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DEPARTMENT OF CIVIL, ARCHITECTURAL AND ENVIRONMENTAL ENGINEERING

IMPROVEMENT OF THE CONSTRUCTION TECHNIQUES OF LANDFILLS IN THE CENTER REGION:

CASE STUDY OF NKOLFOULOU LANDFILL (Yaoundé).

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Engineering (MEng) in Civil Engineering

Curriculum: Geotechnical Engineering

Presented by:

NANKENG DONGMO Buky

Student number: 14 TP20715

Supervised by:

Prof. Simonetta COLA

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DEDICATION

TO ALL MY FAMILY MEMBERS AND

ALL THOSE WHO HAVE ALWAYS

SUPPORTED ME.

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ABSTRACT

The main objective of this thesis was to improve the construction techniques of the Nkolfoulou landfill in order to propose a method for building the excavation bottoms of the waste bins. After a review of the literature on landfills which served as a basis for our study, the rest of our work was organized around two main axes. A general reconnaissance of the site, and the collection of data for the characterization of the soil of the Nkolfoulou landfill with its water retention capacity (geotechnical properties). Following the results of our laboratory tests, it was found that the soil of the Nkolfoulou landfill, mainly composed of clay and sand with a plasticity between 30 and 40% and a minimum permeability coefficient equal to 8*10-8 cm/s, belongs to class A-7-6 according to the ASHTO classification. The values of the different permeability coefficients obtained from these laboratory tests show that for a landfill, this soil is suitable for receiving waste without the need for additional geosynthetic membranes. It should be noted that this permeability value is close to the value obtained by the engineering and design department "Soil and Water Investigation S.A." which carried out similar studies in the same landfill in 2003. On the other hand, the results of the permeability test carried out in situ one month later in this same landfill on another layer at a depth of 5 m gives us a vertical permeability coefficient of 1. 1*10-4 cm/s, making it possible to say that this portion of soil must be coupled with a geosynthetic if it is used for a barrier in a landfill. In general, this work has highlighted the identification and verification of the soil sealing properties of the Nkolfoulou landfill with the joint aim of solving in an efficient and sustainable way, using local materials, the stability and sealing problems of a landfill without the use of geosynthetics. All these results have been convincing indicators of effectiveness for the work carried out at the Nkolfoulou landfill and are certainly recommended for similar future projects.

Keywords: Landfill _ Waste _ Stability _ leachate _ wastes management _ Permeability.

RESUME

Le présent mémoire avait pour objectif principal l'amélioration des techniques de constructions de la décharge de Nkolfoulou afin de proposer une méthode de construction des fonds de fouilles des casiers d'enfouissement des déchets. Après une revue de la littérature sur les décharges qui a servi de base à notre étude, le reste de notre travail s'est articulé autour de deux axes principaux. Une reconnaissance générale du site, et la collecte de données pour la caractérisation du sol de la décharge de Nkolfoulou avec sa capacité de rétention d'eau (propriétés géotechniques). Suite aux résultats des tests que nous avons menés en laboratoire, on a constaté que le sol de la décharge de Nkolfoulou, principalement composé d'argile et de sable avec une plasticité comprise entre 30 et 40% et un coefficient de perméabilité minimum égal à $8*10^{-8}$ cm/s, appartient à la classe A-7-6 selon la classification ASHTO. Les valeurs des différents coefficients de perméabilité obtenus à l'issu de ces tests de laboratoire montrent que pour une décharge, ce sol est apte à recevoir des déchets sans avoir besoin de membranes géosynthétiques supplémentaires. Il est à noter que cette valeur de perméabilité se rapproche de la valeur obtenue par le bureau d'étude « Soil and Water Investigation S.A » qui a réalisé des études similaires dans la même décharge en 2003. En revanche, les résultats du test de perméabilité réalisé in situ un mois plus tard dans cette même décharge sur une autre couche à 5 m de profondeur nous donne un coefficient de perméabilité verticale de $1.\ 1*10^{-4}$ cm/s permettant de dire que cette portion de sol doit être couplé à un géosynthétique s'il est utilisé pour une barrière dans une décharge. De manière générale, ce travail a mis en évidence l'identification et la vérification des propriétés d'étanchéité du sol de la décharge de Nkolfoulou dans le but conjoint de résoudre de manière efficace et durable, en utilisant des matériaux locaux, les problèmes de stabilité et d'étanchéité d'une décharge sans l'utilisation de géosynthétiques. Tous ces résultats ont constitué des indicateurs d'efficacité convaincants pour les travaux effectués dans la décharge de Nkolfoulou et sont certainement recommandés pour des projets futurs similaires.

Mots-clés : Décharge – Déchets – Stabilité – Lixiviat –Gestion des déchets– Perméabilité.

LIST OF ABBREVIATIONS

ACAP:	Alternative Cover Assessment Program
ASHTO	American Association of State Highway and Transportation Officials
BPEM:	Best Practice Environmental Management
CB:	Cement-Bentonite
CCL:	Compacted Clay Liner
CTD :	Centre de Traitement des Déchets
GCLs:	Geosynthetic Clay Liners
CEC:	Cation Exchange Capacity
CMBs:	Clay Membrane Barriers
CQA:	Construction quality assurance
CQC:	Construction quality control
EPA:	Environment Protection Authority
EP Act:	Environment Protection Act
F.C:	Field Capacity
F.O.S:	Factor of Safety
F.E.M.:	Finite Element Methods
G.C.L:	Geosynthetic Clay Liner
G.I.S:	Geographical Information System
GM.:	Geo-Membrane
GRI:	Geosynthetic Research Institute
HC:	High Conductivity
HDPE:	High Density Polyethylene
Hysacam:	« Hygiène et Salubrité du Cameroun »
LCS:	Leachate Collection System
L.E.M.:	Limit Equilibrium Methods
LFG.:	Landfill gas
LGRA:	Landfill Gas Risk Assessment
LLDPE:	Low-density Polyethylene

LPPI:	Landfill Pollution Potential Index
MDPE:	Medium Density Polyethylene
MINEE :	Ministère de I'Énergie et de l'Eau
M.S.W:	Municipal Solid Wastes
PE :	Polyethylene
PET :	Potential Evapotranspiration
PVC. :	Polyvinylchloride
RWMG :	Regional Waste Management Group
RWMP :	Regional Waste Management Plan
SCR:	Stress Crack Resistance
SEPPs:	State Environment Protection Policies
SLCRS:	Secondary Leachate Collection and Removal System
S.R.:	Security Radius
UCY:	Urban Council of Yaoundé
WMP:	Waste Management Policy
WTC:	Washer Treatment Center

LIST OF SYMBOLS

c':	cohesion
γ:	Unit weight
φ':	Frictional angle
k:	Permeability coefficient
Wl:	Liquid limit
Wp:	Plastic limit
PI:	Plasticity index

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GENERAL INTRODUCTION

The central region of Cameroon is described as an area dotted with hills and mountains and semi-arid, therefore, it is considered to be a very vulnerable area to some geotechnical problems, including instability and sealing of landfills near the ravines. The phenomenon of rural exodus observed over the last ten years in the area of the town of Yaoundé has increased significantly the waste rate (1500 to 2000 tons/day) to bury in the landfill of Nkolfoulou. The primary purpose of the geotechnical studies in a given landfill is to ensure the stability and tightness of a waste dump area and to optimize in-depth the storage and waste processing space by giving the optimization of the life of a landfill.

In view of the various instabilities that took place in the landfill of Nkolfoulou; especially the last two landslides of the waste that occurred on July 28 and October 23, 2019 (see annex 1) and the degree of their impact on the environment, strong is to see that this landfill requires in-depth geotechnical studies. Also, the case of the 3G locker of area 3 submitted to our analysis is not spared because very close to a river. Since the waste is complex to define because it depends on the country and the management of it, we can say that: waste is any material, substance or product that has been thrown or abandoned because it no longer has a specific use (Lavagnolo, 2017). The engineering landfill is a great improvement over previous methods of solid waste disposal, especially of open dumps. The municipal landfill is a commonly preferred method for addressing the ever-increasing amount of wastes, even in sparsely populated communities. However, the landfill can also be a source of pollution if not designed and operated properly (Vallero & Geoff, 2019). In recent decades, with the largest demographic explosion in poor countries and in some developing countries, several scientific works have been done to improve the constructive properties of a simple landfill. The studies and discoveries continued to give new values to the landfills while facilitating their implementation in order to reduce landslides in the landfill while protecting the groundwater against infiltrations to the leachates. After many catastrophes observed in landfills on a global scale and also in many of our African countries such as South Africa, Egypt, Ethiopia and Kenya. One of the most touching cases in terms of material and human damage is that of Ethiopia in March 2017 where the authorities of the city of Addis Ababa were obliged to distribute more than $4 million to the victims of a huge garbage landslide in the Koshe landfill that made more than 100 dead. In the same tragedy, hundreds of others were injured or affected by the disaster at the landfill of Koshe on the outskirts of the Ethiopian capital (Salem & Meleskachew, 2017). In view of all this, we can understand the importance to be given in the study of the practices of new construction techniques of landfills in the Cameroonian context, hence the interest of our case study of Nkolfoulou landfill. The main idea of this work is therefore based on the reinforcement of the techniques of geotechnical constructions of the dump areas in a landfill in order to produce a result satisfying the environmental, economic and durability standards.

The major concern is to achieve high performance and optimization of waste landfills with a sensible choice of locally available materials. The need for resolution of this problem has led to the use of well-defined classes and characteristics such as: the clay soils of low permeability ($1.0*10^{-7}$cm/s) and only the geomembranes. The improvement of the construction techniques of a landfill can therefore be done by using the upstream selection of the types of waste well defined, studying geophysics (the level of the water table) and geotechnical (the quality and permeability of the soils) while including the environmental studies (especially when one is close to the ravines) that will make the soil very stable to accommodate waste without geo-environmental risks and sometimes even without the use of some geosynthetics. The main objectives of this study are then to classify the soil constitutive of the landfill of Nkolfoulou, to study their permeabilities according to laboratory test results while performing in-situ permeability test of the 3G locker of the Nkolfoulou landfill. These objectives lie reached by the articulation of this work around three chapters. The first chapter will make a state of the art on the landfills, the second will describe the methodology adopted to carry out this study, while the third will devote all its essence to the analysis and interpretation of the achieved result.

CHAPTER 1. STATE OF ART ABOUT LANDFILLS

Introduction

A landfill site must meet several locations and criteria for geotechnical design and be acceptable to the public and a preliminary list of potential sites is developed satisfying the first two criteria (Amalendu Bagchi, 2015). The landfills are generally designed to maximize the amount of waste that can be accommodated in the space available according to the site's conditions, taking into account the stability of the slope. All this requires a rather specific design of the construction techniques of landfill, especially the geotechnical aspect of the landfills in the African context because the management of solid waste remains a real dilemma on the continent. This chapter aims to present the landfill in a general way, from the history of it and then some approaches namely the criteria for the design of a landfill; the typology of the landfills; and finally the different instabilities with they risk; and the construction techniques of landfills.

1.1. History of landfills.

Land disposal of waste has been practiced for centuries. in the past it was generally believed that leaching from waste are completely attenuated (purified) by soil and groundwater and hence contamination of groundwater was not an issue. Thus, disposal of waste on all landforms (e.g., gravel pits and ravines) was an acceptable practice. However, with increasing concern for the environment in the late 1950's landfills came under scrutiny. Within a short period of time several studies (California Water Pollution Control Board (CWPCB), 1954, 1961; Apagar and Langmuir, 1971; Garland and Mossher, 1975; Kimmel and Braids, 1974; Walker, 1969) showed that landfills do contaminate groundwater. Although percolation of leaching from chemical industry waste to groundwater aquifers was considered unsafe, leaching from nonchemical industry waste and Municipal Waste was considered less harmful.

As a result, waste was divided into two categories: hazardous and non-hazardous. In many countries separate regulations were developed for these two types of wastes. Although collection of leachates from non-hazardous waste was not mandated, leaching from hazardous waste was required to be collect. For nonhazardous waste the emphasis was on transforming waste dumps into "Sanitary landfills" (Amalendu Bagchi, 2015). Disposing waste in landfills is one part of an integrated waste management system. EPA encourages communities to consider the waste management hierarchy; favoring source reduction to reduce both the volume and toxicity of waste and to increase the useful life of manufactured products; when designing waste management systems (www.epa.gov/landfills, accessed on 07/09/19). Landfills have a long and relatively unsorted history. According to (www.saveonenergy.com, accessed on 15/10/19), before the first municipal dumps appeared on the map of the 20^{th} Century, humans either burned their garbage or buried it on the outskirts of towns to avoid disease.

As we can see in figure 1.1, an old landfill named Disposal Gardens and Palos Verdes in 1900s. Located in Rolling Hills Estates in a historic agricultural area with dairy and strawberry farms, this was once rolling fields, known as the 'Ten Hills' with a lake noted on the USGS 1954 map. This site was an operating waste dump from 1952-1980. This property was mined leaving gaping holes underground as well as deep pits, and later became a landfill accepting both liquid and solid hazardous wastes. This type of co-disposal site is not allowed under today's EPA guidelines. The Palos Verdes (PV) is a Class One Landfill, which is the most toxic designation possible by the Federal EPA. The PV Landfill accepted 40% of the hazardous wastes for LA Region, and accepted over 47 Billion pounds of hazardous wastes over the 300-acre site between 1952-1980. PVL was a co-disposal site; injecting toxic liquids into solid wastes on a daily basis from 1952 – 1980 (Hong Kong, 2004).

1963 Disposal Gardens (now Country Hills tract) and Palos Verdes Landfill

Figure 1.1. Disposal Gardens and Palos Verdes Landfill (blogs.dailybreeze.com, 2010).

It is typical of waste management in developing countries, where disposal of waste, often to uncontrolled dumpsites, dominates. This is driven by low landfill gate fees; unwilling municipalities and waste generators to find alternative solutions and (until recently) the plenitude of space in such countries. A number of environmental and human health concerns related to landfills, prompted the South African government to develop policies and regulations aimed at improving the way landfills were designed and operated. This phase was marked by the Environmental Conservation Act (Act 73 of 1989) and the Minimum Requirement Document series published by the Department of Water Affairs and Forestry (DWAF) in 1994, which provided technical guidance for handling; classification and disposal of waste. The Minimum Requirements where later replaced by the "National Norms and Standards for the Assessment of Waste for Landfill Disposal" and the "National Norms and Standards for Disposal of Waste to Landfill". Today the Bisasar Road in Durban, South Africa is one of Africa's largest landfill sites.

1.2. Classification on landfills.

The definition of the landfill in general is so complex and that is why is more convenient to define the landfill according to the specific type. Recommendations include, institutional strengthening, gas recovery or re-assessment of passive gas-ventilation, and introduction of tipping fees (Johannessen, Boyer, & Gabriela, 2012). As detailed in table 1.1, landfills are classified according to the waste types they accept.

Table 1. 1. Classification of landfills (Environment Protection Authority Victoria, 2015).

Type	Waste accepted	Description
2	Putrescible (municipal) waste, solid inert waste and fill material. Specifically licensed sites may receive category C prescribed industrial waste (Best-practice guidelines for landfills receiving Category C prescribed industrial waste)	Reflects the best available technology for a municipal landfill in siting, design, construction, operation, maintenance and after-care. Operated in accordance with an appropriate management system that ensures adequate supervision, control on waste receipt, safe handling, record keeping and placement of prescribed waste in accordance with the requirements for that waste.
3	Solid inert waste, fill material.	Reflects commonly available technology for a municipal landfill in siting, design, construction, operation, maintenance and after-care.

It is important to note that: Type 1 landfills are waste disposal facilities that could accept prescribed industrial wastes including Category B as defined in the Industrial Waste Resource

Guidelines: Solid industrial waste hazard categorization and management. Since this BPEM does not deal with such facilities, that is why a Type 1 landfill is not included in this table. The BPEM document deals with four types of waste: putrescible waste, category C prescribed industrial wastes, solid inert waste, fill material.

Landfills may also be classified into a number of four different types, depending upon the purpose of the classification. For the geotechnical purpose in this work, it is convenient to consider all the four types of classifications since we classify according to the position (above, below and both) with respect to the groundwater and the type of waste filled. In general, we have four principal types of landfills such as: Sanitary landfills, Municipal solid waste (MSW) landfills, Construction and demolition waste, and Industrial Waste Landfills.

1.2.1. Sanitary landfills

This type of landfill is the one that uses a clay liner to isolate the trash from the environment until it is safe. This type is considered safe when it has completely degraded biologically, chemically, and physically. Sanitary landfills use technology to contain the waste and prevent the leaching out of potentially hazardous substances. There are two main methods used in Sanitary landfills, the trench method and the area method and figure 1.2 is showing both the two methods for the sanitary landfills.

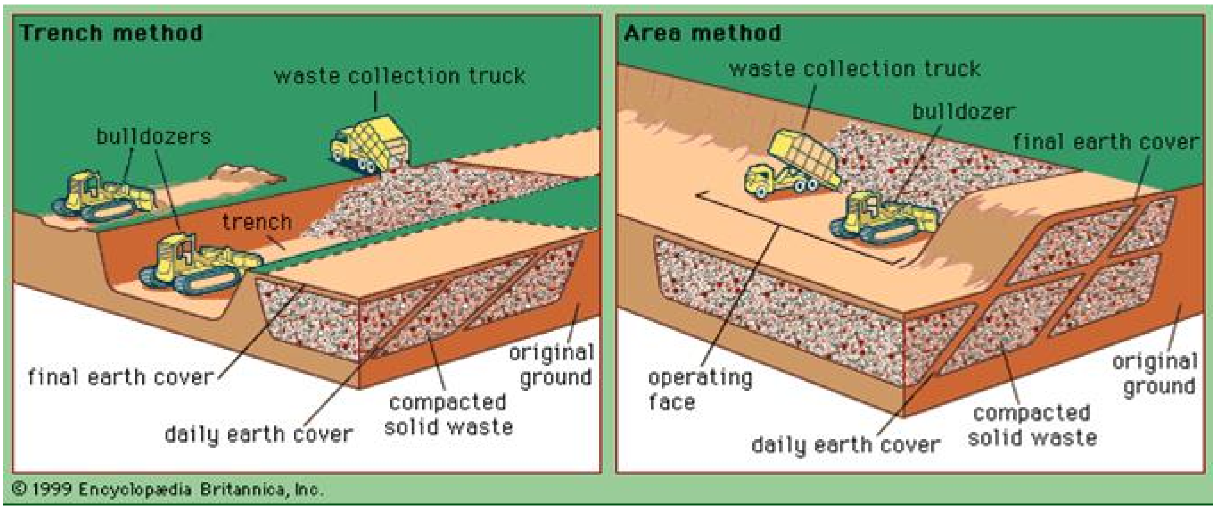


Figure 1. 2. Profile of the Slope landfill (Wroblewski et al., 2009).

a. Trench landfill method

Trench landfill also called "trench sanitary landfill" is an area where solid waste is placed in successive layers in an excavated trench. The waste is spread, compacted, and covered daily with a thin layer of soil excavated at the site. When the trench is full, a final cover of soil material at least 2 feet (0.6m) thick is placed over the landfill. A landfill must be able to bear heavy vehicular traffic. It can result in the pollution of ground water. Ease of excavation and revegetation should be considered.

b. Area landfill method

The area method is best suited for flat or gently sloping areas where some land depressions may exist. The wastes are spread, compacted and then covered with material which may need to be hauled in from adjacent area. The wastes are spread on existing slope, compacted and covered (www.nrccs.usda.gov).

1.2.2. Municipal solid waste (MSW) landfills

This type of landfill is the one uses a synthetic (plastic) liner to isolate the trash from the environment. This type of landfill collects household garbage and are regulated by state and local governments. The environmental Protection Agency (EPA) has established minimum criteria that these landfills must meet. Some materials may be banned from disposal in municipal solid waste landfills. Items such as paints, cleaners, chemicals motor oil, batteries, and pesticides are some of the common items that are banned from MSW's. However, some household appliances can be turned into MSW's for disposal. Figure 1.3 is showing the slope profile of a Municipal solid waste (MSW) landfills.

Figure 1.3. Profile of the Slope landfill (www.epa.gov/industrialwaste).

1.2.3. Above-ground landfill

It is vital that such sites are well planned, designed, operated, and restored. In particular, such sites need to be well engineered, and the following key issues have to be addressed: (I) Site identification and assessment; (ii) Peripheral bounding; (iii) Filling and compaction; (iv) Drainage; (v) Water management; (vi) Landfill gas management; and (vii) Monitoring programs. The practice of above-ground landfilling is gaining greater acceptance in the United Kingdom (UK). In certain respects, such sites can have advantages over conventional infilling of voids. (https://doi.org/10.1111/j.1747-6593.1990.tb01450.x.) It is shown in Landfill Footprint & Design Consultation Paper (page 13). Figure 1.4 the cut section of the Above-ground landfill. Let us remember these two characteristics of the Above-ground landfill:

- The landfill liner sits at ground surface, achieved by backfilling the quarried area.
- The landfill cap would be the height required to contain the volume of waste (approximately 17 million cubic meters). All of the waste would be above ground as a hill.

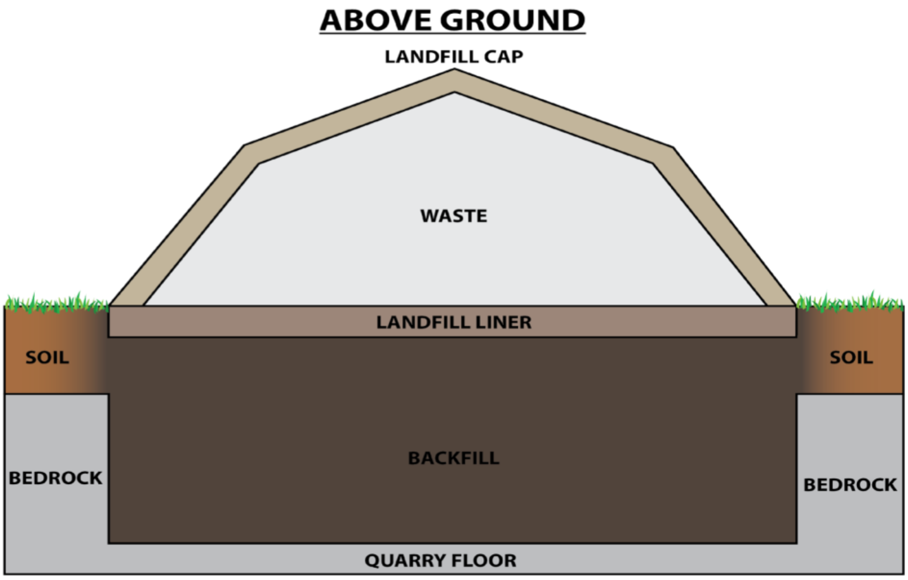


Figure 1.4. Cut section of the Above-ground landfill (Southwestern Landfill Environmental Assessment, 2016).

1.2.4. Slope landfill

Landfill slopes must be carefully designed as land sliding may happen quite frequently in Developing Countries (DCs) particularly when they are located in tropical areas. This is to high degree due to the water saturation of waste layers. It is shown in figure 1.5 by (Munawar & Fellner, 2013) the profile of the Slope landfill.

In case of huge landfills (height of more than 30 m), the maximum slope angle should be reduced or at least one berm should be constructed.

Figure 1.5. Profile of the Slope landfill (Ramon Rivera, 2016).

1.2.5. Above and Below Ground Fill

This type of landfill is like a combination of the two fills of previously mentioned types: Aboveground landfill and Trench Fill. However, the excavation area is much larger than in a Trench Fill landfill. This particular type of landfill lead to know that such sites need to be well engineered: a) Site identification and assessment; (b) Peripheral bunding; c) Filling and compaction; d) Drainage; e) Water management; f) Landfill gas management; and g) Monitoring programs. The depth of excavation normally depends on the depths of the natural clay layer and the groundwater level (Meegoda, Hiroshan, & Hettiarachchi, 2016). Figure 1.6 shows the section of the Above and below ground fill.

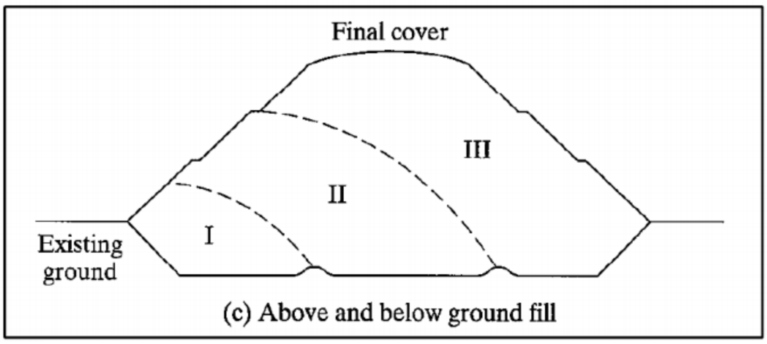


Figure 1.6. Above and below ground fill (Different Landfill configurations source: Adapted from Qian et al. (2002)).

1.2.6. Construction and demolition waste landfills

This type of landfill consists of the debris generated during the construction, renovation, and demolition of buildings, roads, and bridges. The types of debris include: concrete, wood, asphalt, gypsum (the main component of drywall), metals, bricks, plastics, trees, stumps, earth, rock, and building components (doors, windows, plumbing fixtures). Figure 1.7 is showing a view of this type of landfill.

Figure 1.7. Profile of the Slope landfill (www.enviroliteracy.org).

1.2.7. Industrial waste landfills

This is nonhazardous solid waste and consists of nonhazardous waste associated with manufacturing and other industrial activities. Industrial waste landfills as we can see in figure 1.8 a complex type of landfill either by the construction, management or by the monitoring of it. Industrial hazardous waste is a separate form of waste consisting of nonhazardous waste associated with manufacturing and other industrial activities.

Figure 1.8. Industrial waste landfill.

According to our case study in this work, we are working with Municipal solid waste (MSW) landfills. After classifying landfills according to the four previously mentioned types, it is important also to have a look on wastes before take into account the different instabilities and their causes in a landfill for a good design.

1.3. The selection criteria for a landfill.

Since all around the landfill, there are many impacts on air pollution, on the groundwater, and many other effects, the selection criteria for a landfill become one of important question in the construction design of it. Then, the main parameters to consider in the choice of the site and the type of landfill are more based on, Environmental issues, Technological, Logistical and Social aspects (Volkan, Tugba, Sevket, & H. Ebru, 2018).

1.3.1. Environmental issues of landfills.

In general, landfilling is one of the main methods of waste disposal in the world. But despite all the risks linked to this method and global warming, some countries undeveloped and developed continue to practice an uncontrolled open dumping of waste. These uncontrolled landfills constitute a relatively high threat for the various elements of the environment compared to conventional technical landfills used in many developed countries and also given the fact in particular in undeveloped countries, there is generally a burial waste of all types due to the lack of selective collection upstream and sometimes an almost unobservable recycling ((International Solid Waste, 2008). It would there be appropriate for us that before, during and after the establishment of a landfill, an environmental study be made on: Air pollution, Groundwater pollution, and its Impact on the biodiversity. In order to understand the relevance of the issue of Municipal Solid Waste (MSW) of the Developed Countries, it should be noted that population growth in the country is not only higher than in industrialized countries (Hoornweg & Bhada-Tata, 2012), but is mainly concentrated in urban areas.

1.3.1.1 Air Pollution

It is clear that enough attention has been given to modeling of landfill emission in order to quantify the landfill gas and leachate production. But on the other hand, studies that model the impacts of landfill emission are scare. When there is growing urbanization in a country whose state does not control the population completely, its economic richness also increases, but anarchically, while causing the phenomenon of urban sprawl with most of the people under educated in matter of waste management (Lavagnolo, 2017) that in some case cause the air pollution. According to (EnvironmentProtectionAuthorityVictoria, 2015), about two-thirds of landfill waste contains biodegradable organic matter from households, business and industry. As this material decomposes, it releases methane gas. As a potent greenhouse gas, methane traps up to 20 times more heat in the atmosphere compared with carbon dioxide. Oftentimes the air surrounding landfill sites smells unpleasant, due to the decaying organic waste. www.sciencing.com effects of landfills on environment). In the same wake as EPA, one cannot prevent the production of these gases in a landfill and one of the most profitable means for the man as well in the circular economy as for the well-being of the environment would be to transform these two gases (CO2 and CH4) into electricity.

1.3.1.2 Groundwater Pollution

Uncontrolled landfills have the capacity to inflict pollution on various environmental elements such as ambient air, surface water, aquifer layer, flora and fauna, etc. (Canter, 1996); (Deipser & Stegmann, 1997). According to the documentation, it has been determined that six major elements of the environment are directly affected by uncontrolled landfills which most often receive waste that has not often been recycled upstream. These six elements are: Sub-surface water quality; surface water quality; ambient air quality; noise level; flora and fauna; and aesthetics. Based on the interaction of humans and ecosystem with the six elements affected by the landfills, it is clear that these six elements can pose significant risks to human health and the ecosystem. These six pollution elements were proposed to some stakeholders for inclusion in the preparation of the Landfill Pollution Potential Index (LPPI) and after two questionnaires made by them to the populations with the following Results obtained after questionnaires 1 and 2 in Table 1.2 (annex 2).

After having produced the statistical results from questionnaires 1 and 2 by the stakeholders, the real LPPI was calculated using a matrix, in a similar way to that used to calculated the evaluation of the impact on the environment, and is presented in Table 1.3. The weighting factors for the individual elements were previously decided using the Delphi technique. The severity factor for each environmental element should be assigned on a scale of 0 to 5 depending on the concentration/intensity of the variables on which six environmental elements depend. Consequently, the theoretical range of LPPI is from 0 to 500. The gravity factor (0-5) for the six elements varied over time and with the different phases of the landfill.

It also depends on various others factors such as the age of the landfill, the type of waste, the topography of the landfill, climatic conditions, etc. The gravity factors are calculated or chosen with care because they are specific to each case, unlike the weighting factors which are set for any landfill.

As rain falls on landfill sites, organic and inorganic constituents dissolve, forming highly toxic chemicals leaching into groundwater. Water that rinses through these chemicals collects at the base of the landfill and usually contains high levels of toxic metals, ammonia, toxic organic compounds and pathogens. This can result in serious contamination of the local groundwater. Even more dangers, this mixture usually creates a high biological oxygen demand, meaning it can quickly de-oxygenate water. If or when these noxious chemicals reach rivers or lakes, it could result in the death of aquatic life (http://www.ejnet.org/landfills).

1.3.1.3 Biodiversity Impacts

According to the Romanian Ministry of Environment and Forests, the development of a landfill site means the loss of approximately 30 to 300 species per hectare. Changes also occur in local species, with some mammals and birds being replaced by species that feed on refuse, such as rats and crows. Landfills are potential threat to the quality of the environment, although the full extent of this threat has not always been scientifically validated. The main potential impacts are due to landfill gas and leachate. Both are highly complex mixtures and vary from site to site and with waste composition and age of the landfill. Moreover at any uncontrolled dump site there is a potential of health hazard to scavengers, pollution of ground water, spread of infectious diseases, highly toxic smoke from continuously smoldering fires and foul odors from decomposing refuse (OGWUELEKA, 2009).

1.3.2. Technological aspects.

Good landfill design is essential for safe waste disposal and for protecting environmental integrity of soil, air and water (groundwater and surface water systems). (https://diamondsci.com/blog/wp content/uploads/2016/01/Geogrid_on_a_slope.jpg.) Good siting in landfill also yields economic dividends to the extent, it reduces design and/or construction costs and long-term expenses associated with operation, maintenance, and recovery of potential leachate releases. Topography may also have an important influence on the selection of appurtenant structures (USBR, 1984). Although complex and sometimes costly, proper siting minimizes future impacts on public health. The main technological aspects consist in: geology/hydrogeology, Geotechnics and climate.

1.3.2.1. Geology and Hydrogeology

General controls on waste disposal site selection are presented. Geological/hydrogeological criteria primarily control the suitability of waste disposal sites, and the importance of both bedrock and drift geology to the protection of groundwater is underlined. A systematic geological/hydrogeological survey for suitable waste disposal sites in Ireland in order to produce a directory of such sites for future planning with supplementary input by engineers, geographers and biologists, is advocated. However, the capacity to undertake such surveys is severely limited by the absence of a nationwide coverage in basic geological and hydrogeological maps, a deficiency that seems unlikely to be rectified in the short term. (www.researchgate.net/publication/271766197).

1.3.2.2. Geotechnics

Landfills are typically also designed in order to maximize the amount of waste that can be accommodated in the space available according to site conditions, taking slope stability into account. In geotechnical, the main function of the subsoil is to act as the foundation zone for the high and widespread load of the landfill. Therefore, the subsoil has to be stable and non-uniform settlement should be avoided. The subsoil is also a geological barrier preventing propagation of contaminants. For the design and the construction of the landfill: there is a direct relationship between the way a landfill is designed and constructed, and the operation cost and viability of the landfill. The high quality of design and construction does not guarantee high quality of operation, but it is a precondition for accurate operation. The landfill operation aims to the construction of an environmentally acceptable waste volume but that does not lead us to stabilize geotechnicallly the different parts of landfill at the beginning and that is why the geotechnical part is important in the construction of landfill not just at the beginning, but also at the end of it the management of it.

1.3.2.3. Climate

The climate and the environmental status of the landfill location mean area sensitivity to environmental impacts, moisture balance, distance from residential areas and from the aquifers which point out the level of leachate management needed.

1.3.3. Logistical aspects

The waste management and disposal issues one way or another need to be solved in a good manner and especially in developing countries since their facing the very common question of finding the best suitable site for a landfill; also, the fact that landfill engineering design are not well care now a day. Logistical aspects are also important parts in the selection of landfill sites. It consists in: road system, distance from the point of waste collection, local aspect in connection with the management of waste.

1.3.4. Social aspects

Social aspects include: distance from villages and town, presence of restricted area (parks, important water sources for civil use, etc.…). Environmental and geotechnology strives to provide sound design principles and construction procedures to ensure short- and long-term stability and performance of landfill components. However, some parameters like: Strength, stability, and durability of the lining system are of paramount importance. Proper quality control of construction and construction materials that are selected according to design requirements is equally important. Landfill design based on reliable data gathered during the site investigation and using proven scientific methods significantly reduces risk to the environment, Environmental Geotechnics (Lorenzo Brezzi, 2019). But Economic considerations are then applied to classify the available alternatives and make the optimal choice. In many cases, after evaluating all these aspects, several types of landfills could potentially be realized.

1.4. Stabilities in landfills.

Depending on landfill's type (trench landfill, Above-ground landfill, Slope landfill, Above and Below Ground Fill) and the managements of it, different modes of failures and different causes of landfill failures exist.

1.4.1. Causes of instabilities in landfills due to landslide.

A landfill failure is a catastrophic type of failure, characterized by lack of some appropriated stabilizer materials (geosynthetics, geomembranes,) in the construction and the management of landfill and sometimes the disability of scavengers in the collection of some recyclable materials in the landfill. These failures are normally caused by a deficiency in many stages. The different instabilities in a discharge are gelled due to various causes. These causes are the result of the natural faith (loop line passing under a discharge; earthquakes; ...) and human resources (the lack of in-depth geotechnical studies prior to the burial of waste in a site; the garbage recoveries after burial by the scavengers; the mixture of all types of garbage in the landfill; ...). And according to the construction technique and the method of burying in a landfill, one can have various instabilities as presented in the following figure 1.9 that illustrates some instability due to geotechnical problems.

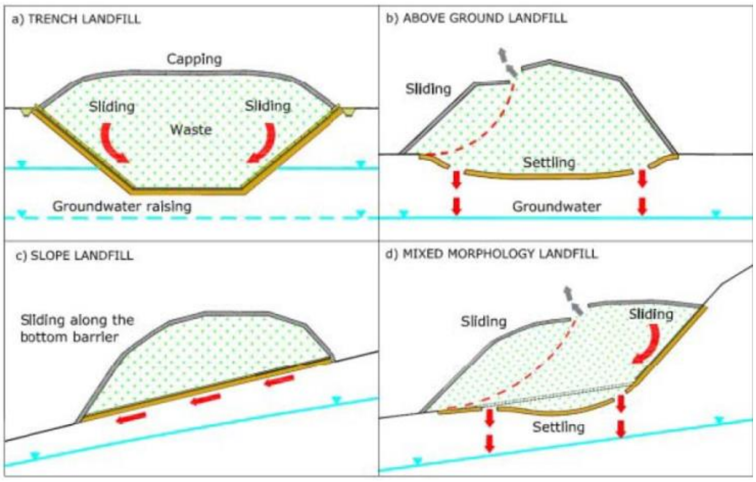


Figure 1. 9. Some instability due to geotechnical problems

To illustrate geotechnically these causes in Africa, a landslide at a huge landfill killed at least 50 people and injured dozens more outside the Ethiopian capital of Addis Ababa, Communications Minister Negeri Lencho said. The following figures 1.10 and figures 1.11 are describing well the damage due to that phenomenon.

Figure 1.10. Picture of Ethiopia trash dump landslide that kills 50 people (2017)

Figure 1.11. Ethiopia trash dump landslide (AFP• 2017) Updated by: (CNN-TV, 2017).

1.4.2. Causes of instabilities in landfills due to management.

Poor management of a landfill could lead to several dangers such as land sliding. In Addis Ababa- Ethiopia, the Koshe landfill has been the only landfill for half a century. As the city expanded, the landfill had become part of the urban landscape, sprawling over an area the size of 36 football pitches. Earlier in 2017, a landslide on the dumpsite killed 114 people, prompting the government to declare three days of mourning (United Nations Environment Program, 2017). Also, in the Mozambican capital Maputo in 2019, 17 people were killed and several others due to the failure of landfill. Failures of landfills can generally be grouped into three classes, landslide failures, uncontrolled management failures and structural failures. Following ten days of extremely heavy rains from two typhoons, a fast-moving slope failure of municipal solid waste was triggered at the Payatas Landfill, Quezon City, Philippines. The wasteslide buried more than 330 persons. Only 58 persons were rescued while, after weeks of recovery efforts, 278 bodies were recovered. We have the fact that: in Guatemala City in the Philippines the slide of landfill rubbish caused by garbage pickers and scavengers who unknowingly destabilized the piles of waste by removing materials from the base caused the death of about 50 people (Dave Petley, 2008). Figure 1.12 relates anymore the events, damages and circumstances that led to the failure.

Figure 1.12. Picture of landslide landfill Payatas, Quezon City, Metro Manila, Philippines (Jafari, Prof. Tim Stark and Prof. Scott Merry, 2000).

LOST IN THE LANDFILL. Most of the garbage generated by Quezon City residents end up in the Payatas landfill. File photo by Pia Ranada/Rappler.

(International Journal of Geoengineering Case Histories; accessed in December, 2019)

1.4.3. Cause of instability due to seepage failures.

Seepage also Induced Landfill Capping Failures and a Conservative Method for Designing landfill lateral drainage layer. The long-term stability of landfill final covers becomes a challenge when a combination of significant slopes and geomembranes are present together. The extreme weather generated by `El Niño' has generated significantly higher precipitation than what USEPA HELP model predicts. The resulting large amount of infiltrating water produces a zone of saturation that generates significant seepage forces in the overlying soil. These seepage forces if not controlled can result in a slope failure during a design surface water event. Such failures have proven to be very costly. This part focuses on a review of the design of geocomposite drainage layers to satisfy critical design considerations and demonstrates how geocomposite drains can be designed to control these seepage stresses.

Actual examples of landfill failure resulting from inadequate drainage are described, and design changes that would have alleviated problems are also discussed. (https://ascelibrary.org November 19, 2019).

1.5. Construction techniques of landfills.

It is important to take into account the bottom liner system of landfill, the construction and operation in the design of landfill.

1.5.1. Landfill construction

Two types of different specifications for the construction of landfills are described according to the type of work based and the based performance (Bagchi, 2004). In the work-type, the contractor is given detailed instructions on "what" and "how" and it is closer to traditional design-bid-build delivery method. Performance based method requires to specify the final product and not the process and more similar to the emerging delivery method of design-build. Performance based specification method is often preferred as the details necessary for the work-type method is difficult to gather and there is huge uncertainly. Hiring independent quality control staff is essential to the successful implementation of the project.

1.5.2. Landfill Operation

It is very important to have a detailed operation plan that is a major asset to make the daily construction operation more convenient and risk-free. (Tchobanoglous & Kreith, 2002) provide a detailed report on the important factors that need to be taken into account when operating a landfill. Planned operation, filling plan, Equipment requirements, operating records, billing information, traffic control, safety and security are among the priorities to be taken into account in the management of a discharge. Other factors that need to be considered are listed (annex 1). An appropriate plan ensures a safe work environment, optimizes space management, and also minimizes environmental damage. Important aspects related to discharge filling and special considerations for filler and Compaction waste are briefly addressed in the next part of the work. For a good geotechnical design that will lead to good environmental prevention, it will be advisable to focus on the following aspects: Salvage; Spreading and compaction; and daily waste coverage.

1.5.2.1. Spreading and compaction

It is important that after the burial of the waste in a discharge, that the compacting process follows because some slip of waste occurs because of the not very adhesive contact between the bottom of the lockers in a dump and the layer of waste that is very remarkable with a strong pluviometry. In the rainy season, the water infiltrates the waste and makes the contact surface very smooth with the background. When the landfill is ready to accept the waste, it is filled with elevators (figure 1.13).

The selection of the compaction equipment depends on the types of slopes according to the nature of the soil and depends on the use of geosynthetics or not. The steeper slopes that 1 in 3 are better compacted by track type tractors, while the shallow slopes are better handled by the release compactors (Vesilind, Worrell, & Reinhart, 2002). The waste in the first lift must be projected to remove all sharp objects so that they cannot damage the coating. The sequence must be defined during the design phase (ibid) and the work face must be large enough to treat the waste disposal of several trucks at the same time.

Figure 1.13. Filling operation of Calgary Biocell.

1.5.2.2. Salvage

Recovery: A phenomenon almost found in the majority of landfills notably those of underdeveloped countries and those of developing countries. It is a waste recovery process after the trucks have been blessed in the dump. And this process, most of them in places close to the ravines, can be a source of flaw and landslide in the waste in a dump.

1.5.2.3. Daily waste coverage

One of an essential part of landfilling operations is the placement of cover over the wastes. And the main purpose of cover waste is to: Minimize landfill odors; Control litter; Prevent the spread of fire; Control disease vectors such as birds, flies, mosquitoes and rodents; Ensure that the landfill is practicable.

It is also important to note that: Landfills that accept only solid inert or building material may not require daily cover provided that emissions (odour, dust litter and so on) are adequately controlled (EnvironmentProtectionAuthorityVictoria, 2015). With strong pluviometry, the saturation of the water, increases the weight of the cover and decreases the friction resistance along the waste.

1.5.3. Bottom liner system of landfill

The lower coating system as any other part of a discharge is an essential part that must be well designed because in the majority of landfills in developed countries and even in some developing countries, it is the part that is in direct contact with the waste and where the infiltration of leak in the ground instead. According to the current Italian law (D.Lgs 36/2003 All. 1), the lower liner system requires as presented in table 1.2 the different geological barriers with their thicknesses, their positions in relation to the water table and the coefficients of permeabilities. The aim of implementing a bottom barrier layer within the landfill is to avert or reduce the contamination of soil, surface water, as well as groundwater by leachate or having polluted water generated from the landfill locations. The bottom barrier layer acts to filter the leachate materials within it and to avoid the lateral surface flow of leachate. The bottom barrier consists of composite materials of compacted soils, which have a low permeability. In the current design, the bottom barrier layer consists of sandy clay with high compaction. The thickness of the bottom barrier layer is 0.6 m, and its saturated hydraulic conductivity is 1.0×10^{-7} cm/s (Ali Chabuk et al, 2018).

Table 1. 2. Different geological barriers with their thicknesses and permeabilities coefficients.

For inert wastes	For no-dangerous wastes	For dangerous wastes
	Drainage layer s > 0.5 m	Drainage layer s > 0.5 m
Geological barrier $k < 10^{-7}$ cm/s and s > 1m (or equivalent **but s>0.5m**)	Geological barrier $k < 10^{-7}$ cm/s and s > 1m (or equivalent)	Geological barrier $k < 10^{-9}$ cm/s and s > 5m
Distance from aquifer (confined or not) ≥ 1.5 m	Distance from aquifer ≥ 1.5 m if confined ≥ 2 m if unconfined	Distance from aquifer ≥ 1.5 m if confined ≥ 2 m if unconfined

1.5.3.1 Subgrade preparation

The subgrade on which a soil liner is placed should be properly prepared, i.e., provide adequate support for compaction and be free from mass movements. The compacted soil liner may be placed on a natural or geosynthetic material, depending on the particular design and the individual component in the liner or cover system. Sometimes it is necessary to "tie in" a new section of soil liner to an old one, e.g., when a landfill is being expanded laterally. It is recommended that a lateral excavation should be about 3 to 6m (10 to 20 ft) into the existing soil liner, and that the existing liner should be stair-stepped as shown in figure 1.14 to tie the new liner into the old one. The surface of each of the steps in the old liner should be scarified to maximize bonding between the new and old sections.

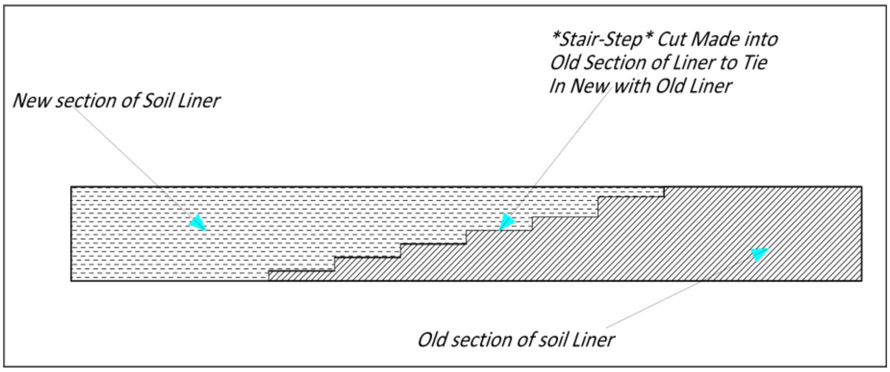


Figure 1.14. Tie-In of New Soil Liner to Existing Soil Line (Compacted soil book, 2019).

1.5.3.2. Subgrade Stabilization

Subgrade Stabilization is the use of geosynthetic reinforcement elements to provide constructability and access over very soft soils. Figure 1.15 illustrates the reinforcement of the subgrade soil with geosynthetic.

Figure 1.15. Reinforcement of the subgrade soil with geosynthetic (www.tencategeo.eu accessed in 2019).

Due to the fact that soils differ from one place to another, it is important to take into account the stabilization of the foundation layer in a landfill in order to promote a good platform and to prevent leakage of leachate. This use establishes a well-compacted non-yielding platform with uniform support. It is important after the Subgrade Preparation, to design the Sub-base of the landfill.

1.5.3.3. Single Composite Liner System

The principal functions of a landfill liner system are to limit contaminant migration to groundwater and to control landfill gas migration. This type of liner is used in landfills; comprises of single leachate collection layer and composite barrier layer. A further function of the liner is to control infiltration of groundwater. In designing a landfill liner, the landfill designer must ensure that the liner system is geotechnically stable between components and as a total system. The Composite liner system of the landfill is usually made of two parts which include: Geomembrane Liner and Compacted Clay.

a) Geomembrane Liner

A thick plastic layer forms a liner that prevents leachate from leaving the landfill and entering the environment. This geomembrane is typically constructed of a special type of plastic called high-density polyethylene or HDPE. HDPE is tough, impermeable and extremely resistant to attack by the compounds that might be in the leachate. In a landfill, the geomembrane liner is put over the composite barrier layer, and the bottom barrier and geomembrane act together to prevent leachate percolation into the groundwater. In a good design, a geomembrane of high-density polyethylene (HDPE) has to be selected for the chosen landfills. The thickness of the geomembrane is 0.15 cm, and its hydraulic conductivity is 2.0×10^{-13} cm/s for a suitable design.

b) Compacted Clay

Is located directly below the geomembrane and forms an additional barrier to prevent leachate from leaving the landfill and entering the environment. As we can see, Geomembrane and Compacted Clay as the two important parts of Composite Liner System, with each of them having its own strength, they finally play same role that is also to help to prevent the escape of landfill gas.

1.5.3.4. Double Liner System

This type of liner is used in landfills; comprises of primary and secondary leachate collection systems as well as primary and secondary composite barrier layers. Secondary leachate collection system is also called the leakage detection layer. Starting at the bottom, a double composite liner consists of: a 0.6m thick compacted (or geocomposite clay that can be equivalent to a 0.6m thick compacted clay liner; a secondary geomembrane, secondary leachate collection (or leak detection) layer; a minimum 0.6m thick primary compacted clay liner (or geocomposite clay liner that can equivalent to a 0.6m thick compacted clay liner); a primary geomembrane and a primary leachate collection system; a 0.6m thick protective sand blanket. The leachate collection system consists of a layer of clean sand or, in alternative, a synthetic geonet coupled with a geotextile. The former provides good in-plane drainage conveyance and the latter good cross-plane drainage together with the ability to exclude (filter out) fines. The geomembrane must be at least 1.5mm thick if HDPE (2mm in Italy), or 0.75mm thick if made from other resins. The permeability of the subbase and compacted clay must not exceed 10^{-9}m/s.

1.5.4. Importance of Leachate Collection System.

The design objectives of the leachate collection system are to ensure that it is: able to drain leachate sufficiently, that the leachate head above the liner is minimized, appropriately sized to collect the estimated volume of leachate (predicted by water balance models), resistant to chemical attack, physical, chemical and biological clogging, able to withstand the weight of waste and the compaction equipment without crushing, able to be inspected and cleaned by readily available video inspection and pipe-cleaning equipment.

1.5.5. Some damages due to bad design of leachate collection system.

Leachate collection systems can fail in less than a decade, in several known ways: they clog with silt or mud, micro-organisms clog the pipes, precipitation from chemical reactions block the pipes, the pipes are damaged during installation or early in the filling of the landfill or the pipes become weakened by chemical attack (acids, solvents, oxidizing agents, or corrosion) and are crushed. To reduce the risk of mechanical failure of the leachate collection pipes, they should be: flexible rather than rigid, placed on evenly prepared bedding material and be protected with adequate surround material. Protected by a traffic-control program minimizing the movement of heavy vehicles across them until sufficient waste has been placed over the drainage layer to avoid crushing pipes. The installation of the leachate collection system must be included in the CQA plan (see section 2.4 in (EnvironmentProtectionAuthorityVictoria, 2015)).

1.6. Design considerations of landfill.

Once a landfill's site has been selected, by geotechnical design, it must be designed also to ensure that it is able to protect the environment. The design of a landfill facility will be influenced by the existing natural environment, adjacent land uses, available infrastructure, waste to be received and the need to provide integrated waste management facilities for both disposal and recycling options. It must be based on a thorough understanding of the existing environment and address each of the site-specific circumstances of each site. This section must be implemented for all landfills and any new cells (EnvironmentProtectionAuthorityVictoria, 2015).

1.6.1. Slope of Landfills

Landfill slopes must be carefully designed as land sliding may happen quite frequently in DCs particularly when they are located in tropical areas. This is to high degree due to the water saturation of waste layers. To minimize the risk, (Munawar & Fellner, 2013) suggest that the incline of the slope should not exceed 25%. In case of huge landfills (height of more than 30 m), the maximum slope angle should be reduced or at least one berm should be constructed.

1.6.2. Sustainability

Sustainability is often misunderstood. There are a number of differently worded definitions which do cause confusion. One must consider the inter-relationship of the environment (environmental factors), people (social factors) as well as the economy (financial factors). If any of these three groups of factors are at risk of not being fulfilled, then the system cannot be regarded as sustainable. One such definition of sustainability is "existing and solving today's problems in a responsible and environment friendly manner thereby not prejudicing the ability of future generations to exist or solve their own problems". In a waste management perspective, one often refers to a cradle to grave approach as being a sustainable approach, however, without considering the stabilization of waste within a landfill sustainable waste management cannot be achieved. The waste within a landfill must be stabilized within "one lifetime" thereby ensuring that no negative effects or risks associated with a landfill are passed on from one generation to the next (Peter Novella, 2014). However, Benson et al. (1992) compiled a data base from Construction Quality Assurance (CQA) documents and related the hydraulic conductivity measured in the laboratory on small, "undisturbed" samples of field-compacted soil to various soil characteristics.

1.7. Soil characteristics for a landfill

However, it is important to specify that in most underdeveloped countries where it is difficult to use geosynthetics in a landfill, to check the quality and permeability of the soil before the burial of waste. These audits can be done by concluding the test results at the laboratory according to the standards defined by other researchers.

1.7.1. Compaction curve on soil of landfill

It is important to compact a soil especially in order to increase its resistance. The proctors conducted on the six samples allowed us to know the optimal value of the water content for good resistance. In view of the above, the soil being clay is a good factor for water tightness and can be used as a waste separation layer and cover soil. On the other hand, a soil of the same characteristics to be used as slope or ground floor in a locker in another area as a borrowing soil, should be compacted to a certain degrade with an optimal water content respecting the compaction criteria of the following figure 1.16. Benson and Boutwell (1992) summarize the maximum dry unit weights and optimum water content measured on soil liner materials from 26 soil liner projects and found that the degree of saturation at the point of (wept, $y_{d,max}$) ranged from 71% to 98%, based on an assumed Gs value of 2.75. The average degree of saturation at the optimum point was 85%.

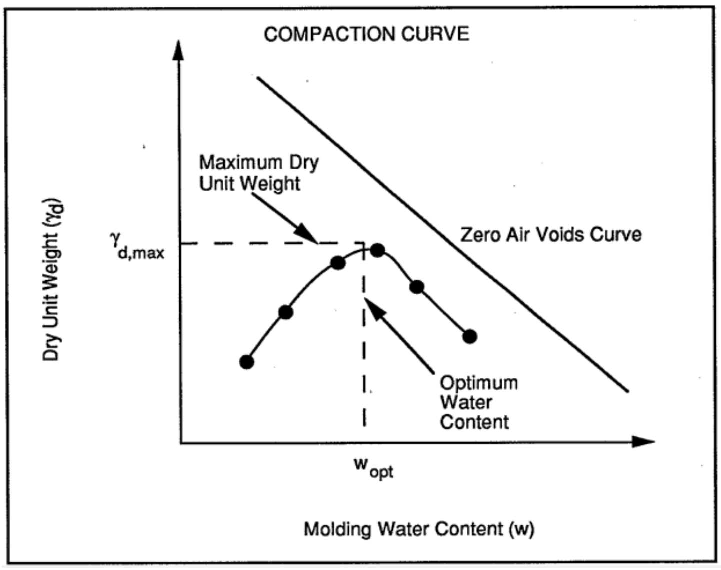


Figure 1. 16. Compaction Curve.

The zero air voids curve, also known as the 100% saturation curve, is a curve that relates dry unit weight to water content for a saturated soil that contains no air. Yd, which is the zero air voids curve defined in the equation 1.1 as:

$$\boldsymbol{Y_d = \frac{Y_w}{[W + \left(\frac{1}{G_s}\right)]}} \qquad \mathbf{1.1}$$

Where: $\boldsymbol{G_s}$ is the specific gravity of solids and $\boldsymbol{Y_w}$ is the unit weight of water.

If the soil's specific gravity of solids changes, the zero air voids curve will also change. Theoretically, no points on a plot of dry unit weight versus water content should lie above the zero air voids curve, but in practice some points usually lie slightly above the zero air voids curve as a result of soil variability and inherent limitations in the accuracy of water content and unit weight measurements (Schmertmann, 1989).

The observed relationship between hydraulic conductivity and plasticity index is shown in figure 1.17. The data base reflects a broad range of construction conditions, soil materials, and CQA procedures. It is clear from the data base that many soils with Plasticity Index as low as approximately 10% can be compacted to achieve a hydraulic conductivity less than 10^{-7}cm/s. It should be noted that even knowing the plasticity index of a soil, one can also determine its permeability coefficient as shown in figure 1.18 of Benson et al.

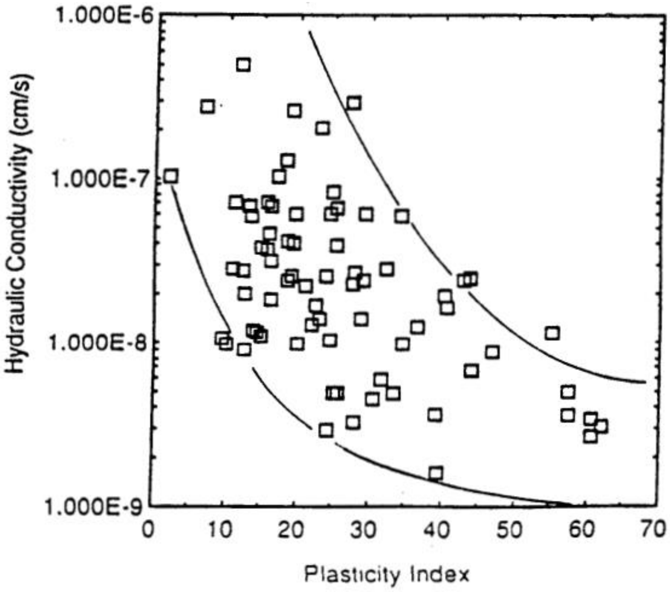


Figure 1. 17. Relationship between Hydraulic Conductivity and Plasticity Index (Benson et al.,1992).

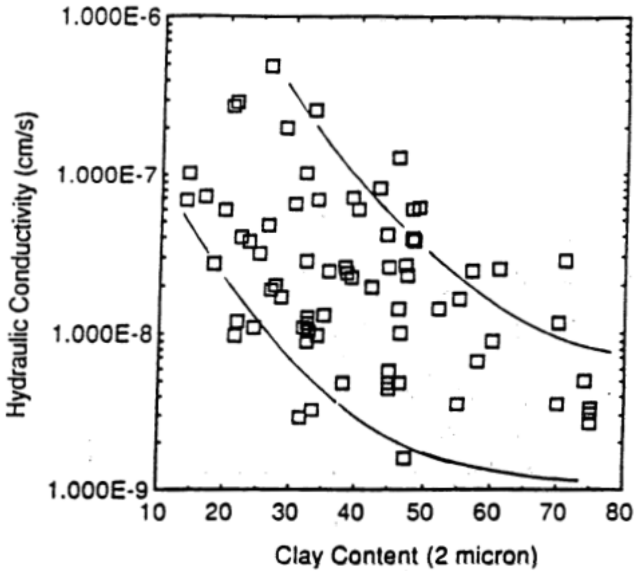


Figure 1. 18. Relationship between Hydraulic Conductivity and Clay Content (Benson et al.,1992).

1.7.2. Advantages and disadvantages of In-situ tests on landfill soils.

The use of specialized in-situ testing in geotechnical engineering practice is rapidly gaining increased popularity. In Europe, specialized in-situ testing has been commonly used for more than 25 years. Improvements in apparatus, instrumentation, and technique of deployment, data acquisition and analysis procedure have been significant. The rapid increase in the number, diversity and capability of in-situ tests has made it difficult for practicing engineers to keep abreast of specialized in-situ testing and to fully understand their benefits and limitations (Suryakanta, 2015). These methods of soil checks can also be directly verified by the in-situ tests which have multiple advantages and sometimes disadvantages (table 1.3) from which the need for verification by both methods.

Table 1. 3. Advantages and disadvantages of In-situ tests.

Advantages	**Disadvantages**
-Tests are carried out in place in the natural environment without sampling disturbance, which can cause detrimental effects and modifications to stresses, strains, drainage, fabric and particle arrangement -Methods are usually fast, repeatable, produce large amounts of information and are cost effective -Tests can be carried out in solids that are either impossible or difficult to sample without the use of expensive specialized methods -The facilitation to make quick decisions while on the site instead of having to wait for a result. Although lab testing is still important for confirmatory and more precise findings.	-Samples are not obtained; the soil tested cannot be positively identified. The exception to this is the STP in which sample, although disturbed, is obtained. -The fundamental behavior of soils during testing are not well understood -Drainage conditions during testing are not known -The stress path imposed during testing may bear no resemblance to the stress path induced by full-scale engineering structure -Most push-in devices are not suitable for a wide range of ground conditions -Some disturbance is imparted to the ground by the insertion or installation of the instrument

Conclusion

The purpose of this chapter was to present the landfill in a general way and its geotechnical construction techniques. The realization of this goal was made by the presentation among other things of the history of the landfill, the classification of landfills, the different instabilities and their causes. Based on all of this, we found that the landfills have experienced a rapid evolution with the time thus posing a number of major problems among which geotechnical construction techniques should be sufficiently taken into account. As a result, in order to ensure the stability of the construction of a landfill, there is a need to practice the right methods of rubbish of waste, avoid the recovery of waste in the site by scavengers and the use of any flammable energy source that has been introduced in some landfills as a fire sources causing many landslides of wastes and loss in human lives. Later in this work, after analysis of the results of the geotechnical tests that we will conduct in laboratories and in-situ on the soil samples of the landfill of Nkolfoulou, we will propose some appropriate construction techniques taking into account the current challenges such as the country's waste management system and the financial aspect of the company in charge of waste management in the center region.

Chapter II: METHODOLOGY OF THE STUDY

Introduction

The methodology is the part allowing to establish the procedure of the research in order to reach the fixed objectives. In other words, it will be a question of describing the different constitutive elements of our research. This will be the presentation of the study area through a site recognition and visit, as well as the presentation of the methodological approach that will guide the present work. In the case of methodological approach, it will be described the data collection based on materials that will be used and the various geotechnical tests carried out. At the end, an exploitation of results will be presented.

2.1. Site recognition

The recognition of the site will be done from a documentary research whose essential goal is to know on one hand the physical parameters (the location of the site, relief, the climate, the geology, the hydrology, the fauna and the flora) of our site to know, and on the other hand the socio-economic parameters that are the demography and economic activities of the region.

2.2. Site visit

This part will consist in one hand on the observation during the descent on the site and in the order hand, to the survey.

2.2.1. Observation

Here, we will illustrate the evolution of the landfill, what we have find in place.

2.2.2. Survey

A survey is that research method used for collecting data from a pre-defined group of respondents to gain information and insights on various topics of interest. A series of questions will be asked to those responsible for the work on the site and to the surrounding populations. The answers obtained will make it possible to evaluate the impact project on the daily life of populations, to know the current state of the landfill, the conditions of implementation of the landfill and the difficulties encountered during the construction of the landfill.

The questionnaire to be submitted to the engineers responsible for the landfill shall include the following questions:

(1) How does the site behave during the rainy season?

(2) How does it behave in the dry season?

(3) Since its commissioning, has the structure suffered any damage?

(4) if yes: of great importance or not?

(5) What is the most likely cause of instability in this structure?

(6) How is the structure inspected?

(7) What was the life of the structure when completed?

(8) What has been the performance of the landfill since it was commissioned?

The questionnaire that will be submitted to the populations includes the following questions:

(1) How did you receive the arrival of this project in this community?

(2) Did this project meet your expectations?

(3) What were your expectations for this project?

(4) What are the advantages and disadvantages of this project in your community?

Data collection

The data collection is based on materials collection and some geotechnical tests.

2.3. Geotechnical tests

Among them, we distinguish particle size analysis, water content, Atterberg's limits, proctor test and In-situ test (Boutwell permeameter test).

2.3.2.1. Particle size analysis (NFP 94-056)

a. Aim of the test

The purpose of the particle size analysis is to determine the dimensional distribution of the grains constituting a soil whose dimensions are between 0.063 and 125 mm and to draw the particle size curve which illustrates the evolution of the percentages by weight passing and cumulative retained as a function of sieve. From this curve, we will assign a nomenclature to identify and classify the corresponding soil.

b. Test principle

The test consists in fractionating, by means of a series of sieves, a material into several granular classes of decreasing sizes. The masses of different refusals and passing are reported to the initial mass of the material. The percentages thus obtained are used in graphic form.

c. Expression of results

The test will be conducted according to the standard NFP 94-056 from the material borrowed. In that sense, it will be question of classifying the material.

Usually, a soil or a material can be granular or cohesive. Thus, two coefficients have been defined to characterize soils based on the distribution of particles:

(a) C_u, which is the coefficient of uniformity defined in the equation 2.1.

$$C_u = \frac{D_{60}}{D_{10}} \qquad 2.1$$

(b) C_c, which is the coefficient of curvature defined in the equation 2.2.

$$C_c = \frac{D^2{}_{30}}{D_{60} * D_{10}} \qquad 2.2$$

Based on these two coefficients, we can classify a soil using the USCS for coarse grained as shown in table 2.1.

Table 2. 1. Classification of soil based on USCS (Lorenzo Brezzi, 2018).

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[a]				Soil Classification	
				Group Symbol	Group Name[b]
(1)	(2)	(3)	(4)	(5)	(6)
COARSE-GRAINED SOILS More than 50% retained on No. 200 sieve	GRAVELS More than 50% of coarse fraction retained on No. 4 sievc	CLEAN GRAVELS Less than 5% fines[c]	$C_u \geq 4$ and $1 > C_c < 3$[e]	GW	Well-graded gravel[f]
			$C_u < 4$ and/or $1 > C_c < 3$[e]	GP	Poorly graded gravel[f]
		GRAVELS WITH FINES More than 12% fines[c]	Fines classify as ML or MH	GM	Silty gravel[f,g,h]
			Fines classify as CL or CH	GC	Clayey gravel[f,g,h]
	SANDS 50% or more of coarse fraction passes No. 4 sieve	CLEAN SANDS Less than 5% fines[d]	$C_u > 6$ and $1 < C_c < 3$[e]	SW	Well-graded sand[i]
			$C_u < 6$ and/or $1 > C_c > 3$[e]	SP	Poorly graded sand[i]
		SANDS WITH FINES More than 12% fines[d]	Fines classify as ML or MH	SM	Silty sand[g,h,i]
			Fines classify as CL or CH	SC	Clayey sand[g,h,i]

Otherwise, we can also classify our soil based on the figure 2.1.

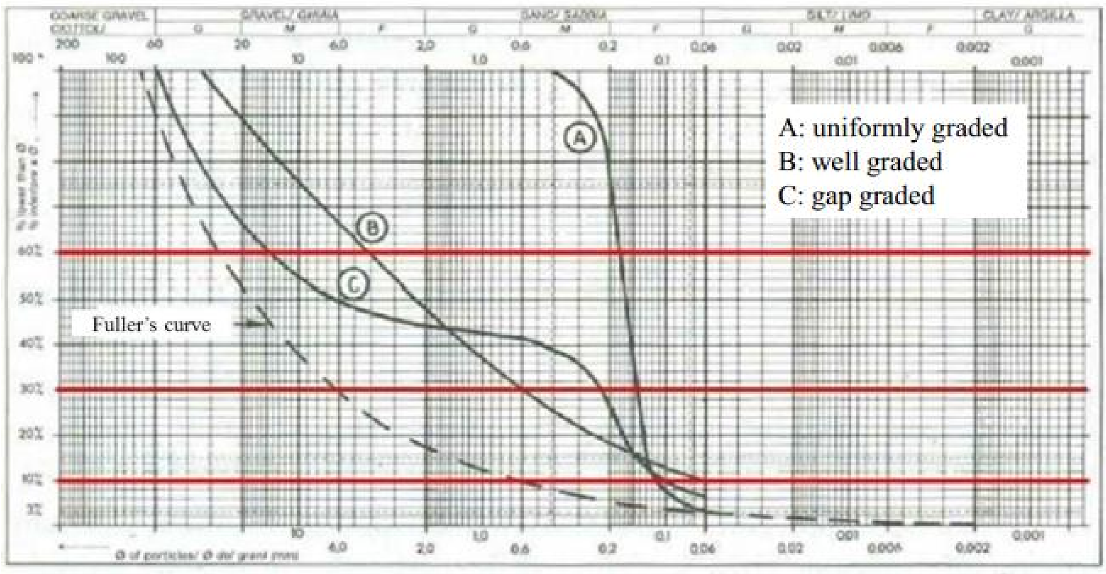


Figure 2. 1. Soil classification (Emiliano Pasquini, 2018).

2.3.2.2. Water content (NFP 94-050)

a. Aim of the test

The purpose of this test is to determine the water content of a material.

b. Principle

The sample of wet material is removed and weighed and placed in an oven at 105 ° C for a period of 24 hours in general until a constant mass (corresponding to the mass of the dry material) is obtained.

c. Expression of results

The present test will be conducted based on the NFP 94-050 standard in order to determine firstly the natural water content of the laterite just after sampling. Secondly, the test will be conducted to determine the water content of the mixture during the following tests.

Usually, it is noted **w** and is determined using the formula of the equation 2.3.

$$w = \frac{water\ weight}{dry\ material\ weight} * 100 \qquad 2.3$$

2.3.2.3. Atterberg's limits (NF P 94-051)

a. Aim of the test

The purpose of this test is to determine on the one hand the limits of consistency of a soil (limits of liquidity, plasticity) and on the other hand its index of plasticity in order to classify this soil. This is one of the most important identification tests. These limits (limits of liquidity and plasticity) are the water contents corresponding to specific states of a soil: liquid, plastic, solid with shrinkage and solid without shrinkage.

b. Principle

It should be noted that the test is carried out with standard equipment, and with a fraction of soil that passes only with a 0.40 mm sieve.

c. Expression of results

i. Determination of the liquid limit

The liquid limit denoted W_L is the water content for which 25 shocks of the cup close the lips of the standardized groove over a length of 10 to 12mm. It is obtained from the graph of Water content in terms of the Number of blows (figure 2.2).

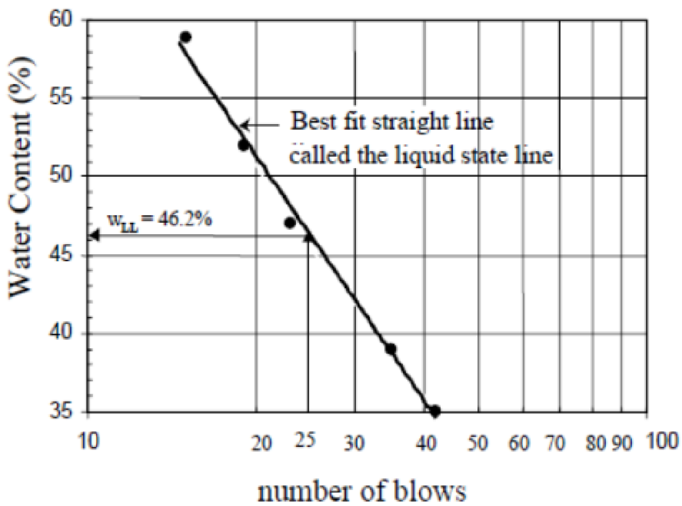


Figure 2. 2. WL determination from Casagrande's cup method (Alberto Bisson, 2017).

ii. Determination of the plastic limit

The plastic limit denoted by W_p is the water content for which a cylinder of diameter equal to 3 mm can be rolled over a length of 10 to 15 mm and when it is lifted from 1 to 2 cm, it breaks. It is necessary to make 2 to 3 measurements.

iii. Determination of plasticity index

The plasticity index noted I_p or PI is deduced from W_L and W_p by the formula (equation 2.4) in order to determine the plasticity of the soil.

$$\mathbf{PI} = \boldsymbol{W_L} - \boldsymbol{W_P} \qquad \mathbf{2.4}$$

Where:

W_L is the liquid limit;

W_p is the plastic limit.

In this study, the Atterberg's limits are done following the **NF P 94-051** standard.

Using the value obtained, it is possible to classify the soil by following the qualitative manner of Burmister (1949) defined in table 2.3.

Table 2. 3. Soil Classification from Burmister (Alberto Bisson, 2017).

PI	SOIL
0-1	No plastic
1-5	Slightly plasticity
5-10	Low plasticity
10-20	Medium plasticity
20-40	High plasticity
> 40	Very high plasticity

2.3.2.4. Proctor test (NF P94-093)

a. Aim of the test

The purpose of this test is to determine, for a compaction of given intensity, the water content to which a soil must be compacted to obtain a maximum dry density. The water content thus determined is called optimal water content.

b. Principle

The Proctor test consists of compacting a soil sample in a standardized mold, using a standardized hammer, in a well-defined process (CBR or Proctor), to determine the optimum Proctor water content and corresponding dry density. The test is repeated several times in succession on the samples taken at different water contents to obtain the points of the curve representative of the dry densities as a function of the water contents. The maximum of this curve, which is in principle a bell turned downwards, is for the abscissa the optimum water content Proctor and for ordinate the maximum dry density.

On stabilization sites, dry densities of 90% are generally required or 95% of the maximum dry density, determined in the Proctor test; hence the importance of having at the time of compaction a water content very close to the optimum water content. This condition is often difficult to fulfill, which limits the possibilities of stabilizing soils. In raining weather, the moisture content of the natural soil is generally greater than the optimum, so we can air the soil to dry or wait for a drier period. In drier period, water is important (the optimum water content varies between 6 and 12% depending on the nature of the soil and the compaction machine used). In this study, the modified proctor test will be performed based on NF P94-093 standard, on the six soil samples from the landfill site.

c. Expression of results

At the end of each test, we will present the maximum dry density corresponding to the optimum water content, obtained from a graph like the one shown in figure 2.2.

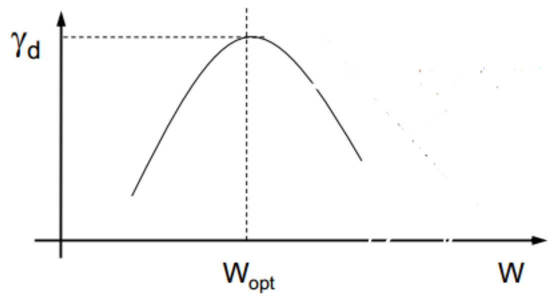


Figure 2. 2. Compaction curve (Lorenzo Brezzi, 2018).

2.3.2.5. Field hydraulic conductivity testing (Boutwell permeameter test)

The two commonly used borehole tests are (1) Boutwell permeameter and (2) constant-head permeameter and in this work, we focused on Boutwell permeameter test.

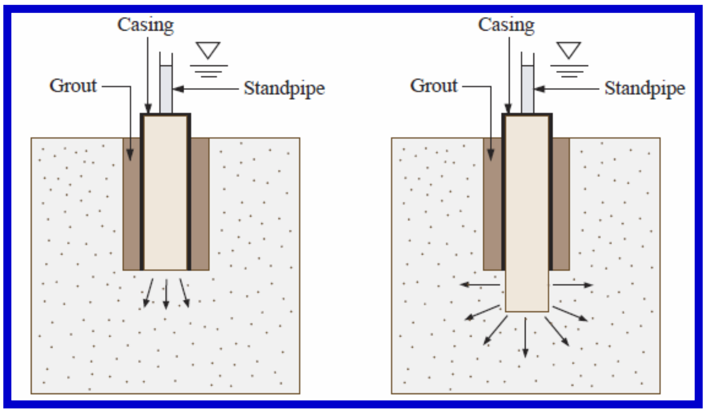
a. Aim of the test

The purpose of this test is to determine the vertical permeability coefficient on a given floor without going through the laboratories in record time.

b. Principe

This consists of embedding a vertical pipe of a section area **A** into a trench of soil such as the pipe height is twice greater than its diameter and recording the quantity of flow **V** over a time **t** by measuring the change in water level in the ring with a hook gauge.

The main test carried out was the infiltration of the leak in the ground of the landfill, more precisely that of the 3G locker in development. Three holes were drilled in the 3G record for the set-up of the device. This device is installed by placing a casing inside a predrilled hole. The annular space between the casing and the hole is sealed with grout. Between the two different cases as the figure 2.3 illustrates, the falling-head hydraulic conductivity test was then performed.



CASE 1 CASE 2

Figure 2. 3. Different cases of Boutwell permeameter test.

c. Expression of results

Assuming that the influence of soil suction is small compared with pressure head. If we define $\mathbf{D'}$ as the length of flow, the apparent hydraulic gradient is:

$$\boldsymbol{i} = \left(\frac{H + D'}{D'}\right) \qquad (2.5)$$

With the infiltration rate defined by:

$$\mathbf{I} = \frac{\mathrm{Q}}{\mathrm{A*t}} = \frac{\mathrm{V}}{\mathrm{t}}\left[\mathrm{m}^3/_\mathrm{s}\right] \qquad (2.6)$$

The method to estimate approximate hydraulic conductivity (**k**) is done by using equations 2.5 and 2.6.

$$\mathbf{k} = \frac{\mathbf{I}}{i} \tag{2.7}$$

Finally, using the following Boutwell's equation the permeability coefficient (**K**) is expressed as:

$$\mathbf{K} = \frac{I * i}{A} = \frac{\frac{V}{t} * (\frac{H + D'}{D'})}{A} * 1000\ [{}^{cm}/_{s}] \tag{2.8}$$

2.3.1. Materials collection

The materials that will be collected will be used for some geotechnical tests in order to achieve our objective.

2.3.2. Data collection

The data collection is based on the collection of soil samples in the site.

2.4 Sizing method

The development of the sizing method begins with the definition of a clear goal to be achieved, then by the definition of some assumptions and considerations and finally the definition of the sizing method. A good condition of the foundation is a mandatory condition for the construction of a landfill. Rarely in a good state, it is necessary to stabilize the foundation base. The choice of the stabilization method generally obeys at certain criteria. Once the stabilization method is chosen, it is customary to carry out a verification of the performance of the work carried out by a numerical analysis in order to ensure the effectiveness of the stabilization method.

2.4.1. The Aim

The goal to ensure the stability of the foundation underlay while preventing a possible rupture, our study consists in:

- Check the **Stability** of the soil under the load of waste using the GeoStudio software;

- Check the **Permeability** of the soil, in particular that of the load base underlayment under GeoStudio software;

- Check the **Bearing capacity** of the foundation of soil;

- In the unfavorable case of all these three checks, it will be a question of reinforcing the soil using the different types of Geosynthetics with high strength so as to obtain a considerable safety factor: in this case, FS=1.2 because we are going to use the Limit Equilibrium Method (LEM).

2.4.2. Choice of the type of geosynthetic.

Geosynthetics are categorized according to the mode of manufacture and each play a specific role. To make a satisfactory choice, we will rely on the features we are looking for on our geosynthetic. Table 2.4 summarizes the functions of the geosynthetics that we will support.

Table 2. 4. Multifunctional nature of Geosynthetics and functionality within various applications (DR. KAVURU SAMBASIVA RAO, LAKSHMI, & Chatterji, 2013).

Type of Geosynthetic (GS)	Separation	Reinforcement	Filtration	Drainage	Containment	Protection	Erosion Control
Geotextile	■	■	■	■		■	
Geogrid		■					■
Geonet				■			
Geomembrane					■		
GCL					■		
Geofoam	■	■					
Geocells	■	■					
Geocomposite	■	■	■	■	■		
Polymer Gabion						■	■
Geobags						■	■
Geotextile Tubes				■		■	■
PVDs			■	■			
Geomats		■		■			■
Geopipes				■			
Natural Fibre Geosynthetics	■	■	■	■			

Mostly used →	■

Conclusion

This chapter presented the methodology adopted to achieve the objectives of our study. It appears that this methodology is based on two main points namely the presentation of the study area, and the geotechnical part. The first one passes by the situation of our case study, as well as of the section of landfill. The geotechnical framework, initially presents the tests of complete identification of the soil, and in a second time, the in-situ test carried out. In the next chapter, it will therefore be a question of presenting our study area in general, of giving the results of the various tests carried out, of seeing the gap between the obtaining of the permeability coefficient in-situ and that obtained by the tests in laboratories. After that, we will carry out an interpretation of all these results.

Chapter III: PRESENTATION OF RESULTS AND INTERPRETATION

Introduction

The results achieved after the implementation of the established work methodology will be the subject of this chapter. After a general presentation of the Nkolfoulou landfill, as well as the site and materials collected, we will first present the results from the complete identification of our soil samples namely the particle size analysis, the water content, the Atterberg's limits, the Proctor test; and the In-situ permeability test. At the end, we will analyze the results obtained and see in which proportion the soil-plastic mixture can be used. So, we will therefore be able to answer the question of whether or not to reinforce the soil of the landfill of Nkolfoulou by geosynthetics.

3.1. General presentation of the site.

Here, we will present the study area through its location, geology, relief and soil, climate, hydrography, vegetation, population and economic activities.

3.1.1. Geographic location.

The Nkolfoulou landfill entirely located in the central region between 3° and 5° latitude North; 11° and 13 ° of East longitude. It is located on the interfluve of the rivers Nyong and Sanaga to the western border of the South plateau Cameroonians. Yaoundé, nicknamed the city of the seven hills, is the capital of the Central Region and the siege of the institutions of the Republic of Cameroon. With a surface area of about 310 km^2, Yaoundé currently has seven (7) boroughs numbered from I to VII (figure 3.1). In this administrative cut corresponds a rather large number of quarters among which one can distinguish the structured quarters of the unstructured quarters (source: Environmental impact assessment of Hysacam; January 2010).

The company Hysacam runs its activities in the so-called districts where it takes care of the collection and transport of the household garbage. These wastes are treated in a controlled landfill in Nkolfoulou located in the division of Mefou-Afamba.

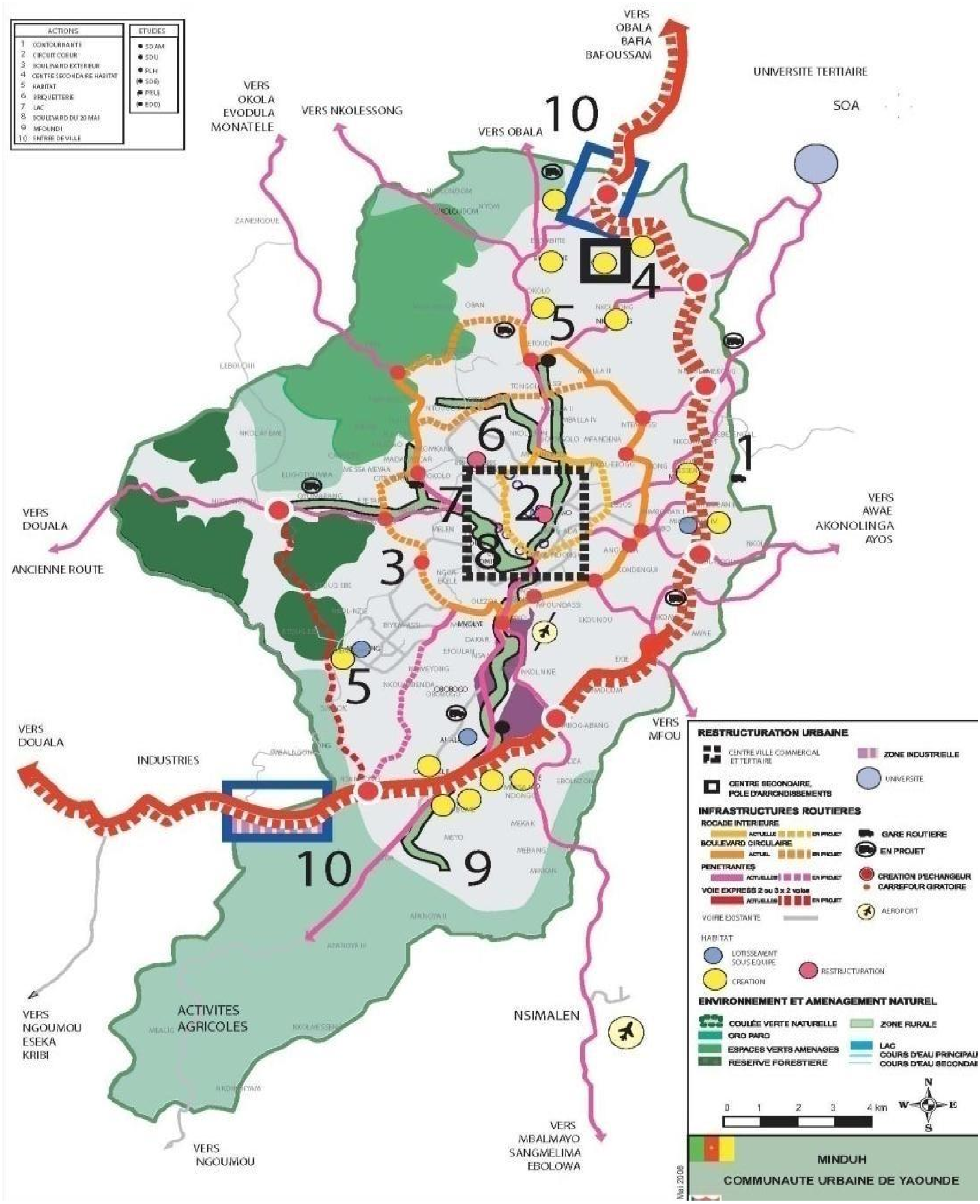


Figure 3. 1. Geographical location of the study area (Urban Community of Yaoundé, 2008).

3.1.2. Geology, relief and soils.

The geomorphological formations of the Yaoundé region present a bedrock made up of two main types of metamorphic rocks (Abuhngiendo, 2004).

- The para-derivative migmatites which occupy most of the region and which are observed to the east and west of the city of Yaoundé, implicitly in the Nkolfoulou area.
- Ortho derivative migmatites which are very dark, massive gneiss and of a basic gabbrodiotic nature. They are composed of biotite, garnet, quartz, alkaline feldspar and plagioclase, and are found in the beds of rivers such as the Foulou, on the peaks and on the hillsides.

A study of soil characterization of the Nkolfoulou landfill conducted by the study office "Soil and Water Investigation S.A." in 2003 showed that the site is located on a sloping area, from the area of laterite thigh with vertical permeability coefficients (K) range from 10^{-5} cm/s to 10^{-7} cm/s and is located on area made up of:

- A slightly sandy clay about 1.80 to 2.50m thick;
- A reddish lateritic clay with a thickness of about 0.70 to 1.50m;
- A lateritic cuirass 3m thick from around 3.20 to 8.00m, followed by a decomposed rock presaging a rocky roof.

The presence of clay gives the soils some waterproof. According to the above, the ground of the discharge is slightly sandy. Normally, the low proportion of the sand does not affect the waterproof character of the soils. The first layer of the Nkolfoulou landfill is waterproof. In the second layer the laterites are well structured and permeable soils.

Under the clay-forming, we find the thighs that are waterproof. However, the thighs are generally discontinuous in space and leave pockets allowing the infiltration of the waters.

If the Nkolfoulou landfill is on a continuous part of the thigh, it will be perfectly waterproof. However, they did not have more information on the continuity of the layers throughout the site of the landfill.

3.1.3. Climate

The weather statistics shown here in table 3.1 represents the average values of the different weather parameters for each month of the year in the UCY. The ability: 03.50N Longitude: 011:31E Altitude: 759m a.m.s.l.

Table 3. 1. Weather Statistics in the UCY (Source: www.meteomedia.com).

Months	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Temperature (°C)												
Max	31	31	30	30	29	28	26	26	27	28	28	28
Min	17	20	14	20	20	19	19	19	19	19	19	19
Moyenne	24	25	25	25	24	23	23	23	23	23	24	24
Precipitations												
Total (mm)	17	51	140	180	220	162	70	102	254	296	111	25
Nombre de jours avec précipitation totale>=1 mm	2	5	12	16	18	16	11	14	22	24	11	3
Other Settings												
Sunshine (h)	172	179	170	165	166	126	96	86	102	130	167	181
Wind speed (km/h)	4	9	9	8	6	8	10	10	8	6	6	6

The city of Yaoundé is located in a subequatorial climate zone. Average temperatures reach 25°C.The climate is marked by the alternation of two dry seasons and two rainy seasons divided as well:

• A large dry season from mid-November to mid-March;

• A small rainy season from mid-March to mid-June;

• A small dry season from mid-June to mid-August;

• A large rainy season from mid-August to mid-November

Given the state of urban road in general, some roads are difficult to make by trucks in the rainy season, making the collection and transport of waste tedious. At the same time, it seems that household rubbish is more important in volume during this season.

3.1.4. Hydrography

The city of Yaoundé is drained by four main rivers:

• The Mefou to the west and to the south;

• The Anga in the east and south west is;

• The Foulou north west is;

• The Mfoundi in the center.

Of all these rivers the Mfoundi, tributary of the Mefou, remains the most significant because it crosses the whole city with a sense of flow from the north to the south.

The site of Nkolfoulou is located in the watershed of the Foulou (see map below), with a network of simple hydrographic, consisting of a few localizable tributaries (Ototong, Ebengui, Akoo, Voumdi, etc.). These tributaries turn into torrents during large rains. Several facilities and constructions have been in the Foulou basin such as the landfill of Nkolfoulou, the University of Yaoundé II in Soa, the roads and the and residential areas. The Foulou River flows to the Afamba which flows into the Sanaga. It is the of Nkolfoulou and the runoff from various origins (MINMEE, 2004).

3.1.5. Vegetation

The area is dominated by two types of forest:

(a) Dense moist evergreen forest which consists of a large number of trees per hectare and a great floristic richness. The dominant families are, among others, Meliasses and Sterculias. The height of the canopy is estimated at about 30 m;

(b) The semi-deciduous forest which is characterized by a great floristic richness with less complexity in approach to the evergreen forest. The main dominant families are Combretaceae, Sterculias and Ochnaceae, which lose their leaves during the dry season. The height of the canopy is here estimated at 25 m.

3.1.6. Population and economic activities

The indigenous population consists of Etones, Bassa'às and Ewondos who remain in the minority. However, there are also a significant number of nationals from other regions of the country. Agriculture, fishing, hunting and livestock are the main income generating activities for the population. Crafts, logging, mining activities and commerce are secondary. It must be emphasized, however, that these activities do not always have facilities because of certain constraints related to the environment. In addition to these social and productive sectors, the situation in the other sectors (security, media coverage in the municipality, telecommunications) would to some extent influence the revitalization of the social and productive sectors. Furthermore, the access to the Nkolfoulou landfill is facilitated by a road more or less maintained and difficult to pass in rainy seasons for the terrestrial route (figure 3.2).

Figure 3. 2. Current state of road leading to the main entrance of the landfill.

However, it can be seen from the previous figure, the fences of the landfill are surrounded by houses of dwellings, which is formally forbidden according to some regulations of (EnvironmentProtectionAuthorityVictoria, 2015) that require the minimum security distance of 500 meters. According to our investigations with these people, it is the company in charge of the management of side that has found them. But the reality from our observations on the site and its surroundings most of these houses has not less than fifteen years of age while the company Hysacam operates the site for more than forty-five years.

3.1.6.1. Views of local residents about the landfill.

The opinions were mixed, some people were in favor because the project promised a number of things that could improve the daily lives of people, namely waste collection in all the surrounding communities, giving donations to students of the nationals of the area.

Other residents (most of them) were not in favor of dumping garbage in the community. The Hysacam company does not recruit almost the area's premises, smells, and the negative impacts of the project have not helped to appease their concerns. Indeed, the destruction of harvest fields, the invasion of their lands, the destruction of hunting areas, the fear of the unknown, the water pollution were so much negative effects of the project. From this project, the population expected development assistance, rehabilitation of schools, places of prayers, and a boost to the local economy. Nevertheless, work has been provided to local residents, young people have occupations that have helped support their families and their own needs and create opportunities for themselves. The presence of the workers certainly contributed to the local economy, because small business at one time was flourishing. Existing water sources have been polluted the destruction of large quantities of forests, including the disturbance of the animal and plant ecosystem. The ingestion of plantations and fields by water, the destruction of crops after the discharge and the precariousness of land ownership are other major problems caused by the landfill.

3.1.6.2. Views of project engineers about the landfill.

According to the project engineers, the landfill has worked well since the acquisition of this site because many efforts have been conceived for the environment such as: the establishment of the systems of the collection of gas and the leachate and in 2011 with the inauguration of flare, and the monitoring system that is carried out regularly by an engineer responsible for the follow-up. The presence of rivers all around the landfill, which is a major difficulty, is to be noted here to ensure a stable barrier of landfill in some places noting on the boundaries of 3G locker constituting one of the future issues of this thesis. Devices of monitors connected to the systems of gas and leachate collection were placed in the landfill to monitor the behavior of the production in quantity of each type of gas (methane, carbon dioxide, ...) and performance at any time.

3.1.6.3. Notice of Engineers of the landfill control mission.

The control mission (the company responsible for the quality control of waste treatment in the site) considers that the discharge of Nkolfoulou changed status by leaving storage site at the Waste Treatment Centre without so far a respect for certain rules of conformity such as: the development of a locker, the blankets of waste by a quantity of soil (50 to 80cm) after the burying wastes and re-profiling process.

According to experts from the same control mission, the dry season favors the risk of fires this under a mishandling of any energy source. Figures 3.3 a; 3.3 b and 3. 5 recorded on the night of February 29, 2020 in the west area of the Nkolfoulou landfill show the severity of the fire occurred on a record that has been scraped and exposed without land covers that are more flammable because exposed and completely dried at high temperatures.

Figure 3. 3.a) Image of the fire in the west area of the landfill of Nkolfoulou (February 29, 2020).

Figure 3. 3.b) Image of the fire in the west area of the landfill of Nkolfoulou (February 29, 2020).

Here we should mention the fact that in order to extinguish this fire, it took the intervention of the Fire Fighters (figure 3.4), which confirms once again the gravity of the fire.

Figure 3. 4. Intervention of Fire Fighters for fire extinguishment in the west area of the Nkolfoulou landfill (February 29, 2020).

It should be noted here that the main cause of these fires in the landfill is the practice of hunting animals with fire traps by local residents.

3.2. Results from the visit

In this part, we will present the studied landfill section, the consistency of the work and standard of the project.

3.2.1. Physical description of the site.

The landfill of Nkolfoulou is located in the center region of Cameroon in the city of Soi, covering an area of 56 ha (figure 3.3) accessible on the ground. The access road leading to the development of the landfill is surrounded by houses all around these fences naturally surrounded with waters in some places. The site has a very wide triangular shape at the base with a ridge width of about 10 m used as the main access road. The presence of trees although important to the environment is a problem that can be critical over time, as their presence reduces the useful volume of the landfill site.

The inside of the landfill is subdivided into four areas and each area severed into several lockers. Inside the landfill there are three main concrete structures, the first of which is the construction of the leachate collection basin, the second being the building containing the staff's office, the third which is building containing the devices for monitoring of the gas analysis

(Carbon dioxide (CO2), Methane (CH4), ...) collected from the different areas. It was to better understand these multiples problems that we decided to pay particular attention to zone 3, more precisely the 3G locker in preparation for operation, as shown in the following figure 3.6.

Figure 3.5. Presentation of the site (December, 2019).

3.2.2. Description of studied section.

However, after analyses and inspections carried out on the site by Pr. Simonetta COLA, Pr. Paolo SIMONINI, Pr. Roberto RAGA, and I in February 2020, it was pointed out that soil of the Nkolfoulou landfill could be mainly good quality soil, even if this should be confirmed by geotechnical tests and also correct the slopes of the embankment especially the western area of the 3G locker located 658 meters from the sea level (figure 3.7).

Figure 3.6. Presentation of the 3G locker during our visit (December, 2019).

A thorough geotechnical study was carried out on a large part of the entire soil of the landfill of Nkolfoulou. After a long analysis, we found that some areas of the landfill were not exploited optimally, some were exploited beyond their capacities in terms of depths; and all this because of the non-control of the level of the water table, the permeability of the ground, and the failure to respect the achievements of the slopes of the embankments (near the river "Foulou").

All these characteristics can therefore be verified by the fact that the remaining operating time of the site is not very long and by certain landslides close to the cone rivers (figure 3.8), the time interval of which is of great concern and requiring geotechnical emergency work and the two most serious cases in 2019 were found near of the river very close to the Foulou village.

Figure 3.7. Presentation of the first landslide in the Nkolfoulou landfill (July, 2019).

3.2.3. Quality of the air.

The quality of the air in Cameroon is not systematically analyzed. Therefore, the use of soils remains one of the benchmark criteria for determining the quality of the air. The quality (figure 3.9) of the air is affected by:

• Red dust by the nature of the soil of the UCY that covers the roads;

• The general transport that produces gases and exhaust fumes containing greenhouse gases and toxic gases (CO, CO_2, SO_x, P_bO, etc.);

• Industry activity.

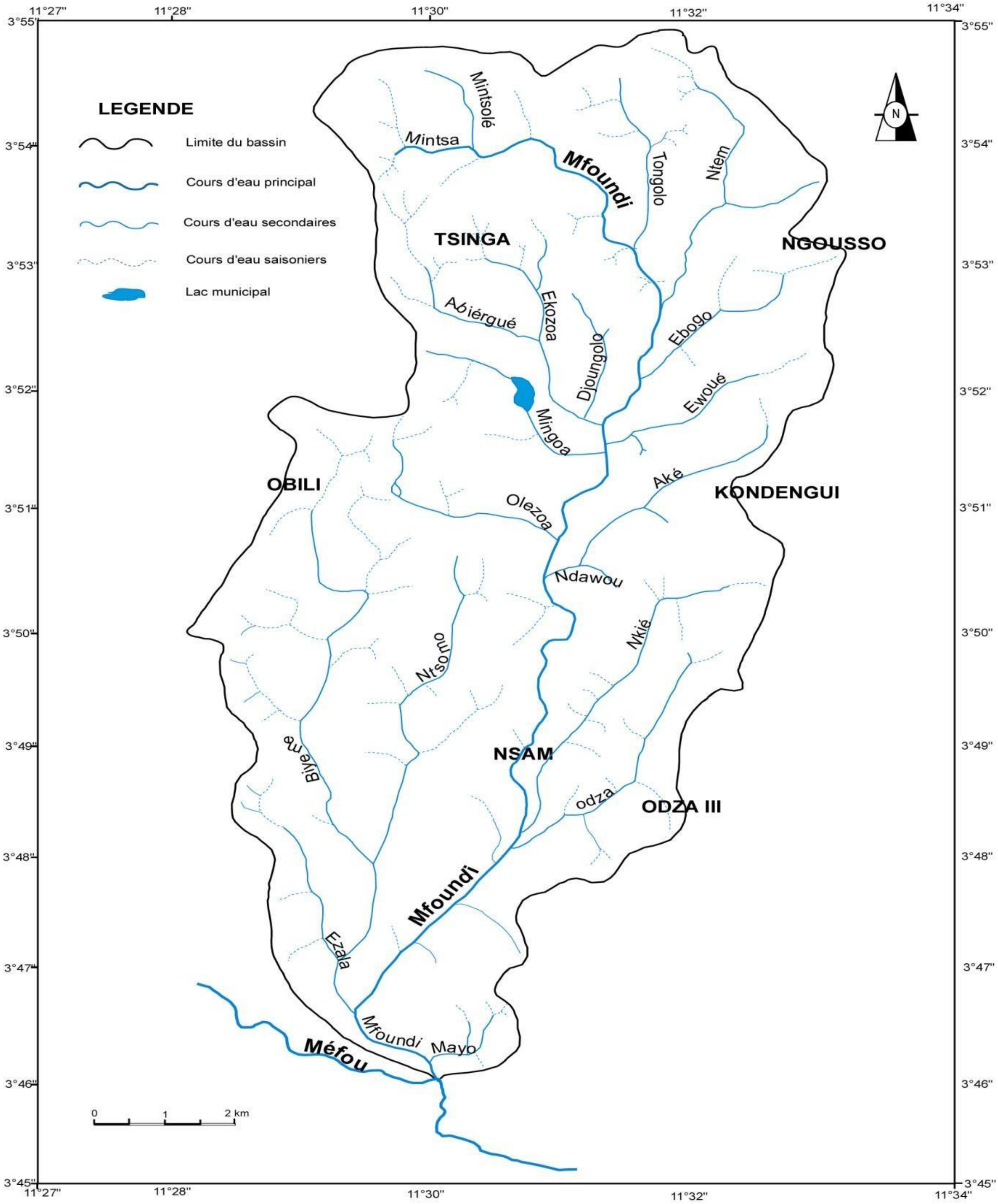


Figure 3.8. Hydrographic network of the watershed of the Mfoundi (extracted from the 3d and 4c maps of Yaoundé at 1/50000: drawn by Tchado, 2008)

3.3. Data collected.

The data collected on the site are of a geometric and geotechnical nature. The geometric data concern the landfill itself, while the geotechnical data are those related to the materials that make it up and the result of in-situ test.

3.3.1. Materials collected.

Since our work is to classify the soil of the Nkolfoulou landfill and find the permeability coefficient of the soil of the landfill (especially the soil of the 3G locker).

3.3.1.1. Collection of natural soils.

The material that have been collected are natural soils generally used for the construction of landfill embankments such as the foundation layer or used for the separation layer of waste. The soil was collected (figure 3.10.) in abundant quantities in the Nkolfoulou WTC site and transported to a geotechnical laboratory to perform the various tests.

Figure 3. 9. Preparation of natural soil used for separation layer of wastes in a landfill.

Concerning the three natural soil samples (usually used for the waste separation layer, two were taken from area 1 to various strata (0.00m and 6.00m of heights) and one in the 3G locker.

3.3.1.2. Collection attacked soils.

After the collection of natural soil samples, three soil samples attacked in the leachate were also taken this in order to see the relative difference (the class of soil and the permeability) between these two soils in a landfill. This material will be collected in abundant quantities in a quarry and transported to a geotechnical laboratory to perform the various tests, as shown in figure 3.11.

Figure 3. 10. Preparation of attacked soil by leachate.

For soils attacked by leachate, it was taken from the borders of the 3G locker to various strata (0. 00m, 3.00m, and 5.00m of heights) and all of these samples were taken on 08 January 2020 at around 11:45 am under a temperature of around 24°C. The reasons for the soil removal were to see if the leachate by attacking a soil could influence its permeability.

3.4. Geotechnical test results.

In this part, the results of the geotechnical tests will be presented. These are complete identification tests, including particle size analysis, water content, Atterberg limits, the modified Proctor test and the in-situ permeability test.

3.4.1. Granulometry

After taking samples from the site of the landfill, studies were conducted in the ENSTP laboratories for Proctors and the granulometric analysis by sifting. The sedimentometry analysis and the Limits of Atterberg, were performing in the laboratories of the company MIPROMALO.

The granulometries of the different samples are recorded in the tables of the table 3.2. They allow us to calculate and obtain the various granulometric curves and determine the percentage of fines. The layout of the six curves on the same marker allows us to better appreciate the peculiarities of each soil compared to others while showing the gap or not existing between the natural soils and those attacked.

Table 3. 2. Particle Size Analyses of soil samples.

Sample	*Depth (m)*	*% of Gravel Φ >2mm*	*% of Sand 2> Φ >0.02mm*	*% of Silt 0.02> Φ >0.002mm*	*% of Clay Φ <0.002mm*
Attacked Soil	**0.00**	1.3	37.2	9.8	51.7
Attacked Soil	**3.00**	18.1	40.7	10.7	30.5
Attacked Soil	**6.00**	7.4	60.6	7.8	24.2
Natural Soil	**0.00**	0.3	36.3	7.8	55.6
Natural Soil	**5.00**	0.7	33.8	9.7	55.8
Natural Soil	**6.00**	6.6	65.3	9.7	18.4

On the basis of figures 3.8 and 3.9, we can conclude that the Nkolfoulou landfill soil is a mostly composed by clay and sand and it is a Clayed soil.

3.4.2. Water content

The material used for this study are different soils collected in the site of the Nkolfoulou landfill at different places, and our tests were conducted at the ENSTP laboratory and MIPROMALO Laboratory of the company. Since we had many samples, the results of the water content of the material (both natural and attacked soil samples) are content in each table (annex 3) of the computation values.

3.4.3. Atterberg limits

The expected results here are the consistency limits of our soil sample namely the liquidity limit W_L and the plasticity limit W_P. Once these values are determined, we deduce the plasticity index PI in order to classify our soil.

The results of the liquid limit and plastic limit for the other samples are also summarized in the table following tables (annex 3).

This parameter measures the extent of the plasticity domain. So according to table 3.3, we can conclude that we have a **Clay with high plasticity** for natural soil collected at zone2. The remain computations of the other samples are in annexes.

Table 3. 3. Summary of the data of the water content and the plasticity index.

Sp	Natural soil (6.00m depth at zone 2)				
Mt (g)	0.22	0.24	0.23	0.23	0.22
Mtw (g)	12.88	12.6	2.82	1.97	2.36
Mtd (g)	9.14	8.95	2.24	1.57	1.88
W (g)	3.74	3.65	0.58	0.4	0.48
Md (g)	8.92	8.71	2.01	1.34	1.66
WC (%)	**41.9**	**41.9**	**28.9**	**29.9**	**28.9**
Wl/Wp		**41.9**		**29.2**	
PI			**12.7**		

3.4.4. Proctor Settings

We opted for the modified Proctor test. This test was carried out on both the unmixed material and the various mixtures.

3.4.4.1. Natural soils

The Proctor curve (Figure 3.12) obtained by the Excel sheet; it gives the dry density according to the water content.

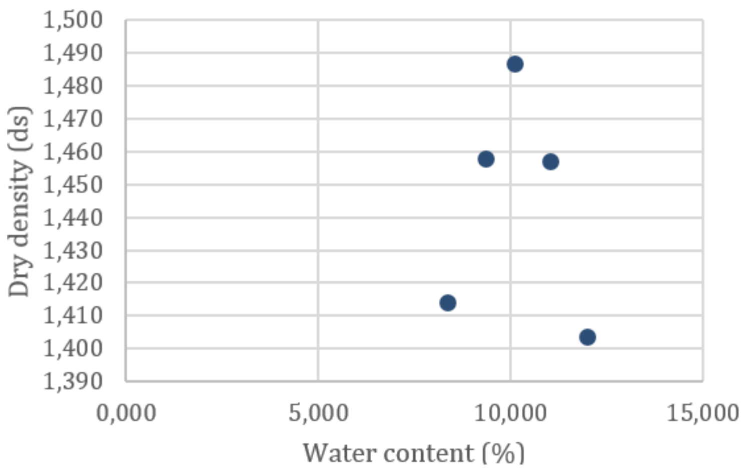


Figure 3. 11. Proctor curve for the natural soil at 5m depth.

The table 3.4 summarizes the experimental results obtained from the modified Proctor test on the natural soil. The other sample results are in the (annex IV).

Table 3. 4. Experimental results obtained from the modified Proctor test on the natural soil.

DESIGNATION (g)	6000g		6000g		6000g		6000g		6000g	
Weigth water add	12%		14%		16%		18%		20%	
Total humid weigth (g)	8505		8648		8747		8702		8597	
Weigth of mold (g)	4976									
Humid weigth of soil (g)	3529		3672		3771		3726		3621	
Volume of the mold (cm^3)	2303.35									
Humid density (dh)	1.532		1.594		1.637		1.618		1.572	
N° TARE	N° I	N° C*	N° I*	N° A	N° 3	N° 2	N° II*	N° 9	N° 7	N° 4
Humid weigth	61	58	69	78	77	74	81	70	67	67
Total dry weigth	58	55	65	73	72	69	75	65	63	62
POIDS TARE	21	20	21	21	21	21	20	20	29	21
Weigth of water	3	3	4	5	5	5	6	5	4	5
Dry weigth of soil	37	35	44	52	51	48	55	45	34	41
Water content %	8.1	8.6	9.1	9.6	9.8	10.4	10.9	11.1	11.8	12.2
Mean water content	8.340		9.353		10.110		11.010		11.980	
Dry density (dS)	1.414		1.458		1.487		1.457		1.404	

DAME		PK or Profil: **Natural SOIL**
N° of layer	**5**	Pick location : **Nkolfoulou LANDFILL**
N° of blows per layer	**56**	Maximum dry Density : DS
Optimum water content		Depth : **5.00m**
N° Sampler	**Natural Separation soil for 3G locker**	Operator : **BUKY Nankeng**

We thus obtain the pair representing the optimum Proctor of the soil. The optimal water content is 10.110 % and the maximum dry density is 1.487 (**W_{optm} = 10.110 % and D_{smax} = 1.487**).

3.4.4.2. Attacked soils

The table 3.5 summarizes the experimental results obtained from the modified Proctor test on the attacked soil and the other sample results are in (annex V).

Table 3. 5. Experimental results obtained from the modified Proctor test on the attacked soil.

DESIGNATION (g)	6000g		6000g		6000g		6000g		6000g	
Weigth water add	12%		14%		16%		18%		20%	
Total humid weigth (g)	9352		9498		9685		9619		9495	
Weigth of mold (g)	4976									
Humid weigth of soil (g)	4376		4522		4709		4643		4519	
Volume of the mold (cm^3)	2303,35									
Humid density (dh)	1.900		1.963		2.044		2.016		1.962	
N° TARE	N° B	N° 3	N° A	N° A"	N° II	N° 4"	N° 1	N° 5	N° III	N° P
Humid weigth	61	70	78	67	68	55	70	66	59	65
Total dry weigth	57	65	72	61	63	50	64	61	54	59
POIDS TARE	21	21	21	11	23	11	20	26	21	21
Weigth of water	4	5	6	6	5	5	6	5	5	6
Dry weigth of soil	36	44	51	50	40	39	44	35	33	38
Water content %	11.1	11.4	11.8	12.0	12.5	12.8	13.6	14.3	15.2	15.8
Mean water content	11.237		11.882		12.660		13.961		15.470	
Dry density (dS)	1.708		1.755		1.815		1.769		1.699	
DAME						PK ou Pofil **Attacked by leachate**				
N° of layer	**5**					Pick location : **Nkolfoulou LANDFILL**				
N° of blows per layer	**56**					Maximum dry Density : DS				
Optimum water content						Depth : **6.00m**				
N° Sampler	**Slope Soil of 3G locker**					OPERATOR : **BUKY Nankeng**				

The Proctor curve obtained by the Excel sheet (figure 3.13); it gives the dry density according to the water content.

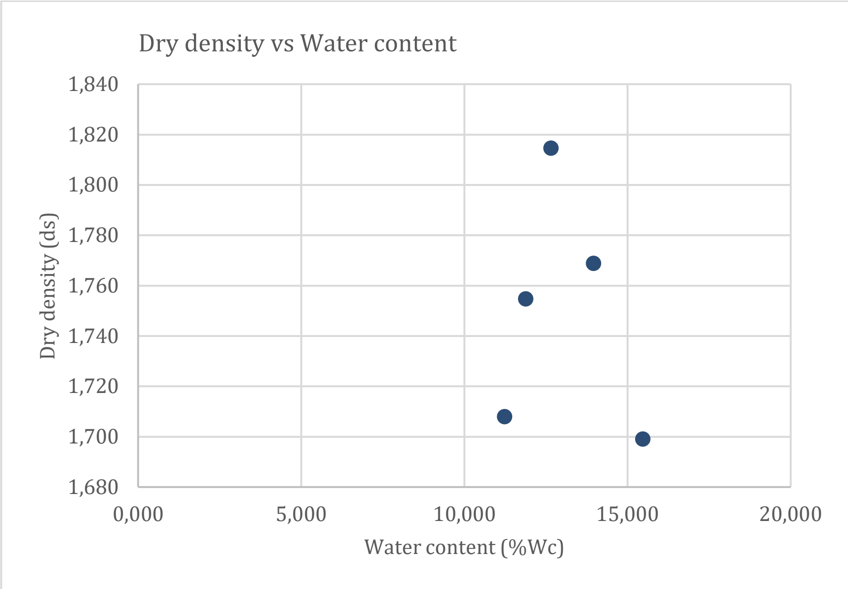


Figure 3. 12. Proctor curve for the attacked soil.

We thus obtain the pair representing the optimum Proctor of the soil. The optimal water content is 12.660 % and the maximum dry density is 1.708 (**W_{optm} = 12.660 % and D_{smax} = 1.708**).

3.4.5. Combined results of laboratory tests.

It is remarkable to know that in a given soil especially that of a landfill which must have the properties of low permeability and high resistance, the clay being responsible for the permeability and the sand of the strength. In the six samples analyzed, a large proportion of sand and clay was observed in both the natural soils and the soiled soils. The clay percentages in both types of soils were greater than 18% that corresponds for a minimum permeability value of $8*10^{-7}$cm/s (sufficient permeability value without need of reinforcement to geosynthetics for a landfill) according to Benson et al. relationship as presented in Figure 1. 18 in the first chapter. After all the results we classified the soils according to AASTHO system and we found the permeability coefficient base on the relationship between Hydraulic Conductivity and Plasticity Index (Benson et al.,1992) as it was presented (figure 1.14) and the results are in the following table 3.6.

Table 3.6. Materials parameters of landfill and permeability coefficients.

Soil Samples	**Depth**	**Natural water content (%)**	**Ranking Procedures**	**Classes**	**Types**	**Permeability Coefficients** (cm/s)
Attacked	0.00m	21.97	Wl=68.5 $\rightarrow (A-5 \; or \; A-7)$; Wp=34; PI=34.5 (A-7); %Passing 0.075mm = 64.1> 35% Wl-30=38.5> PI	A-7-6	Clayed soil	$9*10^{-8}$
Attacked	3.00m	10.85	Wl=67.5 $\rightarrow (A-5 \; or \; A-7)$; Wp=34.2; PI=33.4 (A-7); %Passing 0.075mm = 42.2> 35% Wl-30=37.5> PI	A-7-6	Clayed soil	$8.5*10^{-8}$
Attacked	6.00m	10.52	Wl=50 $\rightarrow (A-5 \; or \; A-7)$; Wp=33.7; PI=16.3 (A-7); %Passing 0.075mm = 66.1> 35% Wl-30=20> PI	A-7-6	Clayed soil	$2*10^{-8}$
Natural	0.00m	11.06	Wl=56.9 $\rightarrow (A-5 \; or \; A-7)$; Wp=32.3; PI=24.6 (A-7); %Passing 0.075mm=67.2> 35% Wl-30=26.9> PI	A-7-6	Clayed soil	$7*10^{-8}$
Natural	5.00	4.94	Wl=57.8 $\rightarrow (A-5 \; or \; A-7)$; Wp=33.3; PI=24.5 (A-7); %Passing 0.075mm =69.7> 35% Wl-30=27.8> PI	A-7-6	Clayed soil	$7*10^{-8}$
Natural	6.00m	2.76	Wl=41.9 (A-2-5) or A-2-7); Wp=29.2; %Passing 0.075mm = 30.9< 35% (A-2) PI=12.7≥ 11 (A-2-7)	A-2-7	Silty or Clayed gravel and sand	$8*10^{-7}$

After these results, we can say almost all the soils of the Nkolfoulou landfill are mostly composed by clay and sand and are good for receiving wastes without the addition of any geosynthetics. It is also important to notice that soils with high plasticity index (between 30% and 40%) tend to form hard clods when dried and sticky clods when wet. Highly plastic soils also tend to shrink and swell when wetted or dried. With highly plastic soils, CQC and CQA personnel should be particularly watchful for proper processing of clods, effective remolding of clods during compaction, and protection from desiccation.

3.4.6. In situ permeability coefficient

After recording the values of this in-situ test for more than 24 hours, we were able to see the behavior of the water infiltration volume as well as the value of permeability (k) over time. The values obtained and saved on the Excel software were recorded in the following table 3.7. Then, figures 3.14 and 3.15 on the Excel software clearly illustrate the look of these different curves over time during the test period. It should be noted here that the method of apparent gradient is more conservative; it gives a low estimate of the hydraulic gradient and a high estimation of hydraulic conductivity. The method assumes that the test pad is completely soaked with water on all the depth of the test pad. For relatively permeable test pads, the full-soaking assumption is reasonable, but for compacted clay lining with k for 10^{-9} m/s, this hypothesis is excessively conservative and should not be used unless verified.

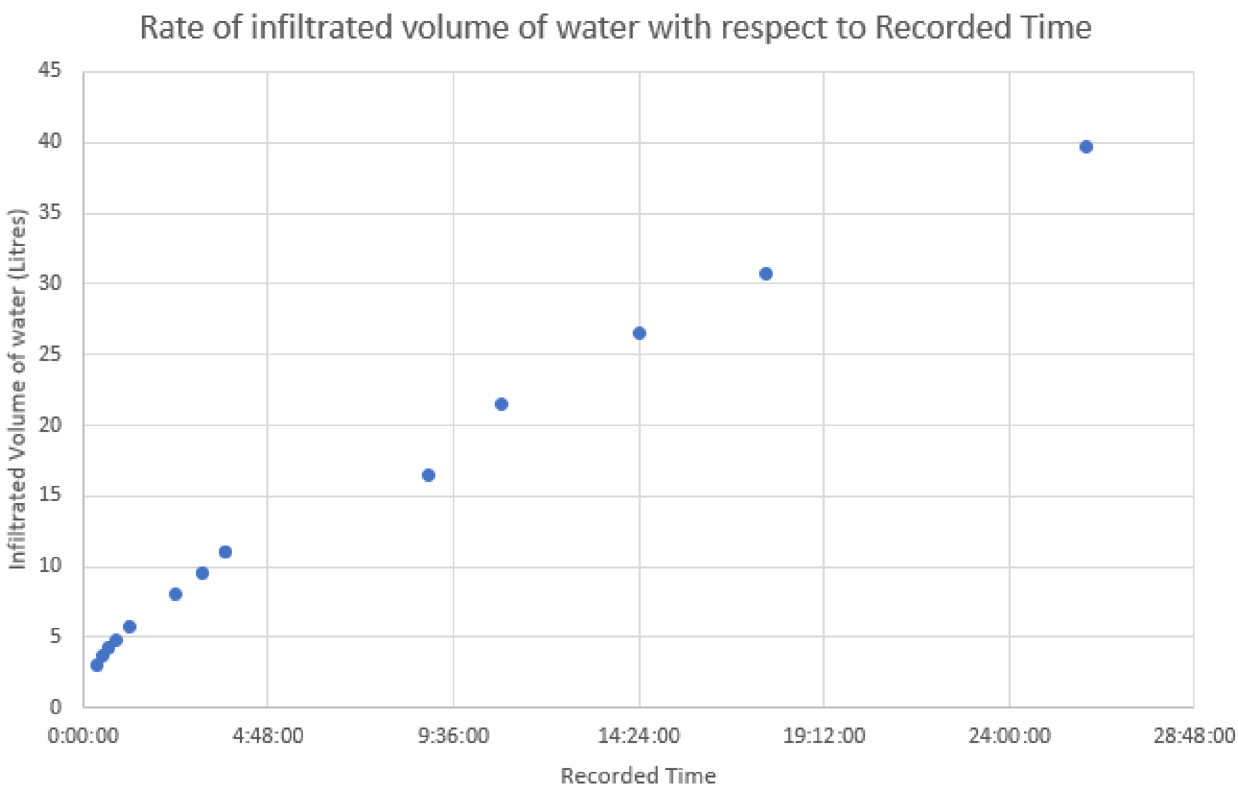


Figure 3. 13. Rate of infiltrated volume of water with respect to recorded time.

The permeability test conducted on February 09, 2020 in the 3G locker (one month later after collecting samples for tests in laboratories), have been conducted on the soil of different characteristics than those originally taken for reasons of respect of the specifications of the work of the site managements by the company.

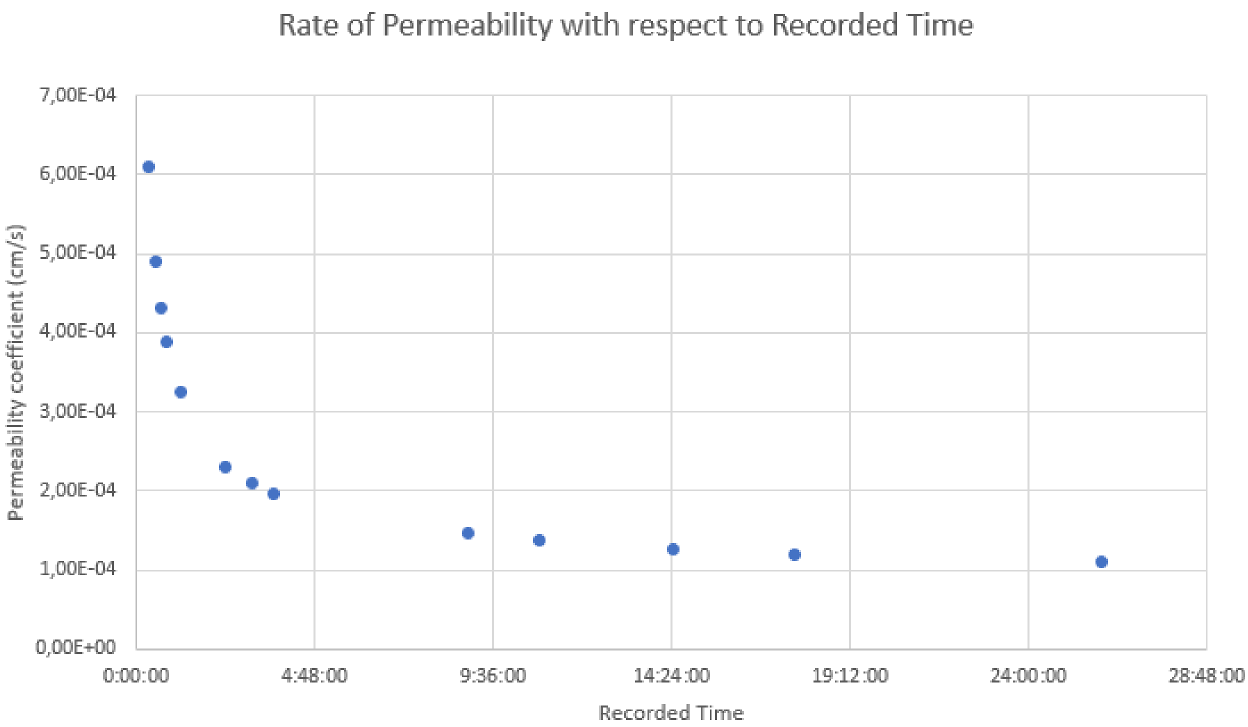


Figure 3. 14. Rate of Permeability with respect to recorded time.

As can be seen on the figure preceding, the coefficient of permeability increases very quickly with time during the first four hours of the test: this translates an important composition of soil by sand. On the other hand, on the next 24 hours of the test, we still observe a variation of this coefficient but that remains more or less constant over the last 12 hours of the experiment. This last slight variation in the last 12 hours of the test translates here the saturation of the ground (filling the empty soil spaces with water).

The main problems with this method when putting up the Boutwell permeameter test are:

- Evaporation loss and measuring flow rates.
- When this test was put in place, as was the case in this work, the thickness of the TUBE (the thickening of the contact surface between the device and the ground) was not taken into account, and as a result, the side water lifts had occurred and the infiltration was no

longer just vertical but horizontal all around the outer side of the tube. In (annex V) is illustrated better the correction of errors during the test.

Table 3. 7. Recapitulative of the values recorded during the in-situ permeability test.

Times	Time(s)	Vol (litres)	DV/Dt	Units
20min17s	1217	3	0.0024651	---
31min29s	1889	3.75	0.0011161	---
40min33s	2433	4.25	0.0009191	---
50min27s	3027	4.75	0.0008418	---
1h13min06s	4386	5.75	0.0007358	---
2h23min56s	8636	8	0.0005294	---
3h06min36s	11196	9.5	0.0005859	---
3h42min11s	13931	11	0.0005484	---
8h56min46s	27826	16.5	0.0003958	---
10h49min57s	38991	21.5	0.0004478	---
14h26min11s	51971	26.5	0.0003852	---
17h41min53s	63713	30.75	0.0003619	---
25h58min33s	89127	39.75	0.0003541	---
mean infiltration rate (I)	//////	//////	0.000446	L/s
Cross section diameter	//////	//////	20	Cm
Cross section Area	//////	//////	314	Cm^2
H	//////	//////	208	Cm
D'	//////	//////	17,5	Cm
I	//////	//////	12,885714	---
K	//////	//////	$1.10 * 10^{-4}$	Cm/s

Hence getting the in-situ permeability value using the (equation 2.9) as **$K=1.10 * 10^{-4}$cm/s.**

Conclusion

In summary, this chapter presented the landfill of Nkolfoulou in general terms, based on the information collected, the location on a map of the area of the project, the type of climate, the geology of the region, as well as the enormous hydrological potential of the region through the Foulou river and its tributaries. Data such as the granulometry specifically the percentage of sand and clay in each sample showed that the six soil samples did not have a very big difference. And in general, it can be said without risk of being mistaken that the soil of the Nkolfoulou landfill is clayed soil type with permeability varying between 10^{-7}cm/s and 10^{-8}cm/s. Then, the landfill itself without the reinforcement of geosynthetics can accommodate the waste without the risk of pollution of the aquifer layer; just that the recommendations of the various geological obstacles in Table 1. 2 in Chapter 1 should be taken into account in the realization of every locker in that site. However, areas close to the ravines still need in-depth geotechnical studies and environmental studies.

GENERAL CONCLUSION AND PERSPECTIVES

The main purpose of this work was to improve the construction techniques of a landfill in the center region, while proposing possible geotechnical solutions with local materials. The permeability of the bottom layer of the lockers in a landfill must be less than 10^{-7}cm/s to avoid the risk of contamination of the underground water table by the leachate.

After a review of the literature on the state of art about landfills and its constituent elements, the thesis work consisted in laboratory analyses (Proctor test, Atterberg limits and granulometric analysis) of six soil samples and the implementation of the in situ permeability test in the 3G locker under construction during our period of internship at the Nkolfoulou landfill. With this in mind and taking into account the financial issues of the company in charge of the management of the landfill, the difficulties in buying the geosynthetic and the lack of qualified experts for the implementation of these, we were obliged to use local materials for the construction of waste landfills.

For laboratory tests of the six samples analyzed, we obtained majority clayey soils with a plasticity index varying between 20 and 30%. The different permeability values of soil samples obtained according to the chart of Benson et al. (1992) (figure 1.18) where we found $2*10^{-8}$; $8.5*10^{-8}$; $9*10^{-8}$; $8*10^{-7}$ and $7*10^{-8}$ [cm/s] which were satisfactory results allowing us to say that these soils are empowered to be used in landfills without need of coupling with geomembrane. In contrast to the in-situ permeability test carried out on a layer of 5m deeper than that of the soils initially analyzed in the laboratory, we obtained a value of $1.1*10^{-4}$ (cm/s). This shows the need to either replace this soil with a low permeability index soil (less expensive solution) or to reinforce it with geosynthetics before use this type of soil in any part of the landfill.

This study showed that it is possible to construct the landfills in Cameroon without using the geosynthetic, but all this provided that the position of the water table and distances of the geological barriers (table 1.2) in addition to being respected is reinforced by a soil of 80 cm with permeability of 10^{-7} cm/s sufficiently compacted for a total guarantee of the waterproofness of the bottoms and the slopes of lockers in the landfills.

Nevertheless, this study can be improved by a thorough study on the obtaining of the different parameters of the soil and that a minimum of 5 in situ permeability tests is carried out on the site for a more effective assessment of the results.

It should be noted that the landfill in the Cameroon context has a mixed functional use, it poses a serious problem of the safety in terms of environmental Geotechnics and whose construction techniques must be well take into account in the design of the landfill. The designs of the landfill parts are in the order of the most important works of art in general because it is a question of being able to manage with the conviction with two materials (the waste and the soil) whose behavior is quite complex because of varies according to location and management policy depending on the country or continent.

The field of geotechnology in the construction of landfills being very large, we can in view of the difficulties encountered in the construction of the dykes on the site of the WTC of Nkolfoulou to do extensive studies and to propose the acceptable angles of the sides of dikes by analyzing local materials for the realization of waste retention dikes near the ravines and rivers. It will be a question for the company in charge of the management of wastes in Cameroon to:

- Set up a geotechnical study cell (in close collaboration with environmental engineers for studies of landfills and its subdivisions into various traps).
- Make a geotechnical test several times (5 times minimum) before the start of a landfilling process in a given soil.
- Do geophysical studies for the recognition of the level of the water table for optimum operation in depth of lockers in a given landfill.
- Do the daily waste cover system in the landfill site to ensure the function of reducing the amount of water in the landfill.
- Study the geometries in order to avoid the collapse of different portions.

However, for the good conduct of this work, it would be possible to do in-depth a study on the stabilization of confinement dyke in the landfill near rivers and ravines with local materials including impacts and mitigation measures.

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ANNEXES

Annex I. Other factors that need to be considered for the landfill operation.

Factors	**Remarks**
Communications	Telephone for emergencies.
Days and hours of operation	Usual practice is 5 to 6 days/week and 8 to 10h/day.
Employee facilities	Rest rooms and drinking water should be provided.
Equipment maintenance	A covered shed should be provided for field maintenance of equipment.
Litter control	Use movable fences at unloading areas; crews should pick up litter at least once per month or as required.
Pest control	Implementation and enforcement of daily cover.
Operation plan	With or without the co-disposal of treatment plant sludges and the recovery of gas.
Operation records	Tonnage, transactions, and billing if a disposal fee is charge
Salvage	No scavenging; salvage should occur away from the unloading area; no salvage storage on site.
Security	Provide locked gates and fencing, lightning of sensitive areas.
Spreading and compaction	Spread and compact waste in layers less than 0.6m thick.

Annex II. Landfill Pollution Potential Matrix (LPPM).

Environmental Element	Weighting	Severity factor (on the scale of 0 to 5)	Pollution score
Sub-surface water	26.25		Σ
Surface	19.90		Σ
Air quality	22.85		Σ
Aesthetics	15.67		Σ
Flora and fauna	11.73		Σ
Noise level	3.60		Σ
Sum of pollution score	100		LPPI

Annex III. Summary of the data of the water content and the plasticity index.

Atterberg limits results												
	Liquid Limits		**Plastic limits**					**Liquid Limits**		**Plastic limits**		
Sp	**Attack 0.00m depth**						**Sp**	**Attack 3.00m depth**				
Mt (g)	0.25	0.25	0.2	0.2	0.2		**Mt (g)**	0.25	0.25	0.23	0.22	0.23
Mtw (g)	12.47	14.87	2.14	2	2.65		**Mtw(g)**	13.67	12.62	2.72	2.56	2.52
Mtd (g)	7.5	8.93	1.65	1.54	2.03		**Mtd (g)**	8.26	7.64	2.08	1.98	1.93
W (g)	4.97	5.94	0.49	0.46	0.62		**W (g)**	5.41	4.98	0.64	0.58	0.59
Md (g)	7.25	8.68	1.45	1.34	1.83		**Md (g)**	8.01	7.39	1.85	1.76	1.7
WC (%)	**68.6**	**68.4**	**33.8**	**34.3**	**33.9**		**WC(%)**	**67.5**	**67.4**	**34.6**	**33.0**	**34.7**
Wl/Wp	**68.5**		**34.0**				**Wl/Wp**	**67,5**		**34.1**		
PI	**34.5**						**PI**	**33.4**				
Sp	**Attack 6.00m depth**						**Sp**	**Natural Soil 0.00m depth**				
Mt (g)	0.23	0.22	0.23	0.22	0.19		**Mt (g)**	0.23	0.23	0.19	0.23	0.19
Mtw (g)	15.51	15.44	3.57	3.93	3.01		**Mtw(g)**	13.69	14.09	3.24	3.32	2,86
Mtd (g)	10.4	10,38	2.73	2.99	2.3		**Mtd (g)**	8.81	9.06	2.5	2.56	2.21
W (g)	5.11	5,06	0.84	0.94	0.71		**W (g)**	4.88	5.03	0.74	0.76	0.65
Md (g)	10.17	10,16	2.5	2.77	2.11		**Md (g)**	8.58	8.83	2.31	2.33	2.02
WC (%)	**50.2**	**49.8**	**33.6**	**33.9**	**33.6**		**WC(%)**	**56.9**	**57.0**	**32.0**	**32.6**	**32.2**
Wl/Wp	**50.0**		**33.7**				**Wl/Wp**	**56.9**		**32.3**		
PI	**16.3**						**PI**	**24.6**				
Sp	**Natural Soil 5.00m depth**						**Sp**	**Natural Soil 6.00m depth**				
Mt (g)	0.23	0,23	0.19	0.19	0.19		**Mt (g)**	0.22	0.24	0.23	0.23	0.22
Mtw (g)	13.2	13.32	2.95	2.03	1.75		**Mtw(g)**	12.88	12.6	2.82	1.97	2.36
Mtd (g)	8.45	8.52	2.26	1.57	1.36		**Mtd (g)**	9.14	8.95	2.24	1.57	1.88
W (g)	4.75	4.8	0.69	0.46	0.39		**W (g)**	3.74	3.65	0.58	0.4	0.48
Md (g)	8.22	8.29	2.07	1.38	1.17		**Md (g)**	8.92	8.71	2.01	1.34	1.66
WC (%)	**57.8**	**57.9**	**33.3**	**33.3**	**33.3**		**WC(%)**	**41.9**	**41.9**	**28.9**	**29.9**	**28.9**
Wl/Wp	**57.8**		**33.3**				**Wl/Wp**	**41.9**		**29.2**		
PI	**24.5**						**PI**	**12.7**				

Water content				
Sample	**Mt(g)**	**Mtw(g)**	**Mtd(g)**	**WC(%)**
Attacked soil 0.00	56.5	606.5	498	**24.58**
Attacked soil 3.00	39,5	637	551,5	**16.70**
Attacked soil 6.00	38	697	631.5	**11.04**
Natural Soil 0.00	50.5	689	605.5	**15.05**
Natural Soil 5.00	38.5	643	556.5	**16.70**
Natural Soil 6.00	37.5	625	584.5	**7.40**

Sp	Sample reference
Mt (g)	Tare mass
Mtw (g)	Tare + wet sample mass
Mtd (g)	Tare + dry sample mass
W (g)	Loss in mass (Mtw - Mtd)
Md (g)	Dry sample mass (Mtd-Mt)
WC (%)	Water content (W/Ms)*100
Wl/Wp	Average Liquid limit / plastic limit
PI	Plasticity index (Wl – Wp)

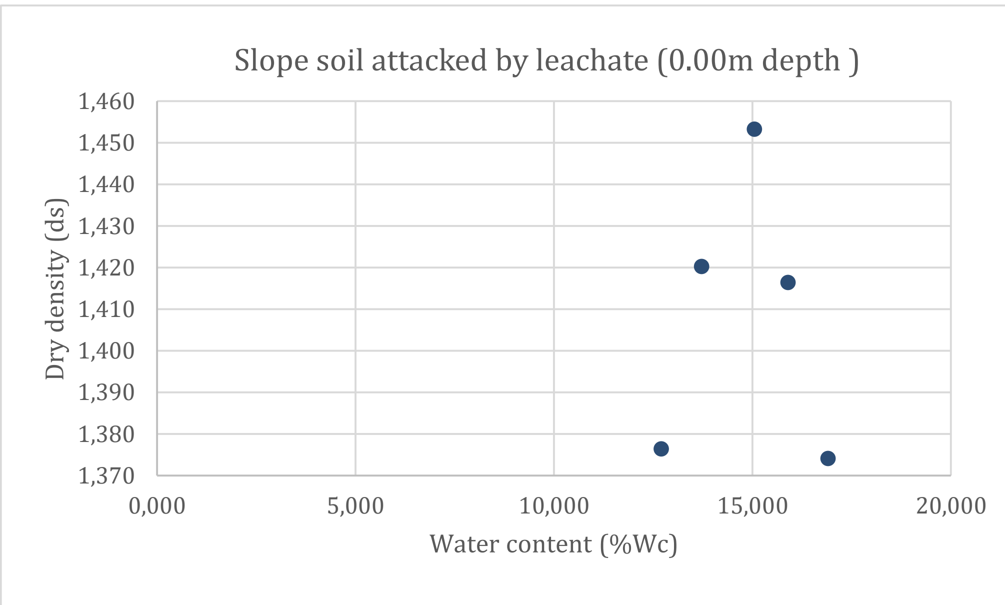
Annex IV. Presentation of the second landslide in the Nkolfoulou landfill (October, 2019).

Annex V. An example of carrying out the trial proctor.

Annex VI Excel sheet and corresponding Proctor curve of soil samples.

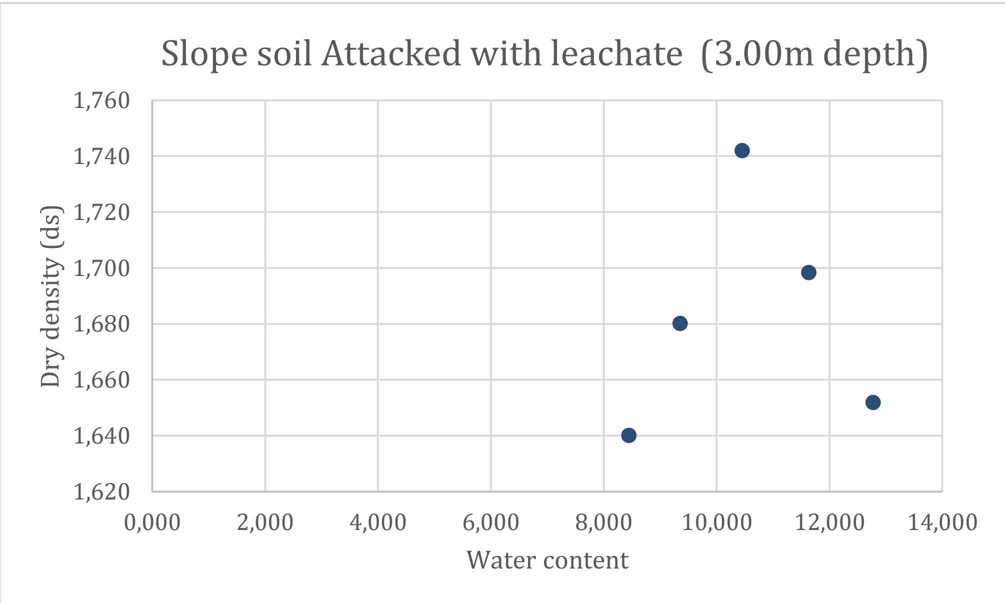
DESIGNATION (g)	6000g		6000g		6000g		6000g		6000g	
Weigth water add	12%		14%		16%		18%		20%	
Total humid weigth (g)	8549		8696		8827		8757		8676	
Weigth of mold (g)	4976									
Humid weigth of soil (g)	3573		3720		3851		3781		3700	
Volume of the mold (cm^3)	2303.35									
Humid density (dh)	1.551		1.615		1.672		1.642		1.606	
N° TARE	N° B°	N° P	N° 5	N° 3	N° iii	N° 7"	N° A"	N° A'	N° 7'	N° SS14
Humid weigth (g)	48	56	52	54	61	26	34	41	68	70
Total dry weigth (g)	45	52	49	50	56	24	31	37	63	64
Weigth of TARE (g)	21	21	27	21	22	11	12	12	33	29
Weigth of water (g)	3	4	3	4	5	2	3	4	5	6
Dry weigth of soil	24	31	22	29	34	13	19	25	30	35
Water content %	12.5	12.9	13.6	13.8	14.7	15.4	15.8	16.0	16.7	17.1
Mean water content %	12.702		13.715		15.045		15.895		16.905	
Dry density (dS)	1.376		1.420		1.453		1.416		1.374	

DAME		PK or Profil **Attacked by leachate**
N° of layer	**5**	Pick location : **Nkolfoulou LANDFILL**
N° of blows per layer	**56**	Maximum dry Density : DS
Optimum water content		Depth : **0.00m**
N° Sampler	**Slope Soil of 3G locker**	OPERATOR : **BUKY Nankeng**



DESIGNATION (g)	6000g		6000g		6000g		6000g		6000g	
Weigth water add	12%		14%		16%		18%		20%	
Total humid weigth (g)	9073		9208		9408		9343		9267	
Weigth of mold (g)	4976									
Humid weigth of soil (g)	4097		4232		4432		4367		4291	
Volume of the mold (cm^3)	2303.35									
Humid density (dh)	1.779		1.837		1.924		1.896		1.863	
N° TARE	N° C3	N° ii	N° A	N° B	N° 10	N° A"	N° C	N° 4	N° 1	N° 3B
Humid weigth (g)	94	97	80	78	77	82	70	69	66	66
Total dry weigth (g)	89	91	75	73	71	76	65	64	61	60
Weight of the rare (g)	28	22	20	21	11	21	21	22	21	14
Weigth of water (g)	5	6	5	5	6	6	5	5	5	6
Dry weigth of soil (g)	61	69	55	52	60	55	44	42	40	46
Water content %	8.2	8.7	9.1	9.6	10.0	10.9	11.4	11.9	12.5	13.0
Mean water content %	8.446		9.353		10.455		11.634		12.772	
Dry density (dS)	1.640		1.680		1.742		1.698		1.652	

DAME		PK or Profil **Attacked by leachate**
N° of layer	**5**	Pick location : **Nkolfoulou LANDFILL**
N° of blows per layer	**56**	Maximum dry Density : DS
Optimum water content		Depth : **3.00m**
N° Sampler	**Slope Soil of 3G locker**	OPERATOR : **BUKY Nankeng**



DESIGNATION (g)	6000g		6000g		6000g		6000g		6000g	
Weigth water add	12%		14%		16%		18%		20%	
Total humid weigth (g)	8450		8575		8735		8637		8545	
Weigth of mold (g)	4976									
Humid weigth of soil (g)	3474		3599		3759		3661		3569	
Volume of the mold (cm^3)	2303.35									
Humid density (dh)	1.508		1.563		1.632		1.589		1.549	
N° TARE	N° 3B	N° B"	N° A"	N° A'	N° 10	N° 4	N° C	N° 032	N° D"	N° E
Humid weigth (g)	46	51	49	50	40	48	54	54	46	45
Total dry weigth (g)	42	47	44	46	36	44	49	50	41	40
Weight of the rare (g)	15	21	12	21	12	21	21	28	14	14
Weigth of water (g)	4	4	5	4	4	4	5	4	5	5
Dry weigth of soil (g)	27	26	32	25	24	23	28	22	27	26
Water content %	14.8	15.4	15.6	16.0	16.7	17.4	17.9	18.2	18.5	19.2
Mean water content %	15.100		15.813		17.029		18.019		18.875	
Dry density (dS)	1.310		1.349		1.395		1.347		1.303	

DAME		PK or Profil **Natural soil**
N° of layer	**5**	Pick location : **Nkolfoulou LANDFILL**
N° of blows per layer	**56**	Maximum dry Density : DS
Optimum water content		Depth : **0.00m**
N° Sampler	**Natural separation soil of 3G locker**	OPERATOR : **BUKY Nankeng**

Annex VII. Implementation of the in-situ permeability test.

Annex VIII. Record data of the in-situ permeability test.