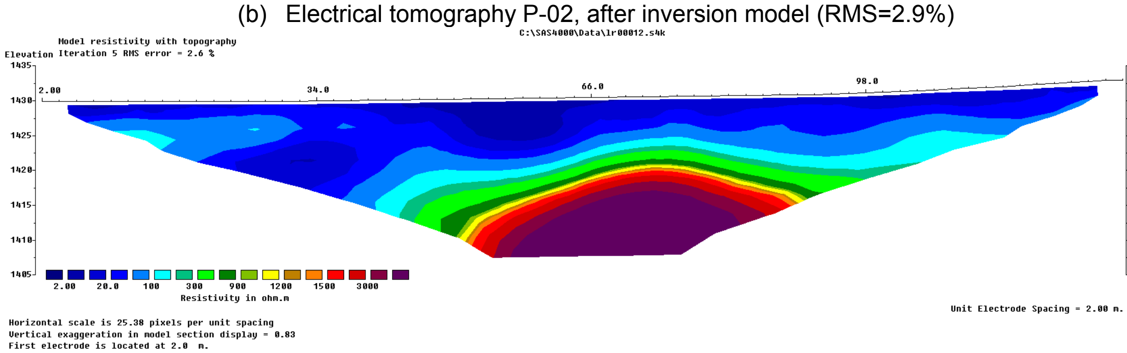
Three seismic refraction profiles (P-01, P-02 and P-03) were acquired along the same transects explored with the electrical methods. The configuration used in this seismic exploration consists in a 24 geophones (frequency 10 Hz) system along a 64 m profile. We performed a seismic compression waves analysis of the observed data.



(a) Electrical tomography P-01, after inversion model (RMS=1.8%)



(b) Electrical tomography P-02, after inversion model (RMS=2.9%)



(c) Electrical tomography P-03, after inversion model (RMS=2.6%)

Figure 8. Transverse and longitudinal electrical tomography: (a) P-01, (b) P-02 and (c) P-03

The seismic data were interpreted using the software "Sardine v1.0" developed at the "Université de Liège" by Demanet (1993). The results show four different layers (table 4). The seismic velocities increase with depth, as a function of the terrains compaction. Thus, the dromochronics show a variation of seismic velocity in the three profiles. However, anomalies due to the sloping topography of the site were observed on these dromochronics. These anomalies were corrected for during the pointing seismic shots.

Table 4. Results of seismic refraction in a quadricouche model P-01, P-02 and P-03

Seismic compression velocities (m/s)		
P-01	P-02	P-03
(0 - 1 m) → 148	(0 - 1 m) → 200	(0 - 1 m)→131
(1 - 5 m) → 329	(1 - 5 m) → 383	(1 - 5 m) → 348
(5 - 14 m) → 800	(5 - 17 m) → 850	(5 - 12 m) →844
(14 - X m) → 2028	(17 - X m) → 3597	(12 - X m) → 3061

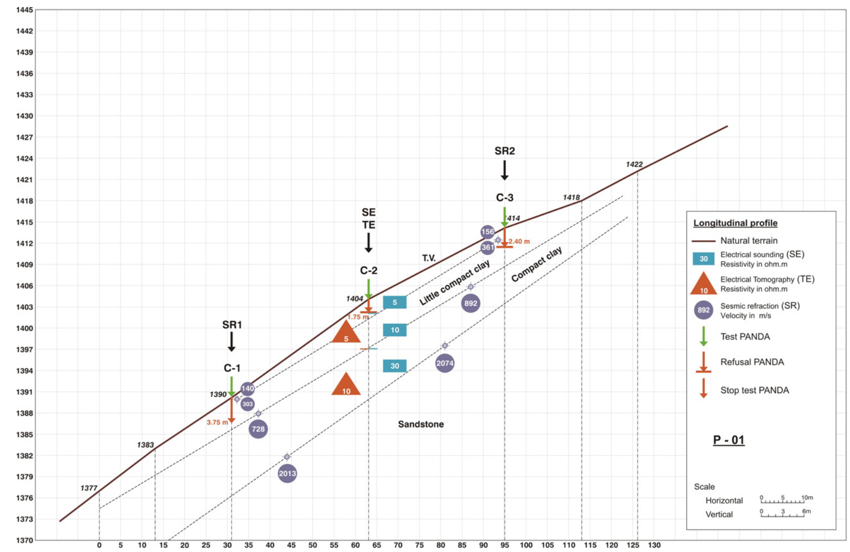


Figure 9. Longitudinal profile P-01

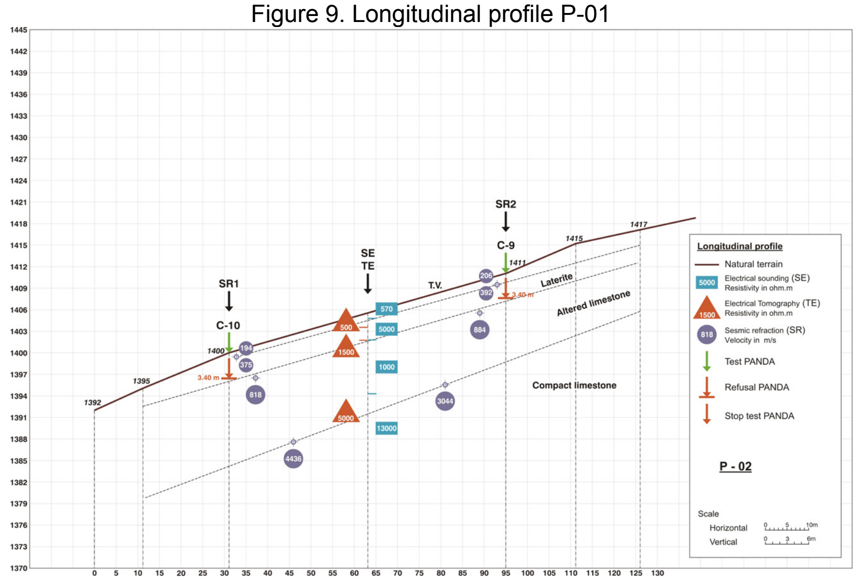


Figure 10. Longitudinal profile P-02

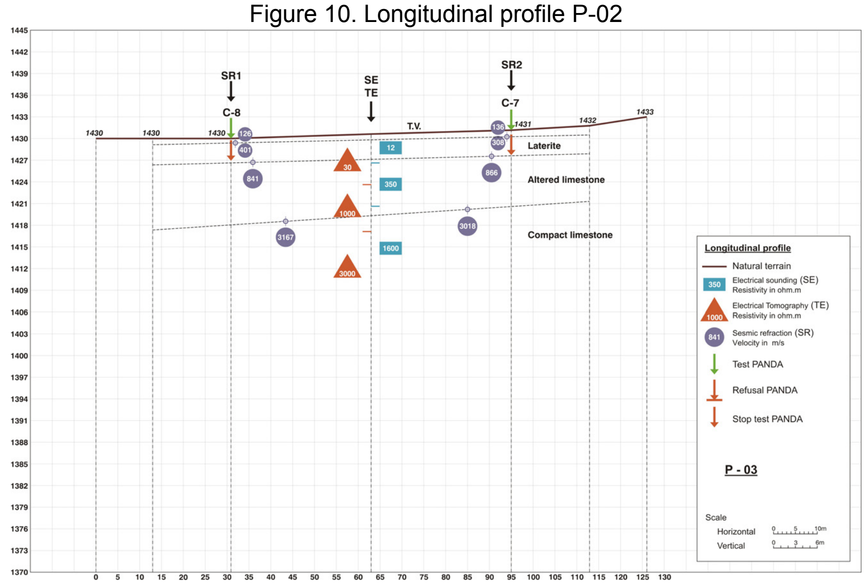


Figure 11. Longitudinal profile P-03

5 SYNTHESES

Comparison between the three approaches (geological, geotechnical and geophysical approaches) and other informations available or collected at the experimental site allow us to make a synthesis of different profiles. For each profile, we compared the velocity, the resistivity and the corresponding thickness. These comparisons also take into account information such as geological reconnaissance and geotechnical identification on the site.

5.1 Longitudinal profile P-01

Profile P-01 (figure 9) summarizes the results on the eastern flank slip during our study. In this area, we observed a 1 m thick layer at the surface that we named “topsoil mixed with some lateritic soils” and a relatively 4 m of compact thick clay followed by a more compact 7 m thick layer of clay and finally sandstone depth probably.

In this profile, the calculated resistivities are similar with the two electrical methods. These values are homogeneous and remain small throughout the depth corresponding to the clay. The presence of clay is also confirmed by seismic refraction test (seismic velocities between 300 m/s and 370 m/s). The geological map and geotechnical analysis (identification tests) show the presence of Paleocene greenish clay. This green clay, as identification study has shown, is very pale when it is dry. This is explained by the fact that the clay analyzed (taken approximately 10 m) from a place somewhat altered by sliding where this was partially pure clay mixed with limestone.

5.2 Longitudinal profile P-02

For the longitudinal profile P-02 (figure 10), a summary of the tests carried out Western flank slip was performed. As shown in this summary, we find a 1 m thick topsoil about at the surface followed respectively by a 2 m thick laterite layer, a 9 m thick layer of altered limestone and finally a compact limestone at greater depth. The results of geophysical test are consistent and confirm the same lithological nature of soil.

The geological observations show the presence of these different formations, which formed the detrital series of Paleocene. The geotechnical analysis performed on the sample taken 2 m on the side confirms the presence of a very plastic lateritic soil.

5.3 Longitudinal profile P-03

The longitudinal profile P-03 (figure 11) provides a summary of the results obtained in the sinkholes at the head of slope. In this profile, we distinguished a topsoil of 75 cm, followed by a layer of laterite, then a layer of crushed limestone 8 m and then the compact limestone at depth. The average apparent resistivity and the seismic velocities along the profile confirm this interpretation.

The geological observations show the presence of Eocene limestone and lateritic soils. The geotechnical analysis performed on the sample collected 11 m confirms the presence of the pure limestone.

6 CONCLUSIONS

The geotechnical identification and geophysical reconnaissance analysis, conducted at the experimental site, were confirmed by appropriate tests and different methods, geological nature and soil characteristics present in the area, namely: clay, limestone, laterite and sandstone probably depth investigated. The geotechnical and geophysical analysis are consistent with the geological data (geological map - figure 2) and allowed us to determine with good reliability the soils conditions in this area. But, they do not validate the dip of geological strata based on the synthetic model Jacmel - Cap-Haitien, Boisson and al. (1993). However, they can further be used to create susceptibility map for slope instabilities.

ACKNOWLEDGEMENTS

The authors would like to thank our colleagues at Purdue University, Symithe S. J. and Douilly R. for their comments. We would also thank URGéo and LNBTP for their help and financial support to GeoQuebec 2015.

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