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Title:

Development of a Technical Management Tool for Settlement and Stability Behaviour of Municipal Solid Waste Landfills

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Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Farzaneh Tahmoorian
December 2014

Abstract

Landfilling is a common method of disposal of municipal solid waste (MSW). Landfills are engineered structures consisting of bottom liners, leachate collection and removal systems, and final covers. With an expanding world and the remarkable growth of industry, the demand for larger and higher capacity landfills is rapidly increasing. As available space becomes scarce in urban areas, development on the top of or adjacent to old landfills has become increasingly common. Redeveloping on or adjacent to a closed landfill can be challenging and complex. In this regard, it is necessary to review a wide variety of engineering and geotechnical considerations for landfill redevelopment including settlement, foundation systems, gas and leachate management, and utility considerations, etc. Among various factors, which would be considered in redeveloping landfill sites, settlement is the most important factor from the perspective of structural and geotechnical stability.

Prediction of the long-term settlement of MSW for the final cover design as well as end-use facility design such as recreational facilities, industrial/commercial facilities is necessary. In addition, estimation of settlement is needed to assess the stability of leachate and gas collection pipes, drainage systems, landfill storage capacity, and the overall landfill operating costs. Excessive settlement may cause fracture in the cover system and may also cause damage to the leachate and gas collection pipes.

Many researchers studied the compression response of MSW and proposed different approaches to predict immediate settlement and time dependent settlement under load. Today, there are many published landfill settlement models. The research has been developed from simple soil mechanics based model to the constitutive model of waste. The stages of waste, which primarily only consider the primary and secondary settlements are improved with the development of constitutive model for long term settlement predictions.

In this study, the critical and comprehensive literature review about the landfill settlement and compressibility is provided. It is concluded that current methods of settlement prediction have serious shortcomings in accounting for the organic (biodegradable) portion of waste streams and the many factors that control its decomposition; they are also unable to account for changing landfill conditions such as rates of filling or changes in waste type that have major effects on settlement rates and magnitude. The existing methods are therefore difficult to use in a predictive manner and require recalibration for changing waste streams.

In this study, a technical management tool for MSW closed landfills has been developed using MATLAB graphical user interface, which aims to understand the process of long term settlement in landfills considering various related parameters, whilst it calculates different properties of wastes, and determines the landfill slope stability under various conditions. Furthermore, to illustrate the role of these parameters in settlement, a detailed parametric study considering variations of different parameters have been conducted in term of the settlement change over time as affected by influencing parameters. This parametric study showed that the variation of parameters can lead to significantly different settlements in landfills. Therefore, it is necessary to carefully select the parameter values for accurate prediction of landfill settlements. Moreover, in order to increase the understanding of the landfill behaviour and to quantify the significance of different parameters, a sensitivity analysis has also been performed to study the sensitivity of the models to variation of input parameters such as the unit weight, the landfill height, the waste properties, and the factors, affecting the biodegradation process of landfills. The results of this sensitivity analysis indicate that there are two prominent characteristics, having significant impacts on the overall landfill settlement. These characteristics are the landfill height and the compressibility parameters, while two other parameters including the gas diffusion coefficient and the van Genuchten parameter have trivial effects when compared to their relevant normal operating point (NOP). However, some other parameters have different degree of impact on the landfill settlement.

In this research, a numerical study has also been carried out by applying PLAXIS 2D for prediction of slope stability of landfills. Additionally, a detailed parametric study is conducted to investigate the influence of the slope geometry on the safety factor (SF) considering the variation of waste geotechnical properties, the landfill height, and the waste compaction conditions, in order to develop a set of design charts in terms of variations of the SF with various heights, the slope inclinations, the effective cohesions of the waste, and the effective friction angles.

Finally, the field data related to Tehran landfill has been collected for the validation of this landfill technical management tool (LTMT). It has been found that LTMT and its adopted model can be effectively used for MSW landfill settlement estimation. It should be noted that using this technical management tool, the effect of different parameters and conditions on settlement can be investigated. It is expected that the parametric study, which has been carried out in this research, can be applied in landfill redevelopment projects to predict the long term behaviour accurately, resulting in reduced construction and maintenance costs.

This dissertation concludes that the most important and influential parameters in landfill redevelopments and prediction of MSW landfill settlement incorporating gas generation and leachate production are the landfill height, the compression ratio, the lift thickness, the waste composition, and the age of MSW.

This dissertation is dedicated to my son

Amir Koorosh Nemati

who really gave me the reason to continue….

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LIST of Publications

During the course of this research, a number of publications have been made which are based on the work presented in this thesis. They are listed here for reference.

- Tahmoorian F., Khabbaz H. , Nemati S., “Numerical Study of Slope Stability of Instrumented Tehran Sanitary Landfill”, International Journal of GEOMATE, 2014.
- Tahmoorian F., Nemati S., “Long-time Settlement Model of Waste Soils for Iranian Landfills”, 4th International Conference on Geotechnique, Construction Materials and Environment, Brisbane, Australia, 2014.
- Nemati S., Tahmoorian F., “Environmental Problems of Iranian Landfill at Seaside of Caspian Sea”, International Journal of GEOMATE, 2014.
- Nemati S., Tahmoorian F., Hasanli E., “A Case Study on Environmental Problems of Iranian Landfills”, 4th International Conference on Geotechnique, Construction Materials and Environment, Brisbane, Australia, 2014.
- Tahmoorian F., Khabbaz H., “Parametric Study and Sensitivity Analysis of Long Term Settlement of Municipal Solid Waste Landfill Coupled With Landfill Gas Pressure and Leachate Flow”, 15th International Waste Management and Landfill Symposium, Cagliari, Italy, 2015 (Abstract has been accepted).
- Tahmoorian F., Khabbaz H., “Numerical Analysis of Slope Stability of Instrumented Tehran Sanitary Landfill”, Abstract has been submitted to 4th GeoChina International Conference, Shandong, China, 2016.
- Tahmoorian F., Khabbaz H., “Design, Construction, and Redevelopment of Instrumented Tehran Sanitary Landfill”, Abstract has been submitted to 4th GeoChina International Conference, Shandong, China, 2016.
- Tahmoorian F., Khabbaz H., “Parametric Study of Long Term Settlement of Municipal Solid Waste Landfill Coupled with Landfill Gas Pressure and Leachate Flow”, Abstract has been submitted to 5th International Conference on Geotechnique, Construction Materials and Environment, Osaka, Japan, 2015.
- Tahmoorian F., Khabbaz H., “Lifecycle Performance Assessment of MSW Landfills through Settlement Prediction”, Abstract has been submitted to 2nd International Conference on Performance-based and Lifecycle Structural Engineering (PLSE 2015), Brisbane, Australia, 2015.

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List of Notations and Symbols

The following symbols including their definitions are used in this report:

Acronyms:

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CS	Centre Space
FEM	Finite Element Method
FT	Forward Time
GCL	Geosynthetic Clay Liner
LCS	Leachate Collection system
LTMT	Landfill Technical Management Tool
MB	Methanogenic Biomass
MC	Moisture Content
MSW	Municipal Solid Waste
NMOC	Nonmethanogenic Organic Compound
SBP	Soybean Peroxidas
SF	Safety Factor
TOC	Total Organic Carbon
VFA	Volatile Fatty Acids
VOC	Volatile Organic Compounds

Latin Letters:

A	Factor representing the final total settlement
a	Primary compressibility parameter
b	Secondary compressibility parameter
b	Coefficient of mechanical creep
b	Coefficient of secondary mechanical compression
B	Interactive constant associated with the biodegradation of organics
B	Factor representing the initial settlement rate
c	Secondary mechanical compression rate
c	Rate constant for mechanical creep
C_1	Slope of the strain versus log-time curve
$C_{\alpha i}$	Compression index (function of stress level and degree of decomposition)
C_{β}	Biodegradation index
C_c	Primary compression index
C_α	Secondary compression index
$C_{\alpha e}$	Modified secondary compression index

C_{ce}	Modified primary compression index
$\mathrm{C}_{\alpha 1}$	Intermediate secondary compression ratio
$\mathrm{C}_{\alpha 2}$	Long term/final secondary compression ratio
$\mathrm{C}_{\alpha \mathrm{f}}$	Creep index
C_i	Initial mass of the biodegradable waste
C^*	Compressibility parameter
$C_c{}^*$	Compression ratio
$C_\alpha{}^*$	Swelling ratio
C'_α	Modified coefficient of secondary compression in terms of strain
D	Gas diffusion coefficient
d	Secondary biological compression rate
$d\varepsilon_v^e$	Volumetric strain due to elastic
$d\varepsilon_v^p$	Volumetric strain due to plastic
$d\varepsilon_v^c$	Volumetric strain due to time dependent mechanical creep
$d\varepsilon_v^b$	Volumetric strain due to biodegradation effects
$d\varepsilon_{vc}$	Volumetric strain increment
E_{dg}	Total compression due to waste degradation
E_m	Secant modulus
e	MSW void ratio
e_0	Initial void ratio of waste
e_p	Void ratio at the end of primary compression
f_{sj}	Initial solids fraction for each waste group
G	Rate of generation of gas per unit volume of waste
G_{si}	Initial overall specific gravity of waste solids
G_{sj}	Specific gravity of jth group of the waste solids
H	Design thickness
H_0	Initial thickness of the waste layer
H_i	Height of solid waste after initial compression
H_p	Height of solid waste after primary compression
h	Matric potential
h_i	Post compression height of layer i
$\frac{H_0}{H_i}$	Relative height corresponding to the existing overburden pressure (σ_0)
$\frac{\Delta H}{H_i}$	Change in relative height corresponding to the stress increment ($\Delta\sigma$)
K	Coefficient of permeability
k	Intrinsic permeability
k	First-order degradation constant
k_g	Unsaturated gas conductivity
k_w	Unsaturated hydraulic conductivity
k_{gs}	Saturated gas conductivity
k_{ws}	Saturated hydraulic conductivity

k'	Decomposition factor
k'	Post filling decay
L_0	Volume of gas a unit mass of waste could produce
m	Molar mass of the landfill gas
m	Van Genuchten parameter
m'	Rate of increase of waste thickness with time
m_a	Mass of air
m_w	Mass of water
m_s	Mass of solids
m_v	Coefficient of volume change
M'	Reference compressibility
N'	Rate of compression parameter
n	Van Genuchten parameter
n	Number of lifts in the landfill
n	Porosity in the landfill
n_i	Initial landfill porosity
p	Van Genuchten parameter
P	Pressure beyond atmospheric pressure
P_a	Atmospheric pressure
P_0	Existing overburden pressure acting at midlevel layer
R	Universal gas constant
S	Total settlement of waste
S_e	Effective saturation
S_{ic}	Settlement due to immediate compression
S_{pc}	Settlement due to primary compression
S_{sc}	Settlement due to secondary compression
T	Average landfill temperature
t	Time since beginning of filling
$\mathrm{t_b}$	Time for completion of biological compression
$\mathrm{t_c}$	Construction period
$\mathrm{t_c}$	Time of completion of filling
$\mathrm{t_{cb}}$	Time for the creep at the end of biological degradation
t_e	Time duration for evaluation of compression
t_i	Duration of filling of layer i
t_{is}	Time at the end of initial settlement period
$\mathrm{t_p}$	Time for primary compression
$\mathrm{t_r}$	Reference time
$\mathrm{t_1}$	Time for completion of primary compression
$\mathrm{t_2}$	Time for completion of secondary compression
$\mathrm{t_3}$	Time for total period of time considered in modeling
t_s	Time at which the slope of the strain versus logarithm time curve changes to a steeper slope

t'	Time elapsed since loading application
t''	Time elapsed since waste disposal
u_a	Excess-gas pressure
u_0	Pore-gas pressure at $t = 0$
U_p	Primary settlement of waste for design thickness
U_d	Decomposition settlement at time $t \leq tc$ after start of filling
$(U_d)_{t \geq t_c}$	Post decomposition settlement at time tpc larger or equal to tc
$V_{i,N}$	Initial volume of each layer of waste in the landfill
$V_{S,N}$	Volume of the waste layer considering spatial and temporal variation
v_a	Volume of air
v_w	Volume of water
v_s	Volume of solids
v	Total volume
w_c	Weight of component c
w_j	Gravimetric water content
w_t	Total weight of waste components
y	Depth below the landfill surface

Greek Letters:

α	Van Genuchten parameter
α	Fitting parameter (=0.00095H +0.00969)
β	Fitting parameter (=0.00035H+ 0.00501)
β	Correlation coefficient of compression due to biodegradation
β	Fraction of waste mass that can potentially be converted to gas
ε_p	Strain resulting from instantaneous response to applied load
ε_c	Time-dependent strain due to mechanical creep
ε_b	Time-dependent strain due to biological decomposition
ε_{pi}	Strain in lift i resulting from instantaneous response to loading from overlying lifts
ε_{ci}	Strain at time t in lift i due to mechanical creep associated with the stresses from self-weight and the weight of overlying lifts
ε_{bi}	Strain at time t in lift I due to biological decomposition of lift i
ε_v	MSW volumetric strain
$\varepsilon_{tot-dec}$	Total amount of compression due to decomposition of biodegradable waste
$\varepsilon(t)$	Strain at time t
ε_0	Initial strain
ε_i^e	Elastic strain
ε_i^p	Plastic strain
ε_i^c	Time-dependent creep strains
ε_i^d	Time-dependent degradation induced strain

θ_r	Residual moisture content
θ_s	Saturated moisture content
σ'	Effective stress
σ	Compressive stress depending upon waste height, density, and external loading
σ_0	Existing overburden pressure acting at midlevel of the layer
σ_v	Vertical overburden stress
λ/b	Rate of secondary compression
λ	First order decay constant
λ_j	First order kinetic constant for the jth group
μ	Dynamic viscosity of water
γ	Unit weight of MSW
γ_a	Average unit weight of MSW
γ_c	Unit weight of component c
γ_i	Unit weight of lift i
γ_w	Specific weight of water
γ_t	Unit weight ofwaste at a given time under confinement
ρ_s	Density of MSW solids
ρ_{sp}	Density of paste particles
ρ_w	Density of water
ρ_s	Density of solid waste
ρ_i	Density of the waste for each layer
τ	Parameter related to the rate of gas production
κ	Bulk viscosity of the solid waste
Δh_i	Long term settlement of waste layer i
ΔP	Increase in overburden pressure acting at midlevel layer
Δv	Volume variation
$\Delta\sigma$	Increment of overburden pressure acting at midlevel of the layer from the construction of an additional layer
$\delta\sigma'$	Difference in effective stress
$\Delta\gamma_c$	Increase in unit weight of component c

Chapter 1

Introduction

1.1. Research Scope

The increased generation of municipal solid waste (MSW) is reflected in the growth in population and economic. Landfilling is still the most prevalent method of disposal of municipal solid waste. As land becomes more valuable, reuse of abandoned land including former landfills is becoming more widespread. Over the past decade, there has been a significant increase in development on closed solid waste landfills due to the increasing value of lands.

Landfills of municipal solid waste often require additional considerations for proper development because of differential settlement, leachate generation and landfill gas emissions. In this regard, waste settlement prediction and monitoring are crucial to understanding and managing the lifecycle of a landfill. During the lifecycle of the municipal solid waste landfill, MSW settles under its own weight and as the external loads, placed on the landfill. External loads include the daily soil cover, the additional waste layers, the final cover, and facilities such as buildings and roads. Several deformation mechanisms can be observed in landfills. Spontaneous elastic-plastic deformations occur directly after emplacement or loading. They are caused by the compression of larger pores as well as the rearrangement and crushing of particles. High loadings together with high water saturation and a low permeability of the material might lead to generation of excess pore pressures. Then short-term settlements increase with time due to consolidation. At a larger time scale, creep of the material itself or compression of micro-pores cause additional deformations. Furthermore, long-term settlements occur due to biological decomposition. Following the biological decomposition, landfill gas will generate. This process implies settlements that extend over many years until complete degradation of the organic matter.

Prediction of MSW landfill settlement is not only critical to structures constructed over the landfill but also to ensure the safety of appurtenant structures placed within the waste (e.g., gas extraction wells/drains) and design cover systems.

The importance of understanding the settlement characteristics of MSW landfills can be realized from the literature that exists today on this topic as well as the development of numerous models to simulate the landfill condition and study its settlement. These models can be used in advanced numerical methods to predict the settlement behaviour of MSW landfills. According to review of the models and studies on landfill settlement, it can be revealed that there are limited number of models that consider all relevant parameters and factors in the settlement estimation. The existing predicting models still have some deficiencies and weaknesses to integrate all mechanisms occurring in landfills and different properties of municipal solid wastes, which affect the landfill settlement as well as gas generation and moisture distribution in the landfill.

In fact, optimizing the utilization of landfills for redevelopment projects relies on an understanding of the compaction, settlement, and stabilization of waste over time. Several parameters must be monitored and optimized in order to attain a reliable data for the landfill settlement in order to execute on top of or adjacent to the landfill. Moreover, the predicted settlement can vary significantly depending on the model selected and the specific values of model parameters used. The appropriateness of these models can be evaluated by modelling the typical settlement behaviour and comparing with the field measurements of landfill settlement.

Therefore, referring to the importance of the landfill redevelopment projects, the development of a landfill technical management tool (LTMT) to evaluate the MSW landfill settlement incorporating gas generation and leachate production is addressed in this research. The LTMT takes into account the organic portion of waste streams and many factors that control the solid waste decomposition. It also accounts for changing conditions of MSW landfills including changes in landfill height as well as the waste type that have major effects on the settlement rate and magnitude.

A comparison of the predicted settlements for typical MSW landfill conditions based on this technical management tool under various conditions and related parameters showed significant differences in time-settlement response depending on the selected model input parameters. Therefore, this involves a detailed parametric study in this research to investigate the performance of the MSW landfill settlement with respect to changes in input parameters. Moreover, it may be stated that while the qualitative influence of these parameters on settlement of MSW is known, it is essential to obtain the values in quantitative terms in terms of time-settlement behaviour for different parameters. This is possible by conducting a sensitivity analysis using suitable parameters and factors. Thus in this study, the sensitivity analysis is performed on key parameters to investigate the influential and non-influential parameters in MSW landfill settlement. The sensitivity analysis is helpful in understanding the landfill settlement behaviour as well as in identifying influential parameters because determining important parameters is extremely crucial to accurate prediction of the long term behaviour of MSW landfills, and subsequently resulting in reduced construction and maintenance cost in landfill redevelopment projects.

In addition, as the stability of the landfill is one of the major geotechnical concerns during the operation and post closure of landfills, this research includes the numerical study on the stability of MSW landfill. This numerical analysis is performed by employing the program PLAXIS 2D, which is a finite element program including special features to deal with numerous aspects of complex geotechnical structures such as advanced constitutive models for the simulation of the time dependent behaviour of materials as soil, MSW, etc. Therefore, in this study, PLAXIS 2D is used to simulate the landfill and its slope stability under various conditions.

Finally, as quantifying the confidence and predictive accuracy of the model helps the decision-makers in making appropriate decisions, the verification procedure is considered in this study based on the gathered field data regarding Tehran landfill to validate the landfill technical management tool.

1.2. Research Objectives, Significance, and Innovations

1.2.1. Objectives

Landfills provide unique opportunities for reuse, although significant development limitations and many relevant considerations must be addressed. Among various factors and conditions that should be considered in landfill redevelopment, settlement of waste can be the most important one and needs to be considered in this regard.

Thus, the primary research objective of this research project is to evaluate the behaviour of landfills and to develop a technical management tool as a means to characterize variations in parameters in waste and landfill. In addition, since the characterization of municipal solid waste is relevant to this project as it impacts the decomposition of the waste and the settlement of the MSW landfill, the evaluation of different properties of municipal solid waste including physical properties, chemical properties, and biological properties is part of the calculations which can be done by employing this technical management tool. Moreover, the data from a specific survey is used to verify the validation of this technical management tool.

Furthermore, a parametric study and sensitivity analysis are conducted to investigate the exact effect of parameters on landfill settlement. The results and analysis of the parametric study and sensitivity analysis are presented in this thesis, as well as the waste settlement model applied to obtain those results.

This work is conducted as a component of a broader environmental engineering project; the aim of which is to pursue an understanding of how environmental and operational parameters affect the rate of waste settlement at a MSW landfill. A better understanding of such parameters will be used to develop models and methods to estimate the waste settlement more accurately as well as to optimize waste stabilization, and subsequently, the landfill redevelopment in a credible condition.

In summary, the specific aims of this research are as follows:

- Studying the factors influencing the time dependent settlement behaviour of MSW landfills
- Studying different settlement models mainly those that consider mechanical, hydraulic and biological processes as well as different phases in MSW landfills including solid, liquid and gas phases
- Developing a technical management tool to predict the time dependent deformation of MSW landfills incorporating gas and leachate generation based on the concepts of above mentioned models and to investigate MSW physical, chemical and biological properties
- Conducting a detailed parametric study considering variations of different parameters in term of variations of the settlement with time as affected by parameters
- Performing a sensitivity analysis to study the sensitivity of the models to variation of input parameters such as unit weight, landfill height, waste properties, and factors affecting the biodegradation process of landfills
- Collecting the field study data of Tehran landfill regarding the landfill geometry, MSW properties and the settlement versus time data
- Performing a numerical study on the slope stability of MSW Landfill as well as a detailed parametric study to investigate the influence of the slope geometry on the safety factor (SF) considering the variation of the landfill height, and the slope inclinations

- Verifying the landfill technical management tool by simulating Tehran landfill based on the relevant collected information, and subsequently the comparison between the measured field study data and the predicted landfill settlement

1.2.2. Significance

According to the objectives mentioned above, this research presents a critical review of models proposed for MSW landfill settlement estimation, describes the applicability and usage of these models, and finally, it involves a thorough study of the settlement model proposed by Hettiarachchi et al. (2005) and its main incorporated parameters. Based on this study, it can be concluded that this model has considered different phases in landfill and mechanical, hydraulic and biological behaviour of MSW landfills. However, it has considered constant parameters for density, waste components percentage, waste moisture content, and other relevant parameters. Therefore, this study presents the development of a technical management tool for predicting landfill settlement based on this which integrates gas generation and leachate movement while some modifications are done to the program written by Hettiarachchi et al. (2005) to convert these constant parameters to variable ones. In addition, as this technical management tool is a User Interface Program, it makes users comfortable to apply the model. Additionally, since the waste properties play an important role in the magnitude and rate of landfill settlement, the calculation of MSW physical, chemical and biological properties is considered as a part of this technical management tool.

Moreover, the role of various parameters and conditions on landfill settlement and slope stability is investigated in this research by applying some software such as MATLAB and PLAXIS. It is expected that the parametric study and sensitivity analysis can be applied in landfill redevelopment projects to predict the long term behaviour of MSW landfills accurately, and hence to reduce the construction and maintenance costs.

1.2.3. Innovation

One of the most important technical post-closure considerations in MSW landfills is the large amount of settlement that can take place for many years after landfill closure. Landfill settlement prediction is difficult as solid wastes undergo the waste decomposition which cannot easily be incorporated into the traditional settlement calculations. This research involves a comprehensive and critical review on different proposed models of MSW landfill settlement. Among these models, a model considering changes of gas generation and leachate movement is studied precisely. As this model considers constant parameters for moisture content, waste composition, landfill height, density, so forth, some modifications are made to it in order to predict more precise long term settlements of MSW landfills with more effective parameters. This modified model is considered as the basis of a technical management tool which is developed by MATLAB during this research to estimate the landfill settlement considering various parameters and conditions. Furthermore, to investigate the role of these parameters in MSW landfill settlement, a detailed parametric study is performed considering variations of different parameters in term of variations of the settlement with time as affected by parameters. Additionally, to quantify the significance of different parameters, a sensitivity analysis is also conducted to study the sensitivity of the models to variation of input parameters such as unit weight, landfill height, waste properties, and factors, affecting the biodegradation process of landfills. This technical management tool is verified based on the comprehensive field study data collected regarding the measurement of Tehran landfill settlement.

Moreover, as the stability of landfill is of importance in landfill engineering and landfill redevelopment projects, a numerical study on the slope stability of landfill is performed by PLAXIS to investigate the influence of the slope inclination and the landfill height on the safety factor (SF).

The outcomes of the study can improve the confidence for design and construction on MSW landfills. It may reduce the uncertainty when predicting the landfill settlement, and enable to apply the landfill redevelopment techniques more effectively and efficiently.

1.3. Organization and Thesis Layout

This dissertation explains the settlement and stability behaviour of the municipal solid waste landfills under various conditions and considering different parameters while presenting the landfill technical management (LTMT) developed during this research. The organization of this dissertation including eight chapters is as follows:

Chapter 1, which is an introductory chapter, outlines the definition of the problem and discusses the significance and innovations of this research. Moreover, the research scope and the brief review of thesis work flow are provided in this chapter.

Chapter 2 provides a critical review on the previous studies associated with landfill settlement as well as a thorough review of the municipal solid wastes properties based on the results of the previous investigations.

Chapter 3 is dedicated to briefly description of the MSW landfill settlement model, which is used as the basis for the development of the landfill technical management tool. It involves the introduction of different equations employed for estimation of landfill settlement, as well as the assumptions and the governing equations used in the proposed model.

Chapter 4 provides the detailed information regarding the numerical analysis, which is conducted on the slope stability of MSW landfill embankments. This chapter describes the thorough procedure of modelling the landfill in PLAXIS 2D and presents the results of the parametric study which is performed on the safety factor of landfill slope stability in terms of the landfill height and the slope inclination.

Chapter 5 focuses on reviewing different parts of the landfill technical management tool (LTMT), and shows how this program can be used in estimation of MSW landfill settlement in addition to evaluation of solid wastes properties as well as the landfill slope stability.

Chapter 6 contains a full description of the parametric study and sensitivity analysis performed to investigate the influence of different parameters on the landfill settlement as well as to determine the influential and non-influential parameters in this regard.

Chapter 7 demonstrates the verification procedure and compares the field study data with the obtained results from the landfill technical management tool regarding the MSW landfill settlement. Firstly, this chapter describes Tehran landfill, which is considered as a case study for validation of this technical management tool in addition to the characterization of the wastes disposed in this landfill. Subsequently, the same landfill is simulated in the landfill technical management tool. Lastly, the results of the settlement prediction by simulation of the landfill in LTMT are compared with the measured field data to verify the LTMT.

Chapter 8 presents a summary of this thesis, including the concluding remarks that can be drawn from the research and its contributions. This chapter also suggests several ideas for related future work.

Chapter 2

Literature Review

2.1. Introduction

2.2. Definitions

2.3. Municipal Solid Waste (MSW) Characteristics

2.4. Landfill Characteristics

2.5. Landfill Settlement

2.6. Settlement Models of MSW Landfills

2.7. Landfill Failure Modes

2.8. Summary of Literature Review

2.1. Introduction

Human activities generate wastes that are often solid. These wastes are normally discarded because they are considered useless or unwanted. Some fraction of municipal solid waste (MSW) must be returned to environment regardless of any other approaches of waste management such as reuse, recycling, and energy recovery. Landfilling is still the most prevalent method of disposal of municipal solid waste. With an expanding world and the remarkable growth of industry, the demand for larger and higher capacity landfills is rapidly increasing. As available space becomes scarce in urban areas, development on the top of or adjacent to old landfills has become increasingly common. Over the past decade, there has been a significant increase in development on closed solid waste landfills.

Landfills of municipal solid waste (MSW) often require additional considerations for proper development because of differential settlement, leachate generation, and landfill gas emissions. In this regard, waste settlement prediction and monitoring are crucial to understanding and managing the lifecycle of a landfill. The compressibility and settlement behaviour of MSW has drawn the attention of several researchers to propose different approaches and settlement models for predicting time dependent settlement under load. Therefore, the main purpose of this chapter is to provide a review of literature in the field of MSW landfill settlement models. However, general topics including some definitions, waste components, municipal solid waste properties, and MSW landfill characteristics are initially discussed in order to gain an understanding of issues specific to landfill waste settlement mechanisms and the existing related models.

2.2. Definitions

Some of the definitions related to this research topic are as follows:

Municipal Solid Waste (MSW): Municipal Solid Waste (MSW) (more commonly known as trash or garbage) consists of all solid or semisolid items that have not sufficient value to be used more and then are thrown away. These items come from our homes, schools, hospitals, and businesses and include product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, batteries, etc.

Dump: Dumps are the least expensive way of waste disposal which has been used before as the most commonly recognized method for the final disposal of solid wastes. The operation of a dump is simple and involves nothing more than a big hole or a big pile of garbage and possibly other dangerous things. They do not prevent the waste from coming into contact with the ground and they don't have leachate and gas collection systems as well. Thus, they cause soil and air pollution. In addition, rats, roaches, and other vermin, at the dump can result in serious public health and aesthetic problems.

Landfill: landfills are engineered structures which are designed, constructed, and operated based on relevant acceptable standards. Landfills can be executed in the ground or built on top of the ground. They are engineered structure for the placement of solid waste on land while prevent any soil and water contamination. The daily covering of Landfills keeps birds, insects, rats, and other animals from moving in and becoming a nuisance. Furthermore, final cover of landfills in addition to landfill gas collection systems avoids air pollution.

Initial compression: initial compression takes place instantaneously during the filling by waste and when an external load is applied. This stage is analogous to the elastic compression of soil and is generally associated with the immediate compression as it results from the expulsion of air which initially present in the voids along with the compression of some types of particles and materials.

Primary compression: Primary compression is defined as the process of dissipation of water and gas from the pores in response to the load. In a closed landfill, settlement due to primary compression will occur quickly within the first 30 days (e.g. Sowers, 1973; Morris and Woods, 1990) after load application.

Creep and secondary settlement*:* The settlement of a landfill continues after the primary compression. The long-term settlement of waste is a time-dependent deformation which does not occur suddenly upon the application of stress. It takes place when strain accumulates as a result of long-term stress. This settlement is attributed to secondary compression which is not due to dissipation of pore water pressure, but rather due to slow rearrangement of fine particles caused by decaying mass within the landfill, as a result of the physicochemical and biochemical decomposition. This process continues until the waste is fully stabilized. In general, the rate of this deformation is a function of the material properties, exposure time, exposure temperature and the applied structural load.

Consolidation: Consolidation is a time-dependent process which involves the volume reduction. According to Terzaghi (1943), "consolidation is any process which involves decrease in water content of a saturated soil without replacement of water by air." In general, it is the process in which pore water drainage is accompanied by a reduction in the volume of an element, which results in settlement. The rate of settlement depends on the rate of pore water drainage.

Settlement: In general, the total vertical deformation at the surface resulting from the load is called settlement. In landfills, when the organic material decomposes and weight is lost as landfill gas and leachate component, the landfill settles. Landfill settlement can be defined as the vertical deformation of landfills as the result of external loads including final and daily cover, overlying wastes, and any added structures such as buildings and roads or even as the result of water percolation into and out of the landfill.

2.3. Municipal Solid Waste (MSW) Characteristics

Municipal solid waste is defined as wastes from different sources including residential, commercial, institutional, and some industrial sources. Therefore, it is obvious that the type and composition of the municipal wastes can vary from region to region and from season to season. This fact can be considered as an important factor in all projects related to municipal solid waste issues. Thus, it is necessary to understand the main features of MSW by categorizing its properties and characteristics into different groups as following which will be discussed in subsequent sections:

2.3.1. MSW Classifications

MSW properties vary widely based on the type and composition of solid waste which is defined as the percentage (by weight) of the individual components that make up a solid waste stream. Information on the composition of solid wastes is important in evaluating the MSW landfill behaviours and in correlating measured engineering properties with existing data. However, to understand mechanical behaviour and engineering properties of waste bodies, it is necessary to consider a classification system based on waste components as well as the waste structure.

The classification of solid waste varies greatly in the literature and in the profession. Many of waste classification systems are based on waste components or the waste materials degradability.

Table 2.1: Existing Classification Systems of Waste Components (after Dixon et al., 2008)

Author	Basis for Differentiation	Parameters Used for Differentiation
Turczynski (1988)	Waste type	Density, shear parameters, liquid/plastic limit, permeability
Siegel et al. (1990)	Material groups	Part of composition
Landva and Clark (1990)	Organic/ Inorganic materials	Degradability (easily, slowly, non) Shape (hollow, platy, elongated, bulky)
ADEME (1993)	Particle size distribution, Composition	Size, material groups, moisture content and degradability
Grisolia et al. (1995)	Degradable, inert, Deformable material groups	Strength, deformability, degradability
Kolsch (1996)	Material groups	Size, dimension
Manassero et al. (1997)	Soil-like, other	Index properties
Thomas et al. (1999)	Soil-like/non-soil-like	Material groups
Dixon and Langer (2006)	Shape-related subdivisions	Material groups, size, dimensions, shape related properties, degradation potential

As presented in Table 2.1, many researchers have provided waste components classification systems. Among them, Landva and Clark (1990) classified the waste components into following groups and subgroups based on their biodegradability as the rate of decomposition is not the same for all materials:

- Inorganic wastes (I)
    - ❖ Degradable components (ID)
    - ❖ Non-degradable components (IN)
- Organic wastes (O)
    - ❖ Putrescible components (OP)
    - ❖ Non-putrescible components (NP)

In this classification, the group OP is defined as highly degradable wastes when favourable conditions are available.

Furthermore, Dixon and Langer (2006) stated that the starting point for a classification system is identification of the main waste components by material type and due to the large variety of materials present in waste; a practical approach is to identify major groups of materials. Selection of appropriate groups requires consideration of component mechanical properties. It is proposed that components are considered in the condition they have on delivery to a landfill site. Definition of this initial state is required because mechanical properties, shape and size of components will change as a result of placement conditions (i.e. compaction) and stresses due to burial, as some particles will deform, and in the long-term due to degradation processes. The classification system must provide the possibility for components to change group as a result of these processes. Moreover, the groupings should be appropriate for every possible type of waste.

This approach has been used to select the following material groups for use in the classification: Paper/Cardboard; Flexible plastics; Rigid plastics, rubber; Metals; Minerals, glass; Wood, leather, textiles; Organics; and Miscellaneous (Figure 2.1). The miscellaneous category is for components that are too small to practically sort.

Organic		**Inorganic**	
Putrescible (Monomers and low resistance polymers, readily biodegradable)	**Non-putrescible** (Highly resistant polymers, slowly biodegradable)	**Degradable**	**Non-degradable**
▪ Food waste ▪ Garden waste ▪ Animal waste ▪ Materials contaminated by such wastes	▪ Paper ▪ Wood ▪ Textiles ▪ Leather ▪ Plastic, Rubber ▪ Paint, Oil, Grease, Chemicals,	▪ Metals (Corrodible to varying degrees)	▪ Glass, Ceramics ▪ Mineral Soil, Rubble ▪ Tailings, Slimes ▪ Ash ▪ Concrete, Masonry (Construction debris)

Figure 2.1: Waste Classification (after Dixon and Langer, 2006)

2.3.2. MSW Physical Properties

In any construction, the physical properties of structure components have to be known so that the accurate analysis and relevant design can be performed in order to ensure the stability of that construction. As landfills are mainly made up of wastes as the largest structural element, it is needed to be familiar with the properties of the waste because it influences stability and whole behaviour of landfill. Important physical characteristics of MSW include unit weight, moisture content, field capacity, particle size and size distribution, and waste porosity. However, the discussion in this research is limited to moisture content, unit weight, porosity, and field capacity.

2.3.2.1. Moisture Content

Moisture content (MC) is a crucial parameter in municipal solid waste landfills because it affects mechanical and biochemical processes in landfills. It influences the compaction condition of wastes in landfills as well as the stability of the waste. In addition, as moisture provides an aqueous environment that facilitates the transport of nutrients and microbes, and hence enhances the substrate access for microorganisms, it improves gas generation.

Moisture content is defined as the ratio of the weight of the less than 20 mm material loss to the weight of the material remained during heating at a temperature of 55 degrees Celsius (Zekkos, 2005). It can be expressed either gravimetrically or volumetrically. The gravimetric moisture content (w) is defined as ratio of the weight of water (w_w) to the weight of solids (w_s), while the volumetric moisture content (θ) is the ratio of volume of water (v_w) to the total volume (v) of air, solids, and water.

Table 2.2: Various Range of Moisture Content (after Hossain, 2002)

Source	Moisture Content (%)
Sowers (1973)	10 - 50
Huitritic (1981)	15 - 40
Gifford (1990)	14 - 68
Landva and Clark (1990)	15 - 125
Blight et al. (1992)	10 - 100
Tchobanoglous et al. (1993)	15 - 45
Coumoulos et al. (1995)	20 - 125
Gabr and Valero (1995)	30 - 130

The moisture content of any waste can be measured based on the data related to the fraction of various waste components and the value of moisture content for those components. The moisture content of loose waste is typically about 20%. However, the moisture content will vary from 15 to 72 percent (Reddy et al., 2008) depending on the waste composition, the humidity and climatic conditions, the season of the year, amount of rain, operating procedures, location of origin, the rate of biological decomposition, amount of organic matter and the capacity and performance of leachate collection systems. Different reported ranges for moisture content is presented in Table 2.2.

In addition, the moisture content of the waste may increase after landfilling because of absorption of water by some of waste components such as paper, cardboard, and textiles. On the other hand, Gabr and Valero (1995) and Gomes et al. (2002) stated that degraded MSW holds higher moisture content due to the increase in particle surface area and moisture holding capacity.

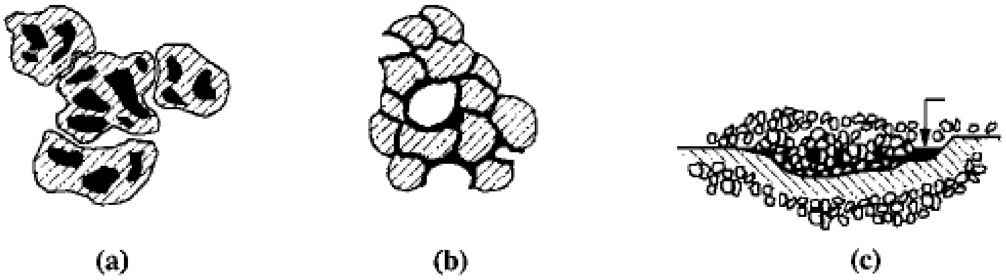

Figure 2.2: Mechanisms of Moisture Retention in Waste Mass

(a) within Particles (Intra-particle Voids); (b) between Particles, Retained by Capillary Forces (Inter-particle Voids); (c) between Particles, Retained by Low Hydraulic Conductivity Layers (Zornberg et al., 1999)

Generally, the moisture holding mechanisms within the waste mass can be grouped as following categories based on Zornberg et al. (1999) researches:

1) Moisture within the waste mass (within the intraparticle voids)
2) Moisture between particles (within inter particle voids), held by capillary stresses
3) Moisture between particles, retained by layers with lower permeability.

Zornberg et al. (1999) stated that the moisture retained within the waste by mechanisms 1 and 2 should be less than the field capacity of the waste. However, moisture accumulated above layers of low-hydraulic conductivity (mechanism 3) often leads to areas within the landfill where moisture is above field capacity of the waste. The above mentioned mechanisms are illustrated in Figure 2.2.

2.3.2.2. Unit Weight

The unit weight of MSW is an important property in landfill engineering. Unit weight of MSW is important when analysing engineering properties of landfills such as settlement, slope stability, and landfill capacity. MSW unit weight in landfill varies markedly with different factors. Like soils, the unit weight of waste is affected by the thickness of layer, the compaction effort, the depth of burial or overburden stress, climatic condition and the moisture content. However, the unit weight of waste unlike soils varies significantly with waste composition, degree of decomposition, age of waste, the geographic location, and season of the year.

Table 2.3: Bulk Densities of Some Waste Components (Worrell and Vesilind, 2002; Tchobanoglous et al., 1993)

Waste Component	Condition	Bulk Density (kg/m^3)
Food waste	Loose	130 – 480
	Baled	593 - 712
Paper	Loose	237 - 475
	Baled	415 – 593
Cardboard	Loose	208
Plastics	Loose	40 - 130
	Baled	235 - 300
Rubber	Loose	100 - 200
Leather	Loose	100 - 260
Textiles	Loose	40 - 100
Glass	Not crushed	297 - 415
	Crushed	1065 - 1600
Aluminium cans	Loose	30 - 44
	Flattened	148
Steel cans	Unflattened	89
	Baled	504
Wood	Mixed	130 - 320
Yard waste	Loose, mixed	150 - 830
Dirt, etc.	Loose	320 - 1000

To calculate the unit weight of waste for different waste composition, Landva and Clark (1990) proposed a general equation for average unit weight of the MSW based on unit weight of individual components of the waste as:

$$\boldsymbol{\gamma}_{\mathbf{a}} = \frac{\mathbf{1}}{\sum_{1}^{\mathbf{n}} \frac{\mathbf{w_c}}{\mathbf{w_t}} \times \frac{\mathbf{1}}{\boldsymbol{\gamma}_{\mathbf{c}}}} \qquad (\mathbf{2.1})$$

where $\frac{w_c}{w_t}$ is the weight of component c as a fraction of the total weight (w_t) of components, γ_c is the unit weight of component c in kN/m^3, and n is number of components. Table 2.3 illustrates the bulk density of various components found in MSW.

In addition, when waste is exposed to water, some of waste components such as food waste, garden refuse, paper, and textiles will absorb water. In this case, the unit weight of these components will increase due to increased moisture content of the intra-particle voids. Consequently, the bulk unit weight of the waste mass will increase. Based on Landva and Clark (1990), the average unit weight when exposed to moisture is given as:

$$\boldsymbol{\gamma}'_{\mathbf{a}} = \boldsymbol{\gamma}_{\mathbf{a}} \left[\mathbf{1} + \sum_{\mathbf{1}}^{\mathbf{n}} \frac{\mathbf{w_c}}{\mathbf{w_t}} \times \frac{\Delta\boldsymbol{\gamma}_{\mathbf{c}}}{\boldsymbol{\gamma}_{\mathbf{c}}}\right] \qquad (\mathbf{2.2})$$

where $\Delta\gamma_c$ is the increase in unit weight of component c in kN/m^3.

Table 2.4: Density of Landfilled Materials (US EPA, 1992)

Waste Component	Density (kg/m^3)
Food waste	1190
Paper	475
Cardboard	460
Plastics	200
Rubber	205
Leather	230
Textiles	260
Glass	1660
Aluminium cans	240
Steel cans	330
Wood	475
Yard waste	890

Moreover, compaction of wastes at landfills is an important factor which affects the waste unit weight in landfill and results in higher efficiency in terms of waste placement in landfills. Increasing waste unit weight will help in reducing the landfill space requirements and prolonging the life of landfill. In addition, waste unit weight influences the stability of a landfill so that high value of waste unit weight can be associated with high value of shear strengths which will consequently lead to higher stability of landfills.

Referring to Dixon and Jones (2005), the unit weight of compacted waste will depend on the following items:

- The waste components
- Thickness of layer
- Weight and type of compaction plant
- The number of times equipment passes over the waste.

To achieve a good compaction and hence high value of waste unit weight, the thickness of layer must range from 0.5 to 1.0 metre. Obviously, considering waste layers with a thickness of 2 to 3 metres will result in poor to moderate compaction. The average density of waste in terms of compaction effort and waste composition are presented in Table 2.5.

Table 2.5: Average Density of Waste in Landfills under Different Placement Conditions (after Sharma et al., 2004)

Source	Waste Placement Condition	Density (kg/m^3)
U.S Department of Navy (1983)	Poor Compaction	320
	Good Compaction	641
	Best Compaction	961
	Shredded	881
Sowers (1968)	MSW density depending on the compaction effort	481-961
NSWMA (1985)	MSW in a landfill after degradation and settlement	705-769
Landva and Clark (1986)	MSW Landfill (waste to soil cover ratio varied from 2:1 to 10:1)	913-1346
EMCON Associates (1989)	Ratio of 6:1 for waste to daily cover soil	737
Fassett et al. (1994)	Poor Compaction	540
	Moderate Compaction	714
	Good Compaction	979

Various studies indicate that the unit weight of waste varies with effective stress, which is a function of depth. In this regard, Gourc et al. (2001) presented the result of their research about the amount of bulk unit weight against overburden stress. These results demonstrate a clear trend of increasing unit weight with stress level.

Moreover, a detailed study which was conducted by Zekkos et al. (2006) proposed a hyperbolic function to describe the relationship between MSW unit weight and depth.

Based on this study, the following equation was derived for MSW unit weight in terms of vertical overburden stress (σ_v):

$$\boldsymbol{\gamma = \gamma_a + \frac{\sigma_v}{\alpha_v + \beta_v . \sigma_v}} \qquad (2.3)$$

where γ_a is the as-placed unit weight near the surface in kN/m^3, α_v ,β_v are modelling parameters, and σ_v is the vertical overburden stress in kN/m^2 .

In this study, it was concluded that writing a unit weight equation as a function of depth will eliminate the requirement for the estimation of the vertical stress or having knowledge about the unit weight of the overburden waste material. Therefore, the proposed hyperbolic MSW unit weight equation was rewritten as:

$$\boldsymbol{\gamma = \gamma_a + \frac{z}{\alpha + \beta . z}} \qquad (2.4)$$

where γ_a is the as-placed unit weight near the surface in kN/m^3, z is the depth in m at which the MSW unit weight ,γ, is to be estimated, and α and β are modelling parameters in m^4/kN and m^3/kN, respectively.

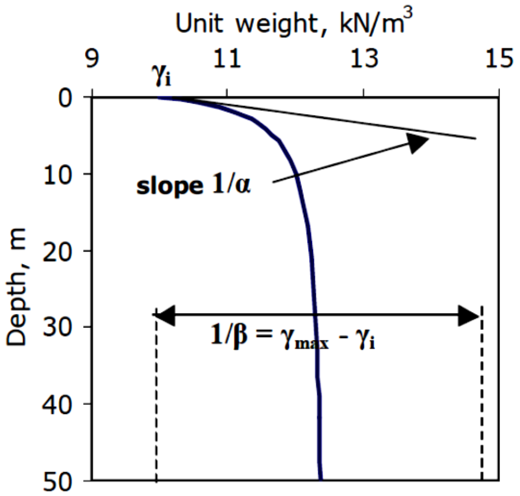

Figure 2.3: Physical Meaning of the Hyperbolic Parameters α and β (Zekkos, 2005)

Referring to Zekkos (2005) and as it is shown in Figure 2.3, the parameter β is a function of the difference in unit weight between the surface and at great depth (or confining stress), where the unit weight becomes approximately constant. The inverse of β is the asymptotic value of the difference in the unit weight at great depth and at the surface. The parameter α is a function of the unit weight increase near the surface. The ratio of 1/α is the initial slope of unit weight increase versus depth near the surface.

In addition, Table 2.6 presents the hyperbolic parameters for different compaction efforts and amount of soil cover. Based on the data available in this table, it can be concluded that the MSW unit weight increases near the surface as compaction effort and the amount of soil cover increases.

Table 2.6: Hyperbolic Parameters for Different Compaction Effort and Amount of Soil Cover (after Zekkos, 2005)

Compaction Effort and Soil Amount	$\gamma_i\ (\frac{kN}{m^3})$	$\beta\ (\frac{m^3}{kN})$	$\alpha\ (\frac{m^4}{kN})$
Low	5	0.1	2
Typical	10	0.2	3
High	15.5	0.9	6

Furthermore, the effect of time under confinement on the unit weight of MSW undergoing mechanical compression was also investigated by Zekkos (2005). Regression of the data obtained from this research resulted in the following relationship between the unit weight and the time under confinement:

$$\frac{\gamma_t(t)}{\gamma_t(t = 1\ \text{day})} = 0.0172.\log(t) + 1.0 \qquad (2.5)$$

where t is the time under confinement in days, $\gamma_t(t)$ is the unit weight at the time under confinement, and $\gamma_t(t = 1\ \text{day})$ is the unit weight after 1 day of time under confinement in kN/m^3.

2.3.2.3. Organic Content

Estimating the organic content in municipal solid waste is of critical importance in evaluating the organics reduction, the decomposition stage, and waste volume change. Organic content is defined as the ratio of the weight of the less than 20 mm material loss to the weight of the material remained during heating at a temperature of 440 degrees Celsius according to the ASTM D2974-87 (1995) procedures (Zekkos, 2005). The organic content in a landfill influences the geotechnical properties of waste such as compressibility characteristics of the waste, MSW unit weight, and shear strength of waste. The organic content of MSW varies significantly under different field conditions. Some of reported values for MSW organic content are depicted in Table 2.7.

Table 2.7: Reported Values for MSW Organic Content under Different Field Conditions

Source	Field Condition	Organic Content (%)
Barlaz et al. (1990)	Major Constituents: Cellulose & Hemicellulose	5-75
Gifford et al. (1990)	Major Constituents: Cellulose & Hemicellulose	5-75
Landva and Clark (1990)	Major Constituents: Cellulose & Hemicellulose	5-75
Gabr and Valero (1995)	Field Samples	33
Hu and Chen (2001)	Chinese Landfill	41.6
Gomes et al. (2005)	Near the surface	43 - 63
	At 11m Depth of Landfill	56

Based on the literature review, the organic content, cellulose and hemicellose, is higher at surface level and will be decreased at a deeper depth due to loss of organics (Barlaz et al., 1990; Hu and Chen, 2001). In addition, Landva and Clark (1990) stated that increasing organic content will result in water content increase as well as surface area increase due to the breakdown of particles. Furthermore, Wall and Zeiss (1995) cited that the increasing organic content leads to increase of the compression index. On the other hand, degradation of components with organic content will lead to a loss of mass, changes in size and the mechanical properties such as compressibility and shear strength. The amount of organic content in a waste mass will also change the density of the waste material because waste degradation causes reduction in void ration and hence the volume of the waste mass. Therefore, it may result in raising the value of waste density (Dixon and Jones, 2005).

Thus, the organic content presented in waste material play a vital role in various properties of waste such as compressibility, unit weight, and decomposition.

2.3.2.4. Field Capacity

Water entering the landfill through precipitation, water in waste material, covering material moisture, etc. which is not consumed or exited as water vapour , can be held within landfill or may appear as leachate. Waste materials as well as cover materials have the ability to hold water against gravity. The amount of water that can be held against gravity is defined as field capacity (Figure 2.4). In a completed landfill, if the field capacity of covering material is exceeded, the water percolates through the soil and into the waste layer. If, in turn, the field capacity of the waste is exceeded, the water will be flowed as leachate into the leachate collection system.

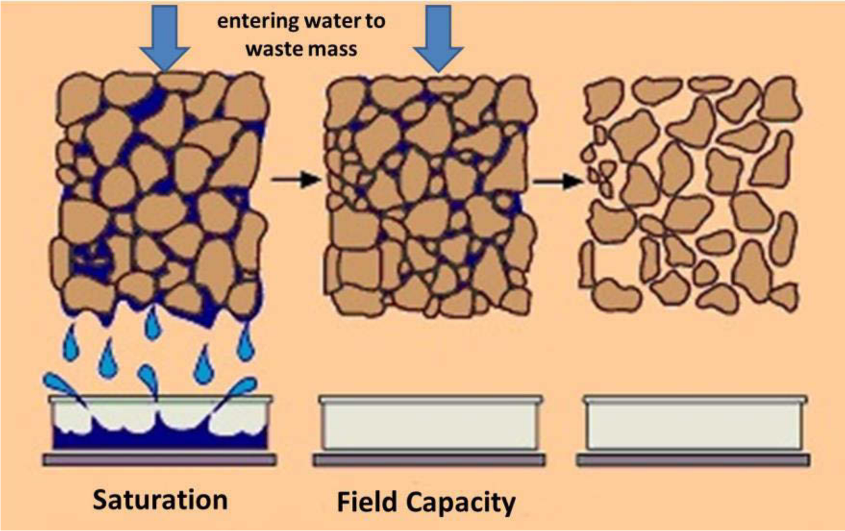

Figure 2.4: MSW Field Capacity Concept (http://bettersoils.soilwater.com.au)

The field capacity of waste material is an important parameter in estimating the leachate formation in landfills. Field capacity of MSW is expressed as the amount of moisture on a weight or volumetric basis as percentage of total refuse mass or volume respectively.

Table 2.8: Typical Field Capacity of MSW Landfills (after Vaidya, 2002)

Source	Field capacity (v/v)
Remson et al. (1968)	29
Holmes (1980)	29 - 42
Straub and Lynch (1982)	30 - 40
Korfiatis et al. (1984)	20 -30
Owens et al. (1990)	20 - 30
Zeiss and Major (1993)	14
Schroeder et al. (1994)	29
Bengtsson et al. (1994)	44

The field capacity for MSW landfills varies depending on the degree of applied pressure, the porosity of material, the waste composition, the stage of waste decomposition, the waste particle size, waste density, and the waste age (Yuen et al., 2000; Reinhart and Townsend, 1998). It typically ranges from 14% to 44% (Hossain, 2002) as presented in Table 2.8.

However, some researchers have stated that the field capacity of uncompacted commingled wastes from residential and commercial sources may range from 50% to 60% (Tchobanoglous et al., 1993; Kiely, 1997).

2.3.2.5. Porosity

The porosity of a waste is defined as the ratio between the volume of voids (V_V) and the overall volume (V_T) which is expressed as a percent (Hudson et al., 2004). Another volumetric parameter which is completely related to the porosity (n) is the void ratio (e). Void ratio is defined as the ratio of volume of voids (V_V) to the volume of solids (V_S) and it is expressed as a decimal. Both of these parameters are interrelated by the following equation:

$$\mathbf{e} = \frac{\mathbf{n}}{\mathbf{1 - n}} \tag{2.6}$$

In the main, the porosity is dependent upon the grain size distribution of the material as well as their arrangement in the given volume. For the municipal solid wastes, the shredding will decrease the porosity of the waste material. Moreover, the compaction of waste will also result in the lower values for porosity. Generally, the porosity of MSW depends on the compaction and composition of the waste (Qian et al., 2002). In addition, the biodegradation of organic fraction of waste influences the void ratio of MSW, and hence the porosity of waste. Biodegradation of waste increases the void ratio of MSW. As the void ratio in waste increases, the porosity which allows liquid flow in waste material will be increased.

Table 2.9: Reported Values of Porosity for MSW

Source	Porosity (%)
Zeiss and Major (1993)	47 – 58
Hudson et al. (2004)	45.5 – 55.5
Stoltz and Gourc (2010)	45 – 62

However, the actual void ratio and porosity of fresh MSW in landfills would depend on initial compaction of the MSW. Zeiss and Major (1993) determined the total porosities for wastes compacted to densities between 170 kg/m^3 and 300 kg/m^3 which was between 58% and 47%. Table 2.9 presents the published values of porosities for MSW.

2.3.2.6. Hydraulic Conductivity and Intrinsic Permeability

Hydraulic conductivity is a property of material which allows the fluid flow through interconnecting pore spaces of any material. Hydraulic conductivity of MSW in landfills is an important parameter to evaluate the overall performance of a landfill. Clear understanding of the MSW hydraulic conductivity and the main factors influencing the hydraulic conductivity is necessary in order to estimate the amount of generated leachate and design of leachate collection systems. The main physical properties of MSW that affect the hydraulic conductivity are density, particle shape and size, porosity, waste composition, compaction, degree of saturation, stage of decomposition and degradation, waste age, thickness of soil cover and type of soil cover, mode of placement (stratification) and depth within the landfill.

The hydraulic conductivity of the waste has been investigated by a number of researchers. Chen et al. (1995) studied the variation in hydraulic conductivity with density of waste. They conducted their investigation on the wastes at densities 160 kg/m^3, 320 kg/m^3, and 480 kg/m^3. The study showed that the hydraulic conductivity reduces from 9.6×10^{-4} m/s to 4.7×10^{-7} m/s when compacted to densities 160 to 480 kg/m^3, respectively. Powrie and Beaven (2005) stated that an increase in density and effective stress and a decrease in porosity will result in a decrease in hydraulic conductivity of MSW. Moreover, Korman et al. (1987) cited that fresh wastes have higher value of hydraulic conductivity in comparison with old wastes. Chen et al. (1995) indicated a decrease in waste hydraulic conductivity by time. Furthermore, Powrie et al. (2000) mentioned that as the waste is compacted in thin lifts during the landfilling, horizontal stratification will be shaped within the landfill which may result in greater value of horizontal hydraulic conductivity compared to vertical hydraulic conductivity.

Hydraulic conductivity (otherwise known as the coefficient of permeability) is normally expressed as:

$$\mathbf{K} = \mathbf{Cd^2}\frac{\boldsymbol{\gamma_w}}{\boldsymbol{\mu}} = \mathbf{k}\frac{\boldsymbol{\gamma_w}}{\boldsymbol{\mu}} \qquad (\mathbf{2.7})$$

where C is dimensionless constant or shape factor, d is average size of pores in m^2, γ_w is specific weight of water in kN/m^3, and μ is dynamic viscosity of water in $\mathrm{kg/m.s}$.

Table 2.10: Reported Values for MSW Hydraulic Conductivity

Source	Test Condition	Hydraulic Conductivity (m/s)
Fungaroli and Steiner (1979)	Unit weight: 2.93 - 4.29 kN/m^3	$1.1 \times 10^{-4} – 2 \times 10^{-6}$
Korfiates et al. (1984)	Waste of six months Unit weight: 8.6 kN/m^3	$3 \times 10^{-5} – 5 \times 10^{-5}$
EMCON Associates (1983)	Average unit weight: 7.33 kN/m^3	$10^{-4} – 4 \times 10^{-4}$
Brandl (1994)	Unit weight: 9 – 12 kN/m^3	$2 \times 10^{-5} – 1 \times 10^{-6}$
	Unit weight: 13 – 17 kN/m^3	$2 \times 10^{-6} – 3 \times 10^{-8}$
Landva and Clark (1990)	Unit weight: 10.1 – 14.4 kN/m^3	$4 \times 10^{-4} – 10^{-5}$
Oweis et al. (1990)	Unit weight: 6.45 kN/m^3	10^{-5}
	Unit weight: 9.4 – 14 kN/m^3	1.5×10^{-6}
	Unit weight: 6.3 – 9.4 kN/m^3	1.1×10^{-7}
Manassero (1994)	Unit weight: 8 – 10 kN/m^3	$2.6 \times 10^{-4} – 1.5 \times 10^{-5}$
Bleiker et al. (1995)	Decomposed waste Unit weight: 5.9 – 11.8 kN/m^3	1.6×10^{-6} - 10^{-8}
Shank (1993)	MSW with more than 10 years old	$6.7 \times 10^{-7} – 9.8 \times 10^{-6}$
Chen et al. (1995)	Unit weight: 1.57 – 4.71 kN/m^3	$9.6 \times 10^{-4} – 4.7 \times 10^{-7}$
Beaven & Powrie (1996)	Unit weight: 5 – 13 kN/m^3	$10^{-4} – 10^{-7}$
Gabr and Valero (1995)	Waste of 15-20 years old Unit weight: 7.4 – 8.2 kN/m^3	$10^{-5} – 10^{-7}$
Blengino et al. (1996)	Unit weight: 9 – 11 kN/m^3	$3 \times 10^{-7} – 3 \times 10^{-6}$
Beaven & Powrie (1999)	Unit weight: 3.8 kN/m^3	$1.5 \times 10^{-6} – 3.4 \times 10^{-7}$
	Unit weight: 7.1 kN/m^3	$2.7 \times 10^{-8} – 3.7 \times 10^{-10}$
Jang et al. (2002)	Unit weight: 7.8 – 11.8 kN/m^3	$1.1 \times 10^{-5} – 2.9 \times 10^{-6}$
Durmusoglu et al. (2005)	-	$10^{-6} – 10^{-4}$
Penmethsa (2007)	Different degradation stage Unit weight: 6.4 – 9.3 kN/m^3	$10^{-4} – 8 \times 10^{-6}$
Hossain et al. (2007)	Different degradation stage Unit weight: 6.86 kN/m^3	$8.8 \times 10^{-5} – 1.3 \times 10^{-5}$
Reddy et al. (2009)	Fresh waste Different degradation stage	$10^{-5} – 10^{-7}$

Generally, the hydraulic conductivity of wastes is an important physical property of MSW which governs the movement of liquid and gases in a landfill. Thus, the accurate estimation of hydraulic conductivity of waste will play a vital role in preventing the problems regarding the uncontrolled leachate and stability problem. Some of published values of hydraulic conductivity of waste are presented in Table 2.10. On the whole, it can be observed that the hydraulic conductivity of MSW varies from 10^{-4} to 10^{-11} m/s.

In the main, hydraulic conductivity is a function of the fluid properties of the liquid as well as the physical properties of the MSW. In this regard, two important fluid properties which should be considered are viscosity and density which in turn, both of them depend on the temperature.

In contrast to hydraulic conductivity, intrinsic permeability only depends on the properties of MSW. The term Cd^2 in the Equation 2.7 is known as the intrinsic permeability. The main factors which affect intrinsic permeability are pore size distribution, specific surface, and porosity. Typical values of intrinsic permeability for compacted solid waste in a landfill range from 10^{-11} to 10^{-12} m^2 in the vertical direction and about 10^{-10} m^2 in the horizontal direction (Tchobanoglous et al., 1993).

2.3.3. MSW Chemical Properties

Previously the physical properties of the MSW was defined and discussed; now the chemical properties of municipal solid wastes will be discussed. Having knowledge about the chemical characteristics of MSW is helpful in estimation of the amount of generated gas in the landfills.

The chemical analysis of a waste mass normally involves determining the chemical composition of waste, i.e. the percentage of main chemical elements in MSW. These elements generally include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and ash. Different methods are being used to define the chemical composition of waste including:

1) Proximate analysis which attempts to define the fraction of volatile organics, moisture, fixed carbon, and ash.
2) Chemical compounds which typically involves the determination of lipids, carbohydrates, lignin, and protein.

3) Ultimate analysis which refers to an analysis of waste to determine the proportion of carbon, hydrogen, oxygen, nitrogen, sulphur, and ash. (Tchobanoglous et al., 1993).

2.3.3.1. Chemical Composition

Among the available approaches to define the chemical composition of waste (as above mentioned), the most common methods are the proximate analysis and the ultimate analysis.

Table 2.11: Proximate Analysis of MSW (US EPA, 1992)

Proximate Analysis	Percent by Weight
Moisture	15 - 35
Volatile matter	50 - 60
Fixed carbon	3 - 9
Non-combustibles	15 - 25

The results of these analyses are highly important in characterizing the chemical composition of MSW. Obviously, the chemical composition of wastes varies in wide ranges due to the heterogeneous nature of waste and its variability with geography and with time. Some published data for both proximate and ultimate analysis are tabulated in Tables 2.11 and 2.12.

Table 2.12: Ultimate Analysis of MSW (US EPA, 1992)

Ultimate Analysis	Percent by Weight
Moisture	15 - 35
Carbon	15 - 30
Hydrogen	2 - 5
Oxygen	12 - 24
Nitrogen	0.2 - 1
Sulphur	0.02 – 0.1
Total non-combustibles	15 - 25

Moreover, as the most analyses of waste are based on different waste components, Tables 2.13 and 2.14 present the data on the typical proximate analysis and ultimate analysis of both MSW and the individual components of MSW.

Table 2.13: Typical Data on the Proximate Analysis of MSW (after Kiely, 1997)

Waste Component	Percent by weight (dry basis)			
	Moisture	Volatiles	Fixed Carbon	Non-combustibles
Food waste	70	21	3.6	5
Paper	10.2	76	8.4	5.4
Cardboard	5.2	77	12.3	5
Plastics	0.2	96	2	2
Textiles	10	66	17.5	6.5
Glass	2	-	-	96 - 99
Metals	2.5	-	-	94 - 99
Wood	20	68	11.3	0.6
Yard waste	60	30	9.5	0.5
Domestic MSW	10 - 40	30 - 60	3 - 15	10 - 30

Table 2.14: Typical Data on the Ultimate Analysis of MSW
(after Tchobanoglous et al., 1993; Kiely, 1997)

Waste Component	Percent by weight (dry basis)					
	C	H	O	N	S	Ash
Food waste	48	6.4	37.6	2.6	0.4	5
Paper	43.5	6	44	0.3	0.2	6
Cardboard	44	5.9	44.6	0.3	0.2	5
Plastics	60	7.2	22.8	-	-	10
Rubber	78	10	-	2	-	10
Leather	60	8	11.6	10	0.4	10
Textiles	55	6.6	31.2	4.6	0.15	2.5
Glass	0.5	0.1	0.4	< 0.1	-	98.9
Metals	4.5	0.6	4.3	< 0.1	-	90.5
Wood	49.5	6	42.7	0.2	0.1	1.5
Yard waste	47.8	6	38	3.4	0.3	4.5
Dirt, ash, etc.	26.3	3	2	0.5	0.2	68
MSW	15 – 30	2 - 5	12 - 24	0.2 - 1	0.02 – 0.1	15 - 25

2.3.3.2. Essential Nutrients

Having knowledge about essential nutrients and elements in MSW is highly important when the organic fraction of MSW is to be used in biological processes for converting to methane and other biogases. The composition of essential nutrients and elements existing in main components that constitute the organic fraction of MSW are presented in Table 2.15.

Table 2.15: Typical Data on the Main Nutrients in MSW (after Tchobanoglous et al., 1993)

Nutrient (Unit)	Waste Component			
	Newsprint	Office paper	Yard waste	Food waste
NH_4-N (ppm)	4	61	149	205
NO_3-N (ppm)	4	218	490	4278
P (ppm)	44	295	3500	4900
PO_4-P (ppm)	20	164	2210	3200
K (%)	0.35	0.29	2.27	4.18
SO_4-S (ppm)	159	324	882	855
Ca (%)	0.01	0.10	0.42	0.43
Mg (%)	0.02	0.04	0.21	0.16
Na (%)	0.74	1.05	0.06	0.15
B (ppm)	14	28	88	17
Zn (ppm)	22	177	20	21
Mn (ppm)	49	15	56	20
Fe (ppm)	57	396	451	48
Cu (ppm)	12	14	7.7	6.9

As shown in Table 2.15, the food waste and yard waste include high amount of nitrogen as well as some other elements such as sulphur, potassium, calcium, and magnesium.

2.3.4. MSW Biological Properties

Municipal solid waste approximately consists of 70% - 80% of organic matters. The organic fraction of MSW can be biologically converted into gases and intermediate products including relatively inert organic and inorganic solids.

Table 2.16: Classification of the Organic Fraction of MSW
(Data taken from Tchobanoglous et al., 1993)

Group	Components
Water-soluble constituents	sugars, starches, amino acids, and various organic acids
Hemicellulose	a condensation product of five- and six-carbon sugars
Cellulose	a condensation product of the six-carbon sugar glucose
Fats, oils, waxes	esters of alcohols and long-chain fatty acids
Lignin	a polymeric material containing aromatic rings with methoxyl groups (-OCH3)
Lignocellulose	a combination of lignin and cellulose
Proteins	chains of amino acids

Generally, the organic content of MSW can be categorized into many groups according to their relative degree of biodegradability as presented in Table 2.16.

The volatile solids content can be used to measure the biodegradability of the organic fraction of MSW. However, referring to Tchobanoglous et al. (1993), the determination of the biodegradability of the organic fraction of MSW by calculating the volatile solid contents may be misleading because some of the organic constituents of MSW such as newsprint and certain plant trimmings are highly volatile but low in biodegradability.

Table 2.17: Data on the Biodegradable Fraction of MSW Based on Lignin Content (after Tchobanoglous et al., 1993; Franklin Associates, 1999)

Group		Biodegradable Fraction
Food waste		0.82
Paper	**Office paper**	0.82
	Newsprint	0.22
Cardboard		0.47
Plastics		0
Rubber		0.5
Leather		0.5
Textiles		0.5
Glass		0
Metals		0
Wood		0.7
Yard waste		0.72
Other materials		0.5
Miscellaneous inorganic		0.8

On the other hand, Lignin is essentially resistant to biodegradation. Therefore, the lignin content of a waste can be used to estimate the biodegradable fraction of MSW. The data on the biodegradable fraction of MSW based on lignin content are tabulated in Table 2.17. Table 2.17 shows that the rate of biodegradation for different components varies noticeably. Therefore, the main organic wastes presenting in MSW are usually classified based on their degree of degradability.

2.3.5. MSW Geotechnical Properties

Having knowledge about the waste geotechnical properties is of crucial importance in designing engineering landfills and studying the landfill slope stability and potential failure modes. The determination of the geotechnical properties of MSW is a difficult and complex task because municipal solid waste is a heterogeneous material consisting of a variety of components in different shape and size with specific mechanical property. The amount of each component and its position within the waste mass will affect the behaviour of waste element. Therefore, Jessberger and Kockel (1993) suggested that the waste materials can be categorized into the following groups:

- Soil-like waste
- Other waste

Soil-like wastes were defined as granular waste which it was possible to apply the conventional soil mechanics principles for them. The engineering properties of this kind of wastes such as compressibility, shear strength, shrinkage and swelling behaviour can be determined based on typical methods provided that the soil-like wastes are fine grained. However, it is necessary to take into account some modifications and considerations for soil-like wastes which are mixed and coarse-grained.

On the other hand, the specific methods and theories must be considered for those kind of wastes which put in “other waste” group. Generally, two common and most important geotechnical properties of waste include compressibility and shear strength which is described in this section.

2.3.5.1. Compressibility

The compressibility of municipal solid wastes has been studied for many decades. These studies have shown that various factors can substantially affect the geotechnical properties of waste including compressibility and shear strength. In the main, these properties depend on the waste composition and the mechanical properties of individual components of waste. In addition, these geotechnical properties are time dependent and they vary based on the decomposition stage of waste (Castelli and Maugeri, 2014).

The compressibility property of MSW is an important parameter in the evaluation of landfill capacity, the design of landfill structure, and the execution of landfill redevelopment projects. Based on existing literature, compression parameters have large variations. The main factors affecting the settlement of waste materials are the waste composition and the waste components mechanical properties, waste decomposition, distortion and reorientation of the waste, erosion of fine materials into large voids due to the nature of waste and long term creep process. Therefore, it is extremely difficult to predict the landfill settlement and its compressibility due to the heterogeneity nature of the waste coupled with biodegradation of organic fraction of wastes. Therefore, it is necessary to take into account the proper classification of the waste materials.

Moreover, it is required to consider some parameters such as Young's modulus (elastic modulus), stiffness modulus or compression indices in order to identify the compression behaviour of waste, (Dixon et al., 2004).

Elastic modulus (E') can be defined as the slope of the stress-strain curve. This parameter is a measure of the resistance deformation of the materials. Therefore, the higher value of elastic modulus indicates the stronger materials. Poisson's ratio (ν') is defined as the ratio of the horizontal strain to the vertical strain. Referring to Sharma et al. (1990) and Houston et al. (1995), the value of Poisson's ratio for MSW is in the range of 0.2 to 0.5.

Table 2.18: Elastic Parameters of MSW (after Singh et al., 2008)

Property	**Waste Components**	**Range (% by weight)**	**E' (MPa)**	**ν'**
Rigid and incompressible	Metals, Glass, Wood, Ceramic	5 - 17	75 - 110	0.26 - 0.49
Soil-like material	Demolition Waste, Cover Soil, Ash	6 - 25	10 - 20	0.25 – 0.33
Degradable and compressible	Food, Yard, and Animal Wastes	16 - 43	0.5 – 0.7	0.05 – 0.15
Reinforcing and tensile elements	Paper, Cardboard, Flexible and Rigid Plastics, Tires	16 - 60	1.5 - 3	0.28 – 0.32

Table 2.18 presents typical values of some elastic parameters such as Young's modulus (E') and Poisson's ratio (ν') for different groups of waste components. Furthermore, reported elastic modulus values for MSW are in the range of 40 MPa to 120 MPa (Houston et al., 1995).

Evaluating compressibility property in MSW is more complex than in soils due to the waste nature and a variety of processes in waste. Referring to Jessberger et al. (1995), as municipal solid waste can be considered as a mixture of soil-like and non-soil-like components, it is necessary to study its behaviour more carefully. Waste settlement will take place in different phases as a result of different mechanisms. Many of these mechanisms comply with the soil mechanics theories. However, there are still some mechanisms which are specific to waste. As compressibility characteristics of

MSW covers many concepts, the issues regarding MSW settlement and compression behaviour of waste as well as the subject of compression indices which play an important role in MSW landfill settlement and compressibility property of waste, will be discussed in more detail in following sections.

2.3.5.2. Shear Strength

In soils, the strength of soil is a key design parameter in designing building foundations, embankments, retaining structures, and more importantly slope stability analysis. Soil strength is attributed to two different mechanisms of materials including frictional resistance and cohesive resistance along the shearing zone. Frictional resistance (τ_{friction}) follows Coloumb's friction law ($\tau_{\text{friction}} = \sigma \tan \varphi$) where σ is the normal stress and φ is called the angle of internal friction of soil.

Internal angle of friction (φ) is a function of mineralogical composition, shape, gradation, void ratio, and organic content of the soil and is measured in degrees (Holtz and Kovacs 1981, Coduto 1999). Friction angle is related to the friction and interlocking of particles and is a stress dependent component. In other words, a higher confining stress on the soil will result in a higher friction angle.

Cohesion resistance (c) is called cohesion. Cohesion is a function of the colloidal forces within soil. Cohesion is a stress independent component (Holtz and Kovacs, 1981) which is generally the resistance due to the forces tending to bond or hold the soil particles together in a solid mass. As mentioned above, it is possible to use the usual soil mechanics theories for studying the mechanical properties of "soil-like" wastes. However, geotechnical studies of municipal solid wastes require extensive knowledge on the mechanical properties of the waste materials based on the specific methods and theories relating to wastes.

In addition to compressibility, MSW shear strength is an important mechanical property of wastes in designing landfills, waste slopes, and landfill redevelopment projects, as well as evaluating the stability of landfills.

Table 2.19: Published Values for Shear Strength Parameters of MSW

Source	Test Condition	c (kPa)	φ (Degree)
Landva and Clark (1986)	Old waste	16 – 19	38 – 42
Landva and Clark (1986)	Old waste after one year	16	33
Landva and Clark (1986)	Fresh shredded waste containing a large amount of plastic sheet	23	24
Siegel et al. (1990)	5 waste samples with different compositions of waste	0	39 – 53
Howland and Landva (1992)	10 to 15 years old waste	17	33
Cowland et al. (1993)	Deep trench in waste	10	25
Del Greco and Oggeri (1993)	Baled waste , lower density	15.7	21
	Baled waste , higher density	23.5	22
Golder Associates (1993)	Project specific testing	0	41
Jessberger (1994)	MSW; Unit weight: 13 kN/m^3	7	38
Jessberger (1994)	Unit weight: 7 - 11 kN/m^3	10	15 – 17
Jessberger (1994)	MSW including ashes; Unit weight: 8 - 12 kN/m^3	0	30 – 40
Jessberger (1994)	MSW including sewage sludge after 9 months of biodegradation; Unit weight: 9 - 12 kN/m^3	7	42
Jessberger (1994)	Fresh MSW; Unit weight: 8 - 11 kN/m^3	28	26.5
Jessberger (1994)	Fresh MSW	23	24
Jessberger (1994)	Old MSW	16	38
Jessberger (1994)	Recommended values	16 – 32	19 – 24
Fassett et al. (1994)	Municipal solid waste	10	23
Gabr and Valero (1995)	10 to 15 years old waste	0 – 28	20 – 39
Kolsch (1995)	Municipal solid waste	18	22
Kolsch (1995)	Municipal solid waste	15	15
Benson et al. (1994)	Municipal solid waste	20	35
Benson et al. (1994)	For moist and soaked waste samples	24	42
Thomas et al. (1999)	Waste samples with different plastic content	23.4	29.6
Pelky et.al (2001)	Municipal solid waste	0 – 50	26 – 35
Kavazanjian (2001)	Fully degraded waste	16 – 30	33 – 59
Reddy et al. (2009)	Fresh waste	31 – 64	26 – 30
Reddy et al. (2009)	Fresh waste	38	16

A number of studies have been conducted on the shear strength of MSW and a large database is available on the shear strength parameters of MSW. Based on these studies, the shear strength of MSW varies widely. The shear strength of MSW is a function of the waste age, waste type and composition, compaction, the density of waste, daily cover, the moisture content, decomposition, overburden pressure, and the test method (Gabr and Valero, 1995; Edincliler et al., 1996).

Some of published values for shear strength parameter of municipal solid wastes are tabulated in Table 2.19. As shown in this table, reported values of MSW friction angle range from 10 to 53 degrees, while MSW cohesion ranges from 0 to 67 kPa. This range is caused by various factors including the heterogeneity of waste, sample age, degree of decomposition, composition of the waste, specimen size, unit weight, test conditions. However, the reasonable values recommended for cohesion is in the range of 0 kPa to 30 kPa and for friction angle in the range of 20 degrees to 35 degrees (Durmusoglu, 2002).

2.4. MSW Landfill Characteristics

In spite of arising new methods and technologies for waste management, some fractions of MSW still must be disposed of in landfills. Landfills are engineered structures which are widely used for disposal of municipal solid wastes all over the world. Various mechanisms and processes take place in landfills. The physiochemical and biological processes that occurs in the landfills causes the waste degradation resulting in the leachate formation and landfill gas generation. Since leachate contains many contaminations which causes soil and water pollution, it is necessary to be collected properly. In addition, as the generated gases in landfills have adverse impact on atmosphere, they must be gathered efficiently to prevent air pollution. Thus, the landfills should be designed correctly in order to minimize the problems associated with the leachate formation and gas generation. A sanitary landfill consists of different components including bottom liner systems, leachate collection and removal systems, gas collection systems, and final covers.

In general, landfills of municipal solid waste (MSW) often require additional considerations for proper development because of differential settlement, leachate generation, and landfill gas emissions. Therefore, the purpose of the subsequent sections is to understand the landfill structure and the processes and mechanisms resulting in leachate formation, gas generation, and finally landfill settlement.

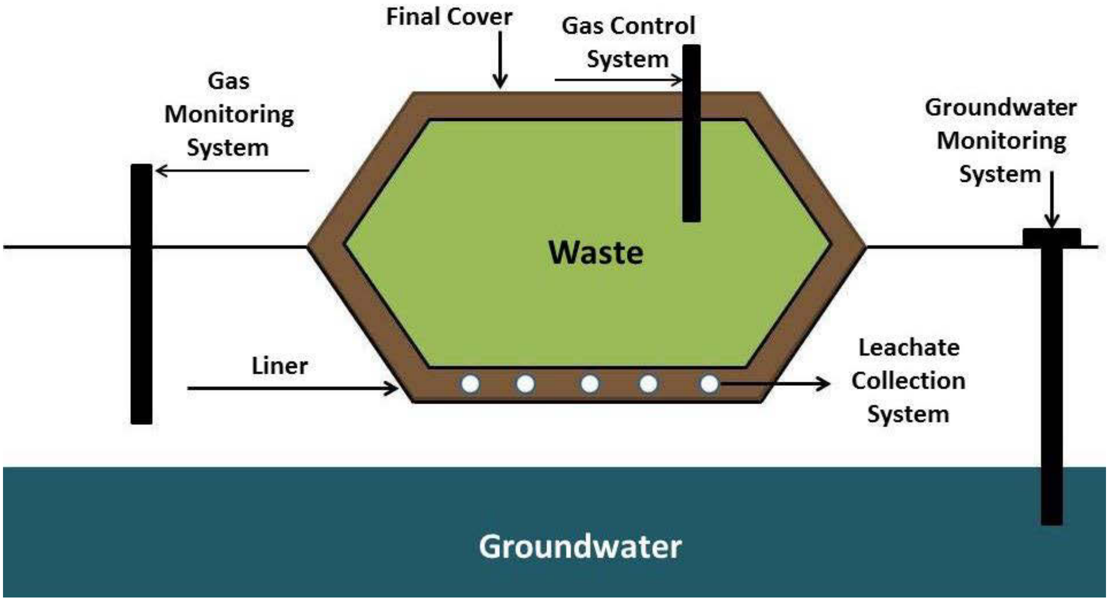

Figure 2.5: Main Parts of a MSW Sanitary Landfill

2.4.1. MSW Landfill Components

The basic parts of a MSW landfill are illustrated in Figure 2.5. As shown in this figure, these parts include:

- Base liner system,
- Leachate collection system,
- Gas collection system,
- Gas monitoring system,
- Final cover system or cap,
- Ground water monitoring system.

The above mentioned components are briefly described in the following sections.

2.4.1.1. Base Liner Systems

Liner systems are considered in landfills to create a barrier between the waste and the soil. This system will help the leachate to be drained into the leachate collection systems or leachate treatment facilities.

Landfill liner systems may consist of one or more layers of clay or polymeric flexible membranes or a combination of these materials. Regardless of the material used as liner system, it is important that liner layers have suitable permeability in order to prevent the uncontrolled release of leachate into the environment.

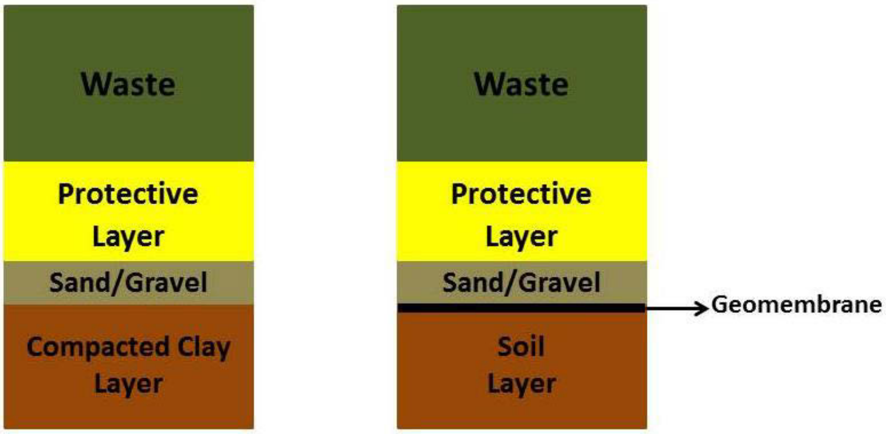

Figure 2.6: Typical Single Liner Systems for Landfills

In fact, the type of liner system required for a landfill is determined based on the potential threat posed by the waste. Referring to Toolkit Landfill Technology published by Germany Technical Committee (Ramke,2009), the main liner systems are single (simple), composite, or double liners. Single liners consist of a compacted clay layer or a geosynthetic clay liner or a geomembrane liner (Figure 2.6).

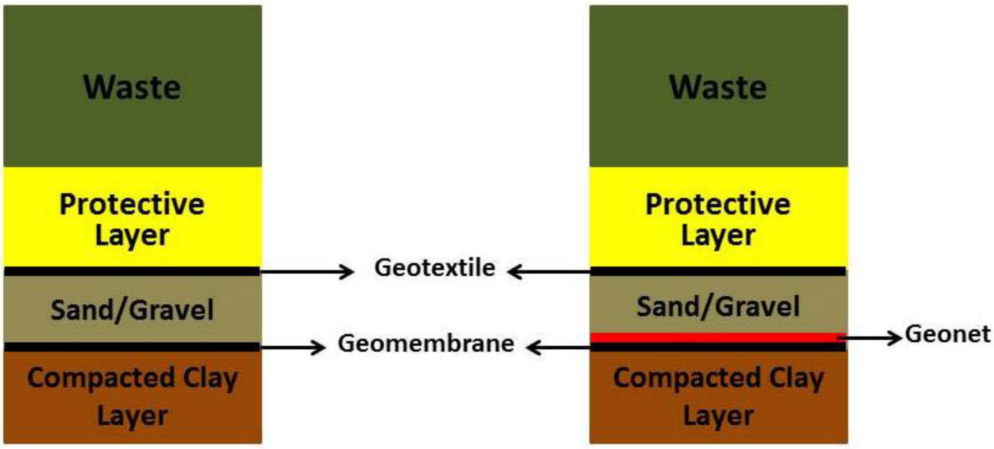

Figure 2.7: Typical Composite Liner Systems for Landfills

Composite liners are composed of a geomembrane liner in combination with a compacted clay layer (Figure 2.7). Double liners are made up of either two single liners, two composite liners, or a single and a composite liner (Figure 2.8).

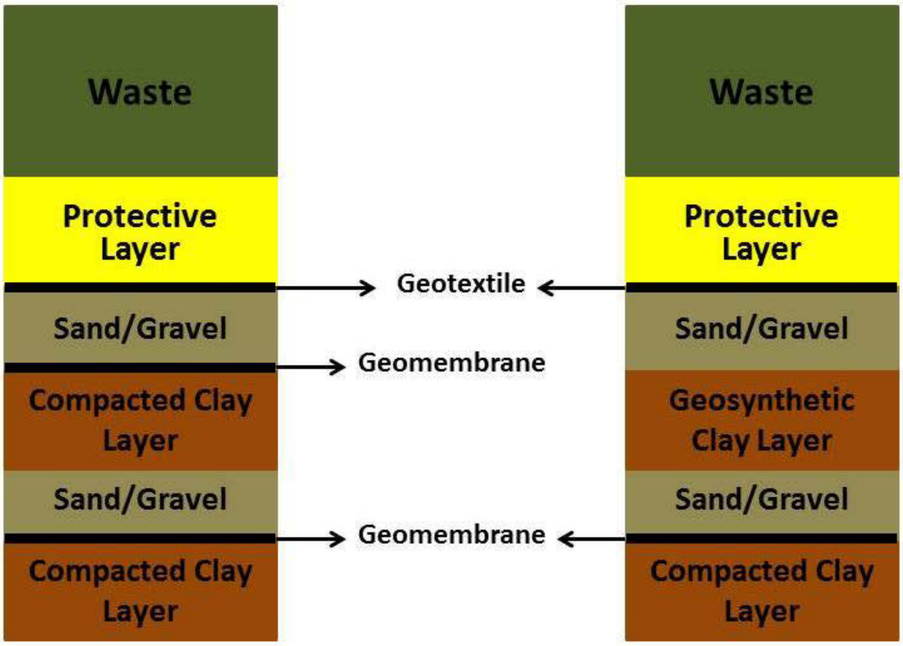

Figure 2.8: Typical Double Liner Systems for Landfills

In general, the bottom liner system for MSW landfills must have a permeability of less than 1×10^{-9} m/sec and a minimum requirement for MSW landfills is a composite liner (Stepniewski et al., 2011). In this system, the compacted clay layer must have at least 60cm thickness and the thickness of geomembrane liner shouldn't be less than 1.5 mm (Durmusoglu, 2002). In addition, the liner system needs to be protected by a layer called "the protective layer" in order to minimize the liner puncture by the sharp materials in waste.

2.4.1.2. Leachate Collection System

A complex sequence of physical, chemical, and biological processes within a landfill results in waste degradation or transformation. As water percolates through the landfill, many contaminants including biological and chemical constituents are leached from the solid waste into solution. If leachate is not collected properly, it will cause the surface and groundwater pollution. In addition, if leachate is not removed landfills, it will seep out from the landfill sides and will cause slope stability failure of the landfill. Landfill sliding in Manila (Philippines) is an example of this kind of failures. Therefore, considering a system for collecting and treating the leachate is part of landfill design and engineering. The leachate collection system (LCS) mainly consists of a drainage layer with high permeability, perforated pipes foe draining the leachate, collection and inspection shafts, and collection pipes for removing leachate from landfill into a leachate collection pond. Figures 2.9 to Figure 2.11 illustrate the LCS for different landfill bottom slope, the cross section of LCS, and the schematic of LCS, respectively.

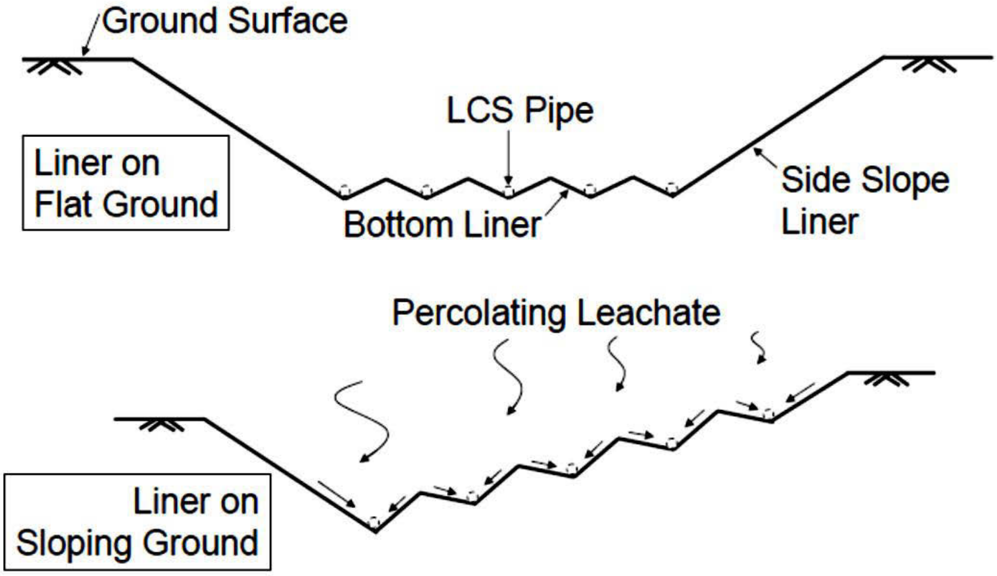

Figure 2.9: The Leachate Collection System in Different Landfills (Haydar et al., 2005)

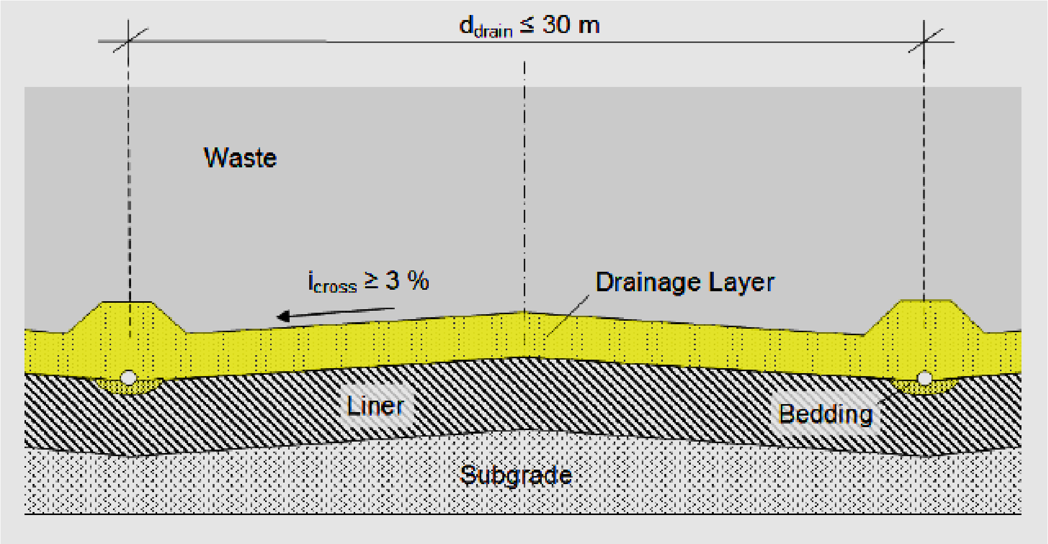

Figure 2.10: The Cross Section of Leachate Collection System (Ramke, 2009)

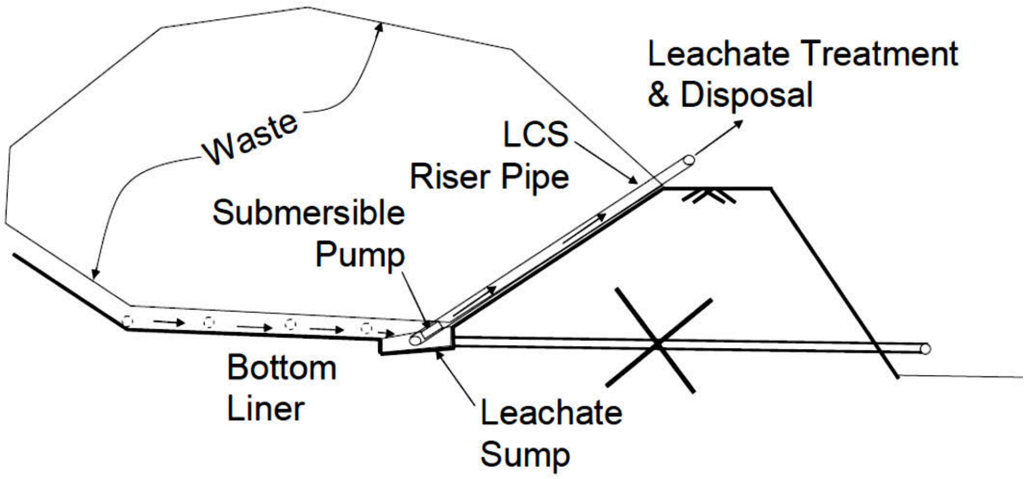

Figure 2.11: The Schematic of Leachate Collection System (Haydar et al., 2005)

The drainage layer, pipes, and containers that transport or hold leachate must be made up of special materials in order to prevent leakage and hold up to the various chemicals of the leachate. Therefore, they need to accomplish the requirements presented in Table 2.20.

Table 2.20: The Requirements for Different Components of Landfill Leachate Collection System (Data taken from Ramke, 2009)

LCS Component	Characteristic	Requirement
Drainage Layer	Thickness	≥ 0.30 m
	Permeability	≥ 0.001 m/s
	Material	Gravel/Sand
	Grain Size	16 – 32 mm
Drainage Pipe	Inside Diameter	≥ 300 mm
	Drainage Length	< 15 m
	Drain Spacing	For landfills with liner on flat ground: ≤ 30 m For landfills with liner on sloping ground: ≤ 15 m
Slope	Cross Slope	≥ 3 %
	Longitudinal Slope	≥ 1 %

2.4.1.3. Gas Collection and Control System

MSW landfills contain a lot of organic wastes. Anaerobic reactions within the landfill generate leachate as well as various gases. In general, landfill gas will be generated due to three processes as following:

- Bacterial decomposition which occurs when organic waste including food waste, yard waste, textile, wood, and paper products is broken down by bacteria that naturally exist in the soil and in the cover soil.
- Volatilization which can be defined when some of waste components especially organic compounds convert into a vapour.
- Chemical reactions can create landfill gas. In these reactions, some chemicals produce a gas when they come into contact with each other within the landfill.

Landfill gas is composed of a mixture of different gases which primarily contains 45% to 60% methane and 40% to 60% carbon dioxide by volume (Tchobanoglous et al., 1993).

The management of landfill gas is a key issue in the operation of landfills. By applying the landfill gas collection and control systems, the landfill gas movement into the atmosphere or through the surrounding soil can be prevented in order to address environmental and safety concerns, and to control odours. Moreover, recovered landfill gas can be used directly either for generating electricity or converting to chemicals or fuels (Worrell and Vesilind, 2002).

2.4.1.4. Final Cover System or Cap

When the landfill reaches design height, it is capped with a final cover. The primary purposes of the landfill final cover are:

- To minimize the infiltration of rainwater,
- To minimize dispersal of wastes,
- To limit the fire potential,
- To limit the uncontrolled release of landfill gases,
- To accommodate settling,
- To facilitate long-term maintenance of the landfill,

The cap consists of many layers. It can be composed of natural clay soils, a combination of soil and geosynthetic liner system, or only soil cover with vegetation.

A typical cap used for MSW landfills is illustrated in Figure 2.12. In addition, the main components that constitute a landfill cover along with their special function are presented in Table 2.21.

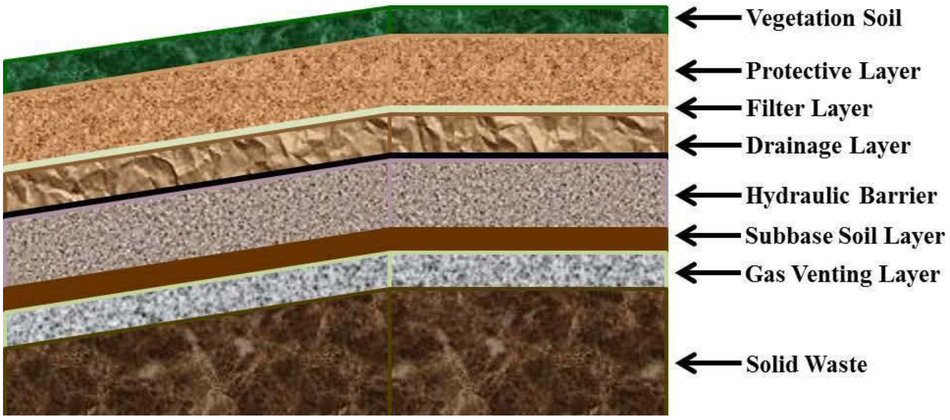

Figure 2.12: The Cross Section of a Landfill Final Cover System

In general, EPA regulations require that the landfill final cover be less permeable than the bottom liner. Many regulations suggest that the permeability of this cover (the cap) must not be greater than 1×10^{-7} m/sec.

Table 2.21: Main Components of a Landfill Final Cover System

Final Cover System Component	Typical Material	Special Function
Vegetation Soil/Top Soil Layer	Soil and pea gravel with at least 0.15 m thickness and with a mixture of gravel-soil at a ratio of 1:4	▪ To allow vegetation to take root and grow, ▪ To stabilise the layers of cover,
Protective Layer (Biotic Barrier)	Cover native soil with a normal thickness of 0.6 m	▪ To protect the drainage and barrier layer from frost, desiccation, root penetration, burrowing animals, etc.
Filter Layer	geotextile	▪ To prevent the soil from migrating into the drainage layer,
Drainage Layer	At least 0.3 m of sand with permeability of 10^{-4} m/sec or equivalent geosynthetic	▪ To drain overlying layers and transport percolating rainwater away from the barrier layer, ▪ To reduce the water pressure on the barrier layer, ▪ To minimize infiltration into the landfill,
Hydraulic Barrier Layer	Both geomembrane with at least 0.5 mm thickness and clay with at least 0.6 m thickness and permeability of less than 10^{-9} m/s	▪ To stop water from seeping into the waste, ▪ To minimize the amount of gas emission into the atmosphere,
Subbase Soil Layer	Compacted and graded native soil	▪ To contour the surface of the landfill, ▪ To serve as a foundation for the barrier layer,
Gas Venting Layer	0.3 m sand or equivalent geosynthetic	▪ To collect and transport gas to gas management facilities for processing or discharge,

In addition to permeability, two more parameters which can be considered as critical concerns for landfill final covers include slope stability and soil erosion (Worrell and Vesilind, 2002). Typical side slopes for landfill caps are 1:3 to 1:4. Furthermore, some considerations must be taken into account for soil erosion. In this regard, the interface friction between adjacent layers should hold out against the seepage forces and the contact stresses between layers caused by water and gas pressure must be decreased.

2.4.2. Waste Decomposition Mechanisms in Landfills

Municipal solid waste contains about 50% to 80% organic waste which can be transformed into gaseous, liquid, and solid conversion products by the biochemical processes. Organic fraction of MSW varies with many factors such as geographical location, season, climatic change, etc. organic materials in MSW are a source of cellulose, sugar starch and other matters which are valuable in bioconversion processes. The three components of municipal solid wastes which are of great interest in the biochemical processes are food waste, paper products, and yard wastes. The average analysis of organic components of MSW is presented in Table 2.22.

Table 2.22: Organic Analysis of MSW (after Bell, 1964)

MSW Fraction	Amount (Percent by Weight)
Organics (including cellulose and sugar starch, lipids, protein, and other organics)	**54.4**
Cellulose, Sugar starch	46.6
Lipids (fats, oil, waxes, etc.)	4.5
Protein	2.1
Other organics (e.g., plastics)	1.2
Inorganics	**24.9**
Moisture	**20.7**

In addition to the degree of intrinsic biodegradability of each single component in organic fraction of MSW, however, a number of chemical and physical and biological factors also are important, such as type of microorganisms, nutrients, and environmental conditions including temperature, pH, presence or absence of oxygen, moisture, salinity, toxic constituents and other inhibitors.

In the main, the microbial decomposition of MSW in landfills primarily takes place in a two-stage process involving five steps and a number of metabolic pathways. These stages are called aerobic and anaerobic stages which are discussed in the following sections.

2.4.2.1. Biodegradation of MSW in Landfills

Municipal solid wastes decompose in the landfill under different processes and phases depending on various conditions in term of presence or absence of oxygen, the available microorganisms and the environment condition. However, all these processes and phases occur in two main stages.

The first stage of waste decomposition is called aerobic stage which takes place shortly after landfill closure. During this stage, the aerobic microorganisms break the complex organic materials including the long molecular chains of complex carbohydrates, proteins, and lipids, down to simpler materials through a series of exothermic reactions. In these reactions, organic fraction of MSW reacts with the oxygen that present in the waste. The aerobic transformation of solid wastes basically follows the Equation 2.8 to form carbon dioxide, water, new cells, other less complex organics, and heat (Tchobanoglous et al., 1993)

$$\begin{aligned}\mathbf{complex\ organics} + \mathbf{O_2} + \mathbf{nutrients} \xrightarrow{\text{aerobic microorganisms}} \mathbf{CO_2} + \mathbf{H_2O} + \mathbf{NH_3} + \mathbf{SO_4^{2-}} \\ + \cdots + \mathbf{new\ cells} + \mathbf{less\ complex\ organics} + \mathbf{heat} \qquad (\mathbf{2.8})\end{aligned}$$

Based on the above equation, the primary by-product of this process is carbon dioxide. Nitrogen containing molecules are high at the beginning of this phase. However, as the landfill shifts to the anaerobic stage, the nitrogen content declines.

The aerobic stage will be often performed by a single bacterial species while the waste contains oxygen. Available oxygen level depends on different factors such as waste compaction, landfill moisture content, and the permeability of the soil cover. Obviously, when the oxygen depletes, the waste decomposition slows and anaerobic microorganisms appear leading the biodegradation mechanisms into anaerobic stage.

The anaerobic stage for bioconversion of the organic fraction of MSW involves a number of anaerobic microorganisms. This stage includes a multistep processes in which the aerobic stage products and organic portion of MSW will be sequentially converted to stable end products.

Table 2.23: Chemical Constituents of MSW and Their Methane Potential (after Barlaz et al., 1990)

Chemical Constituents	Amount (Percent by Dry Weight)	Methane Potential (Percent)
Cellulose	51.2	73.4
Hemicellulose	11.9	17.1
Protein	4.2	8.3
Lignin	15.2	0
Starch	0.5	0.7
Pectin	< 3	-
Soluble sugars	0.35	0.5
Total volatile solids	78.6	-

Many researchers have studied the anaerobic stage of MSW waste decomposition in landfills. Referring to Senior and Balba (1987), the biodegradable polymeric constituents of MSW are mainly categorized into carbohydrates (lignocelluloses, polysaccharides), fat-containing organic molecules, and proteins. Lignocelluloses primarily composed of three major groups of polymers including cellulose, hemicellulose, and lignin. According to Barlaz et al., (1989), cellulose and hemicellulose are the major biodegradable constituents in MSW which comprise 45% to 60% of the dry weight of municipal solid wastes (Table 2.23). Moreover, Barlaz et al. (1990) stated that the cellulose and hemicellulose fraction account for 91% of MSW methane potential.

The microorganisms responsible for anaerobic decomposition can be divided into three broad categories:

1) Hydrolytic bacteria: This group are responsible for hydrolysing complex organic matters such as proteins, fats, and carbohydrates into soluble fatty acids, monosaccharides, amino acids, and other organic monomers (Christensen et al., 1989).
2) Acid formers bacteria: Acidogens convert the breakdown products from the first group (amino acids, fatty acids, and sugars) into simple organic acids such as volatile fatty acids (VFAs), alcohols, etc. These products will be further converted into acetic acid, carbon dioxide, and hydrogen by acetogenic bacteria. In addition, some by-products, including ammonia and hydrogen sulphide, are also produced in this process by this group of bacteria (Strik et al., 2005).

3) Methanogenic bacteria: This group of bacteria convert the products of acidogenesis and acetogenesis into methane and carbon dioxide. Two main types of microorganisms in this group are acetoclastic methanogens and hydrogen-utilizing methanogens. Acetoclastic methanogens split acetate into carbon dioxide and methane (Lachavanne et al., 1997). Hydrogen-utilizing methanogens reduce carbon dioxide to form methane (Mara et al., 2003).

The anaerobic microorganisms decompose the solid waste in four steps including hydrolysis, acidogenesis, acetogenesis, and methanoenesis.

In the first step which is called hydrolysis step, complex organic materials transform into smaller organic molecules in order to be used suitably as a source of energy. Since small sized organic molecules can pass through bacteria cell walls to be used by them, hydrolysis can be considered as an important step in waste biodegradation (Christensen et al., 1989). Because cellulolytic matter accounts for a large part of biodegradable constituents in MSW, the metabolic pathway associated with the anaerobic decomposition processes of cellulose is described in this section. Consequently, the following Equation shows the hydrolysis of cellulose to glucose:

$$\mathbf{C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6} \qquad (2.9)$$

In the acidogenesis step, the product of hydrolysis step will be converted to organic acids such as fatty acids, alcohols which make the landfill highly acidic. In addition, the gaseous by-products of this step are carbon dioxide and hydrogen. The following equations show the main possible reactions for acidogenesis of glucose:

$$\mathbf{C_6H_{12}O_6 \rightarrow CH_3(CH_2)_2COOH + 2H_2 + 2CO_2} \qquad (2.10)$$

$$\mathbf{C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2} \qquad (2.11)$$

$$\mathbf{C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O} \qquad (2.12)$$

$$\mathbf{C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + 2CO_2} \qquad (2.13)$$

where $CH_3(CH_2)_2COOH$, CH_3CH_2OH, CH_3CH_2COOH, and CH_3COOH are butyric acid, ethanol, propionic acid, and acetic acid, respectively.

In the acetogenesis step, some of products of acidogenesis step such as butyric acid, ethanol, and propionic acid transform into acetic acid, hydrogen, and carbon dioxide based on the following equations.

$$\mathbf{CH_3(CH_2)_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2} \qquad (2.14)$$

$$\mathrm{CH_3CH_2OH + H_2O \rightarrow CH_3COOH + 2H_2} \qquad (2.15)$$

$$\mathrm{CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + 3H_2 + CO_2} \qquad (2.16)$$

Referring to Senior and Balba (1990), there are two major types of acetogenic bacteria which are responsible for bioconversion in this step including hydrogen producing and hydrogen consuming bacteria. Hydrogen producing bacteria achieve their energy through conversion of alcohol and longer chain acids into acetic acid and hydrogen while hydrogen consuming bacteria catabolize carbohydrate, hydrogen and some organic compounds into acetic acid. The cooperation of different microorganisms will help in consumption of hydrogen and prevention of the accumulation of acidogenesis products. If the acidogenesis products remain, the pH would fall which would consequently affect the methanogenesis process and inhibit methane formation.

Last step of anaerobic phase is called methanogenesis step in which microorganisms convert acetate or carbon dioxide to methane based on the following equations:

$$\mathrm{CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O_2} \qquad (2.17)$$

$$\mathrm{CH_3COOH \rightarrow CH_4 + CO_2} \qquad (2.18)$$

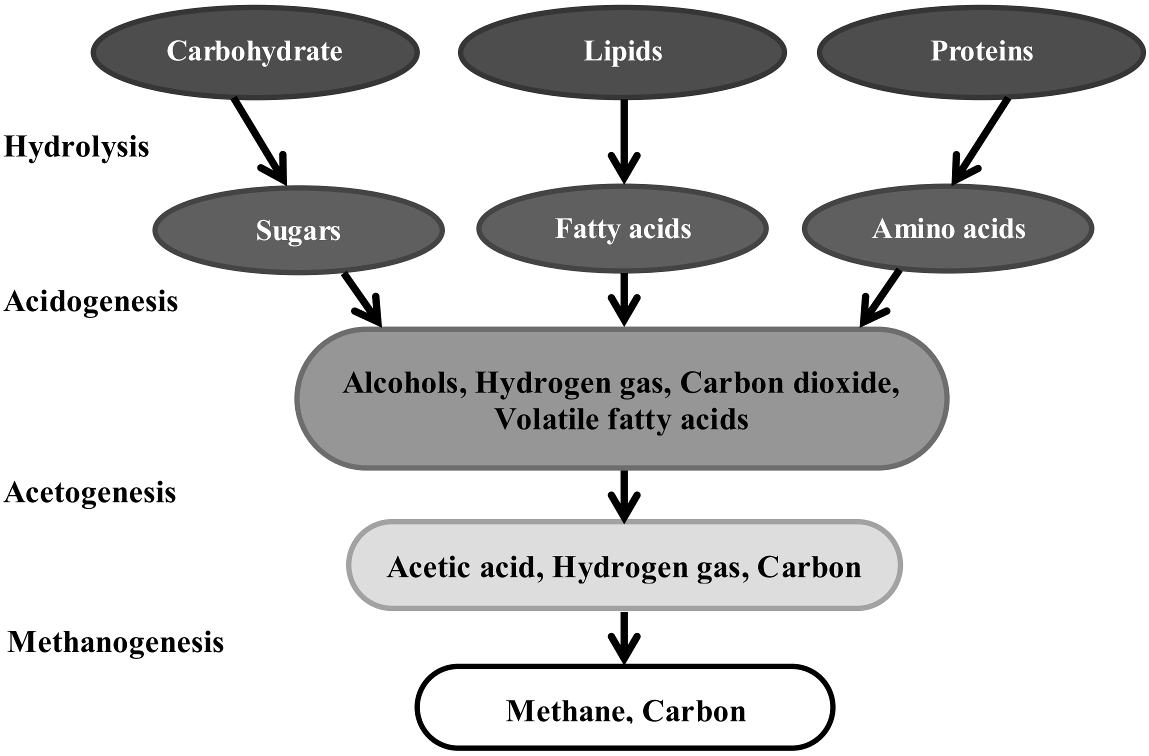

Figure 2.13: Anaerobic Processes of MSW Decomposition in Landfills (after Rees, 1980)

Two different groups of microorganisms are involved in methanogenesis step including hydrogenophilic and acetophilic organisms. As shown in equations 2.17 and 2.18, the first group (hydrogenophilic) reduces carbon dioxide to methane by elimination of hydrogen while the other group (acetophilic) convert acetic acid to methane and carbon dioxide.

Therefore, the overall anaerobic transformation of cellulose can be summarized as following equation (Tchobanouglous et al., 1993):

$$\mathbf{C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2} \qquad (\mathbf{2.19})$$

The anaerobic phase of MSW decomposition in landfills including different steps and the products of each step is broadly illustrated in Figure 2.13.

2.4.2.2. Factors Controlling MSW Biodegradation in Landfills

The bioconversion of municipal solid wastes in landfills is affected by many factors including pH, temperature, moisture content, oxygen concentration, density, waste composition, available nutrients, and the percentage of inhibitors and toxic constituents.

The pH of the liquid phase inside the landfill can have a significant effect on waste decomposition processes because it may influence the growth of microorganisms especially when it is outside the range of 6 to 9 (Tchobanoglous et al., 1993). In general, the optimum pH for microbial growth and waste biodegradation is between 6.8 and 8 (Warith, 2003). However, this range will vary depending on the type of microorganisms. The acetogenic bacteria have a wider range of pH in comparison with methanogenic bacteria. Methanogens are sensitive to pH and their growth outside neutral range is adversely affected. Acidogenic microorganisms will also be influenced by the level of pH. In this case, the lower pH changes the type of produced organic acids. For example, a lower pH can result in the production of some acids such as butyric acid, propionic acid, etc. and consequently problems in converting these kind of acids to acetate which can be considered as a noticeable effect on MSW decomposition (Miller and Clesceri, 2002).

In addition to pH, temperature is another environment condition which has an important effect on the growth and activity of microorganisms. Warm temperatures increase bacterial activity while colder temperatures inhibit bacterial activity. All microorganisms have an optimum temperature range. The optimum temperature for aerobic decomposition is between 54°C and 71°C, while the optimum temperature for anaerobic bacteria ranges from 30°C to 41°C (Rajaram et al., 2011). It has been noted that bacterial growth rates double with every 10°C increase in temperature until the optimum temperature is reached. Moreover, a substantial drop in activity of anaerobic bacteria has been observed at temperatures below 10°C (Tchobanoglous et al., 1993). Although the temperature within a landfill tends to be higher than the ambient air temperatures due to anaerobic decomposition which is an exothermic process, the landfill depth influences the temperature within the landfill. In other words, weather changes have much greater effect on microbial activity in shallow landfills because the microorganisms are not enough insulated against temperature changes in comparison with deep landfills. Generally, a capped landfill maintains a stable temperature resulting in increased bacterial activity and hence more gas production.

Another key environmental parameter affecting waste decomposition is oxygen. Oxygen and temperature are linked with each other and both fluctuate in response to microbial activity, which consumes oxygen and generates heat. Oxygen and temperature are also linked by a common mechanism of control called aeration.

In fact, MSW biodegradation will occur under both aerobic and anaerobic conditions. In aerobic condition, oxygen dependent bacteria produce carbon dioxide and water, while in anaerobic condition; the anaerobic microorganisms begin to produce methane when oxygen is used up by the aerobic bacteria. If waste is loosely buried in landfills, more oxygen is available. Therefore, the aerobic bacteria can live longer and decompose waste in aerobic stage for longer periods. On the other hand, if the waste is highly compacted, methane production will begin earlier as the aerobic bacteria are replaced by methane-producing anaerobic bacteria. Aerobic decomposition takes place at a much faster rate. However, the anaerobic decomposition is the dominant mode of waste biodegradation (Alam et al., 2014).

Moisture content is another essential factor which controls MSW biodegradation. In fact, moisture content can be considered as a prerequisite for microbial function by which chemical substances and microorganisms pass through the waste mass. The presence of a certain amount of moisture in a landfill increases the activity of all microorganisms because it encourages bacterial growth and transports nutrients as well as microorganisms to all areas within a landfill. Referring to Baldwin et al. (1998), the wastes with high moisture content are more quickly decomposed.

Moreover, the density and particle size of the waste influence the waste decomposition rates by affecting the transport of nutrients and moisture throughout the landfill. Smaller particles usually increase the surface area of organic wastes, enhancing opportunities for microbial activity on their surfaces, which leads to rapid decomposition of waste. However, if the particle size of wastes becomes too small, they pack closely together leading to high value of waste density. Solid wastes with high density have not enough void spaces to allow the proper transfer of moisture, nutrients and other essential elements for microbial growth and activities. Therefore, the particle size of waste is associated with waste density. The optimum particle size has enough surface area for rapid waste biodegradation, but also sufficient void space for movement and maintenance of essential elements for microbial activity in order to improve the MSW biodegradation mechanisms (Rajaram et al., 2011; O'Leary, 1999).

Waste composition is one of the most important factors in MSW biodegradation in landfills. The maximum rate of MSW biodegradation depends on the quantity and type of organic content within the waste mass. The more organic waste present in a landfill, the more bacterial decomposition will be occurred. Some types of organic waste contain nutrients, such as sodium, potassium, calcium, and magnesium, which help bacteria survive. When these nutrients are present, microbial growth and activity increases because Microorganisms require a source of energy to perform their functions properly. This source of energy includes carbon and inorganic elements or nutrients.

Microorganisms in MSW biodegradation processes have different levels of nutrient needs for their growth and microbial cell synthesis. In fact, microorganisms degrade waste until their nutrient sources are depleted and the remaining nutrients are no longer capable of supporting microbial growth. In general, nutrients are adequate in most landfills. However, it has been observed some nutrient-deficient conditions due to waste heterogeneity (Yuen, 1999). The main inorganic nutrients needed by microorganisms are nitrogen (N), sulphur (S), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), iron (Fe), sodium (Na), and Chlorine (Cl). However, some other nutrients such as zinc (Zn), manganese (Mn), molybdenum (Mo), cobalt (Co), copper (Cu) are required for microbial activities (O'Leary, 1999).

Alternatively, some wastes contain inhibitors and toxic compounds that harm bacteria, causing less MSW decomposition. Therefore, it is necessary that the environment be free of these inhibitory materials in order to establish the proper condition for waste bioconversion. The main elements or compounds that can inhibit the biodegradation of MSW are high concentration of heavy metals, oxygen, and hydrogen as well as improper pH, carbon dioxide, sulphides, and high concentrations of some cations such as sodium, potassium, calcium, magnesium, ammonium, and other toxic constituents (Christensen et al., 1996).

The technologies used to enhance the biodegradation of MSW have attracted the attention of many researchers in all over the world since the 1970s. These methods will be applied to accelerate the MSW decomposition in landfills and mainly include leachate recirculation, pH buffering, sludge addition, temperature control, waste particle size reduction, landfill layer (or lift) development, nutrient addition, partially degraded refuse addition, moisture addition, and waste compaction.

The goal of these and other techniques is to control or enhance decomposition within the landfill, which usually includes enhancement of methane production. Discussion on these MSW biodegradation enhancement methods are beyond the scope of this research.

2.4.3. MSW Landfills Leachate

Biological, chemical, and physical processes that occur within the landfill, promote the MSW biodegradation resulting in the production of leachate and gases.

Properly designed and engineered landfill sites can mitigate the risks of leachate generation. Therefore, this section involves the subjects regarding the composition, formation, and movement of leachate within the landfill.

2.4.3.1. Landfill Leachate Formation

The main sources of water for leachate formation are precipitation and other liquids onto the operating landfill, infiltration through the cover of the completed landfill, groundwater and underground springs, water contained within the solid wastes and cover material placed in the landfill, surface runoff into the landfill from exterior areas, and the liquid produced from the waste decomposition. Some part of this liquid forms surface runoff, some other parts evaporate. The rest will be remained within the landfill. If the remaining water be greater than the field capacity of the waste, it will be run as leachate. A generalized pattern of leachate formation is presented in Figure 2.14. In addition, the water balance of a landfill can be expressed as the following equation:

$$\mathbf{Leachate} = (\mathbf{P_r} + \mathbf{W_m} + \mathbf{G_w}) - (\mathbf{R_r} + \mathbf{E_v} + \mathbf{E_t} + \mathbf{W_v}) \pm \Delta\mathbf{W} \pm \Delta\mathbf{S} \qquad (2.20)$$

where P_r is precipitation, W_m is moisture of waste and cover material at place, G_w is groundwater inflow, R_r is runoff, E_v is evaporation, E_t is evapotranspiration, W_v is water vapour, ΔW is chemical and biological water production/consumption, and ΔS is field capacity.

The leachate generation rate is affected by many factors such as surface runoff, field capacity, initial moisture content of waste, evaporation and evapotranspiration, permeability of the cover layer, soil moisture, type and amount of vegetation on the top, waste composition, waste density, volume of rainfall entered into the waste, climate and hydrology, landfill operation, waste pre-treatment (Dass et al., 1977; El-Fadel et al., 1998; Rees, 1980; Farquhar, 1989).

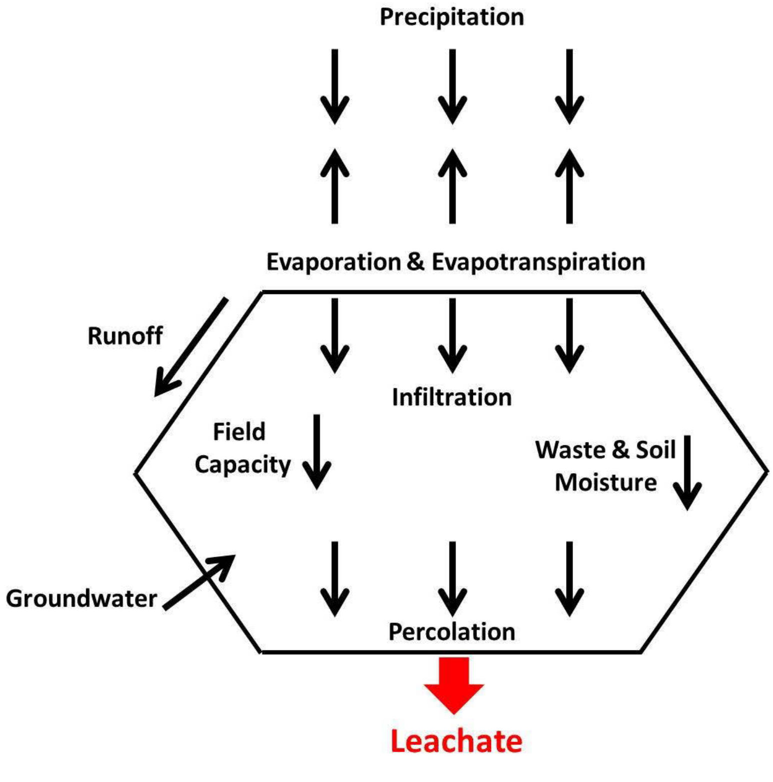

Figure 2.14: A Generalized Pattern of Leachate Formation in Landfills

As the leachate is moving through the landfill, it will react with the solid wastes chemically and biologically. These reactions result in the addition of contaminants to the leachate. Once the leachate reaches the bottom of the landfill, it is necessary to be drained into the leachate collection systems. If no leachate collection system is provided, the leachate will enter the environment and can become a source of contamination for the groundwater tables and aquifers underlying the landfill.

2.4.3.2. Landfill Leachate Composition

Landfill leachate is generated by excess rainwater percolating through the waste layers which are undergoing decomposition in a landfill. During the percolation, many pollutants including biological materials and chemical constituents causing from a combination of physical, chemical, and microbial processes in the waste will be transferred from the waste material to the percolating water (Christensen and Kjeldsen, 1989).

The main pollutants existing in landfill leachate can be categorized into four groups:

- Dissolved organic matter measured as Chemical Oxygen Demand (COD) or Total Organic Carbon (TOC), and Volatile Fatty Acids (VFAs), etc.
- Inorganic components including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), ammonium (NH^{4+}), iron (Fe^{2+}), manganese (Mn^{2+}), chloride (Cl^{-}), sulphate ($SO4^{2-}$) and hydrogen carbonate ($HCO3^{-}$).
- Heavy metals including cadmium (Cd^{2+}), chromium (Cr^{3+}), copper (Cu^{2+}), lead (Pb^{2+}), nickel (Ni^{2+}), and zinc (Zn^{2+}).
- Xenobiotic organic compounds including aromatic hydrocarbons, phenols, chlorinated aliphatic, pesticides, and plastizers in low concentrations of less than 1 mg/l of individual compounds (Kjeldsen et al., 2002).

The leachate characteristics are strongly related to the state of waste decomposition.

In general, the moisture released from the waste due to compaction as well as precipitation through the buried wastes involves the main parts of leachate produced during aerobic stage. As oxygen sources are depleted, the landfill shifts to anaerobic condition. In the early steps of anaerobic stage, the hydrolytic, fermentative, and acetogenic bacteria dominate, resulting in an accumulation of carboxylic acids, and eventually a pH decrease. Therefore, the highest Biological Oxygen Demand (BOD) and COD concentrations in the leachate will be observed during this phase (Barlaz and Ham, 1993; Reinhart and Grosh, 1998). It has been reported that the BOD: COD ratio in this step is above 0.4 (Ehrig, 1988) or 0.7 (Robinson, 1995). The leachate producing in this phase contains many compounds because the acidic pH in this phase increases the solubility of many compounds. As the methane production begins, the acids that accumulated in the acid phase are converted to methane and carbon dioxide by methanogenic bacteria. The methane production rate will increase until it reaches to its maximum rate. At this time, the BOD: COD ratio will decrease to less than 0.1 because carboxylic acids are consumed as rapidly as they are produced (Christensen and Kjeldsen, 1989; Barlaz et al., 1990).

Table 2.24: Typical Data on the Composition of Leachate from New and Mature Landfills (after Tchobanoglous et al., 1993)

Parameter	Value (mg/L)[1]		
	New Landfills (less than 2 years)		Mature Landfill (greater than 10 years)
	Range	Typical	
BOD_5	2000 – 30000	10000	100 – 200
TOC	1500 – 20000	6000	80 – 160
COD	3000 – 60000	18000	100 – 500
Total suspended solids	200 – 2000	500	100 – 400
Organic nitrogen	10 – 800	200	80 – 120
Ammonia nitrogen	10 – 800	200	20 – 40
Nitrate	5 – 40	25	5 – 10
Total phosphorous	5 – 100	30	5 – 10
Ortho phosphorous	4 – 80	20	4 – 8
Alkalinity as $CaCO_3$	1000 – 10000	3000	200 – 1000
pH	4.5 – 7.5	6	6.6 – 7.5
Total hardness as $CaCO_3$	300 – 10000	3500	200 – 500
Calcium	200 – 3000	1000	100 – 400
Magnesium	50 – 1500	250	50 – 200
Potassium	200 – 1000	300	50 – 400
Sodium	200 – 2500	500	100 – 200
Chloride	200 – 3000	500	100 – 400
Sulphate	50 – 1000	300	20 – 50
Total iron	50 – 1200	60	20 – 200

In summary and based on the existing data, landfill leachate contains high concentration of all of the above contaminants in the early acid phase because of strong decomposition in this phase. However, a more stable leachate with lower concentrations of pollutants and a low BOD/COD ratio is observed in the methanogenic phase.

Referring to Kjeldsen et al. (2002), landfill leachates may contain high concentrations of dissolved organic matter and inorganic components. In general, the concentrations of these components may be up to a factor 1000 to 5000 higher than concentrations found in groundwater.

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[1] Except pH which has no units.

2.4.4. MSW Landfills Gas

The MSW biodegradation results in the generation of gases in landfills and the decomposition products can be considered as the primary constituents of the generated gas. Landfill gas is a mixture of gases which are mainly generated in the anaerobic stage of waste decomposition in landfills. Generally, the nature of waste and the decomposition stage controls the landfill gas composition. Due to the importance of gas generation in landfill redevelopment related subjects, this section discusses the materials about the landfill gas generation, gas composition and gas quantity.

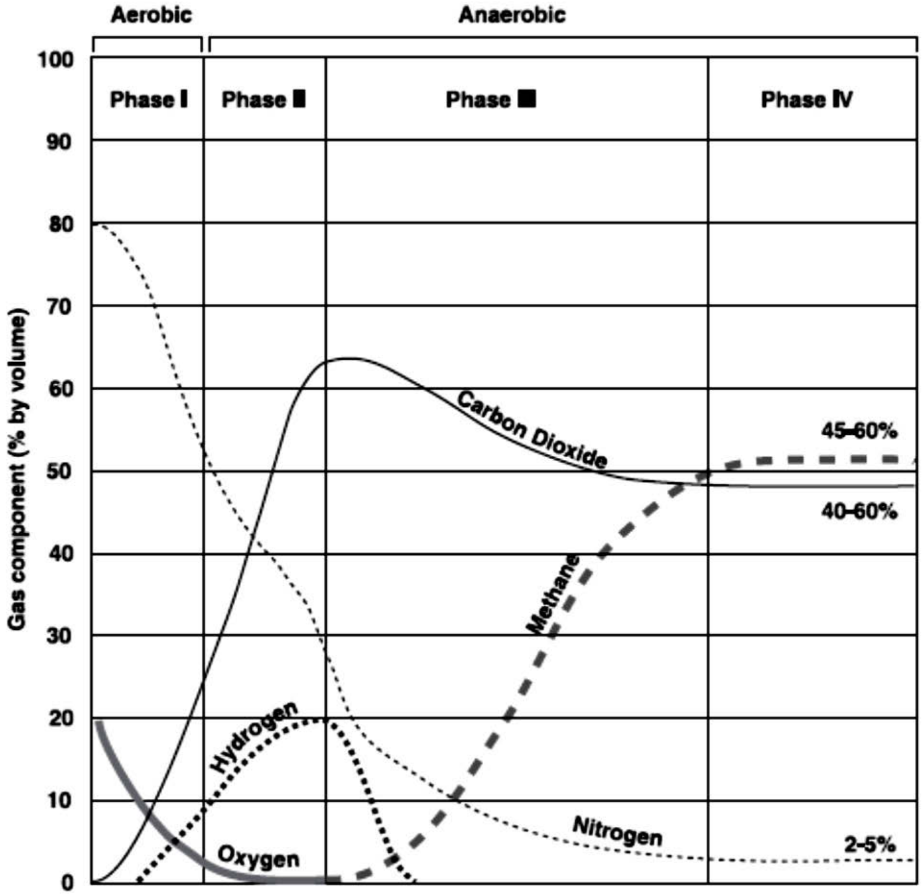

Figure 2.15: The Production Phases of Typical Landfill Gas[2] (US EPA, 1997)

2.4.4.1. Landfill Gas Generation

The landfill gas generation has been studied by many researchers. These studies numbered the variations in gas composition in different phases. However, all researches indicate that gas generation rate and composition is strongly associated with the

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[2] Phase duration time varies with landfill conditions

decomposition stage. This variation has been described in four phases by many researches as presented in Table 2.25 (US EPA, 1997; Farquhar and Rovers, 1973) and as illustrated in Figure 2.15.

Table 2.25: The Four Phases of Gas Production in MSW Landfills

Phase Name	Description	Duration
Aerobic	During this phase, aerobic bacteria consume oxygen and produce carbon dioxide while breaking down the complex molecules of carbohydrates, proteins, and lipids. This process is exothermic so that the landfill temperature may exceed 60°C - 70°C. Very little displacement of nitrogen occurs in this phase.	This phase can last for days or months depending on the amount of available oxygen
Anaerobic non-methanogenic	Anaerobic decomposition starts after the oxygen in the landfill has been used up. In this phase, the landfill is highly acidic because of the formation of various acids by anaerobic bacteria. Mixing acids with the moisture cause nitrogen and phosphorus become available to the increasingly diverse species of bacteria in the landfill. Therefore, the nitrogen amount will be reduced. Furthermore, an excessive amount of carbon dioxide and also hydrogen will be produced. Methane is not produced in this phase yet.	10 to 40 days
Aerobic methanogenic steady	In this phase, the landfill becomes a more neutral environment in which methane producing bacteria begin to establish themselves. The increase in methane production as well as a decrease in nitrogen and carbon dioxide is observed in this phase. However, methane disappears at the beginning of this phase because methanogenic microorganisms use hydrogen at a high rate.	180 to 250 days
Aerobic methanogenic unsteady	In this phase, both the composition and generation rates of landfill gas remain relatively constant.	Referring to Crawford and Smith (1985), gas is produced at a stable rate for about 20 years. Gas emission will be continued for 50 or more years after the waste is placed.

According to Rees (1980), the fifth phase of gas production can be considered as a transition phase. This phase is at the end of fourth phase when all organic materials are converted to methane and carbon dioxide. In this phase, landfill gas generation diminishes and gaseous conditions are re-established. The starting time for this phase is between 50 to 100 years after waste placement in landfills.

As mentioned in previous sections, landfill gas production is a function of biodegradation of solid wastes in landfills. Therefore, to maintain a landfill system that will degrade organic waste efficiently, many factors including environmental factors need to be considered.

Table 2.26: Key Parameters for Methane Production in MSW Landfills

Influencing Factor	Optimal Range/Comments	Source
pH	6.8 – 8 6 – 8 6.4 – 7.2	Warith (2003) Ehrig (1983) Farquhar and Rovers (1973)
Temperature	36°C - 41°C 34°C – 38 °C	Hartz et al. (1982) Mata-Alvarez et al. (1986)
Oxygen	Optimum redox potential: -200mV -300mV below -100mV	Farquhar and Rovers (1973) Christensen and Kjelden (1989) Pohland (1980)
Moisture	Generally above the field capacity 60% and more (by wet weight)	Pohland (1980) Rees (1980)
Density	800 kg/m^3 - 1000 kg/m^3	
Nutrients	Generally adequate in most landfill except local systems due to heterogeneity	Christensen and Kjelden (1989)
Inhibitors	Cation concentrations producing moderate/severe inhibition (mg/ l) : ▪ Sodium (3500-5500) ▪ Potassium (2500-4500) ▪ Calcium (2500-4500) ▪ Magnesium (1000-1500) ▪ Ammonium(total) (1500-3000) ▪ Heavy metals : No significant influence ▪ Organic compounds : Inhibitory only in significant amount	McCarty and McKinney (1961) Ehrig(1983) Christensen and Kjelden(1989)

Based on the existing information, it can be noted that research conducted during the last decades regarding municipal solid wastes has made possible to identify the key process parameters that influence the waste biodegradation mechanisms, and hence gas production potential in landfills. The optimal ranges for these fundamental factors that can affect the efficiency of degradation in a landfill system are summarised in Table 2.26. Detailed discussions of these factors can be found in the previous sections.

2.4.4.2. Landfill Gas Composition

Landfill gas is made up of a combination of different gases in various amounts including the principal gases in large amounts and minor compounds as well as the trace gases in very small amounts. Methane and carbon dioxide are the main gases generated from the anaerobic decomposition of organic fraction of MSW. Landfill gas typically contains 45% to 60% methane and 40% to 60% carbon dioxide, by volume. Minor compounds include small amounts of ammonia, hydrogen, hydrogen sulphide, nitrogen, and carbon monoxide. In addition, trace gases mainly involve volatile organic compounds (VOCs) and nonmethanogenic organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride (Tchobonoglous et al., 1993). Table 2.27 lists the typical percentage distribution of gases found in a MSW landfill.

Table 2.27: Typical Landfill Gas Component (after Tchobonoglous et al., 1993)

Component	Percent (dry volume basis)
Methane	45 – 60
Carbon dioxide	40 – 60
Nitrogen	2 – 5
Oxygen	0.1 – 1
Sulphides	0 – 1
Ammonia	0.1 – 1
Hydrogen	0 – 0.2
Carbon monoxide	0 – 0.2
Trace constituents	0.01 – 0.6

2.4.4.3. Landfill Gas Generation Rate

In general, gas production is a function of waste composition and biodegradability rate. However, the rate and volume of gas generated in a landfill depends on many parameters including waste characteristics such as waste composition and age of the waste as well as different environmental factors like moisture content, pH, microbial population, microbial activity, temperature, the presence of oxygen in the landfill, and available nutrients (Cheremisinoff, 2003 ; McBean et al., 1995).

The rate of generation of some landfill gases such as carbon dioxide, methane, nitrogen, and hydrogen sulphide correspond to the amount of organic waste in a landfill. On the other hand, the increase in amount of chemicals disposed of in the landfill may increase the production of NMOCs and other gases through volatilization or chemical reactions.

As the waste components in a landfill have different characteristics and various degree of biodegradability, estimation of the gas generation rate can be complex. However, many researches and studies performed in this field have shown that landfills usually produce considerable amounts of gas within 1 to 3 years depending on the waste composition, amount of moisture or other factors. Gas production usually reaches its highest point 5 to 7 years after waste placed in the landfill (US EPA, 1997).

The amount of organic material in the waste and their biodegradability can be considered as important factors in variation in gas production with time. Some highly biodegradable wastes are decomposed within days after placement in landfills. The gas generation from anaerobic decomposition of some rapidly biodegradable waste starts after 5 years or less. On the other hand, the gas production from slowly biodegradable wastes begins approximately 5 years after waste disposal and it lasts for 50 years. Generally, almost all gas is produced within 20 years after waste is disposed of in the landfill unless a small quantities of gas which may continue to be migrated from a landfill for 50 or more years (Tchobanoglous et al., 1993).

Many methods have been proposed to characterize the rate and amount of landfill gas generation which are mainly based on either Theoretical or experimental approaches.

In theoretical approach primarily uses stoichiometric concepts and assumes that all the biodegradable organic waste will be completely converted to carbon dioxide and methane. Accordingly, biological decomposition of one ton of municipal solid waste produces 442 m^3 of landfill gas.

In real condition, only part of the waste converts to methane because of many reasons such as moisture limitations, non-biodegradable wastes, inaccessible waste, etc. therefore, it has been estimated that the actual average methane yield is about 100 m^3 per ton of MSW (Worrell and Vesilind, 2002).

2.5. Landfill Settlement

Settlement in sanitary landfills is a complex process because of the waste heterogeneity, time-varying properties of waste, and influencing factors and mechanisms, such as mechanical compression due to the load application and creep, and physical-chemical and biological processes caused by the wastes decomposition.

Moreover, the large number of variables involved in the settlement process including type of waste, organic content, moisture content, compaction density, compressibility, level of nutrients available for biological activities, pH, temperature, and time since placement, make accurate prediction of landfill settlement as a challenge. Settlement in landfills is governed by many mechanisms and interaction among these mechanisms. Therefore, this section discusses the mechanisms of waste settlement as well as different stages of MSW settlement in landfills.

2.5.1. Mechanisms of Waste Settlement

The mechanisms of MSW settlement are many and complex due to heterogeneous nature of waste in landfills, large particle sizes, compression of refuse particles, and the loss of solids because of waste biodegradation.

Many researchers have studied on mechanisms of waste settlement in MSW landfills. Among others, Oweis and Khera (1998) and Yen and Scanlon (1975) described the waste settlement based on the following main mechanisms:

1) Consolidation processes which is much the same as those occurring in soils. This mechanism includes the expulsion of pore fluid, and reorientation of particles.
2) Movement of the fine materials into larger voids.
3) The volume change caused by biological decomposition of organics with time as well as chemical reactions.

Furthermore, many researchers (e.g. Sowers, 1973; watts and Charles, 1990; Edil et al., 1990; Manassero et al., 1996; Leonard et al., 2000) classified the MSW settlement behaviour in several distinct phases as occurring. They identified these mechanisms as mechanical, ravelling, consolidation phenomena, biological processes, and physiochemical processes. Based on their studies, distortion, bending, crushing, and reorientation of the materials occur after waste placement in landfills, hence leading to mechanical compression and creep. In addition, migration of smaller size particles into the voids among large particles is called ravelling and can be the cause of further settlement. Subsequently, consolidation phenomena and viscous behaviour involve both side skeleton and single particles. Moreover, waste decomposition processes result in biochemical decay while corrosion, oxidation, and combustion cause physiochemical changes. Both physiochemical changes and biochemical decay lead to a mass loss, and hence additional landfill settlement.

Table 2.28: Settlement Mechanisms in MSW Landfills (Data taken from Leonard et al., 2000)

Settlement Mechanism	Short-term/ Long-term Mechanism	Explanation	Contribution to Long-term Settlement
Mechanisms causing large settlements			
Mechanical/primary compression	short-term	Associated with air void reduction due to distortion, bending, crushing and reorientation of materials caused by the placement of overlying fill and compaction.	———
Biodegradation	long-term	Associated with biological activity which transforms cellulose and water in the MSW into primarily methane and carbon dioxide.	High
Physical creep compression	long-term	Associated with erosion and movement of the fine materials into larger voids, material moving into voids due to biodegradation, and elastic deformation of the structure of inert material remaining.	Moderate
Mechanisms causing small settlements			
Physical - Chemical/ Corrosion	long-term	Associated with the corrosion of steels and combustion of organics.	Low
Interaction	long-term	Associated with the occurrence of other mechanisms. Representation of a significant amount of settlement is not expected by this mechanism.	Generally Low; Potentially High in Localized Areas
Consolidation	long-term	Associated with squeezing excess water from pore spaces in low permeable soil formations.	None to low

El-Fadel and Khoury (2000) indicated that the interaction between these mechanisms may promote the settlement in landfills. As an example, organic acids and heat resulting from waste decomposition processes induce corrosion, and consequently physiochemical changes in waste.

Based on the above mentioned information, the main settlement mechanisms occurring at a landfill are presented in table 2.28. According to the data given in this table, as long-term settlement is considered to be studied in this research, the mechanisms with high contribution to long-term settlement will be taken into account in this study.

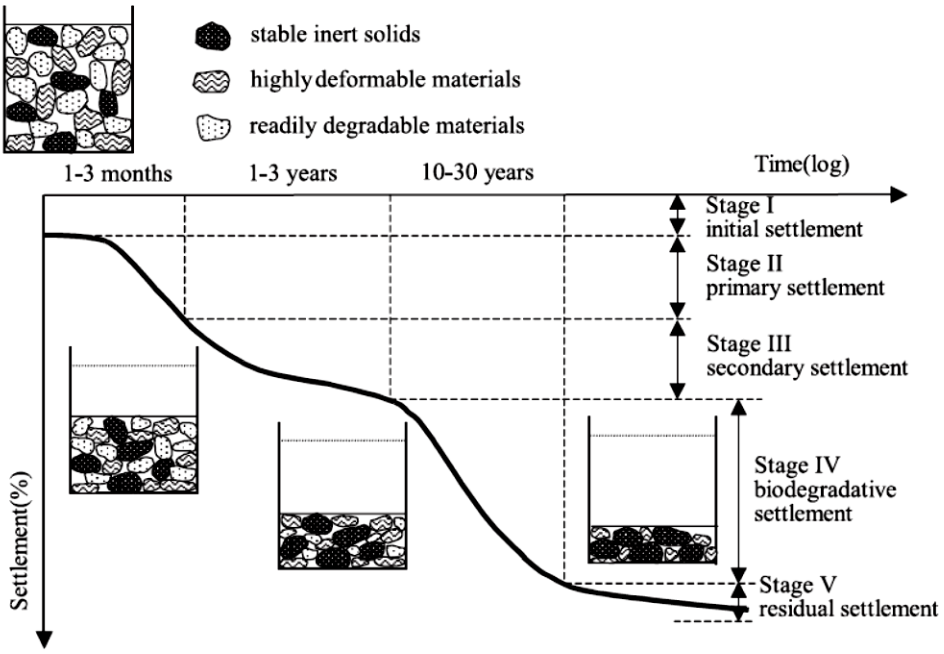


Figure 2.16: The Typical Time-Settlement Data (Grisolia and Napoleoni, 1995)

Additionally, Grisolia and Napoleoni (1995) developed a qualitative model to represent the compression behaviour of waste in a landfill under a certain load as shown in Figure 2.16. This curve is divided into the following stages:

- Initial settlement (Stage I): the instant mechanical compression induced by compression of highly deformable waste components,
- Primary settlement (stage II): the mechanical settlement with continuous compression or reorientation of waste,
- Secondary settlement (stage III): the mechanical deformation due to the creep of waste and the initial decomposition of organic material,
- Decomposition settlement (stage IV): the decomposition of organic material,
- Residual settlement (stage V): the residual deformation of mechanical settlement and organic decomposition.

Based on the above classification, stages I and II are not a main concern in redevelopment projects because the settlement associated with these stages will be completed in about 1 to 3 months after landfill closure. In contrast, stages III to V involves mechanical compression of waste as well as its time-dependent biodegradation.

Generally, the decomposition of organic wastes present in landfills takes place in stages III to V (particularly stage IV). Therefore, these stages cause a substantial settlement, and hence can be considered as a major concern from geotechnical viewpoint (Wong et al., 2013).

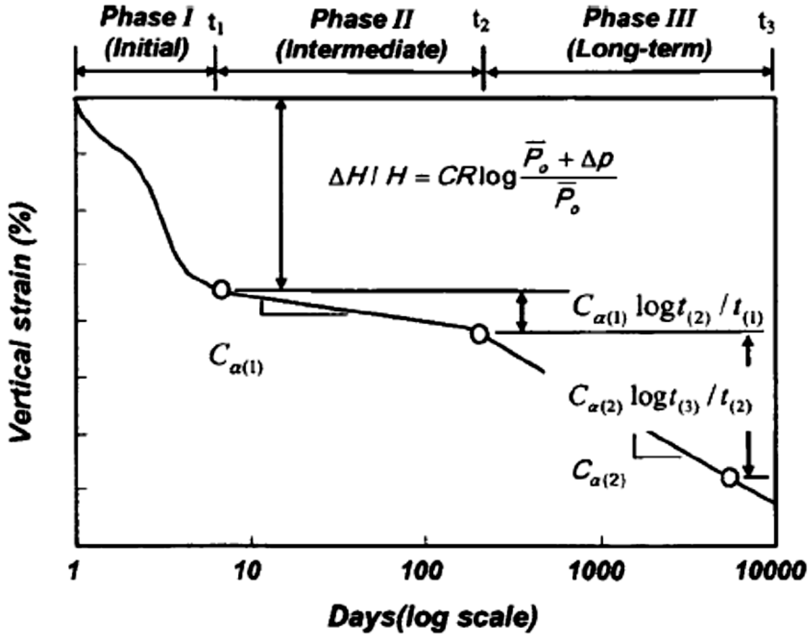


Figure 2.17: Waste Settlement Phases (Bjarngard and Edgers, 1990)

2.5.2. Waste Settlement Phases

Many studies (e.g. Bjarngard and Edgers, 1990; Morris and Woods, 1990; Wall and Zeiss, 1995; Powrie et al., 2005) on actual municipal landfill performance have shown that the waste settlement in landfills can be classified into three main phases (as shown in Figure 2.17):

- Initial settlement (immediate compression)
- Intermediate settlement (primary compression)
- Long term settlement (secondary compression)

Initial settlement is rapid settlement that takes place instantaneously after an external load is applied to the waste. Immediate compression is generally associated with the expulsion of air present in voids as well as the immediate compaction of voids and some types of particles due to superimposed load at the time of waste placement.

Table 2.29: Published Values for Primary Compression Index of MSW

Source	C_c	Condition
Sowers (1973)	$0.15e_0$ $0.55e_0$	MSW with low organic content MSW with high organic content
Sowers (1973)		MSW with age:
	0.106	< 200 days
	0.184	200 – 2000 days
	0.174	2000 – 20000 days
	0.163	> 20000 days
Sheurs and Khera (1980)	0.18	5 to 15 years old MSW
Burlingame (1985)	0.15	5 to 15 years old MSW
Landva and Clark (1990)	0.35	Fresh waste
Oweis and Khera (1998)	0.06 – 0.26	15 to 20 years old MSW
Hossain et al. (2003)	0.16 – 0.25	Fresh waste
Vilar and Carvalho (2005)	0.21	15 years old MSW
Hettiarachchi (2005)	0.18 – 0.21	Fresh waste
Zekkos (2005)	0.36 – 0.55	Low unit weight MSW (5 kN/m^3)
	0.13 – 0.22	Typical unit weight MSW (10 kN/m^3)
	0.015 – 0.04	High unit weight MSW (15.5 kN/m^3)
Durmusoglu et al. (2005)	0.13 – 0.26	10 years old MSW
Jang et al. (2005)	0.106	MSW with age 600 days
Hunte et al. (2007)	0.21	0.5 years old MSW
Reddy et al. (2009)		Fresh waste with moisture content:
	0.28	44%
	0.25	60%
	0.33	80%
	0.24	100%
Reddy et al. (2009)		1.5 years old MSW with moisture content:
	0.19	44%
	0.20	60%
	0.20	80%
	0.24	100%

Initial settlement can be calculated based on the following equation:

$$\mathbf{S_{ic} = H_0 \frac{1}{E} \Delta P} \tag{2.21}$$

where S_{ic} is the settlement due to immediate compression in m, H_0 is the initial height of solid waste layer in m, E is elastic modulus of waste in N/m^2, and ΔP is the increase in overburden pressure acting at midlevel of layer in N/m^2.

Referring to Moore and Pedler (1977), elastic modulus of waste is in the range of 50 kPa to 700 kPa.

Intermediate settlement is a slower and shorter process that occurs due to the consolidation of the waste as a result of dissipation of water and gas from the pores in response to the load. In a completed landfill, primary compression may occur quickly and shortly after the waste placement, usually within the first 30 days after load application (Sowers, 1973; Gordon et al., 1986; Dodt et al., 1987; Edil et al., 1990; Morris and Woods, 1990).

Table 2.30: Published Values for Secondary Compression Index of MSW

Source	C_α	Condition
Sowers (1973)	$0.03e_0$ $0.09e_0$	unfavourable condition for decay favourable condition for decay
Walker and Kurzeme (1985)	0.08	MSW with variable age , 3 to 15 depth
Burlingame (1985)	0.022 0.008	Old landfill, 3 m depth Old landfill, 12 m depth
Gifford et al. (1990)	0.020	Old landfill
Edil et al. (1990)	0.075 0.012	Fresh waste, 10 to 30 m depth Old waste, 10 m depth
Gabr and Valero (1995)	0.03 – 0.09	15 to 30 years old MSW
Vilar and Carvalho (2005)	0.021 – 0.044	15 years old MSW
Dixon et al. (2004)	0.02 0.24 0.02 0.04 0.001 – 0.005	10 years old landfill 15 years old landfill 15 to 20 years old landfill Old landfill Old landfill with high soil content
Jang et al. (2005)	0.030 – 0.140	MSW with age 600 days
Pauzi et al. (2010)	 0.350 0.015 – 0.350	Waste with age: 25 days 200 days

Settlement due to primary compression can be determined based on the following equation:

$$\mathbf{S_{pc} = H_i \frac{C_c}{1 + e_0} \log\left(\frac{P_0 + \Delta P}{P_0}\right)} \qquad (2.22)$$

where S_{pc} is the settlement due to primary compression in m, H_i is the height of solid waste after initial compression in m, C_c is the primary compression index, e_0 is the initial voids ratio of waste, P_0 is the existing overburden pressure acting at midlevel of layer in N/m^2, and ΔP is the increase in overburden pressure acting at midlevel of layer in N/m^2.

The reported values for primary compression index are listed in Table 2.29.

Secondary compression generally caused by waste mass decay within the landfill due to the physicochemical actions and biochemical decomposition in addition to slippages, reorientation of particles, and delayed compression of some waste constituents over a longer period of time. This phase is primarily associated with the creep of the waste skeleton as well as the waste biological decay and physiochemical action (Sowers, 1973; Gordon et al., 1986). Secondary compression is a steady phase that lasts for many years until the waste is fully stabilized. Thus, it is sometimes called long-term settlement. This phase of settlement can account for a major portion of the total landfill settlement (Rao et al., 1977). Lang-term settlement can be estimated from the following equation:

$$\mathbf{S_{sc} = H_p \frac{C_\alpha}{1 + e_p} \log\left(\frac{t}{t_p}\right)} \qquad (2.23)$$

where $\mathrm{S_{sc}}$ is the settlement due to secondary compression in m, $\mathrm{H_p}$ is the height of solid waste after primary compression in m, $\mathrm{C_\alpha}$ is the secondary compression index, $\mathrm{e_p}$ is the void ratio after primary compression, t is the time in days, $\mathrm{t_p}$ is the time (in days) for primary compression to occur.

Some published values for secondary compression index are presented in Table 2.30.

Table 2.31: Typical Values for Modified Compression Indices of MSW (after Durmusoglu, 2002)

Source	$\mathbf{C_{ce}}$	$\mathbf{C_{\alpha e}}$
Sowers (1973) for $\mathbf{e_0 = 3}$	0.1 – 0.41	0.02 – 0.07
Zoino (1974)	0.15 – 0.33	0.013 – 0.03
Converse (1975)	0.25 – 0.3	0.07
Rao et al. (1977)	0.16 – 0.235	0.012 – 0.046
Landva et al. (1986)	0.2 – 0.5	0.0005 – 0.029
Oweis and Khera (1986)	0.08 – 0.217	–
Bjarngard and Edgers (1990)	–	0.004 – 0.04
Wall and Zeiss (1995)	0.21 – 0.25	0.033 – 0.056
Gabr and Valero (1995)	0.2 – 0.23	0.015 – 0.023
Boutwell and Fiore (1995)	0.09 – 0.19	0.006 – 0.012
Stulgis et al. (1995)	0.16	0.02
Green and Jamenjad (1997)	–	0.01 – 0.08
Landva et al. (2000)	0.17 – 0.24	0.01 – 0.016

Based on the above mentioned information, the primary compression index and the secondary compression index can be expressed as a function of the initial void ratio (Wall and Zeiss, 1995 ; Oweis, 2006):

$$\mathbf{C_c = (0.15\ to\ 0.55)\ e_0} \qquad (2.24)$$

$$\mathbf{C_\alpha = (0.03\ to\ 0.09)\ e_p} \qquad (2.25)$$

As it is difficult to reliably predict the initial void ratio of waste, Sowers (1973) showed that the primary and secondary compression indices can be modified in order to avoid the need to estimate the void ratio, therefore, the modified primary compression index and the modified secondary compression index can be defined as the following equations:

$$\mathbf{C_{ce} = \frac{C_c}{1 + e_0}} \qquad (2.26)$$

$$\mathbf{C_{\alpha e} = \frac{C_\alpha}{1 + e_p}} \qquad (2.27)$$

Some typical values for modified compression indices are listed in Table 2.31.

Table 2.32: Main Factors Affecting the Magnitude and Rate of Settlement in MSW Landfills (after El-Fadel and Khoury, 2000)

Factor	Effect
Initial density (initial void ratio of waste)	Higher initial density of MSW due to the greater compaction decreases the final settlement as well as the rates of primary and secondary settlement
Waste composition	Higher amount of decomposable materials in landfills leads to reduction in waste void ratio as well as increase in waste compressibility
Landfill depth	Deeper landfills have faster rate of settlements. Additional increase in settlement rates cannot be observed after a threshold depth because biodegradation rate decreases
Applied stress and stress history	Some settlement mechanisms such as creep and pressure dissipation are affected by load increase leading to reduction in primary and secondary compressibility
Environmental conditions	Secondary compressibility increases if waste be exposed to favourable conditions decomposition.

2.5.3. MSW Landfill Settlement Rate

The waste decomposition and the total stress are the primary factors causing the landfill settlement. However, there are many other factors which affect the landfill settlement rate including operational practices, moisture content, and other circumstances influencing solid waste biodegradation in landfills (Edil et al., 1990; James, 1977; Zehnder et al., 1979). Settlement rates usually decrease with time. Referring to Bleiker et al. (1995), the rate of settlement varies not only with time but also with depth. As a general rule, the magnitude of rate of settlement decreases with time and depth of landfill. The main factors affecting the magnitude and rate of settlement are summarized in Table 2.32.

2.6. Settlement Models of MSW Landfills

As available space becomes scarce in urban areas, development on the top of or adjacent to old landfills has become increasingly common. Over the past decade, there has been a significant increase in post-closure development on closed solid waste landfills. Parks, golf courses, roads, and buildings are some examples of post-closure developments on top of closed landfills. Among various factors which would be considered in redeveloping landfill sites, settlement may be the most important factor from the perspective of structural and geotechnical aspects.

Settlement influences the progress of hydraulic and biodegradation processes, affects the performance of landfill infrastructure including the capping, cover materials, side slope liners and leachate and gas management systems, and is a key factor in landfill redevelopment. Thus, the compressibility and settlement behaviour of MSW has drawn the attention of several researchers to propose different approaches and settlement models for predicting time dependent settlement under load. This section attempts to make a comprehensive explanation for the existing landfill settlement models while these models are categorized based on their main characteristics.

2.6.1. Models Considering Secondary Compression (Soil Mechanics-based Models)

Landfill settlement has been studied by many researchers. Among all researchers on landfill settlement, Gibson and Lo (1961), Sowers (1973), Chen(1974), Rao et al. (1977), Oweis and Khera (1986), Bjarngard and Edgers (1990), Morris and Woods (1990), and Edil et al. (1990), Wall and Zeiss (1995), El-Fadel and Al-Rashed (1998), Hossain et al. (2003), Hossain and Gabr (2005) and Oweis (2006) used primary and secondary compression models to describe the stress-strain-time relationship in waste.

Sowers (1973) was the first researcher who used the basic soil mechanics-based model of consolidation to estimate the settlement of MSW. The model of sowers is divided into two phases and can be expressed by the following equation as the sum of the equations for primary compression and secondary compression:

$$\mathbf{S = H_0 \frac{C_c}{1+e_0} \log\left(\frac{P_0 + \Delta P}{P_0}\right) + H_p \frac{C_\alpha}{1+e_p} \log\,(\frac{t_2}{t_1})} \qquad (\mathbf{2.28})$$

where S is the total settlement of waste in m, H_0 is the initial thickness of the waste layer in m, C_c is the primary compression index, e_0 is the initial void ratio of waste, P_0 is the existing overburden pressure acting at midlevel of the layer in N/m^2, ΔP is the increase of overburden pressure acting at midlevel of the layer in N/m^2, H_p is the height of waste after primary compression in m, C_α is the secondary compression index, e_p is the void ratio at the end of primary compression, t_1 is the time (in days) for completion of primary compression, and t_2 is the time (in days) for completion of secondary compression.

Chen (1974) pointed out that equation (2.28) can be written in different form as follows to avoid the need to estimate the void ratio because it is difficult to reliably predict the initial void ratio of refuse:

$$\mathbf{S = H_0 C_{ce}\ \log\,(\frac{P_0 + \Delta P}{P_0}) + H_p C_{\alpha e} \log\,(\frac{t_2}{t_1})} \qquad (\mathbf{2.29})$$

where C_{ce} is the modified primary compression index, and $C_{\alpha e}$ is the modified secondary compression index.

Similar to Sowers (1973), Bjarngard and Edgers (1990) proposed a settlement model considering three phases of settlement as in the following equation:

$$\mathbf{S = H\, C_c \log\,(\frac{P_0 + \Delta P}{P_0}) + HC_{\alpha 1} \log(\frac{t_2}{t_1}) + HC_{\alpha 2} \log(\frac{t_3}{t_2})} \qquad (\mathbf{2.30})$$

where S is the settlement due to primary and secondary consolidation in m, H is the initial thickness of the waste layer in m, C_c is the primary compression index, P_0 is the existing overburden pressure acting at midlevel of the layer in N/m^2, ΔP is the increment of overburden pressure acting at midlevel of the layer in N/m^2, $C_{\alpha 1}$ is the intermediate secondary compression ratio, $C_{\alpha 2}$ is the long term or final secondary compression ratio, t_1 is the time (in days) for the initial compression, t_2 is the time (in days) for intermediate secondary compression, and t_3 is the time (in days) for total period of time considered in modelling.

Bjarngard and Edgers' model stated that ($C_{\alpha 1}$) ranged from 0.003 to 0.038, while ($C_{\alpha 2}$) ranged from 0.017 to 0.51. Typical parameter values are reported to be $C_c = 0.205$, $C_{\alpha 1} = 0.035$, $C_{\alpha 2} = 0.215$, $t_1 = 1$ to 25 days, and $t_2 = 200$ days.

In further research, Fasset et al. (1994) proposed a model identical to Bjarngard and Edgers (1990) with the exception that the two secondary compression indices for intermediate and long term phases are combined into one denoted as C_α which is applied to calculate compression over a time period between t_1 and t_2. Moreover, Xuede et al. (2002) published some formulas regarding landfill settlement which were utilized to estimate immediate and long term MSW settlement at the site. Furthermore in an extensive study, Zekkos (2005) collected and evaluated in-place unit weight values for MSW in more than 37 landfills. The resulting C_c values are presented in Table 2.29.

2.6.2. Models Considering Different Layers in MSW Landfill

The entire landfill depth has been used in settlement models by most researchers. Considering the entire waste thickness for calculation of landfill settlement cannot provide an accurate estimation because it does not allow calculating the strains at different depths. Therefore, many researchers studied the landfill settlement while taking into account different layers of waste in landfill. Among them, Yen and Scanlon (1975) analysed the settlement data recorded over 9 years for three landfills with depths varying from 6 to 31 meters, and construction times varying from 1 to 7 years. Based on their study, they understood the settlement rate increased with the depth of fill until it reached a maximum limit. Therefore, they suggested that settlement rates decrease linearly with the logarithm of the median fill age and expressed a logarithmic function as following:

$$\mathbf{S = H_0\left[\alpha + \beta\left(t - \frac{t_c}{2}\right)\right]} \qquad \mathbf{(2.31)}$$

where S is the settlement rate in m, H_0 is the initial height of the landfill in m, α is the fitting parameter (=0.00095H +0.00969), β is the fitting parameter (=0.00035H+ 0.00501), t is the time since beginning of filling in days, and t_c is the construction period in days. Although their assumption was supported by the field data observed by other investigators, the method over predicted settlement for shallow landfills and under predicted settlement for very deep landfills (Merz and Stone, 1962 and Sowers, 1973).

Morris and Woods (1990) proposed a mathematical model to calculate the settlement of different layers within the waste. The basic assumption used in this model was that the landfill is constructed at one point in time. Moreover, Sohn and Lee (1994) proposed a simple model and showed that settlement rate is linearly proportional to the fill height. Furthermore, Bleiker et al. (1995) noted that many factors including the increased strain in the waste layers due to the weight of the overlying layers results in the variation of the settlement rate with depth in addition to time. They developed an approach for calculation of settlement at different depths as well as different loading histories. In a comprehensive attempt, Gourc and Olivier (2005) proposed the ISP model which identifies nominal layers of waste. This model is mainly based on the controlling function as following:

$$\mathbf{\Delta h_i = h_i C_\alpha \log\left(\frac{t}{t_i}\right)} \qquad (\mathbf{2.32})$$

where Δh_i is the long term settlement of waste layer i in m, h_i is the post compression height of layer i in m, t_i is the duration of filling of layer i in days, t is the time since the beginning of filling in days.

Based on this model, the surface settlement is the sum of individual layer settlements considering settlements occurred due to load as well as decomposition. As shown in Figure 2.18, the settlement in this model is measured on the landfill final cover in reference to the column height at the end of construction H_n.

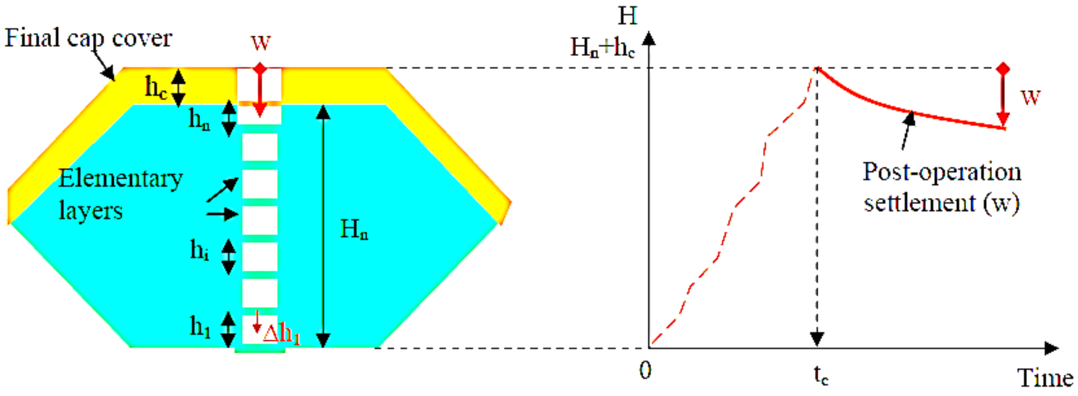


Figure 2.18: ISP Model Concept (Gourc and Olivier, 2005)

Additionally, Chen et al. (2009) studied the changes in the mechanical compressibility of MSW as a function of the fill age of MSW as well as the embedding depth of MSW. They prepared some samples representative of various fill ages from a landfill in China and measured different waste properties such as waste composition, waste unit weight, void ratio, and waste moisture content. The results of this study showed that the MSW void ratio decreases with depth. In addition, an increase in the fill age provides a decrease in the compressible components of the MSW such as organic wastes, plastics, paper, wood and textiles.

All these studies demonstrate that the variation of MSW compressibility with fill age or depth should be taken into account in the settlement prediction.

2.6.3. Rheological Models for Settlement Estimation

Gibson and Lo (1961) proposed a model which is especially suitable for estimating the settlement of soil such as peat where a high concentration of organic materials is present. They assumed that waste will be subject to a gradually increasing stress with time due to a load increment. As shown in Figure 2.19, the model consists of two Hookean springs connected in series to a dashpot element in which the waste will settle immediately due to an applied load with strain in Hookean element "a" and eventually, the waste skeleton supporting the load will creep, rearrange and settle at a rate "k" with additional strain in Hookean element "b".

This physical model estimates the rate and magnitude of settlement as a function of time and the initial waste thickness based on the following function:

$$\mathbf{\frac{S}{H_0} = \sigma a + \sigma b\left(1 - e^{-(\lambda/b)t'}\right)} \qquad (\mathbf{2.33})$$

where S is the settlement in m, $\mathrm{H_0}$ is the initial height of waste in m, σ is the compressive stress depending upon waste height, density, and external loading in kPa, a is the primary compressibility parameter (=1.0×10^{-4} to 8.0×10^{-5} /kPa), b is the secondary compressibility parameter (=2.0×10^{-3} to 1.6×10^{-2} /kPa), λ/b is the rate of secondary compression (=1.4×10^{-4} to 9.0×10^{-4} /day), and $\mathrm{t'}$ is the time since load application in day.

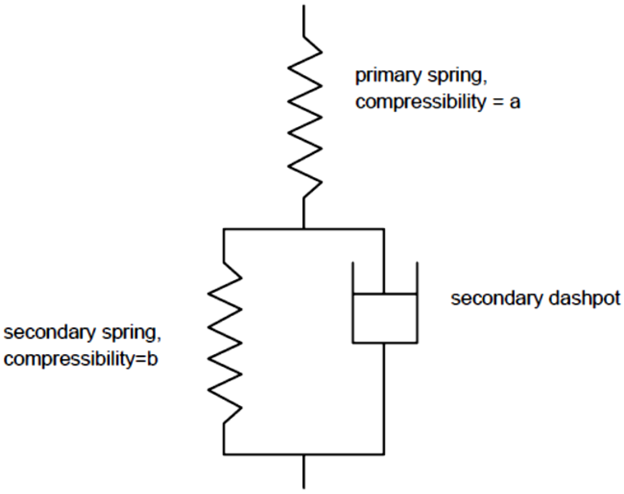


Figure 2.19: Gibson and Lo Model Concept (Gibson and Lo, 1961)

Moreover, Rao et al. (1977) used the following equation and developed a model to predict the total settlement of the waste as a function of load neglecting the time effect on the settlement.

$$\mathbf{S = H_0 \frac{\frac{\Delta H}{H_i}}{\frac{H_0}{H_i}}} \qquad (2.34)$$

where S is the settlement in m, H_0 is the initial thickness of waste layer in m, $\frac{H_0}{H_i}$ is the relative height corresponding to the existing overburden pressure (P_0), and $\frac{\Delta H}{H_i}$ is the change in relative height corresponding to the pressure increment (ΔP). As this model does not consider time dependent settlement due to the biodegradability of the waste over time, it is not very popular among the waste settlement models.

Edil et al. (1990) used the model which was proposed by Gibson and Lo (1961) to predict long-term total settlement of MSW and pointed out that as average strain rate increases, the rate of secondary compression will increase. They proposed the following equation for the estimation of the time-dependent settlement using this method:

$$\mathbf{\Delta H = H_0\, \sigma\, M'(\frac{t}{t_r})^{N'}} \qquad (2.35)$$

where S is the settlement in m, H_0 is the initial thickness of waste in m, σ is the compressive stress depending upon waste height, density, and external loading in kPa, M′ is the reference compressibility (=1.6×10^{-5} to 5.8×10^{-5} /kPa), N′ is the rate of compression parameter, t is the time since load application in day, and t_r is the reference time which is typically introduced to make time dimensionless (usually taken as 1 day). The settlement prediction based on this model is very sensitive to the values of (M') and (N').

El-Fadel and Al-Rashed (1998) used Gibson and Lo, power creep model and one-dimensional consolidation model to simulate laboratory and field settlement data. Based on this observation El-Fadel and Al-Rashed (1998) suggested the following two equations to represent the time dependent settlement behaviour in waste:

$$\varepsilon = \mathbf{C_{\alpha 1}} \log\left(\frac{\mathbf{t}}{\mathbf{t}_{is}}\right) ; \quad \mathbf{t_{is}} \geq \mathbf{t} \geq \mathbf{t_s} \tag{2.36}$$

$$\varepsilon = \mathbf{C_{\alpha 2}} \log\left(\frac{\mathbf{t}}{\mathbf{t_s}}\right) ; \quad \mathbf{t} \geq \mathbf{t_s} \tag{2.37}$$

where $C_{\alpha 1}$ is the coefficient of intermediate secondary compression, $C_{\alpha 2}$ is the coefficient of long term secondary compression, t_{is} is the time at the end of initial settlement period in day, and t_s is the time in day at which the strain slope versus logarithm time curve changes. When time reaches t_s , the first mechanism of waste settlement given by first above mentioned equation suddenly stops and then starts a new mechanism (second equation) but this sudden change in mechanism is not justified and the selection of the time at which the second mechanism starts, is also highly subjective.

Furthermore, Marques (2001) developed a composite rheological model considering primary and secondary compression mechanisms as well as waste degradation. The model is represented by the following equation:

$$\frac{\mathbf{S}}{\mathbf{H}} = \mathbf{C'_c} \log \left(\frac{\mathbf{P_0} + \Delta\mathbf{P}}{\mathbf{P_0}}\right) + \Delta\mathbf{P}.\mathbf{b}.\left(\mathbf{1} - \mathbf{e^{-ct'}}\right) + \mathbf{E_{dg}}.\left(\mathbf{1} - \mathbf{e^{-dt''}}\right) \tag{2.38}$$

where S is the settlement in m, H is the initial height of waste in m, C'_c is the primary compression ratio, b is the coefficient of secondary mechanical compression, c is the secondary mechanical compression rate in day^{-1}, E_{dg} is the total compression due to waste degradation, d is the secondary biological compression rate in day^{-1}, t' is the time elapsed since loading application in day, and t'' is the time elapsed since waste disposal in day.

2.6.4. Models Incorporating Biodegradation

Following many other previous researches regarding the contribution of biodegradation to landfill settlement, Wall and Zeiss (1995) conducted a laboratory experiment to determine the effects of biodegradation on settlement. They used the waste settlement model which was originally proposed by Sowers (1973) and assumed linear time dependent settlement behaviour with respect to a logarithmic time where the variation of strain with time was expressed by following Equation:

$$\varepsilon = \mathbf{C_1} \, \mathbf{log}\left(\frac{\mathbf{t}}{\mathbf{t_p}}\right) \; ; \mathbf{t} \geq \mathbf{t_p} \qquad (\mathbf{2.39})$$

where ε is the strain, C_1 is the slope of the strain versus log-time curve and t_p is the time in day taken for finishing the primary compression. This study showed that there is no significant increase in the settlement rate due to biodegradation in the short term (250 days). However, settlement rate will likely increase as the effects of decomposition becomes more significant in the long term.

Park and Lee (1997) also studied the settlement causing by decomposition of biodegradable wastes. They divided the long term settlement into two parts including mechanical compression as well as decomposition and proposed a settlement model incorporating time-dependent compression of wastes due to decomposition of organic solids. This model lacked field validation. In addition, Gabr et al. (2000) identified two stages of decomposition and proposed a conceptual two stage model for modelling the settlement behaviour of a biocell landfill. In this approach, they assumed that compressibility of the waste does not conform to the traditional Terzaghi's model during early stage of biological decomposition and is governed by changes in the void ratio due to solids loss which results in a physical change in the particle size and distribution. As decomposition takes place, the material breakdown may lead to increase in the surface area of the solid matrix. Therefore, assuming the amount of compression due to the increase in void ratio as well as the compressibility of solids controlled by the matrix stiffness changes under the waste weight and external loads, Gabr et al. (2000) suggested implementation of such Terzaghi's model with primary and secondary settlement, for the later stage of decomposition. They also recommended that the waste thickness must be subdivided into several layers in order to avoid the complications and to address the changes of the waste properties with depth.

In an attempt to estimate landfill settlement, Hossain (2002) studied the changes in waste compressibility as a function of the waste decomposition state. The state of decomposition was quantified by the methane yield and the cellulose (C) plus hemicellulose (H) to lignin (L) ratio. This study showed that the magnitude of compressibility increased as waste decomposed. Moreover, initial settlement and the coefficients of primary compression (C_c) increased with decreasing (C + H)/L ratio while the creep index was fairly independent of the state of decomposition.

Considering biodegradation and creep, Marques et al. (2003) integrated three mechanisms for one dimensional compression of MSW including instantaneous response to load, mechanical creep, and biological decomposition and developed a composite compressibility model using Boussinesq theory for determination of change in vertical stress. This model considered the following equation for calculation of total settlement:

$$\mathbf{S} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{H_0}\ [\varepsilon_{\mathbf{pi}} + \varepsilon_{\mathbf{ci}}(\mathbf{t}) + \varepsilon_{\mathbf{bi}}(\mathbf{t})] \qquad (\mathbf{2.40})$$

where S is the settlement in m, H_0 is the initial height of compacted lift i in m, n is the number of lifts in the landfill, ε_{pi} is the strain in lift i resulting from instantaneous response to loading from overlying lifts, ε_{ci} is the strain at time t in lift i due to mechanical creep associated with the stresses from self-weight and the weight of overlying lifts, and ε_{bi} is the strain at time t in lift i due to biological decomposition of lift i.

In addition, Hettiarachchi et al. (2003) used first order reaction kinetics to estimate waste settlement considering the relationship between waste decay and the reduction in waste mass. The following equation was used to predict the settlement in a biocell landfill:

$$\varepsilon(\mathbf{t}) = \varepsilon_{\mathbf{0}} + \boldsymbol{\beta}\mathbf{C_i}(\mathbf{1} - \mathbf{exp}(-\boldsymbol{\lambda}\mathbf{t})) \qquad (\mathbf{2.41})$$

where t is the time since placement in day, $\varepsilon(t)$ is the strain at time t, ε_0 is the initial strain, β is the correlation coefficient of compression due to biodegradation in kg^{-1}, C_i is the initial mass of the biodegradable waste in kg, and λ is the first order decay constant in day^{-1}.

In a much more comprehensive attempt, Hossain and Gabr (2005) proposed a settlement prediction model for bioreactor landfills consisting of four components including initial strain, initial creep, biological strain and final creep. They measured compressibility parameters of waste at four different decomposition states. The state of decomposition was quantified by the methane yield and the cellulose (C) plus hemicellulose (H) to lignin (L) ratio. The following equation was expressed for evaluation of long-term settlement based on this model:

$$\frac{\Delta \mathbf{H}}{\mathbf{H}} = \mathbf{C_{\alpha i}} \log(\frac{\mathbf{t_e}}{\mathbf{t_{is}}}) + \mathbf{C_\beta} \log(\frac{\mathbf{t_b}}{\mathbf{t_e}}) + \mathbf{C_{\alpha f}} \log(\frac{\mathbf{t_{cb}}}{\mathbf{t_b}}) \qquad (2.42)$$

where $C_{\alpha i}$ is the compression index as a function of stress level and degree of decomposition (≈0.03), t_{is} is time for completion of initial compression (≈10–15 days), t_2 is time duration for which compression is to be evaluated (≈100 to 2,000 days), C_β is biodegradation index (≈0.19), t_b is time for completion of biological compression (≈3,500 days), $C_{\alpha f}$ is creep index, and t_{cb} is time for the creep at the end of biological degradation in days. The mechanical compression under applied stress and the pressure due to self-weight were not included in this model.

Machado et al. (2008) proposed a mathematical model to predict long-term or secondary settlement of sanitary landfills considering two main processes including mechanical creep compression and the biodegradation of waste. In this model, the MSW solids are divided into two groups: fibrous materials including mainly plastic wastes and the MSW paste basically composed of other non-fibrous material such as wood, organic compounds, rubber, glass, water, liquid phases generated during the decomposition process, etc. A biodegradation parameter relating mass loss to volumetric variations was introduced in this model. It was assumed that the strains are related to the fibrous material and the paste while the volumetric strains as well as all the void ratio of the MSW are only related to the paste. This model has enough credibility for predicting long term landfill settlements. Additionally, Babu et al. (2010) proposed a constitutive model of MSW to calculate total compression under loading based on soil mechanics theory incorporating elastic and plastic behaviour as well as mechanical creep and time dependent biological decomposition. This model used the following equation to estimate the total volumetric strain of the MSW under loading:

$$\mathbf{d\varepsilon_v = d\varepsilon_v^e + d\varepsilon_v^p + d\varepsilon_v^c + d\varepsilon_v^b} \qquad (2.43)$$

where $d\varepsilon_v^e$, $d\varepsilon_v^p$, $d\varepsilon_v^c$, and $d\varepsilon_v^b$ represent increment of volumetric strain due to elastic effects, plastic effects, time dependent mechanical effects, and biodegradation effects, respectively. This model is useful in assessment of the settlement and stability of landfills for landfill redevelopment projects.

2.6.5. Models Incorporating Liquid and Gas Generation

Meissner (1996) considered two parts for the compressibility of the MSW including settlement and subsidence and proposed a model in which settlement is related to the elastoplastic deformations taking place in the first days of loading and Subsidence or bioconsolidation is related to the gas production process.

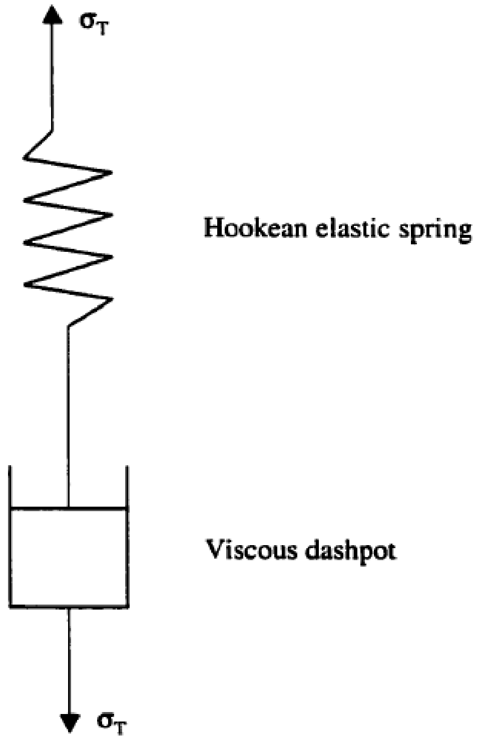


Figure 2.20: Schematic Representation of Maxwell's Body (Suklje, 1969)

Following the studies conducted by Meissner, many researchers developed various mathematical models to simulate liquid and gas flows in landfills. These models assume the landfill is a rigid medium. Durmusoglu et al. (2002) performed a comprehensive study on waste settlement for two different landfills namely deformable and rigid. This study showed that the results for modelling of the fluid flows under deformable landfill conditions are quite different from that of the rigid landfills. Based on the results, Durmusoglu et al. (2002) developed a one-dimensional multiphase mathematical model to simulate the vertical settlement under more realistic landfill conditions involving liquid and gas flows in a deformable (settling) MSW landfill. As MSW is not elastic solid matrix, Durmusoglu et al. (2002) applied the Maxwell's body rather than a Hookean spring as a viscoelastic approach to incorporate the time-dependent deformation of the solid matrix. As shown in Figure 2.20, the Maxwell's body consist of two basic elements joined in series including the Hookean spring, characterized by its compressibility, and a dashpot, characterized by its viscosity. Therefore, the rate of strain was expressed as following equation in this model:

$$\frac{\partial \varepsilon}{\partial t} = m_v \frac{\partial \sigma'}{\partial t} + \frac{1}{\kappa}\sigma' \tag{2.44}$$

where ε is the strain, m_v is the coefficient of volume change in m^2/kN , σ' is the effective stress in kPa, and κ is the bulk viscosity of the solid waste in kN/m^2.

Hettiarachchi et al. (2005) also proposed a conceptual model to predict landfill settlement based on two main mechanisms including mechanical compression, and biodegradation-induced settlements. This model assumes that the waste mass is comprised of horizontal waste layers that are parallel to each other and infinite in length. As illustrated in Figure 2.21, the construction of a new layer causes an instant increase in the stress followed by gradual decrease in stress due to biodegradation.

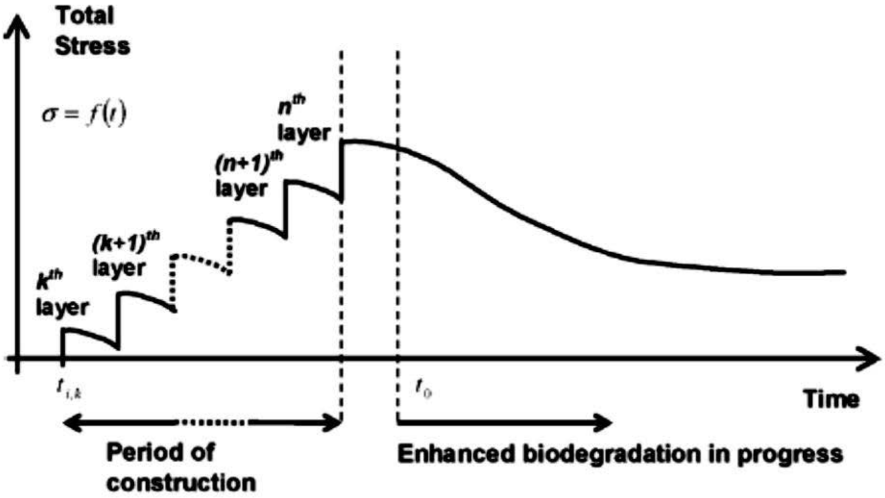


Figure 2.21: Stress at k^{th} Layer as a Function of Time (Hettiarachchi et al., 2005)

Liu et al. (2006) developed a model considering gas generation due to waste decomposition in which the increase of gas pressure calculated based on the concept of steady gas flow through an unsaturated medium. Moreover, the landfill settlement is assumed to be the sum of the decomposed solid proportion and the outflow proportion of gas. Oweis (2006) also developed a model for settlement prediction according to mechanical and decomposition processes including mechanical settlements due to compression of waste by loads from subsequent lifts, mechanical settlement due to creep under constant effective stress, and decomposition settlement due to mass loss or conversion of the organic part of waste to gas. Furthermore, as the model proposed by Hettiarachchi et al. (2005) demonstrated a few promising features over the other available settlement models, Elagroudy (2008) developed a simplified biodegradation-induced settlement model considering some conditions such as the presence of municipal sludge from treatment plants, the addition of Soybean Peroxidas (SBP) enzymes, etc. In addition, Chakma et al. (2007) assumed that the waste mass comprises layers of waste having a finite thickness and studied the landfill settlement by incorporating the effect of temperature, pH and moisture content, and the waste biodegradation.

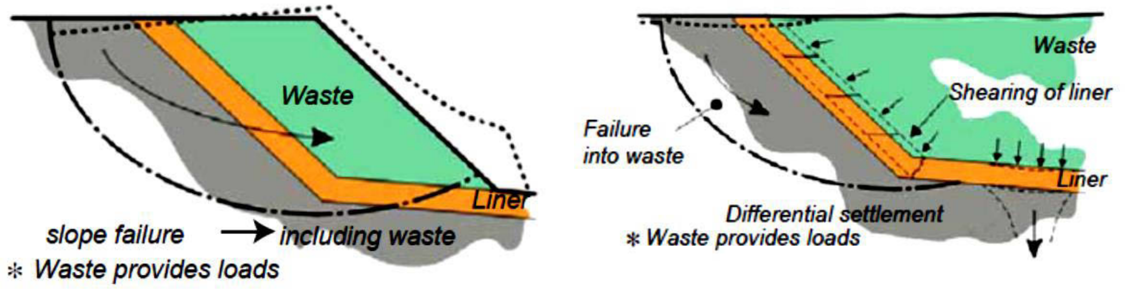
In an extensive and comprehensive study, McDougall et al. (2007) identified a relationship between void volume changes and decomposition of solid matter. The HBM (Hydraulic, Biological and Mechanical) model of waste degradation proposed by McDougall et al. (2007) simulates the actual processes involved in the settlement of landfill wastes. The hydraulic model is an unsaturated flow model in which the main system variables are hydraulic pressure head and moisture content. The biodegradation model describes a two-stage anaerobic digester in which indicative volatile fatty acid (VFA) and methanogenic biomass (MB) concentrations are the main field variables which control the mineralization of organic matter. The mechanical model combines load, creep and biodegradation-induced effects to predict landfill settlement. Finally, total settlement is calculated based on the following equation:

$$\boldsymbol{\varepsilon}_{\mathbf{i}} = \boldsymbol{\varepsilon}_{\mathbf{i}}^{\mathbf{e}} + \boldsymbol{\varepsilon}_{\mathbf{i}}^{\mathbf{p}} + \boldsymbol{\varepsilon}_{\mathbf{i}}^{\mathbf{c}} + \boldsymbol{\varepsilon}_{\mathbf{i}}^{\mathbf{d}} \qquad (2.45)$$

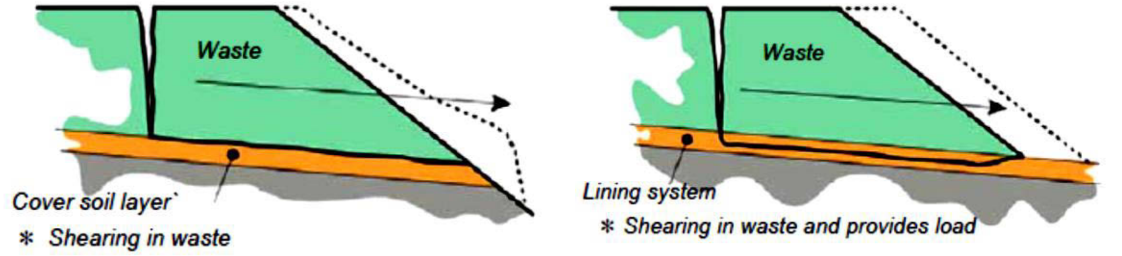
where ε_i^e, ε_i^p, ε_i^c, ε_i^d represent the strain due to elastic, plastic, time-dependent creep, and degradation, respectively.

2.7. Landfill Failure Modes

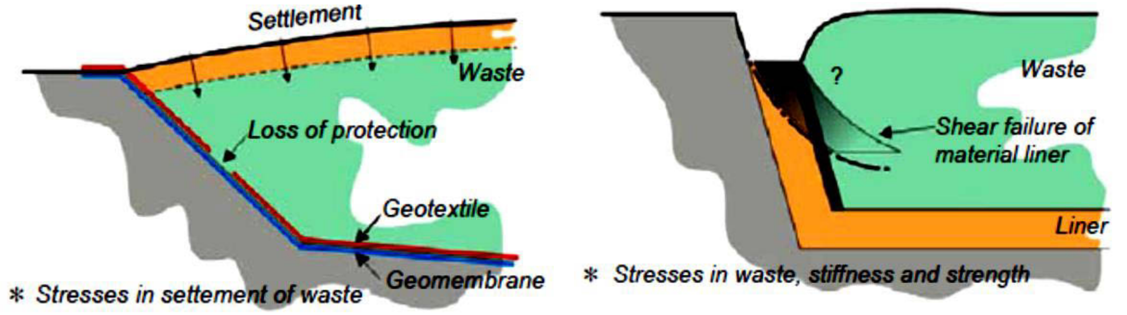
The stability of modern landfills has been receiving more and more concern because of major landfill failures occurred in all over the world. Landfill failures can have disastrous result including life loss, damage to property, and pollution of the surrounding environment and groundwater. Slope failure of landfill can occur during the construction of landfill, during filling or after closure of the landfill.



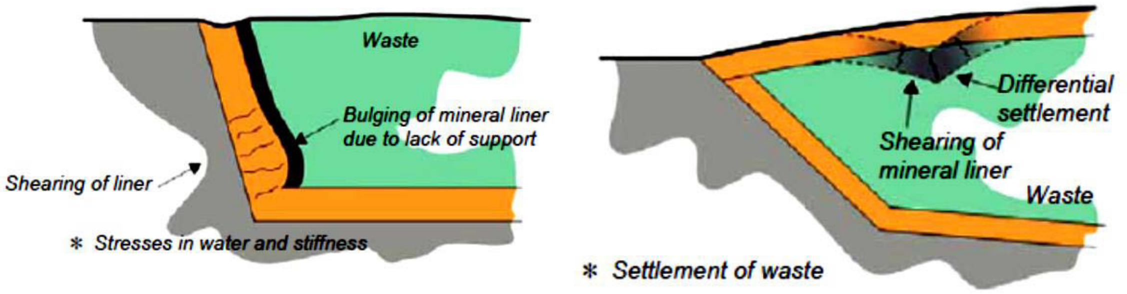
(a) Subgrade Stability (b) Subgrade Integrity



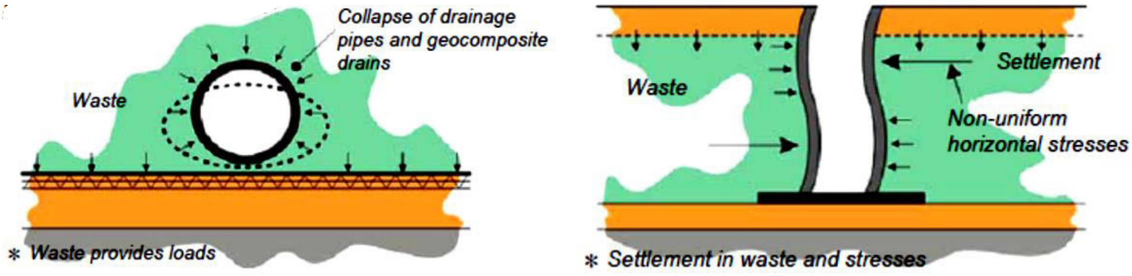
(c) Waste Slope Stability (d) Shallow Slope Lining Stability



(e) Shallow Slope Lining Integrity (f) Steep Slope Lining Stability



(g) Steep Slope Lining Integrity (h) Cover System Integrity



(i) Drainage System Integrity (j) Leachate/ Gas Well Integrity

Figure 2.22: Potential Modes of Failure in Landfills (Dixon et al., 2008)

Referring to Qian et al. (2002), the main factors affecting slope stability of landfills are landfill geometry, shear strength of materials, loading conditions, pore water pressure, settlement and landfill operations. However, the most important and controlling factor in landfill stability is the behaviour of waste body.

Several types of failures are possible for landfills. An understanding of the various types of failures that occur in landfills is critical. Therefore, general modes of failure in landfills, in which the behaviour of waste body has played a role, are summarized schematically in Figure 2.22. Obviously, knowledge of engineering properties of waste and its basic behaviour is required to assess each mode and hence to design against their occurrence. However, it is not possible to fully characterize the engineering properties of waste due to its heterogeneous nature.

2.8. Summary of Literature Review

This chapter has provided a critical review on the previous studies about municipal solid waste properties, landfill settlement, and modes of failure in landfills. From the existing literature, it can be concluded that the settlement mechanisms in municipal solid waste (MSW) landfills are complex in comparison to soils because the waste has an inherent heterogeneity that is very difficult to be characterized. In addition, the variations in some waste properties such as compaction condition, waste unit weight, daily cover, moisture content, composition, and biodegradation together with the unsaturated nature of most landfills have impose certain limitations on the use of classical soil mechanics approaches to predict landfill settlements. Nevertheless, numerous models have been developed to simulate the landfill condition and study its settlement. Generally, to simulate the actual landfill settlement behaviour, it is needed gas generation and dissipation and moisture distribution be coupled to the settlement. The existing predicting models still have deficiencies and weakness to integrate all mechanical, physical, and biological parameters in this regard. Therefore, it has a huge potential for further research, which is beyond the scope of this thesis.

Chapter 3

Theory of Landfill Technical Management Tool (LTMT)

3.1. Introduction

To date, the approaches for the prediction of MSW landfills has been improved. There are mathematical models available to evaluate the settlement behaviour of MSW landfills. However, many of these models assume landfill as non-deformable medium. At the same time, many existing waste settlement models focus on compression of waste solids but overlook the contribution from other phases. An effective model for landfill settlement should be able to consider settlement, gas generation and fluid transport simultaneously. Therefore, in this study, a technical management tool has been developed based on a model, which focuses on more accurate prediction of the time dependent settlement of MSW landfills considering both gas and leachate generation and the organic portion of waste streams and their effect on settlement rate and magnitude. This chapter aims at describing the theory adopted for development of the landfill technical management tool (LTMT).

3.2. Principles of Landfill Technical Management Tool (LTMT)

Landfill technical management tool (LTMT) has been developed based on a model which couples the landfill settlement with the generation and transport of landfill gases as well as the production and distribution of moisture in a compressible condition.

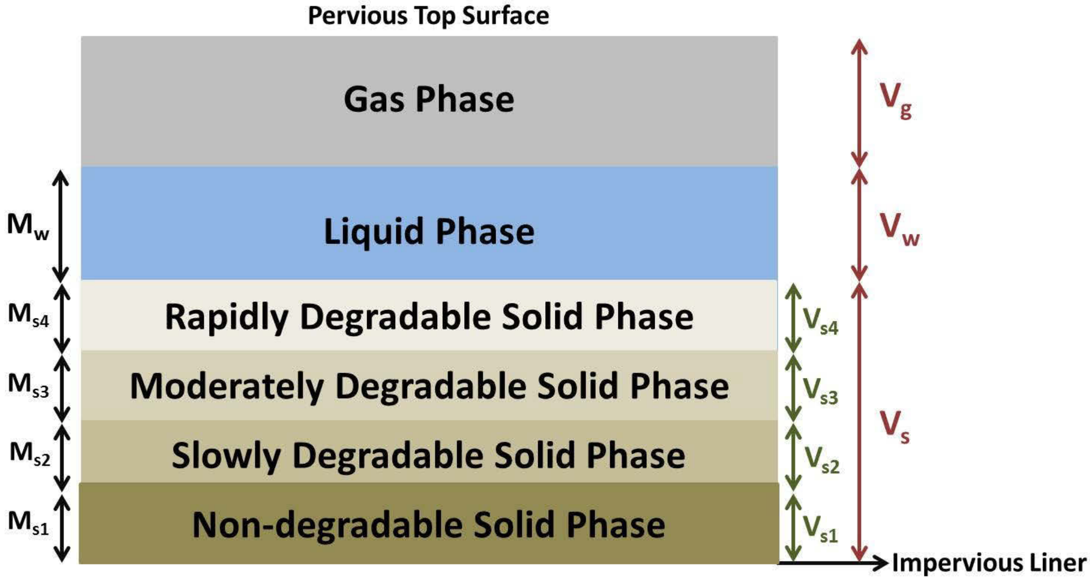


Figure 3.1: Schematic Diagram of Landfill Idealization for LTMT

As illustrated in Figure 3.1, in this model, it is assumed that the landfill is comprised of three phases including a deformable solid matrix, a liquid phase, and a gas phase. All these phases contribute to the landfill settlement since they make the total volume of landfill as:

$$\mathbf{V} = \mathbf{V_s} + \mathbf{V_w} + \mathbf{V_g} \tag{3.1}$$

where, V is the total volume of landfill, and V_s , V_w , V_g are the volume of solid mass, liquid phase, and gas phase, respectively.

Moreover, it is supposed that the top surface of the landfill is considered to be pervious, while the bottom of the landfill is assumed to be impervious.

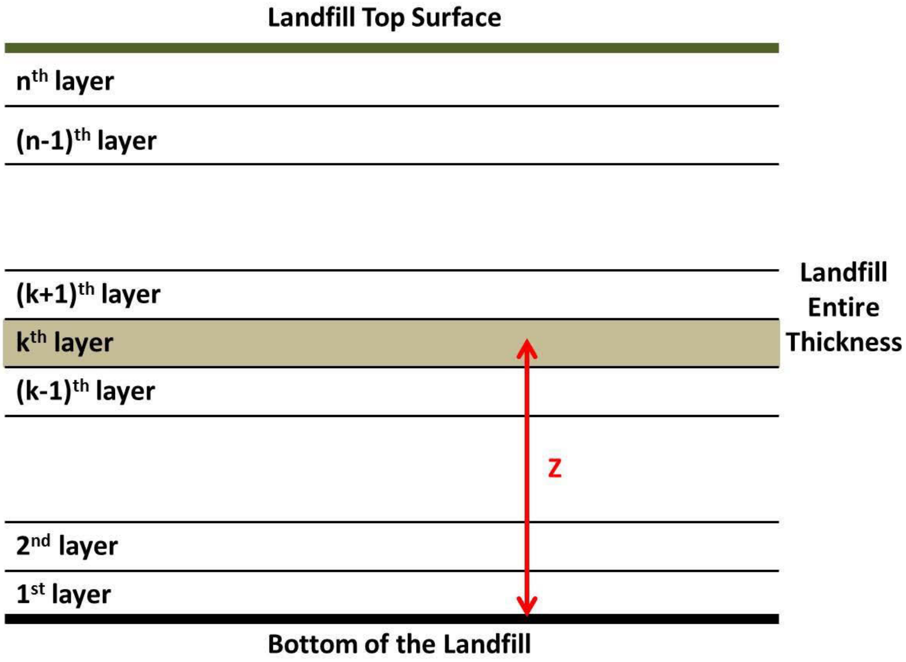


Figure 3.2: Cross Section of Considered MSW Landfill in LTMT

Wastes disposed in landfills undergo the decomposition. The waste decomposition leads to production of a mixture of gas in landfills which subsequently causes the change in gas and liquid pressures in the landfill. These processes leads to the changes of volume of all phases in landfills, and in turn causes landfill settlement, as these processes affect the porosity, total stress, and the saturation degree of liquid and gas. To simplify the settlement estimation, the landfill has been considered as layers of waste, which are extended in horizontal direction infinitely (Figure 3.2). Thus, assuming a per unit area of landfill, all calculations are carried out based on the heights as:

$$\mathbf{Z} = \mathbf{Z_s} + \mathbf{Z_w} + \mathbf{Z_g} \tag{3.2}$$

3.2.1. Landfill Settlement Mechanisms

The change in volume of waste mass in landfills primarily occurs as a result of overburden stresses and waste decay. Therefore, the main settlement mechanisms, which have been considered in this adopted model for the evaluation of landfill settlement, include the mechanical compression due to the weight of overlying waste layers, and the biodegradation induced settlement due to the waste decomposition and its subsequent mass loss.

The basic equation for calculation of mechanical compression (ε_m) can be expressed as:

$$\boldsymbol{\varepsilon_m = C^* \log\left(\frac{\sigma' + \delta\sigma'}{\sigma'}\right)} \qquad (3.2)$$

where C^* is the compressibility parameter, σ' is the effective stress in kPa, and $\delta\sigma'$ is the difference in effective stress in kPa. As depositing a new waste layer increases overburden stress and mass loss due to biodegradation causes swelling, the compressibility parameter denotes compression ratio (C_c^*) and swelling ratio (C_s^*). The waste biodegradation over time causes the changes in nature of waste, which subsequently affect the compressibility parameters. Therefore, different values have been considered for compressibility parameters depending on the waste age.

Table 3.1: The Categories of Municipal Solid Waste Considered in LTMT

Waste Category	Components	Waste Decay Constant (1/day)
Rapidly Degradable Wastes	Food waste, Yard waste	0.001
Moderately Degradable Wastes	Paper, Cardboard, Wood, Textile, Leather	0.0001
Slowly Degradable Wastes	Plastic, Rubber	0.00001
Non-degradable Wastes	Glass, Metal scraps, Dirt	0

On the other hand, waste biodegradation and large number of MSW components as well as heterogeneous nature of waste prevents employing the soil mechanic concepts for accurate evaluation of landfill settlement. Therefore, the solid phase of MSW has been categorized into four groups according to their biodegradability with their corresponding properties including waste decay constant and specific gravity. The waste categories considered in this model are presented in Table 3.1.

Moreover, the main equation used to estimate the biodegradation induced settlement (ε_b) can be defined as:

$$\varepsilon_b = (1 - n_i) \sum_{j=1}^{4} f_{sj} \left(\frac{G_{si}}{G_{sj}}\right) (1 + w_j(t) G_{sj}) [1 - \exp(-\lambda_j t)] \tag{3.3}$$

where n_i is the initial landfill porosity, w_j is gravimetric water content, G_{si} is the initial overall specific gravity of waste solids, G_{sj} is the specific gravity of j^{th} group of the waste solids, λ_j is the first order kinetic constant for the j^{th} group in day^{-1}, and f_{sj} is the initial solids fraction for each waste group.

3.2.2. Mass Conservation

Solid wastes in a landfill are varying over the time due to the waste biodegradation. Therefore, it is required to consider the conservation of mass for the solid phase as well as for the liquid phase and gas phase.

Referring to Hettiarachchi et al. (2005), the following equations have been considered for the mass conservation of the solid phase in a landfill:

$$\frac{dM_{sj}}{dt} = -\lambda_j M_{sj} \tag{3.4}$$

$$M_{sj} = M_{sj,i} e^{(-\lambda_j t)} \tag{3.5}$$

Based on the waste categories illustrated in Figure 3.1, the initial solid fractions for each group can be defined as:

$$f_{sj} = \frac{M_{sj,i}}{M_{si}} \tag{3.6}$$

Thus, the following equation can be used to express the total solid waste mass:

$$M_s(t) = M_{si} \sum_{j=1}^{4} f_{sj}\, e^{(-\lambda_j t)} \tag{3.7}$$

Defining G_{sj} as the specific gravity of the waste groups provides the following equation for finding the landfill volume change due to waste decomposition:

$$Z_s(t) = \frac{M_{si}}{\rho_w} \sum_{j=1}^{4} \frac{f_{sj}}{G_{sj}} e^{(-\lambda_j t)} \tag{3.8}$$

Subsequently, Equation (3.8) gives the following equation to estimate the landfill height at a given time considering both aforementioned settlement mechanisms:

$$\mathbf{Z(t) = Z_i - \delta Z_s - Z_i C^* \log\left(\frac{\sigma' + \delta\sigma'}{\sigma'}\right)} \tag{3.9}$$

Moreover, the volume of liquid phase (Z_w) at a given time can be determined based on the following equation by considering the concept of volumetric water content as the ratio of water volume to total volume:

$$\mathbf{Z_w(t) = \theta(t)Z(t)} \tag{3.10}$$

Furthermore, the volume of gas phase (Z_g) can be calculated as follows:

$$\mathbf{Z_g(t) = Z(t) - Z_s(t) - \theta(t)Z(t)} \tag{3.11}$$

The above mentioned equations indicate that deformation occurs as the waste decomposition causes changes in volume of different phases in landfill, and hence the changes in gas and liquid pressures. Hettiarachchi et al. (2005) have considered the effect of gas generation and moisture production in their landfill settlement model and based on mass balance for gases and Darcy's equation, they proposed the following governing equation to link landfill gas pressure to settlement:

$$\mathbf{\frac{\partial p}{\partial t} + (P_a + p)\frac{\partial(\ln Z_g)}{\partial t} = \left(\frac{Z}{Z_g}\right)\left(k_g\frac{\partial p}{\partial z} + D\frac{\partial^2 p}{\partial z^2} + \frac{RT}{m}G\right)} \tag{3.12}$$

where P_a is the atmospheric pressure, p is the pressure beyond atmospheric pressure, k_g is the gas conductivity of waste, D is the gas diffusion coefficient in m^2/day, R is the universal gas constant, T is the average landfill temperature in Kelvin, and m is the molar mass of the landfill gas. In the above equation, Hettiarachchi et al. (2005) defined parameter G as the rate of generation of gas per unit volume of waste which can be obtained through the Equations (3.13) and (3.14):

$$\mathbf{G(t) = C_0\frac{M_{si}}{Z}\left(\sum_{j=1}^{4} f_{sj}\,\lambda_j\right)\left(\frac{t}{t_0}\right) \qquad ;for\ t \le t_0} \tag{3.13}$$

$$\mathbf{G(t) = C_0\frac{M_{si}}{Z}\sum_{j=1}^{4} f_{sj}\,\lambda_j\left(e^{(-\lambda_j(t-t_0))}\right) \qquad ;for\ t > t_0} \tag{3.14}$$

where C_0 is the proportionality constant and can be defined by defining the parameter L_0 as the volume of gas a unit mass of waste could produce:

$$\mathbf{C_0 = \frac{0.86L_0}{\left(\sum_{j=2}^{4} f_{sj}\right)}} \qquad (3.15)$$

Moreover, moisture distribution affects the settlement process. Therefore, Hettiarachchi et al. (2005) have taken into account the moisture in their proposed model based on the Richards' equation (Richards, 1931) as:

$$\mathbf{\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(k_w\frac{\partial h}{\partial z}\right) + \frac{\partial k_w}{\partial z} - S_w(t)} \qquad (3.16)$$

where S_w is a sink used for extraction of water from system.

The Van Genuchten's (1980) formula and parameters were employed to solve the governing equation of moisture distribution presented in Equation (3.16), as follows:

$$\mathbf{h(\theta) = -\frac{1}{\alpha}\left((S_e)^{\left(-\frac{1}{m}\right)} - 1\right)^{\frac{1}{n}}} \qquad (3.17)$$

$$\mathbf{k_w(\theta) = k_{ws}(S_e)^p\left(1 - \left(1 - (S_e)^{\left(\frac{1}{m}\right)}\right)^m\right)^2} \qquad (3.18)$$

where h is matric potential, k_w is unsaturated hydraulic conductivity, α , n , m , and p are Van Genuchten parameters, k_{ws} is the saturated hydraulic conductivity. S_e is the effective saturation which can be defined in terms of saturated moisture content (θ_s) and residual moisture content (θ_r) as follows:

$$\mathbf{S_e = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)} \qquad (3.19)$$

It should be noted that the variable saturated volumetric moisture content due to varying nature of waste can be calculated through the Equation (3.20):

$$\mathbf{\theta_s(t) = 1 - \frac{Z_s(t)}{Z(t)}} \qquad (3.20)$$

In addition, the following equation proposed by Scanlon et al. (2002) has been employed for calculation of unsaturated gas conductivity:

$$\mathbf{k_g(\theta) = k_{gs}(1 - S_e)^p\left(1 - \left(1 - (1 - S_e)^{\left(\frac{1}{m}\right)}\right)^m\right)^2} \qquad (3.21)$$

where k_{gs} is the saturated gas conductivity.

3.2.3. Solution Procedure

In the model proposed by Hettiarachchi et al. (2005), it was assumed that the waste is typically deposited in stages known as "lifts", with each lift having a thickness of between 5 m, and each lift comprising of a series of layers of approximately 0.25 m. Therefore, they considered the landfill cross section as illustrated in Figure 3.4 and performed the numerical computations to calculate the height of each phase in the kth waste layer for the (l+1)th time step using the following equations:

$$(\Delta z_s)_k^{l+1} = \left(\frac{\rho_c \Delta z_i}{\rho_w}\right)\sum_{j=1}^{4}\left(\frac{f_{sj}}{G_{sj}}\right)e^{\left(-\lambda_j(l\Delta t)\right)} \tag{3.22}$$

$$(\Delta z_w)_k^{l+1} = \left(\frac{\theta_k^l + \theta_{k+1}^l}{2}\right)(\Delta z)_k^{l+1} \tag{3.23}$$

$$\left(\Delta z_g\right)_k^{l+1} = (\Delta z)_k^l - (\Delta z_s)_k^{l+1} - (\Delta z_w)_k^{l+1} \tag{3.24}$$

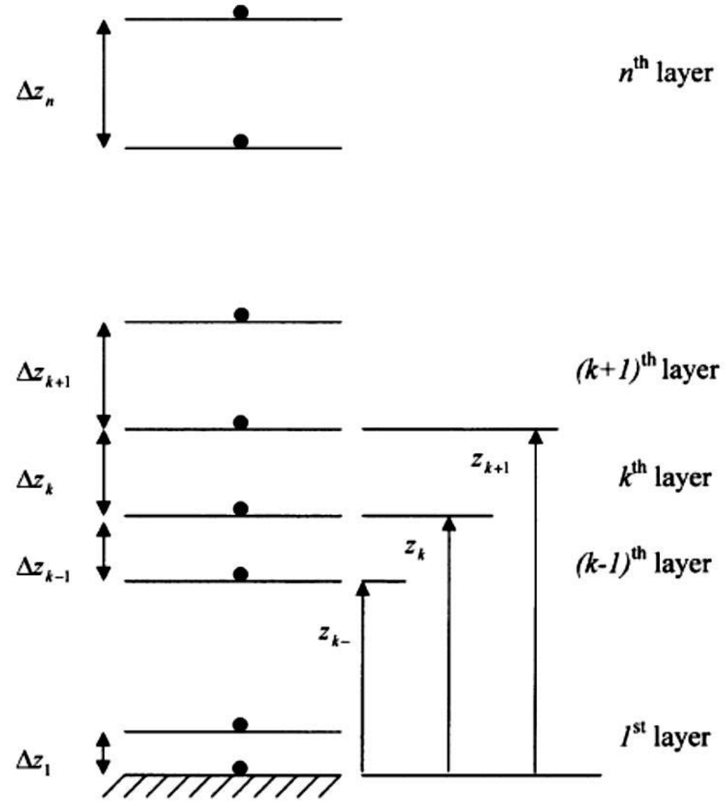


Figure 3.3: Cross Section of Considered MSW Landfill in the Numerical Analysis (Hettiarachchi et al., 2005)

Moreover, the thickness of the kth waste layer for the (l+1)th time step can be estimated by the following equation based on the appropriate compressibility parameters (Equation 3.26):

$$(\Delta z)_k^{l+1} = (\Delta z)_k^l - \left((\Delta z_s)_k^l - (\Delta z_s)_k^{l+1}\right) - \Delta z_i C^* \log\left(\frac{(\sigma')_k^{l+1}}{(\sigma')_k^l}\right) \tag{3.25}$$

$$C^* = \begin{cases} C_c^* \;, & (\boldsymbol{\sigma}')_{\mathbf{k}}^{\mathbf{l+1}} > (\boldsymbol{\sigma}')_{\mathbf{k}}^{\mathbf{l}} \\ C_s^* \;, & (\boldsymbol{\sigma}')_{\mathbf{k}}^{\mathbf{l+1}} < (\boldsymbol{\sigma}')_{\mathbf{k}}^{\mathbf{l}} \end{cases} \qquad (3.26)$$

In addition, the governing equation obtained for mass balance of gases in Equation (3.12) is solved using finite difference approximations based on the conditions illustrated in Figures 3.4 to 3.5 and the concepts of forward time (FT) scheme by Hoffman (2001) and the centre space (CS) scheme as shown in following equations:

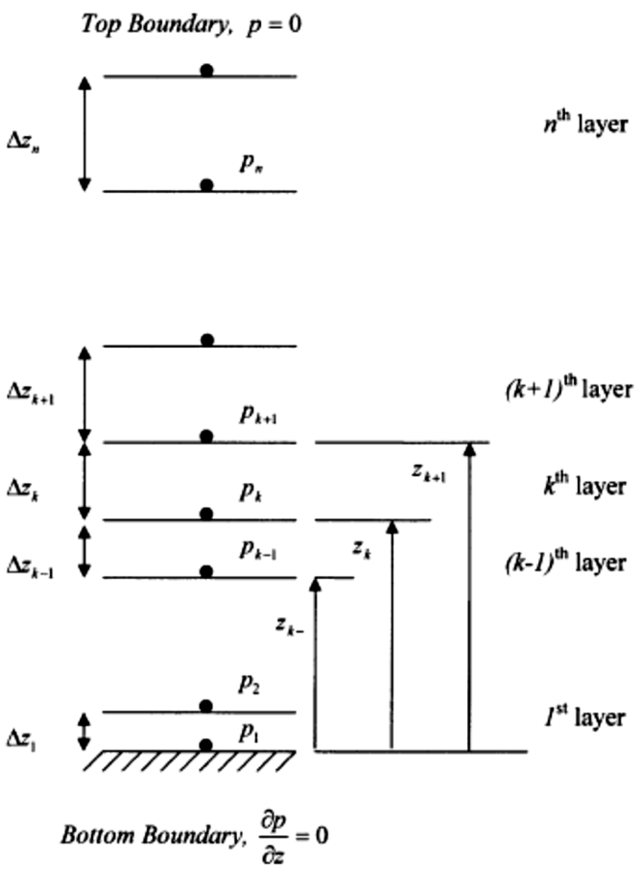


Figure 3.4: Computation Grid and the Boundary Conditions for Gas Pressure Equation (Hettiarachchi et al., 2005)

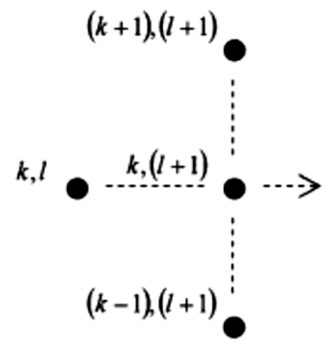


Figure 3.5: The Stencil used for Numerical Calculations of Gas Pressure Equation (Hettiarachchi et al., 2005)

$$\left(\frac{\partial p}{\partial t}\right)_k^{l+1} = \frac{p_k^{l+1} - p_k^l}{\Delta t} \tag{3.27}$$

$$\left(\frac{\partial(\ln Z_g)}{\partial t}\right)_k^{l+1} = \frac{1}{\Delta t}\ \ln \frac{(\Delta\, Z_g)_k^l}{(\Delta\, Z_g)_k^{l-1}} \tag{3.28}$$

$$\left(\frac{\partial p}{\partial z}\right)_k^{l+1} = \frac{p_{k+1}^{l+1} - p_{k-1}^{l+1}}{\Delta z_{k-1}^l + \Delta z_k^l} \tag{3.29}$$

$$\left(a_k^{l+1}\right) p_{k-1}^{l+1} + \left(b_k^{l+1}\right) p_k^{l+1} + \left(c_k^{l+1}\right) p_{k+1}^{l+1} = \left(d_k^{l+1}\right) \tag{3.30}$$

The coefficients of the gas pressure equation generated in Equation (3.30) are defined as:

$$a_k^{l+1} = \Delta t \left(\frac{\Delta z}{\Delta z_g}\right)_k^l \left(\frac{(\,k_g)_k^l}{\left(\Delta z_{k-1}^l + \Delta z_k^l\right)} - \frac{2D}{\left(\Delta z_{k-1}^l\right)\left(\Delta z_{k-1}^l + \Delta z_k^l\right)}\right) \tag{3.31}$$

$$b_k^{l+1} = 1 + \ln \frac{(\Delta\, Z_g)_k^l}{(\Delta\, Z_g)_k^{l-1}} + \Delta t \left(\frac{\Delta z}{\Delta z_g}\right)_k^l \frac{2D}{\left(\Delta z_{k-1}^l\right)\left(\Delta z_k^l\right)} \tag{3.32}$$

$$c_k^{l+1} = -\Delta t \left(\frac{\Delta z}{\Delta z_g}\right)_k^l \left(\frac{(\,k_g)_k^l}{\left(\Delta z_{k-1}^l + \Delta z_k^l\right)} + \frac{2D}{\left(\Delta z_k^l\right)\left(\Delta z_{k-1}^l + \Delta z_k^l\right)}\right) \tag{3.33}$$

$$d_k^{l+1} = p_k^l + \Delta t \left(\frac{\Delta z}{\Delta z_g}\right)_k^l RTG_k^l - P_a \ln \frac{(\Delta\, Z_g)_k^l}{(\Delta\, Z_g)_k^{l-1}} \tag{3.34}$$

It should be noted that the k$^{\text{th}}$ node settles with time as a result of the landfill settlement processes. Therefore, it is necessary to consider the correction to the pressure of the previous time step $\left(p_k^l\right)$ mentioned in Equation (3.34) and substitute it by the corrected pressure $\left(\bar{p}_k^l\right)$ defined as:

$$\bar{p}_k^l = p_k^l + \left(p_{k-1}^l - p_k^l\right)\left(\frac{\sum_{j=1}^{k-1}\left(\Delta z_j^l - \Delta z_j^{l+1}\right)}{\Delta z_{k-1}^l - \sum_{j=1}^{k-1}\left(\Delta z_j^l - \Delta z_j^{l+1}\right)}\right) \tag{3.35}$$

Additionally, the following boundary conditions have been considered for the pressure equations discussed above:

1) the pressure at the upper boundary always remains at atmospheric pressure and it is not affected by the settlement of top surface of landfill:

$$\mathbf{p_{n+1}^{l+1} = 0} \qquad (3.36)$$

2) the bottom of the landfill is comprised of the impermeable boundary, and hence no gas flow condition can be considered at the bottom node:

$$\left(\frac{\partial \mathbf{p}}{\partial \mathbf{z}}\right)_2^{\mathbf{l+1}} = \frac{\mathbf{p_3^{l+1} - p_1^{l+1}}}{\mathbf{\Delta z_1^l + \Delta z_2^l}} = \mathbf{0} \qquad (3.37)$$

3) in case of existing a gas extraction point at the bottom of landfill, the pressure would be at the atmospheric pressure:

$$\mathbf{p_1^{l+1} = 0} \qquad (3.38)$$

The governing equation for distribution of moisture given in Equation (3.16) is also solved as presented in Equation (3.42) using finite difference approximations based on the conditions shown in Figures 3.6 to 3.7.

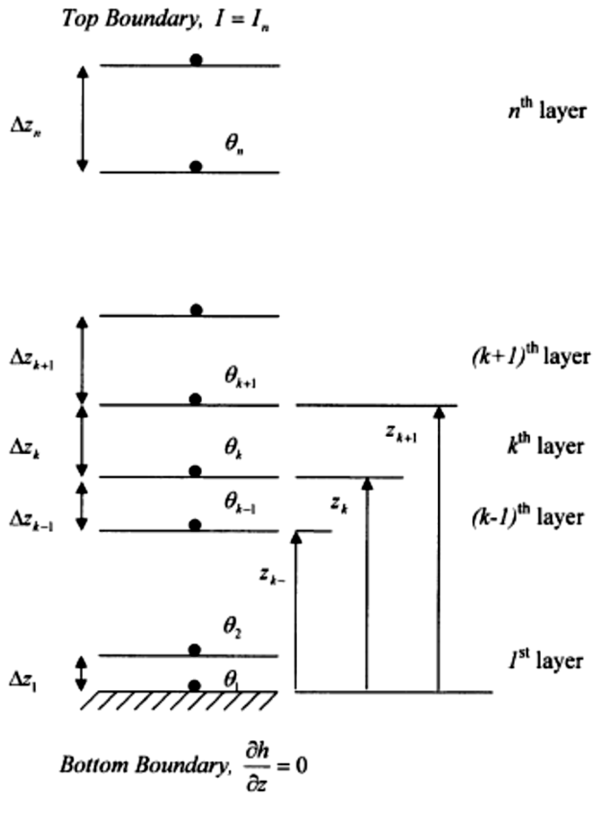


Figure 3.6: Computation Grid and the Boundary Conditions for Moisture Equation (Hettiarachchi et al., 2005)

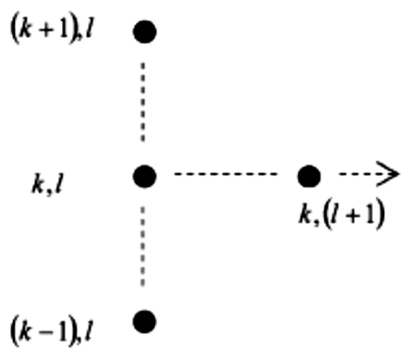


Figure 3.7: The Stencil used for Numerical Calculations of Moisture Distribution Equation (Hettiarachchi et al., 2005)

The concepts of forward time (FT) scheme by Hoffman (2001) and the centre space (CS) scheme as presented in following equations, has been employed in this solution procedure:

$$\left(\frac{\partial \theta}{\partial t}\right)_{k}^{l+1} = \frac{\theta_{k}^{l+1} - \theta_{k}^{l}}{\Delta t} \tag{3.39}$$

$$\left(\frac{\partial k_{w}}{\partial z}\right)_{k}^{l+1} = \frac{(k_{w})_{k+1}^{l} - (k_{w})_{k-1}^{l}}{\Delta z_{k-1}^{l} + \Delta z_{k}^{l}} \tag{3.40}$$

$$\left(\frac{\partial}{\partial z}\left(k_{w}\frac{\partial h}{\partial z}\right)\right)_{k}^{l+1} = \frac{\left(\frac{(k_{w})_{k}^{l} + (k_{w})_{k+1}^{l}}{2}\right)\left(\frac{h_{k+1}^{l} - h_{k}^{l}}{\Delta z_{k}^{l}}\right) - \left(\frac{(k_{w})_{k-1}^{l} + (k_{w})_{k}^{l}}{2}\right)\left(\frac{h_{k}^{l} - h_{k-1}^{l}}{\Delta z_{k-1}^{l}}\right)}{0.5\left(\Delta z_{k-1}^{l} + \Delta z_{k}^{l}\right)} \tag{3.41}$$

$$\left(A_{k}^{l+1}\right) h_{k-1}^{l} + \left(B_{k}^{l+1}\right) h_{k}^{l} + \left(C_{k}^{l+1}\right) h_{k+1}^{l} + D_{k}^{l+1} = \left(\theta_{k}^{l+1}\right) \tag{3.42}$$

The coefficients of the moisture distribution equation generated in Equation (3.42) are defined as:

$$A_{k}^{l+1} = \frac{\Delta t\left((k_{w})_{k-1}^{l} + (k_{w})_{k}^{l}\right)}{\Delta z_{k-1}^{l}\left(\Delta z_{k-1}^{l} + \Delta z_{k}^{l}\right)} \tag{3.43}$$

$$B_{k}^{l+1} = -\frac{\Delta t\left((k_{w})_{k}^{l} + (k_{w})_{k+1}^{l}\right)}{\Delta z_{k}^{l}\left(\Delta z_{k-1}^{l} + \Delta z_{k}^{l}\right)} - \frac{\Delta t\left((k_{w})_{k-1}^{l} + (k_{w})_{k}^{l}\right)}{\Delta z_{k-1}^{l}\left(\Delta z_{k-1}^{l} + \Delta z_{k}^{l}\right)} \tag{3.44}$$

$$\mathbf{C}_{\mathbf{k}}^{\mathbf{l+1}} = \frac{\Delta t\left((\mathbf{k_w})_{\mathbf{k}}^{\mathbf{l}} + (\mathbf{k_w})_{\mathbf{k+1}}^{\mathbf{l}}\right)}{\Delta \mathbf{z}_{\mathbf{k}}^{\mathbf{l}}\left(\Delta \mathbf{z}_{\mathbf{k-1}}^{\mathbf{l}} + \Delta \mathbf{z}_{\mathbf{k}}^{\mathbf{l}}\right)} \tag{3.45}$$

$$\mathbf{D}_{\mathbf{k}}^{\mathbf{l+1}} = \boldsymbol{\theta}_{\mathbf{k}}^{\mathbf{l}} + \frac{\Delta \mathbf{t}\left((\mathbf{k_w})_{\mathbf{k+1}}^{\mathbf{l}} + (\mathbf{k_w})_{\mathbf{k-1}}^{\mathbf{l}}\right)}{\left(\Delta \mathbf{z}_{\mathbf{k-1}}^{\mathbf{l}} + \Delta \mathbf{z}_{\mathbf{k}}^{\mathbf{l}}\right)} - \Delta \mathbf{t}\mathbf{S}^{\mathbf{l}} \tag{3.46}$$

Similar to gas pressure calculations, the moisture content $\left(\theta_k^l\right)$ is required to be corrected due to the compression of the waste layers below and above the k^th^ node and between two consecutive time steps and be substituted by the corrected moisture content $\left(\bar{\theta}_k^l\right)$ in Equation (3.46):

$$\bar{\boldsymbol{\theta}}_{\mathbf{k}}^{\mathbf{l}} = \left(\frac{\Delta \mathbf{z}_{\mathbf{k}}^{\mathbf{l}} + \Delta \mathbf{z}_{\mathbf{k-1}}^{\mathbf{l}}}{\Delta \mathbf{z}_{\mathbf{k}}^{\mathbf{l+1}} + \Delta \mathbf{z}_{\mathbf{k-1}}^{\mathbf{l+1}}}\right) \boldsymbol{\theta}_{\mathbf{k}}^{\mathbf{l}} \tag{3.47}$$

In addition, the following boundary conditions have been considered for the moisture distribution equations discussed above:

1) the head at the top surface of landfill is constant:

$$\mathbf{h}_{\mathbf{n+1}}^{\mathbf{l}} = \boldsymbol{h_t} \tag{3.48}$$

2) the bottom of the landfill is comprised of the impermeable boundary, and hence no flow condition can be considered at the bottom node:

$$\left(\frac{\partial \mathbf{h}}{\partial \mathbf{z}}\right)_{2}^{\mathbf{l+1}} = \frac{\mathbf{h}_{3}^{\mathbf{l+1}} - \mathbf{h}_{1}^{\mathbf{l+1}}}{\Delta \mathbf{z}_{1}^{\mathbf{l}} + \Delta \mathbf{z}_{3}^{\mathbf{l}}} = \mathbf{0} \tag{3.49}$$

To obtain numerical solution for settlement based on the adopted model, the flowchart illustrated in Figure 3.8 is employed. Based on this flowchart, strain is firstly calculated by considering waste properties and the landfill geometry. Subsequently, the equations for gas pressure are solved for each time step. Then, the stress will be updated for the mass loss causing by biodegradation as well as for the increase instress due to the addition of a new waste layer. As it is demonstrated in this flowchart, this procedure will be repeated for each waste layer and the calculated strain for waste layers are summed up to provide the total settlement of landfill incorporating leachate and gas generation.

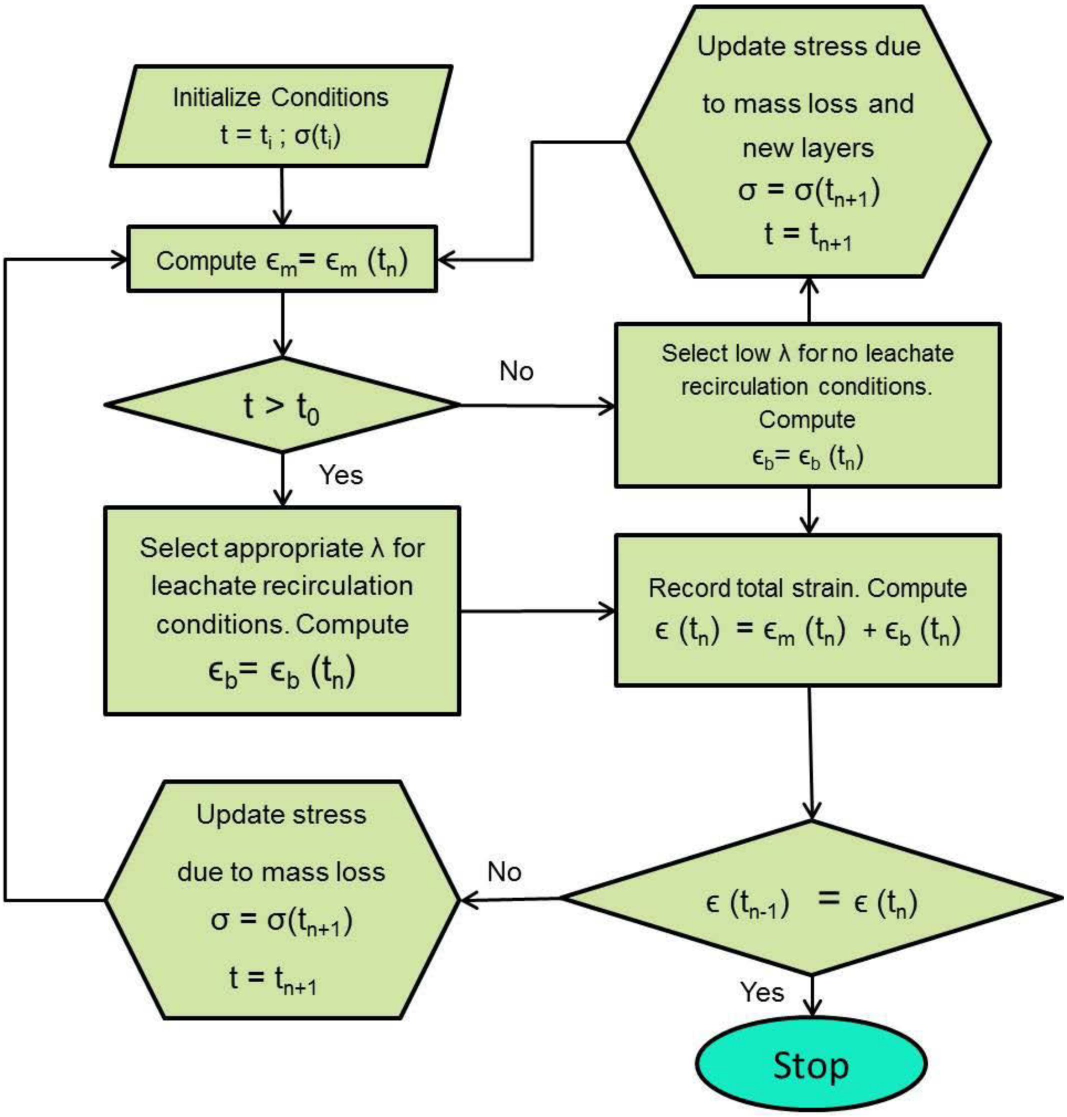


Figure 3.8: The Flowchart of Numerical Solution for a Given Waste Layer Based on the Adopted Model for LTMT

3.3. Summary

In the model developed by Hettiarachchi et al. (2005) which was adopted in the landfill technical management tool (LTMT), a one-dimensional landfill containing three phases of solid, liquid, and gas, is considered. This landfill is divided into the layers with equal heights. The governing equations have been obtained for all three phases and the change in the height of each phase is taken into account for the numerical solution by finite difference approximation to estimate the landfill settlement. The height of each phase has been adjusted in each time step in order to consider the change in landfill height occurring as the result of the waste decomposition and the overburden pressure.

Chapter 4

Numerical Analysis for Landfill Slope Stability

4.1. Introduction

Due to environmental and health risks from landfills in recent decades, specific rules have been developed for the design, operation and management of landfills. Many geotechnical aspects should be taken in consideration in the landfill management. Landfill stability is one of the major geotechnical concerns during the operation and aftercare of landfills. Slope stability of a MSW landfill mainly depends on the waste geotechnical properties, landfill geometry and loading conditions.

Therefore, the purpose of this chapter is to describe briefly the numerical study on the stability of a MSW landfill. It can be noted that this numerical analysis was carried out using the program PLAXIS2D, which is a finite element package, specifically developed for the analysis of deformation and stability in geotechnical engineering projects.

4.2. Landfill Modelling with PLAXIS

In the design of a landfill, it is important to consider the final stability of landfill. Therefore, it is necessary to evaluate the safety factor of landfill slope stability. Accordingly, evaluation of the slope stability of landfill has been considered as a part of the landfill technical management tool (LTMT) developed in this research and the finite element program PLAXIS has been used to investigate the slope stability of MSW landfills. For this reason, three kinds of landfills in terms of their total landfill heights have been considered for this investigation. In order to be consistent with other parts of LTMT, however, the depth of considered landfill has been assumed to be 15 m.

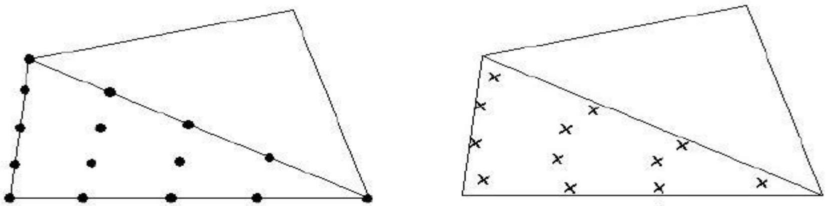


Figure 4.1: 15 Nodded Triangular Element Used in Numerical Analysis

In contrast, the height of landfill which is above the earth level defines the kind of landfill as short landfill with total height of 20 m, medium landfill with total height of 25 m, and long landfill with total height of 30 m. Moreover, to assess the influence of the slope geometry on the safety factor (SF) of landfill slope stability, the landfills are analysed with various slope inclinations (V: H) including 1:2, 1:2.5, 1:3, 1:4, and 1:5.

4.2.1. Input of Geometry Model and Boundary Conditions

In this numerical analysis, all landfills have been modelled as a two dimensional plane strain model. In addition, the 15 nodded triangular elements containing 12 stress points are employed in this modelling as indicated in Figure 4.1. The creation of geometry models for these landfills is described in the following sections.

4.2.1.1. Geometry Model of Landfill with Total Height of 20 m

As mentioned previously, different slope inclinations have been considered in order to investigate the influence of the slope geometry on safety factor of the landfill slope stability. The cross sections of the short landfills considered in this numerical analysis in terms of slopes as well as the models dimensions are illustrated in Figures 4.2 to 4.7.

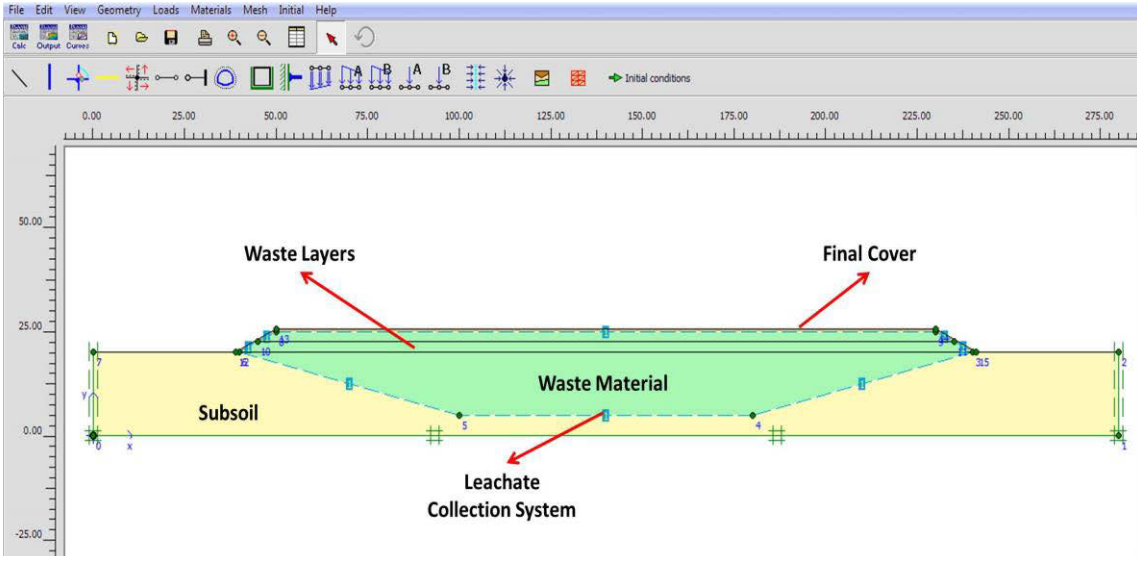


Figure 4.2: Cross section of the Short Landfill

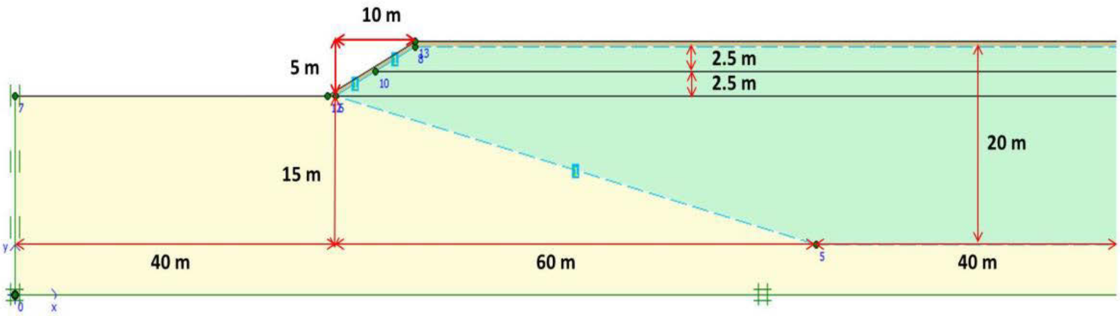


Figure 4.3: Dimensions of the Short Landfill with the Slope 1:2

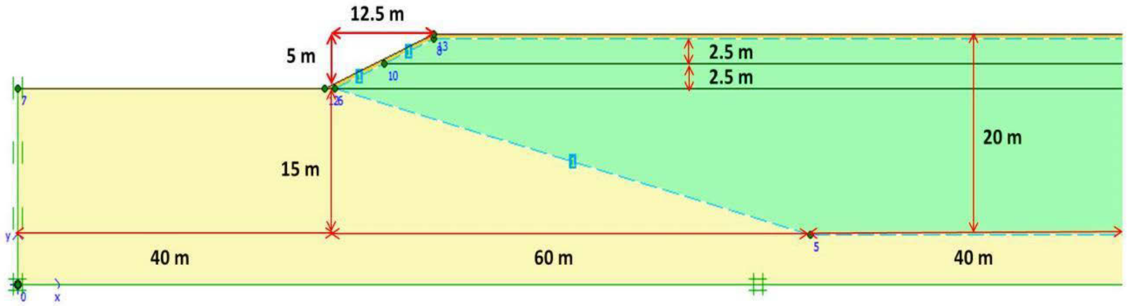


Figure 4.4: Dimensions of the Short Landfill with the Slope 1:2.5

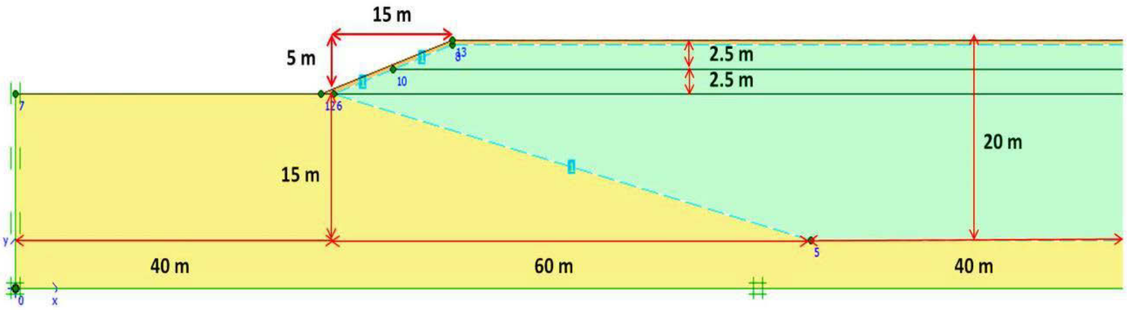


Figure 4.5: Dimensions of the Short Landfill with the Slope 1:3

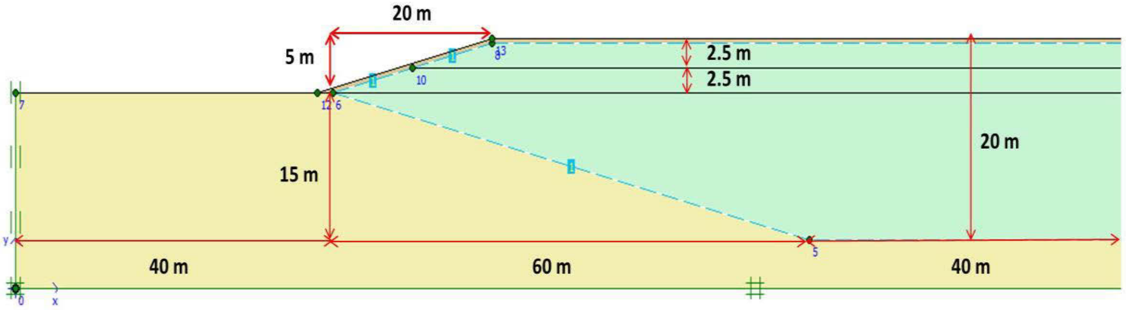


Figure 4.6: Dimensions of the Short Landfill with the Slope 1:4

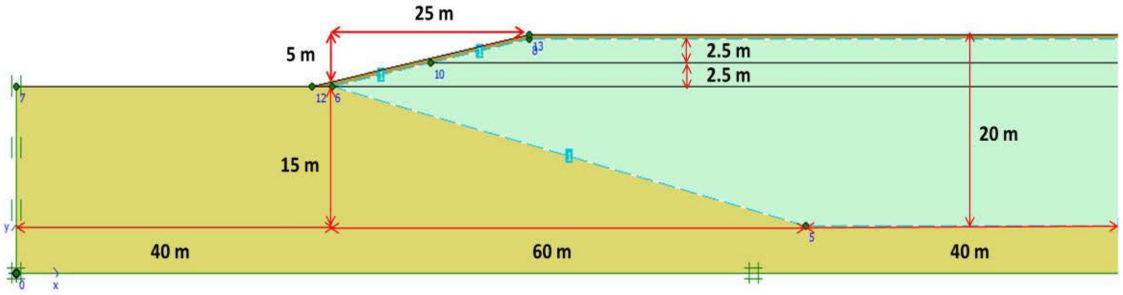


Figure 4.7: Dimensions of the Short Landfill with the Slope 1:5

4.2.1.2. Geometry Model of Landfill with Total Height of 25 m

To examine the effect of the slope geometry on the slope stability safety factor of the landfills with different heights, a landfill with total height of 25 m (medium landfill) modelled in different conditions. The cross sections of the medium landfill considered in this numerical analysis in terms of slopes as well as the models dimensions are illustrated in Figures 4.8 to 4.13.

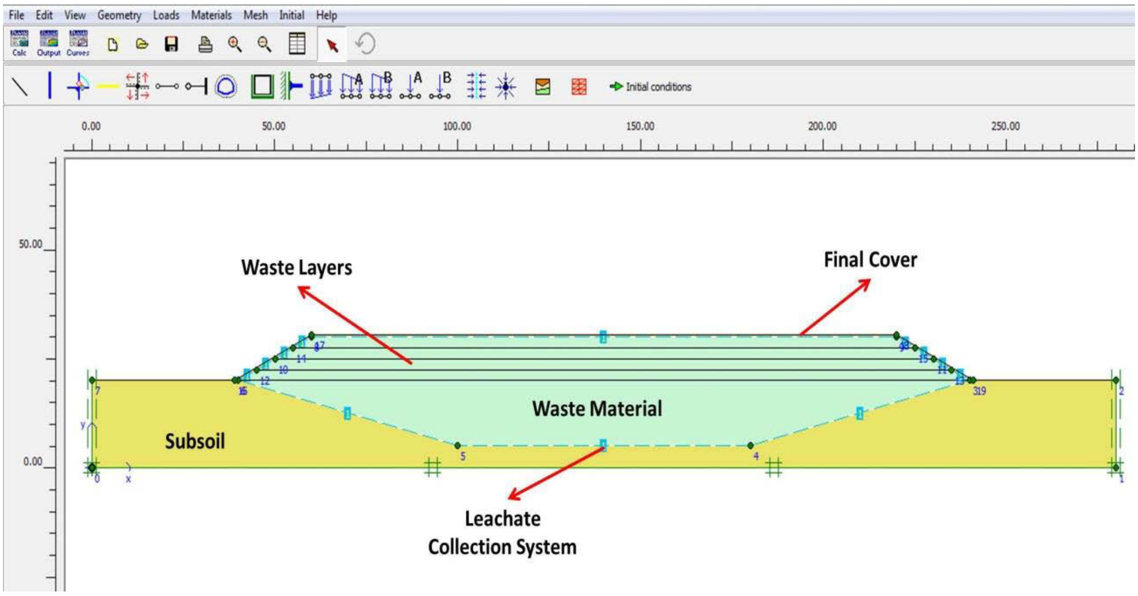


Figure 4.8: Cross section of the Medium Landfill

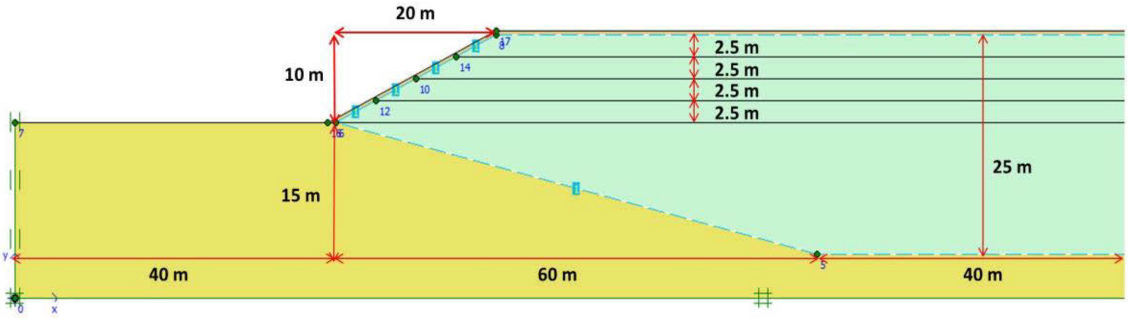


Figure 4.9: Dimensions of the Medium Landfill with the Slope 1:2

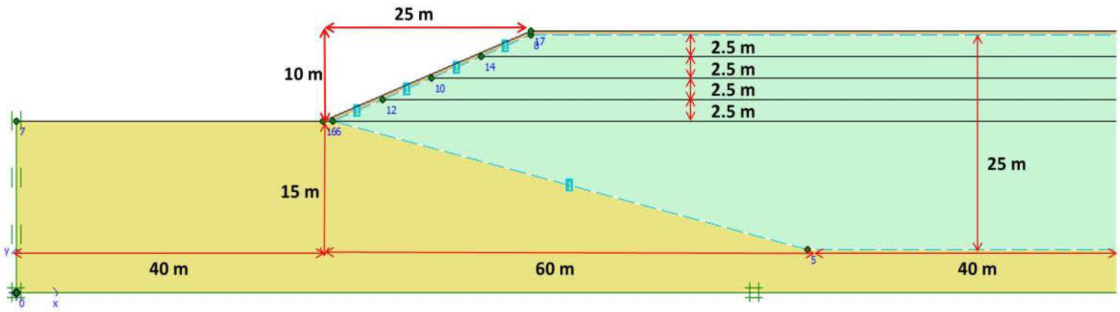


Figure 4.10: Dimensions of the Medium Landfill with the Slope 1:2.5

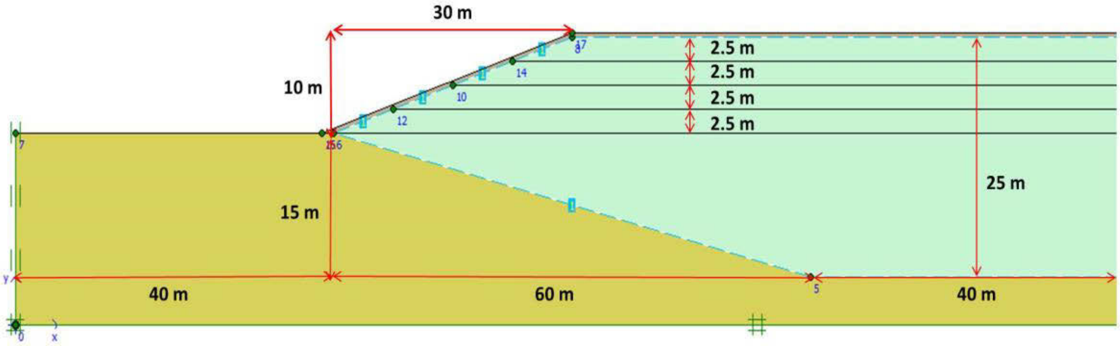


Figure 4.11: Dimensions of the Medium Landfill with the Slope 1:3

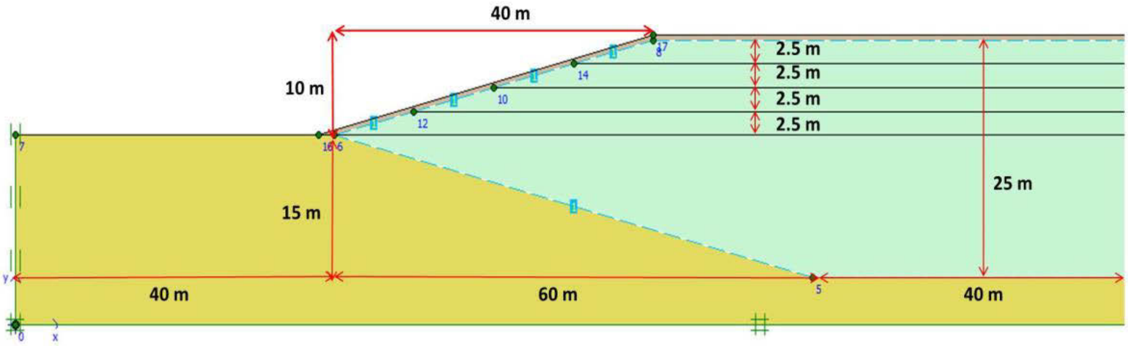


Figure 4.12: Dimensions of the Medium Landfill with the Slope 1:4

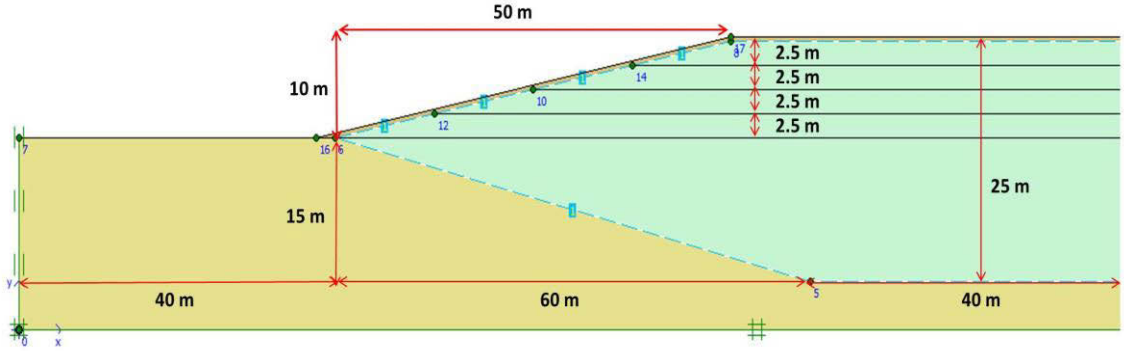


Figure 4.13: Dimensions of the Medium Landfill with the Slope 1:5

4.2.1.3. Geometry Model of Landfill with Total Height of 30 m

Similar to previous sections, the cross sections of the landfills with total height of 30 m (long landfill) in different slope inclination considered in this numerical analysis as well as the models dimensions are illustrated in Figures 4.14 to 4.19.

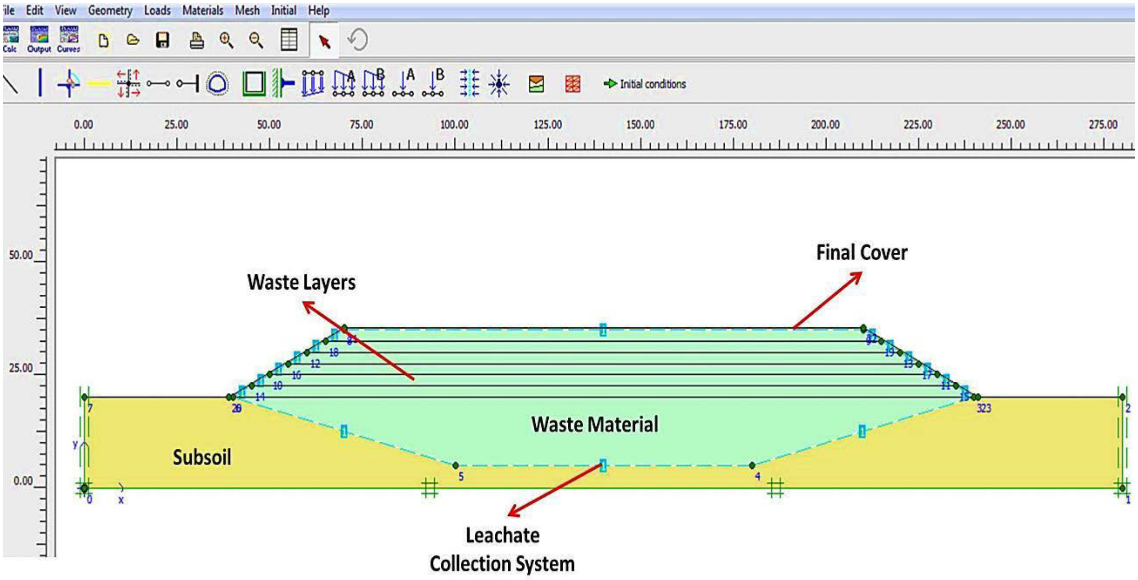


Figure 4.14: Cross section of the Medium Landfill

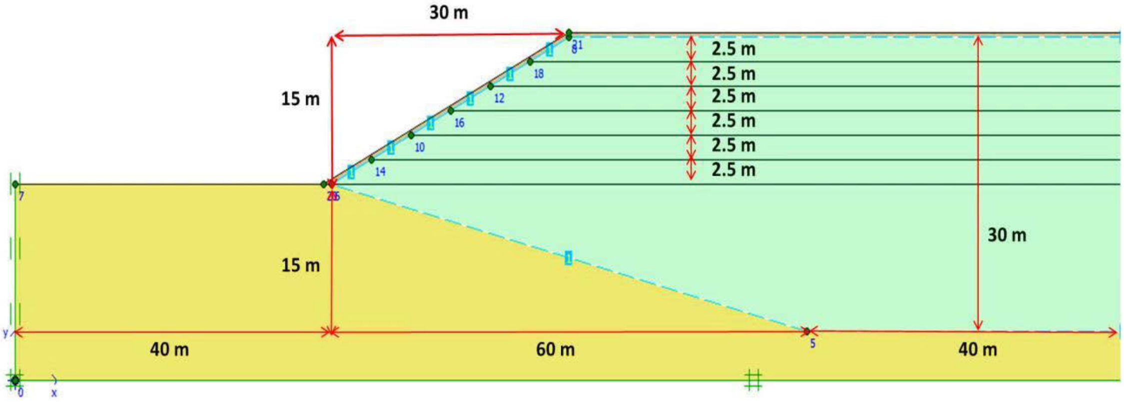


Figure 4.15: Dimensions of the Long Landfill with the Slope 1:2

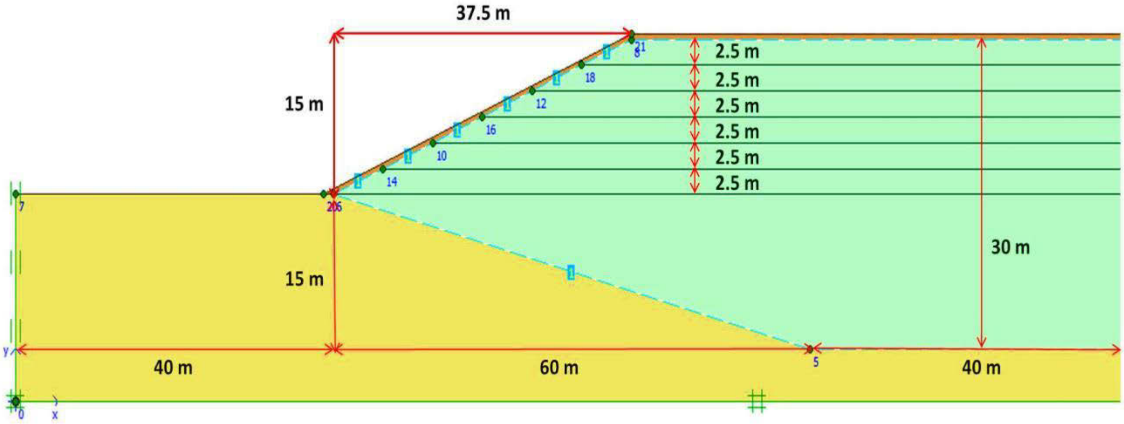


Figure 4.16: Dimensions of the Long Landfill with the Slope 1:2.5

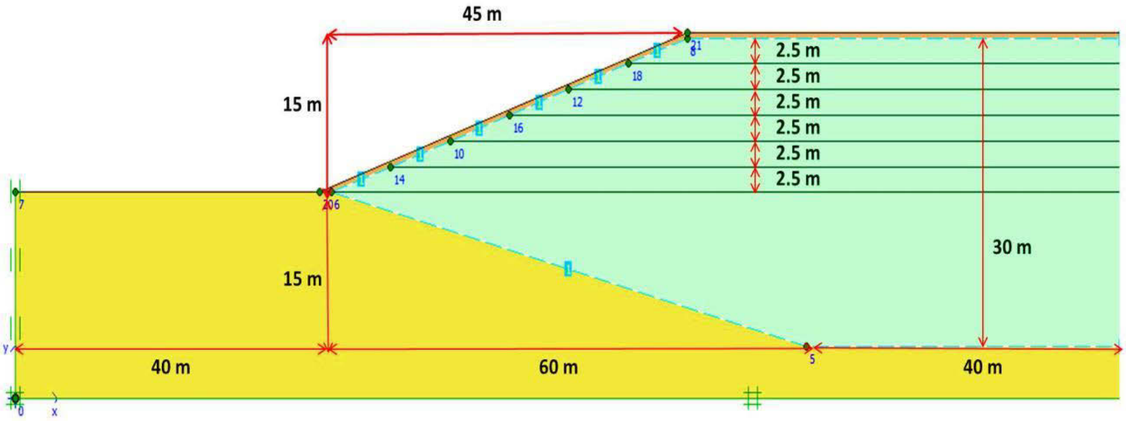


Figure 4.17: Dimensions of the Long Landfill with the Slope 1:3

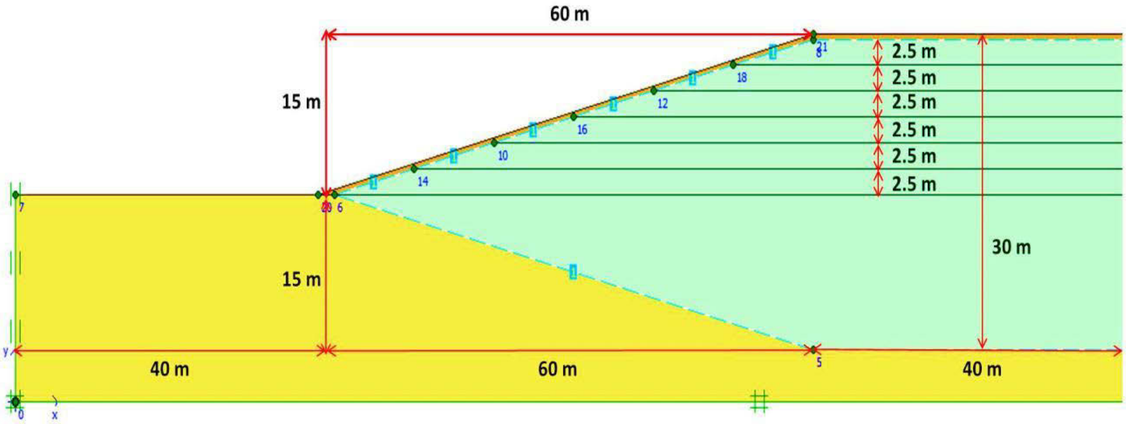


Figure 4.18: Dimensions of the Long Landfill with the Slope 1:4

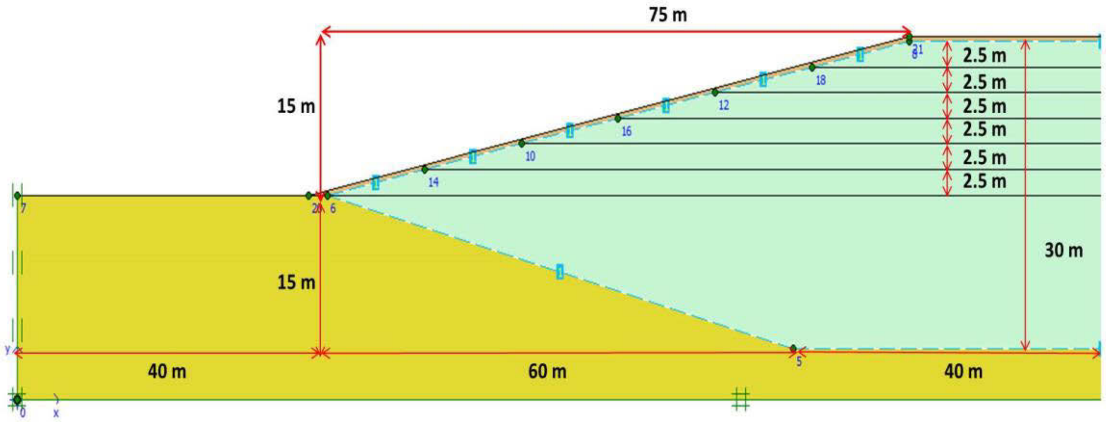


Figure 4.19: Dimensions of the Long Landfill with the Slope 1:5

4.2.2. Material Models and Data Sets

To simulate the behaviour of the landfill properly, it is necessary to employ a suitable model and appropriate material properties. As it is assumed that waste materials in landfills undergo creep and primary compression followed by a certain amount of secondary compression, the Soft Soil Creep Model has been chosen for modelling waste material in this numerical analysis. In contrast, the Mohr-Coulomb Model is selected for the final cover and subsoil, which represents an approximation of soil behaviour.

Generally, the material parameters must be assigned to the geometry model after the input of boundary conditions and before mesh generation. Parameters assigned to final cover, waste material, and subsoil are summarized in Tables 4.1 to 4.3. Obviously, the values considered for material parameters are defined based on the selected models in this FEM analysis.

Table 4.1: Material Properties of Final Cover

Parameter	Name	Value	Unit
Material Model	Model	Mohr-Coloumb	-
Type of Material Behaviour	Type	Drained	-
Unit weight above the Phreatic Level	γ_{unsat}	16	kN/m^3
Unit weight below the Phreatic Level	γ_{sat}	17.5	kN/m^3
Permeability in Horizontal Direction	k_x	1.5×10^{-7}	m/day
Permeability in Vertical Direction	k_y	1.5×10^{-7}	m/day
Young's Modulus	E	25000	kN/m^2
Poisson's Ratio	υ	0.35	-
Cohesion	c	10	kN/m^2
Friction Angle	φ	25	°
Dilatancy Angle	Ψ	0	°

4.2.3. Mesh Generation and Boundary Conditions

After completing the geometry model, the finite element model (or mesh) can be generated based on the mesh generation algorithm of PLAXIS 2D. Following the mesh generation procedure, the geometry is divided into the elements of the basic element type considering the exact position of layers, loads, and structures. In the modelling, the mesh has been optimized by performing global coarseness. Cross-sections of generated mesh for different landfills have been shown in subsequent sections. It should be noted that the boundary conditions considered for this modelling include two vertical boundaries on both sides of the landfill will allow free movement in vertical direction. However, the fixed horizontal boundary at the landfill base prevents any movement in both vertical and horizontal directions as it can be observed in all figures. Moreover, the subsoil has been considered to be stiff enough to influence the stability and deformation in this simulation.

Table 4.2: Material Properties of Waste

Parameter	Name	Value	Unit
Material Model	Model	Soft Soil Creep	-
Type of Material Behaviour	Type	Drained	-
Unit weight above the Phreatic Level	γ_{unsat}	12	kN/m^3
Unit weight below the Phreatic Level	γ_{sat}	14.6	kN/m^3
Permeability in Horizontal Direction	k_x	0.012	m/day
Permeability in Vertical Direction	k_y	0.012	m/day
Void Ratio	e_0	0.63	-
Cohesion	c	11	kN/m^2
Friction Angle	φ	29	o
Dilatancy Angle	Ψ	0	o
Recompression Index	C_s	0.075	-
Compression Index	C_c	0.33	-
Secondary Compression Index	C_α	0.052	-

Table 4.3: Material Properties of Subsoil

Parameter	Name	Value	Unit
Material Model	Model	Mohr-Coloumb	-
Type of Material Behaviour	Type	Drained	-
Unit weight above the Phreatic Level	γ_{unsat}	16	kN/m^3
Unit weight below the Phreatic Level	γ_{sat}	20	kN/m^3
Permeability in Horizontal Direction	k_x	1	m/day
Permeability in Vertical Direction	k_y	1	m/day
Young's Modulus	E	3000	kN/m^2
Poisson's Ratio	υ	0.3	-
Cohesion	c	1	kN/m^2
Friction Angle	φ	30	o
Dilatancy Angle	Ψ	0	o

4.2.3.1. Mesh Generation of Landfill with Total Height of 20 m

As discussed before, different landfills in terms of their height and the slope inclinations are modelled in this numerical analysis in order to study the effect of the slope geometry on safety factor of the landfill slope stability. The cross sections and closer view of the generated mesh for short landfills provided in this numerical analysis are illustrated in Figures 4.20 to 4.24.

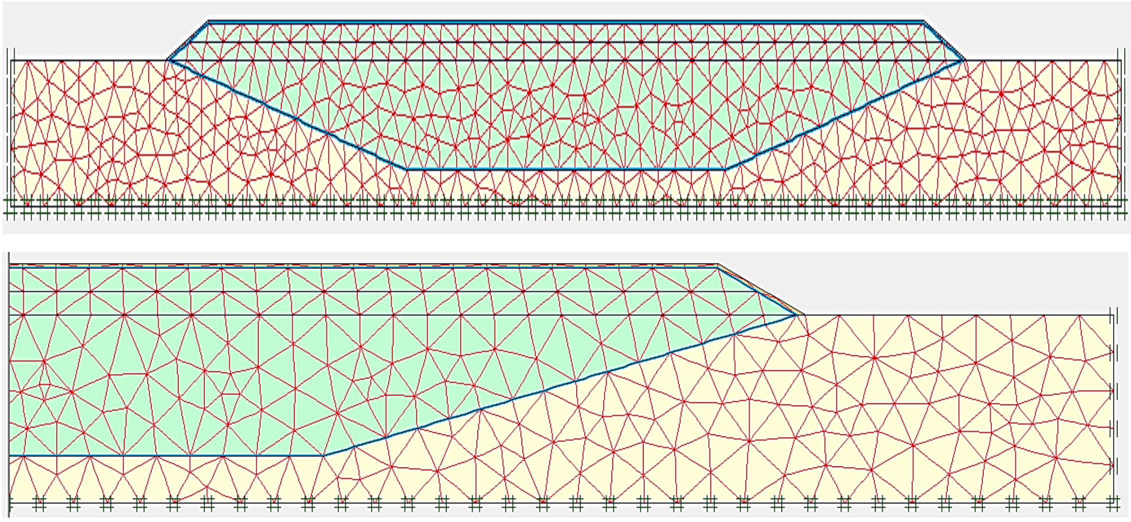


Figure 4.20: Cross Section and Closer View of Generated Mesh for Short Landfill (Slope 1:2)

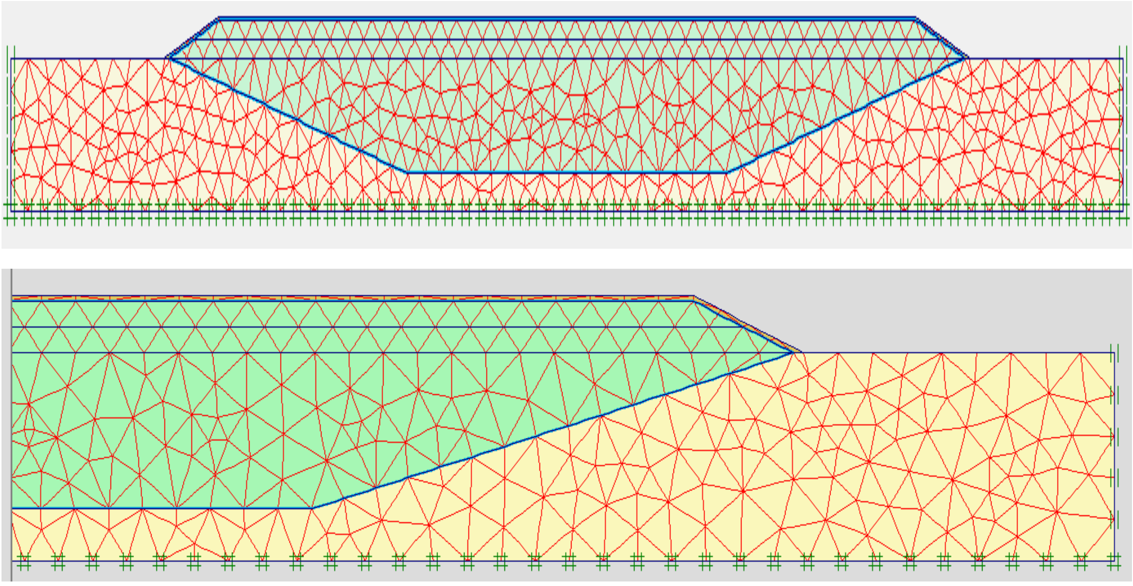


Figure 4.21: Cross Section and Closer View of Generated Mesh for Short Landfill (Slope 1:2.5)

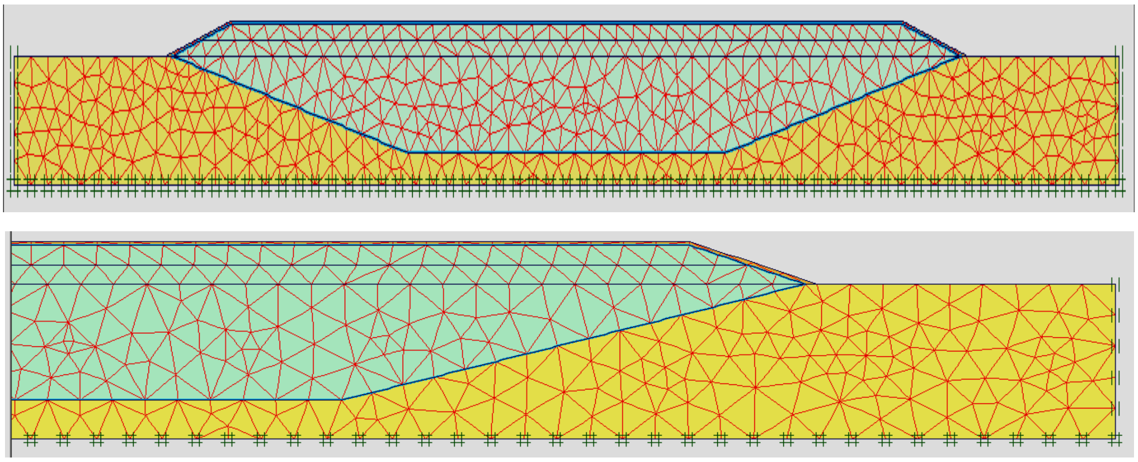


Figure 4.22: Cross Section and Closer View of Generated Mesh for Short Landfill (Slope 1:3)

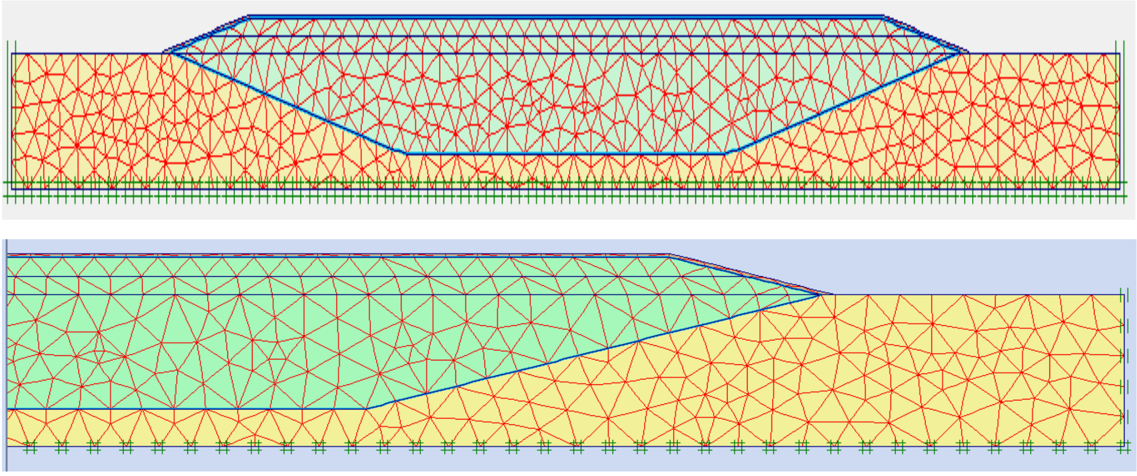


Figure 4.23: Cross Section and Closer View of Generated Mesh for Short Landfill (Slope 1:4)

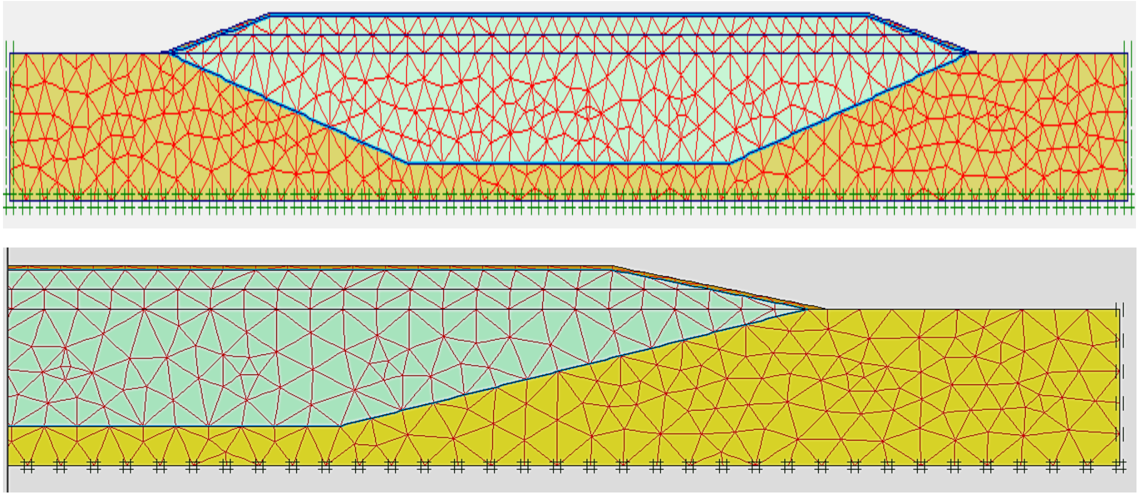


Figure 4.24: Cross Section and Closer View of Generated Mesh for Short Landfill (Slope 1:5)

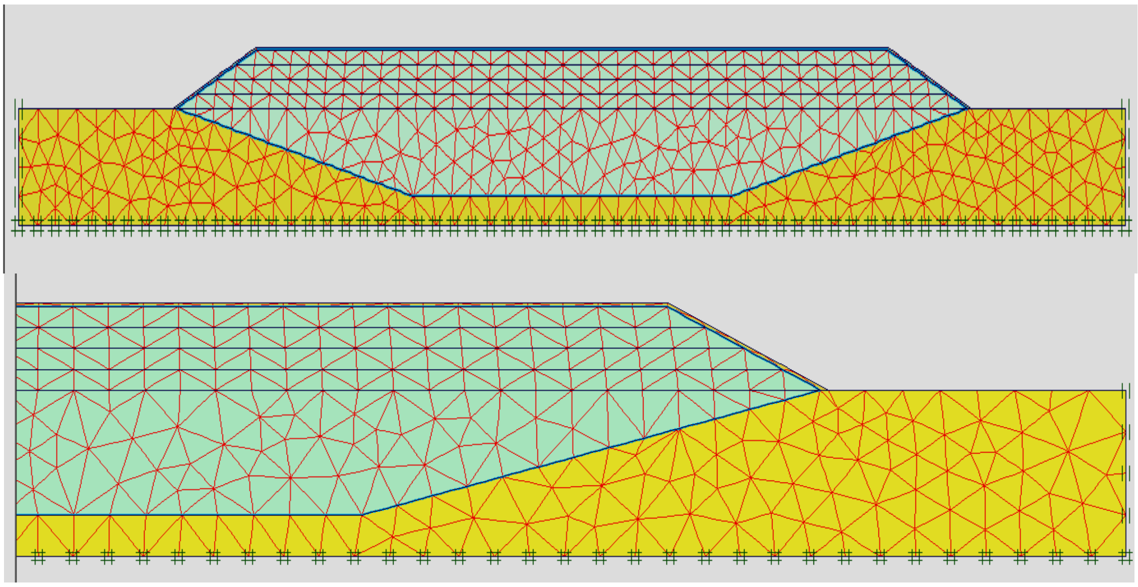


Figure 4.25: Cross Section and Closer View of Generated Mesh for Medium Landfill (Slope 1:2)

4.2.3.2. Mesh Generation of Landfill with Total Height of 25 m

Similar to previous section, the cross sections and closer view of the generated mesh for medium landfills with different slope geometry are presented in Figure 4.25 to Figure 4.29.

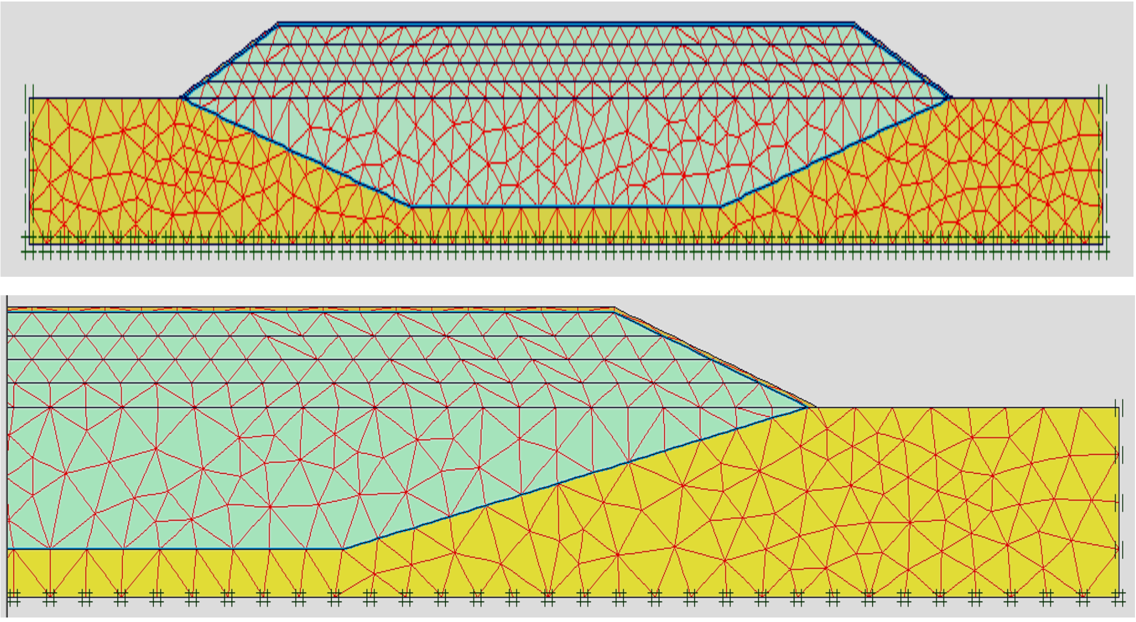


Figure 4.26: Cross Section and Closer View of Generated Mesh for Medium Landfill (Slope 1:2.5)

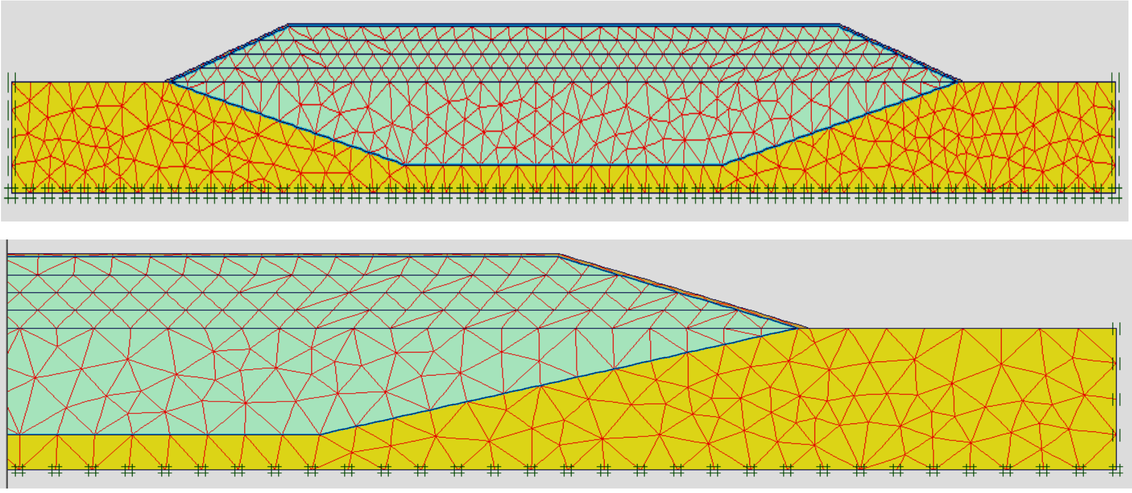


Figure 4.27: Cross Section and Closer View of Generated Mesh for Medium Landfill (Slope 1:3)

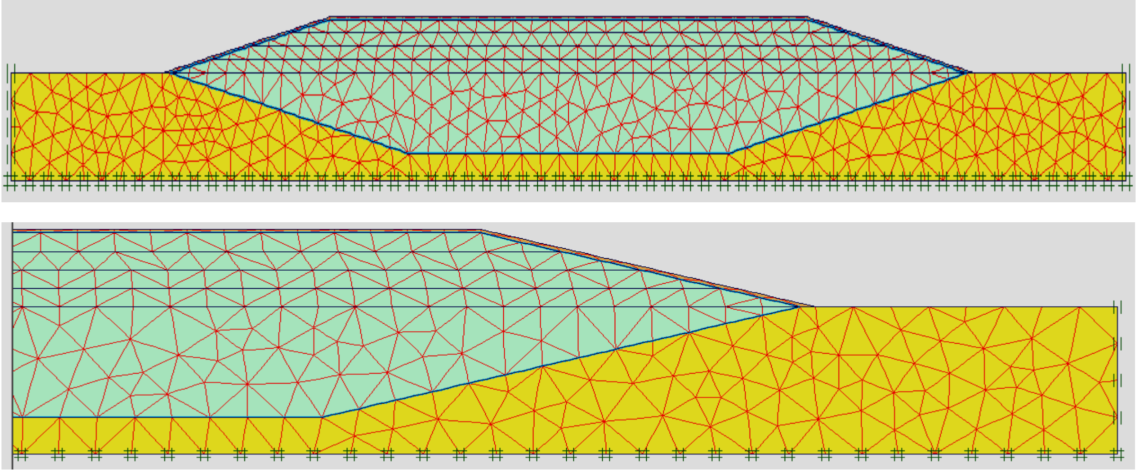


Figure 4.28: Cross Section and Closer View of Generated Mesh for Medium Landfill (Slope 1:4)

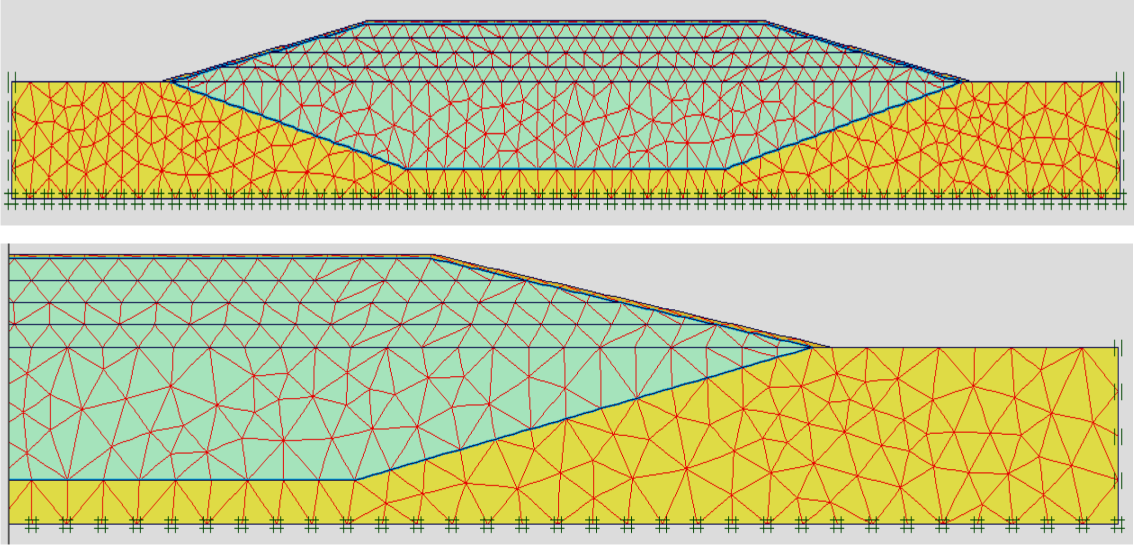


Figure 4.29: Cross Section and Closer View of Generated Mesh for Medium Landfill (Slope 1:5)

4.2.3.3. Mesh Generation of Landfill with Total Height of 30 m

Similarly, the cross sections and closer view of the generated mesh for long landfills with different slope geometry are presented in Figure 4.30 to Figure 4.34.

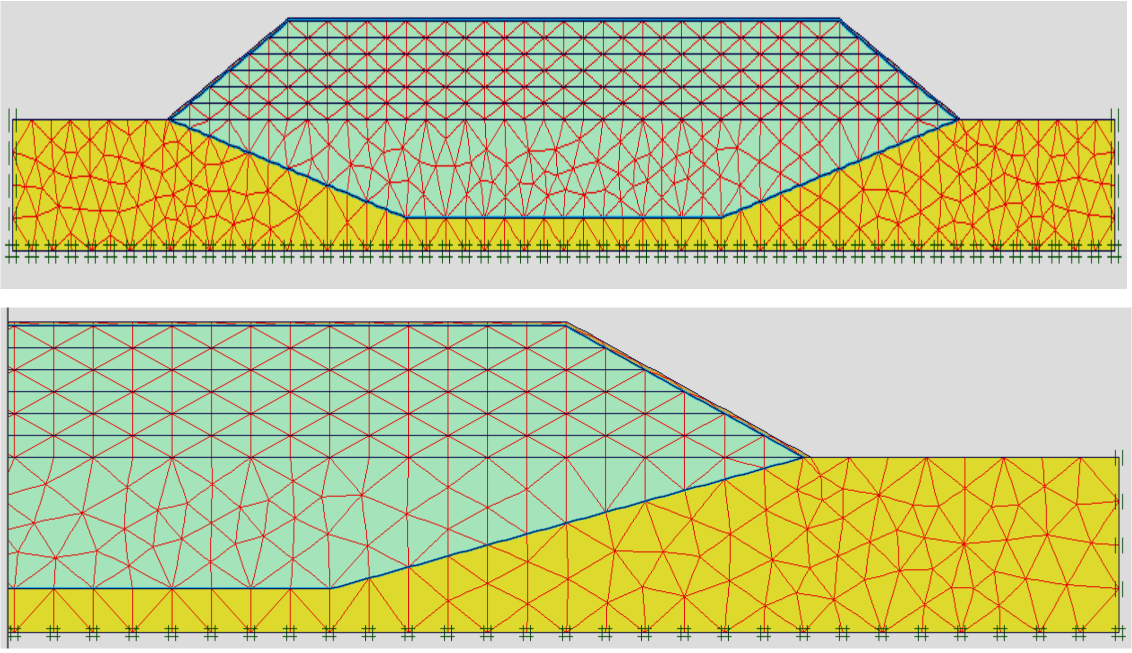


Figure 4.30: Cross Section and Closer View of Generated Mesh for Long Landfill (Slope 1:2)

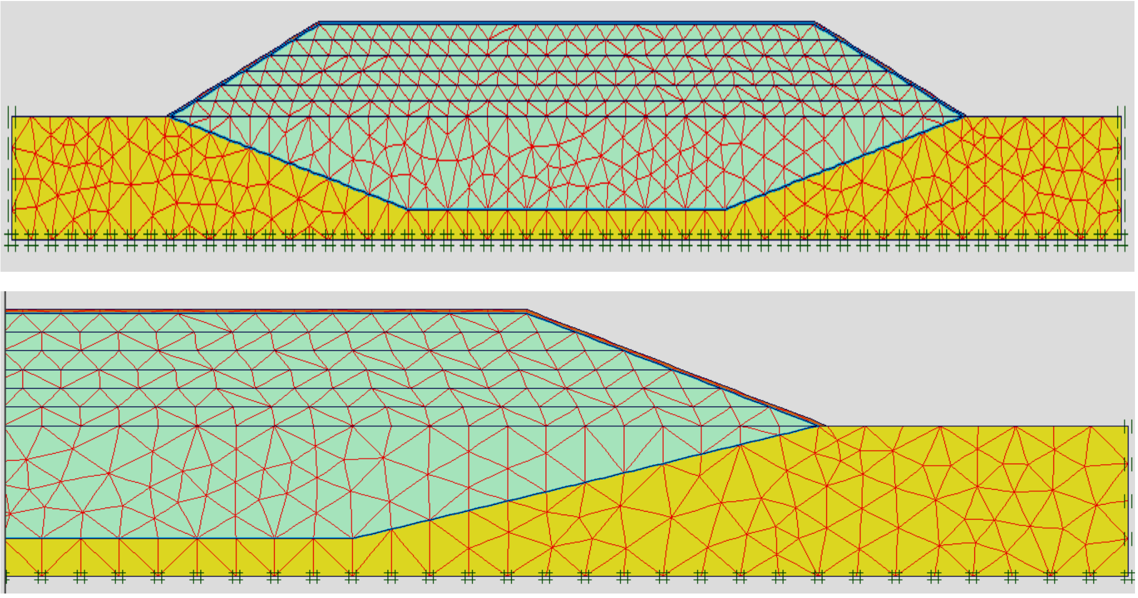


Figure 4.31: Cross Section and Closer View of Generated Mesh for Long Landfill (Slope 1:2.5)

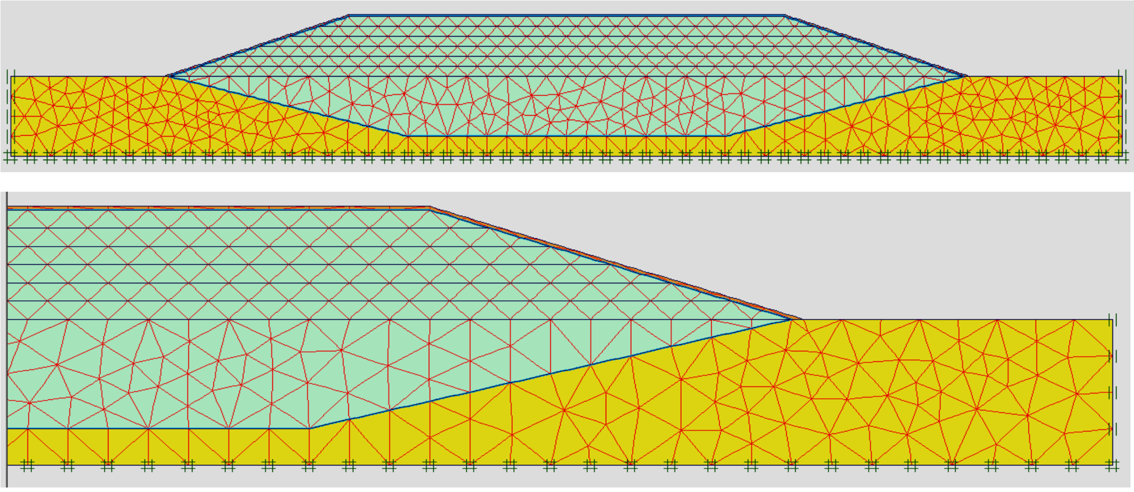


Figure 4.32: Cross Section and Closer View of Generated Mesh for Long Landfill (Slope 1:3)

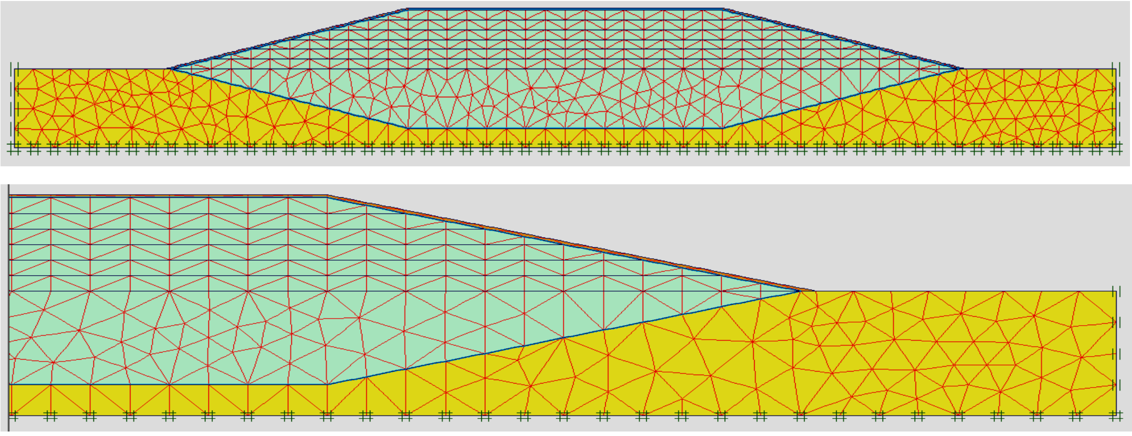


Figure 4.33: Cross Section and Closer View of Generated Mesh for Long Landfill (Slope 1:4)

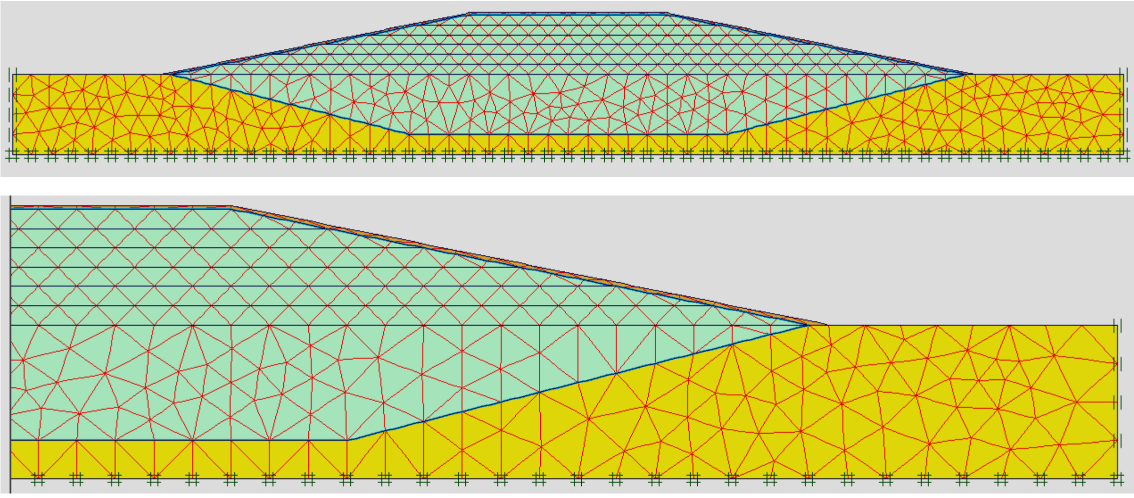


Figure 4.34: Cross Section and Closer View of Generated Mesh for Long Landfill (Slope 1:5)

4.2.4. Initial Conditions and Calculations

As mentioned before, evaluation of the safety factor of landfill slope stability is of crucial importance in landfill engineering.

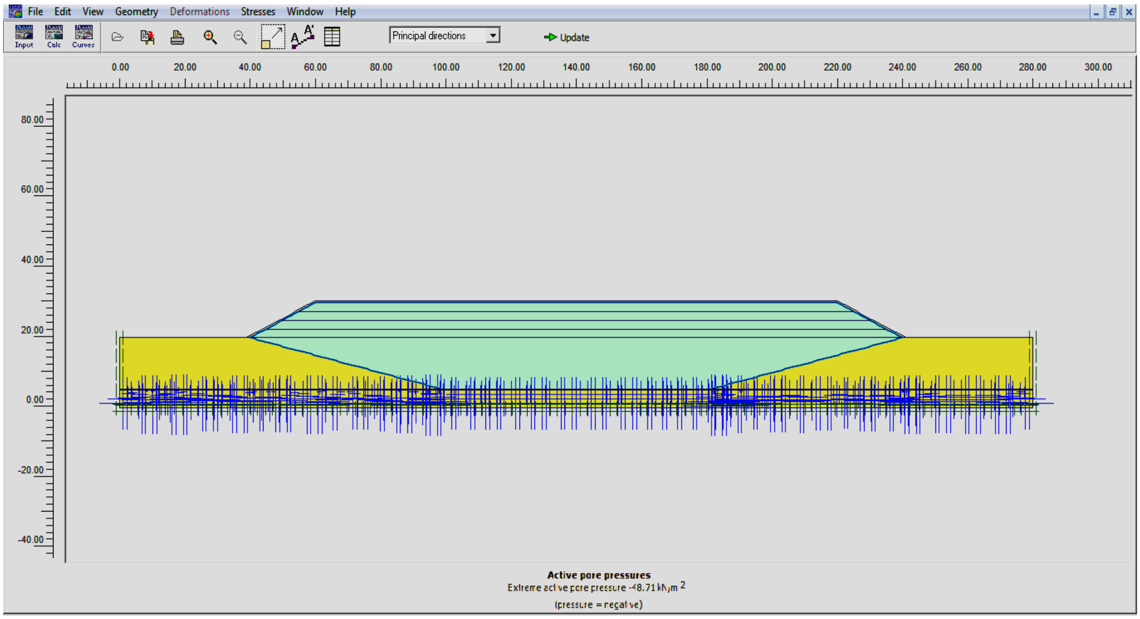
In general, safety factor is defined as the ratio of the collapse load to the working load. In landfills, however, most of loading is caused by the material weight and an increase in material weight will not necessarily lead to collapse. Therefore, the safety factor can be defined as following equation based on the coulomb condition:

$$\mathbf{SF} = \frac{\mathbf{c} - \boldsymbol{\sigma}_\mathbf{n} \tan \boldsymbol{\varphi}}{\mathbf{c}_\mathbf{r} - \boldsymbol{\sigma}_\mathbf{n} \tan \boldsymbol{\varphi}_\mathbf{r}} \qquad (\mathbf{4.1})$$

where c and φ are the input strength parameters; σ_n is the actual normal stress component; $\mathrm{c_r}$ and φ_r are reduced strength parameters which are large enough to maintain equilibrium. The above mentioned equation is the basis for the Phi-c-reduction method which is used for calculation of safety factor in this numerical analysis by PLAXIS. In this method, the cohesion (c) and tangent of friction angle $(\tan \varphi)$ will be reduced in the same proportion and the reduction of these strength parameters is controlled by the total multiplier $(\sum \mathrm{Msf})$ as presented in following equation:

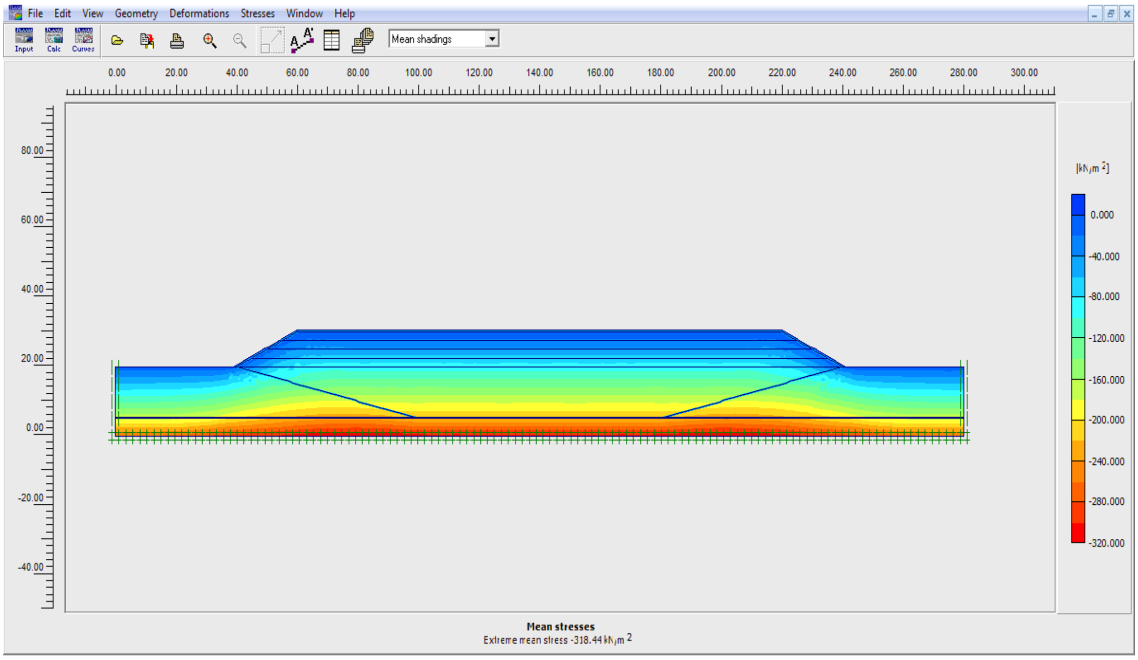
$$\sum \mathbf{Msf} = \frac{\mathbf{c}}{\mathbf{c}_\mathbf{r}} = \frac{\tan \boldsymbol{\varphi}}{\tan \boldsymbol{\varphi}_\mathbf{r}} \qquad (\mathbf{4.2})$$

In the Phi-c-reduction approach, the parameter $\sum \mathrm{Msf}$ is increased in a step by step procedure until failure occurs and the safety factor is defined as the value of this parameter at failure. To perform the calculation accurately, it is necessary to define the initial condition properly. As the geometry of landfill includes a non-horizontal surface, the K_0 procedure cannot be used for calculation of the initial stress and the initial stresses must be calculated in calculation phase through the gravity loading method. In this method, the proper initial water pressures will be generated in advance during the input of the initial conditions, and the soil weight will be considered during defining the phases of calculation, in which the multiplier for the material weight $(\sum \mathrm{Msf})$ is increased from 0 to 1 in order to calculate the initial stresses in a plastic calculation. Figure 4.35 and Figure 4.36 illustrate the distribution of pore pressure and total stress for one of modelled landfills, respectively.



Active pore pressures
Extreme active pore pressure -48.71 kN/m 2
(pressure = negative)

Figure 4.35: Distribution of Pore Pressure



Mean stresses
Extreme mean stress -318.44 kN/m 2

Figure 4.36: Distribution of Total stress

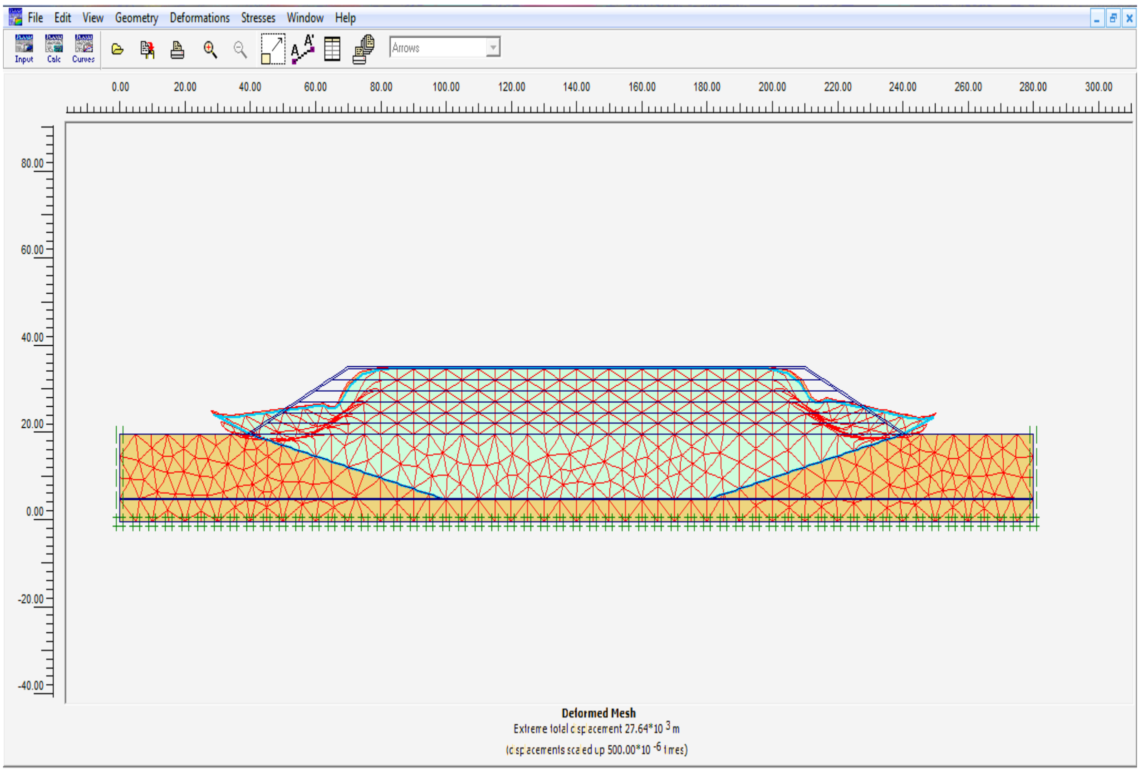
4.2.5. Results of Calculations

As a result of the procedure employed for this numerical analysis, as discussed in previous sections, the calculations were done. The results of the calculations obtained through these modelling regarding the safety factor of landfill slope stability for different landfills in terms of landfill height and the slope geometry are summarized in Table 4.4. The result of calculations presented in this table clearly shows the increase of the safety factor by increasing the slope inclination. Furthermore, it can be noted that the safety factor of landfill slope stability decreases as the landfill height increases at the same slope inclination.

Table 4.4: Calculated Safety Factor for Modelled Landfill in Numerical Analysis

Landfill Height (m)	Slope (V:H)				
	1:2	1:2.5	1:3	1:4	1:5
20	2.4776	2.8324	3.1653	3.8838	4.6342
25	2.0246	2.3485	2.6827	3.3470	4.0001
30	1.7896	2.1217	2.4285	3.0856	3.7189

In addition, the figures related to deformed mesh and displacements created in one of landfills are presented in Figure 4.36 to Figure 4.38 as an example.



Deformed Mesh
Extreme total displacement $27.64*10^{3}$ m
(displacements scaled up $500.00*10^{-6}$ times)

Figure 4.37: Deformed Mesh for one of the modelled Landfill

To illustrate the role of the landfill height and the slope inclination in landfill slope stability, the result of this numerical analysis regarding landfill slope stability safety factor as affected by the variations of the slope geometry and landfill height is shown in Slope Stability part of Landfill Technical Management Tool (LTMT).

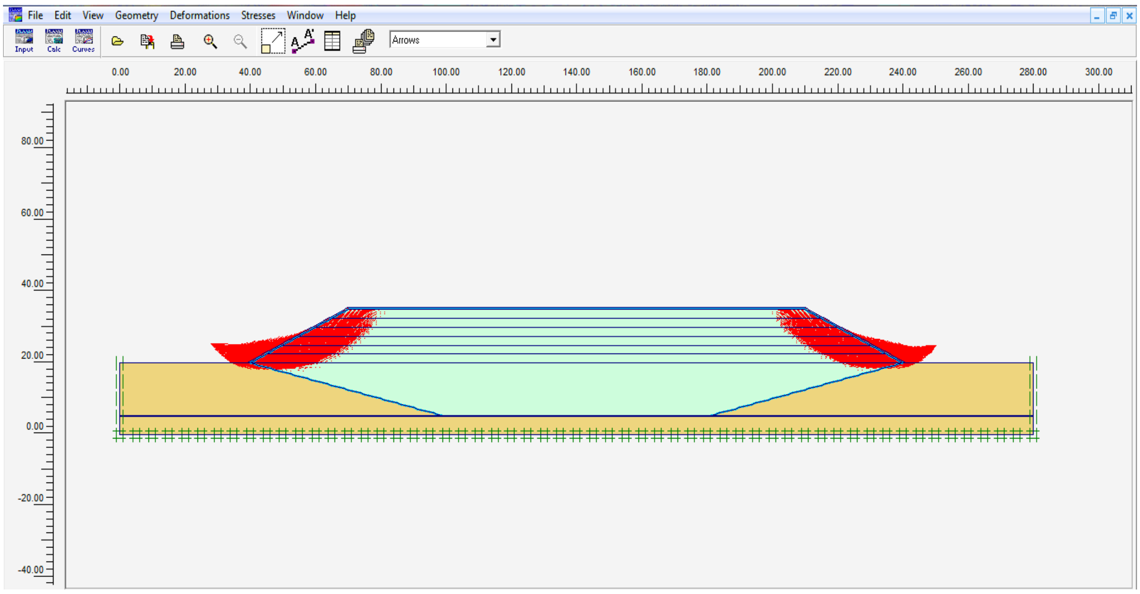
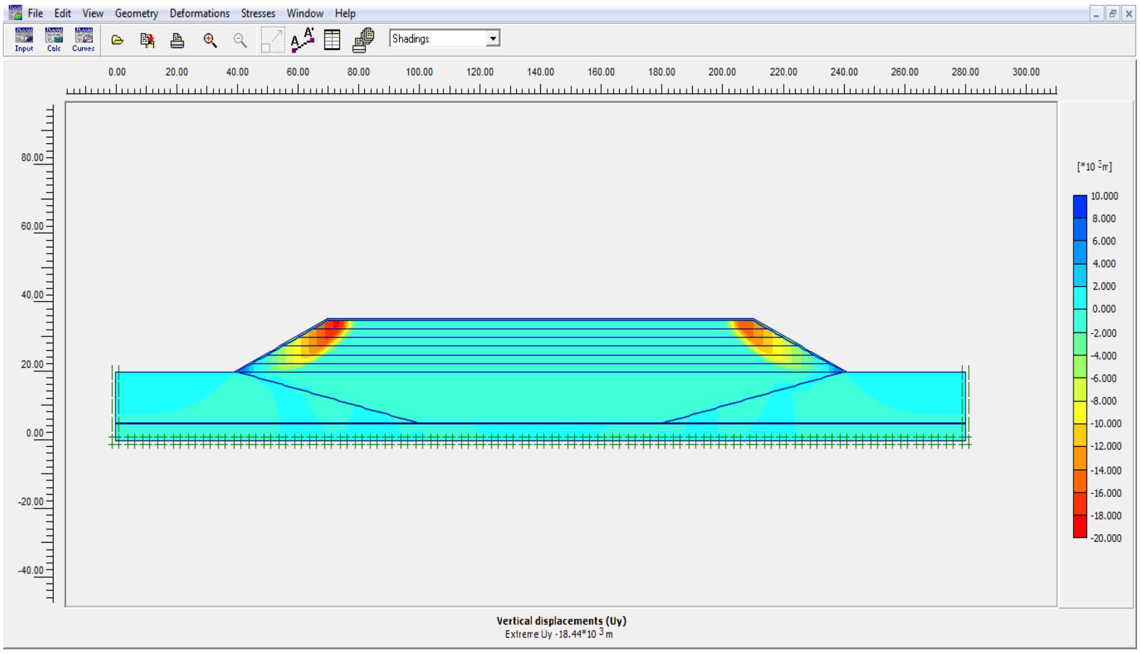


Figure 4.38: Total Displacement for one of the modelled Landfill



Vertical displacements (Uy)
Extreme Uy -18.44*10^{3} m

Figure 4.39: Vertical Displacement for one of the modelled Landfill

4.3. Summary

This chapter describes the numerical analysis conducted for safety factor of landfill slope stability. The finite element program, PLAXIS 2D has been used to carry out the analysis. To conduct this study, a series of 15 modelling for different landfills in terms of landfill heights and slope inclinations has been undertaken in order to calculate the safety factor. The results of these calculations are presented in Table 4.4. Based on this study, it was noted that the safety factor of landfill slope stability increases by the increase of landfill slope inclination. In contrast, it decreases as the landfill height increases at the same slope inclination.

In addition, these results have been implemented in the developed Landfill Technical Management Tool (LTMT) to illustrate the effect of landfill height and slope geometry on slope stability for a typical landfill with the excavation height of 15 m and different total heights.

Chapter 5

Development of Landfill Technical Management Tool (LTMT)

5.1. Introduction

5.2. LTMT Description

5.3. Summary

5.1. Introduction

The amount of wastes generated and disposed in landfills on an annual basis increases despite the increasing rates of source reduction, recycling and reuse. As available space becomes scarce in urban areas, development on the top of or adjacent to old landfills has become increasingly common. Redeveloping on or adjacent to a closed landfill can be challenging. In this regard, it is necessary to review a wide variety of engineering and geotechnical considerations for landfill redevelopment including settlement, stability, gas and leachate management, and utility considerations, etc. Among various factors, which would be considered in redeveloping landfill sites, settlement is the most important factor from the perspective of structural and geotechnical stability.

Waste settlement prediction and monitoring are crucial to understanding and managing the lifecycle of a landfill. Many researchers studied the compression response of MSW and proposed different approaches to predict immediate settlement and time dependent settlement under load. Today, there are many published landfill settlement models. However, the current models of settlement prediction have serious shortcomings in accounting for the organic portion of waste streams and the many factors that control its decomposition. They are also unable to account for changing landfill conditions such as changes in waste type that have major effects on settlement rates and magnitude. The existing methods are therefore difficult to use in a predictive manner and require recalibration for changing waste streams. In this study, it is planned to obtain a technical management tool for MSW closed landfills which intends to understand the process on long term settlement in landfills considering various related parameters as well as to evaluate different properties of waste as they have a strong effect on landfills behaviour. Therefore, this chapter aims at describing different parts of this technical management tool which has been designed as a user friendly program to calculate different properties of wastes, and determine the landfill settlement and slope stability under various conditions.

5.2. Landfill Technical Management Tool (LTMT) Description

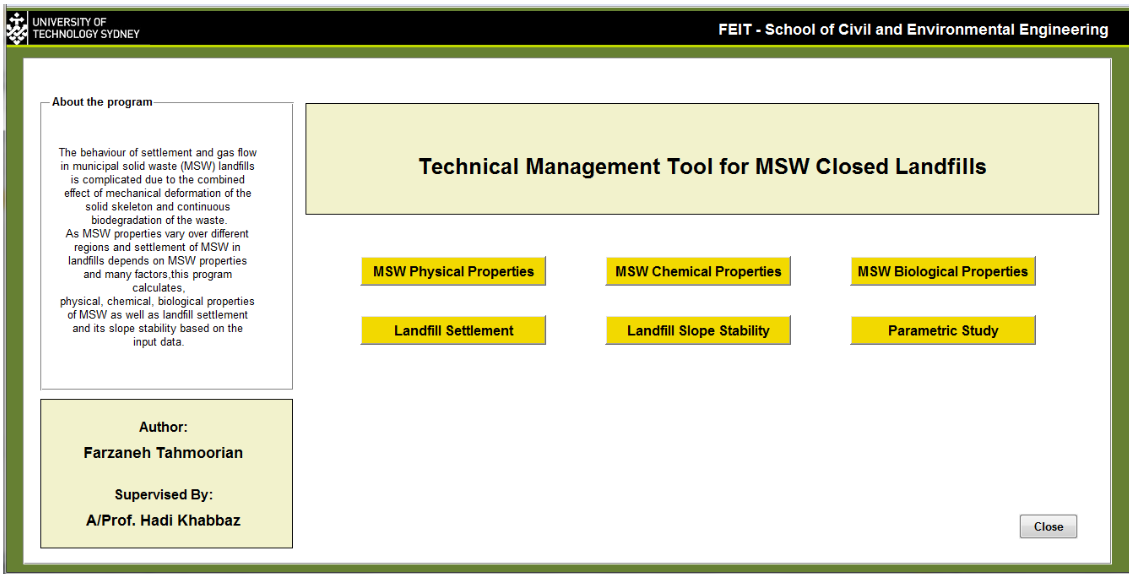
Municipal solid waste is normally assumed to include all community waste with the exception of industrial process wastes and agricultural wastes. Municipal solid waste

(MSW) comprises many materials which each of them are unique in its nature. Therefore, determining the MSW properties will always remain an engineering challenge because of the heterogeneity of the materials.

The fundamental philosophy underlying this research is evaluating settlements incorporating leachate formation and gas generation. We found that the existing waste settlement models which consider the processes of biodegradation, gas generation and transport and distribution of moisture within a landfill are very limited and still remain with many difficulties to integrate all mechanical, physical, and biological parameters and its variations in settlement evaluation.

Therefore, this research aimed at developing a landfill technical management tool (LTMT) for estimation of MSW landfill settlement as well as evaluation of landfill slope stability while it works as a User Interface Program in order to enable researchers in this area to use it much more efficient.

Moreover, there are many factors such as waste composition, moisture content, waste density, etc., which have significant effects on analysing waste settlement. These parameters in almost all existing landfill settlement models have been considered as constant parameters. However, this program enables user to change these parameters and to evaluate the effect of their variations on landfill settlement.



Technical Management Tool for MSW Closed Landfills

The behaviour of settlement and gas flow in municipal solid waste (MSW) landfills is complicated due to the combined effect of mechanical deformation of the solid skeleton and continuous biodegradation of the waste.
As MSW properties vary over different regions and settlement of MSW in landfills depends on MSW properties and many factors,this program calculates,
physical, chemical, biological properties of MSW as well as landfill settlement and its slope stability based on the input data.

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Figure 5.1: Graphical Interface of Landfill Technical Management Tool (LTMT)

In addition, as landfill settlement is highly associated with different properties of MSW, it is necessary to have a proper understanding of the waste characteristics affecting landfill settlement behaviour. Thus, the most important and relevant properties of MSW can be easily evaluated using different parts of LTMT (Figure 5.1). This section and the subsequent sections provide more information on this landfill technical management tool and its application.

5.2.1. LTMT Assumptions

This section describes the main assumptions which are made in LTMT to the input data, the landfill condition, waste nature, etc.

5.2.1.1. MSW Classification in LTMT

As municipal solid wastes comprises a large variety of materials, it would be helpful to consider a proper classification for waste components presented in MSW in order to realize the type and engineering properties of the waste materials and hence to anticipate likely behaviour of waste mass and to aid the development of methodologies for evaluating related properties and estimating waste mass behaviours.

Therefore, as a basis for subsequent discussions in this research, waste components observed in MSW are mainly categorized into organic and inorganic groups (as shown in Figure 5.2) which include some subgroups as food waste, paper, cardboard, plastics, metals (ferrous/nonferrous), glass, rubber, leather, textiles, wood, and yard trimmings.

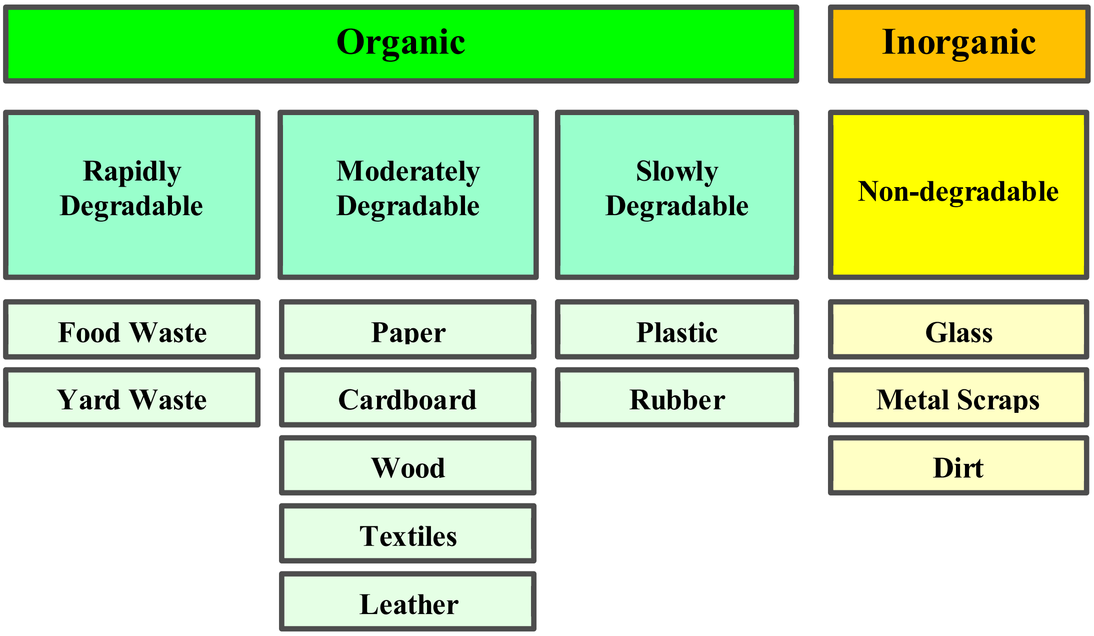


Figure 5.2: Municipal Solid Waste Classification

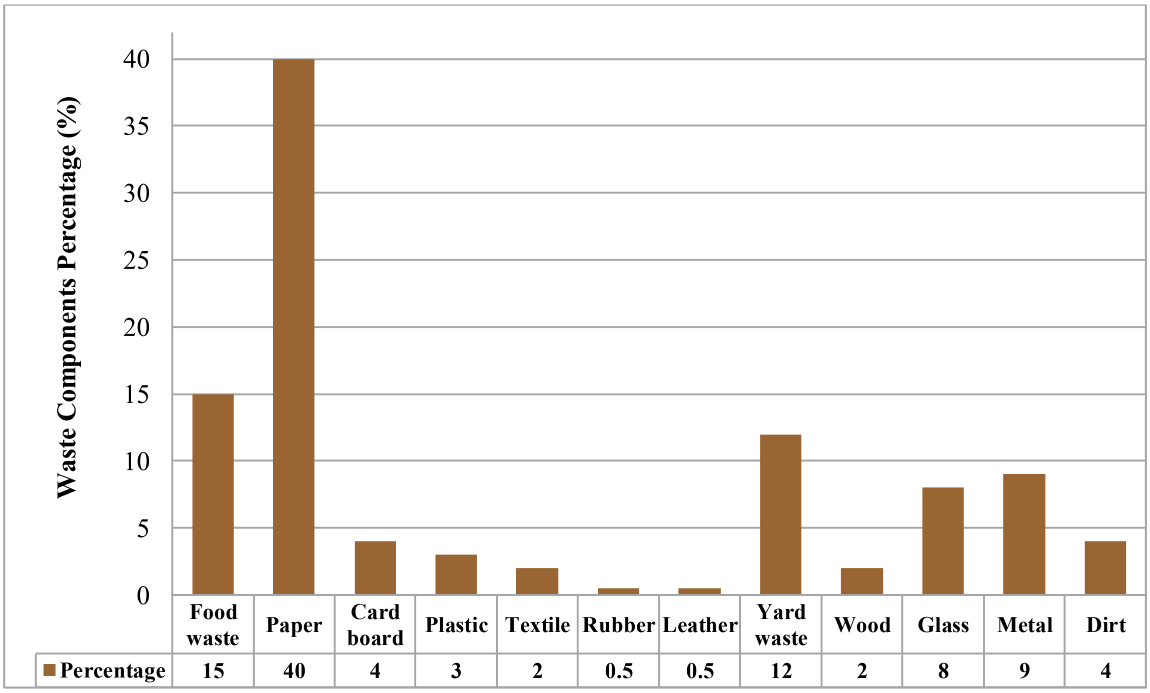


Figure 5.3: Typical Composition of Municipal Solid Waste Considered in LTMT

Typical waste composition data considered in this technical management tool is summarized in Figure 5.3. The typical values for waste composition can be helpful for evaluation of municipal solid waste properties in a comparable condition. Obviously, the waste composition can be changed in this management tool.

Table 5.1: Considered MSW Density Values in LTMT According to Compaction Effort

Waste Component	Density (kg/m^3)		
	Low Compaction	Moderately Compaction	High Compaction
Food waste	400	550	1050
Paper	240	400	590
Cardboard	210	350	460
Plastics	110	230	300
Textiles	110	190	320
Rubber	105	150	400
Leather	100	180	400
Yard waste	250	450	900
Wood	500	700	800
Glass	600	800	1650
Metal waste	110	550	1750
Dirt, etc.	450	870	1000

5.2.1.2. MSW Density Variation in LTMT

This study is based on this concept that with increasing compaction effort, the density of waste increases. Thus, to calculate the waste density, three compaction conditions are considered which include low compaction, moderately compaction, and high compaction. Hence, the initial density of waste components for each compaction effort is assumed as presented in Table 5.1. The values presented in this table are considered based on the data published in March 2001 by the California Integrated Waste Management Board.

5.2.1.3. Landfill Gas Generation and Transport in LTMT

In this program, it is assumed that the unsaturated voids of the waste are filled with the landfill gas at atmospheric pressure when time is zero (t=0). The landfill gas mixture has been considered to be comprised of methane (CH_4) and carbon dioxide (CO_2) in order to simplify the landfill gas transport and avoid the complexities regarding multicomponent gases. Moreover, as this management tool calculates the rate of gas generation by different methods, a mixture of 50% methane and 50% carbon dioxide is considered in order to achieve a relative consistency of measurement techniques and provide the result comparison condition. Furthermore, the vertical direction has been assumed for the movement of gas in landfill.

5.2.1.4. Moisture Distribution within Landfill in LTMT

Landfills are an interacting multiphase medium consisting of gas, liquid, and solid phases in which any of these phases present spatial and temporal variations. The main parameters that influence the amount of generated moisture (leachate) in MSW landfills are illustrated in Figure 5.4.

In this technical management tool, Darcy's law has been considered in combination with the principle of conservation of mass resulting in the Richards equation to simulate the distribution of moisture in MSW landfills. In fact, Richards's equation is used to estimate the spatial and temporal variation of volumetric moisture content (θ) concerning matric potential (h) in an unsaturated medium. Since Van Genutchen Model (van Genutchen, 1980) considers matric potential (h) and unsaturated hydraulic conductivity (k_w) as functions of volumetric water content (θ), this model has been employed to solve Richards equation.

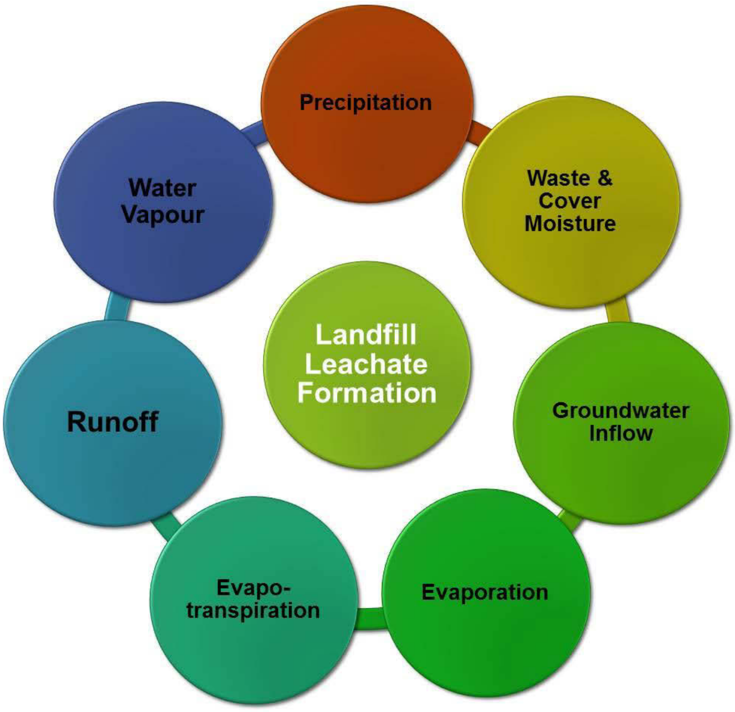


Figure 5.4: Main Factors Affecting the Leachate Formation in MSW Landfills

It should be noted that the assumption of moisture movement in the vertical direction has been considered in this program. In addition, the increase in moisture content as a result of precipitation during construction is neglected. Moreover, the effect of landfill intermediate covers on the fluids distribution is not considered in this program.

5.2.1.5. Settlement Estimation in LTMT

In general, waste settlement in landfills follows an irregular trend as it starts with a large deformation within one or two months after construction and continues by further compression over an extended period of time. As discussed before, many factors affect the landfill settlement. Among them, it has been observed that the settlement rate decreases with time as well as with depth. Hence, a proper model for landfill settlement should consider the settlement during construction and the filling sequence, in order to allow for the calculation of strains at different depths of landfill.

Therefore, this technical management tool doesn’t use the entire landfill thickness to calculate the landfill settlement. In this program, it is assumed that the MSW landfill, as discussed previously in chapter three, is made up of layers of wastes which are extended in horizontal direction unlimitedly. These layers are composed of wastes with just about similar nature in same thickness.

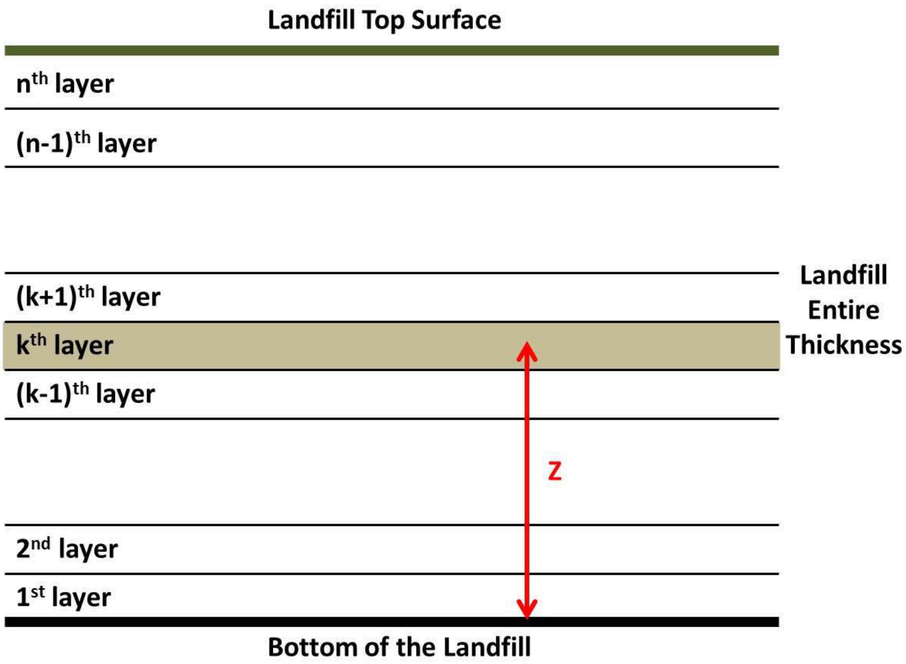


Figure 5.5: Cross Section of Considered MSW Landfill in LTMT

As landfill is an interacting multiphase medium, the real settlement of the landfill depends on involvement of all these phases (gas, liquid, and solid). Therefore, it is necessary to consider landfill gas generation and dissipation and moisture distribution as integral parts of the process of landfill settlements. Moreover, due to heterogeneous nature of waste in landfills, it is understood that soils mechanics concepts cannot be applied in landfill settlement calculations. It is believed that although the addition of new waste layers leads to increase in stress, mass loss taking place as a result of waste biodegradation can cause swelling or rebound in landfills. Hence, the settlement calculation in this program is based on taking into consideration two waste settlement mechanisms including mechanical compression and biodegradation-induced settlements. This assumes that landfill volume primarily changes as a result of the superimposed load (or stress) as well as the waste mass loss due to decomposition. The effect of intermediate covers on density is not considered in calculations.

Furthermore, to avoid misleading settlement estimations by considering average properties for municipal solid waste, different kinds of waste depending on their biodegradability is considered in this LTMT as described in previous sections.

The first order kinetics is used to estimate the decomposition rate of a biodegradable wastes and mass loss in landfill while it is assumed that nutrient, pH, and moisture are at optimum levels for microbial activities. The assumption of lack of inhibitors and toxic materials has been considered in this program.

In addition, temperature variation is not considered in landfill. In other words, it is assumed that the temperature to be at a constant value of 42 Celsius degree, which based on Chynoweth and Pullammanappallil (1996), is the proper temperature to provide favourite condition for microorganisms.

5.2.2. Physical Properties Evaluation in LTMT

To understand landfill settlement behaviour and ensure stability of a landfill, the physical properties of wastes have to be known as the waste presents the main component and the largest structural element which influences landfill relevant analysis, design, stability, and post-closure developments.

Based on the critical role of physical properties in landfill settlement and stability, evaluation of some important and relevant physical properties of MSW such as MSW unit weight, moisture content, and porosity can be estimated in LTMT under different conditions. In addition, the typical range and considered value of some of physical properties of MSW which are taken into account in LTMT to estimate landfill settlement are summarized in Table 5.2. Obviously, these values are chosen according to key references in this area and comprehensive detailed discussion in chapter two.

Table 5.2: Considered ranges of MSW Physical Properties in LTMT

Parameter (Unit)	Typical Range	Considered Value
Intrinsic permeability (m^2)	$10^{-13} – 10^{-10}$	10^{-13}
Field capacity (%)	15 – 60	The ratio of field capacity and the total porosity : 0.6
Porosity (%)	30 – 60	
Ratio of field capacity to porosity	0.50 – 0.77	
Gravimetric moisture content (%)	15 – 60	20
MSW density (kg/m^3)	300 – 1500	500

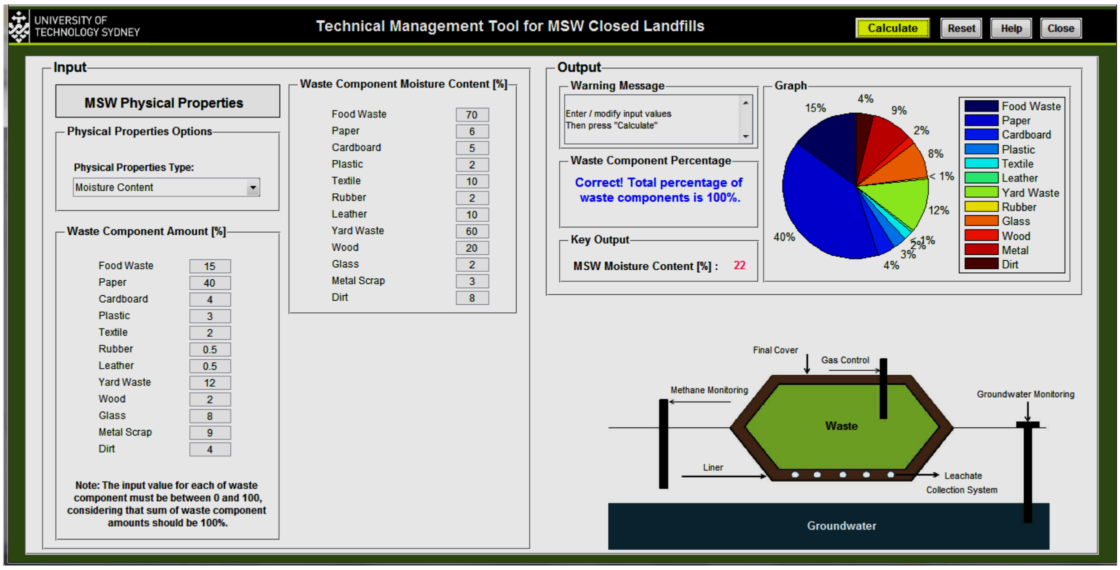
5.2.2.1. Moisture Content in LTMT

As mentioned before, the user can calculate landfill settlement based on the typical ranges of properties considered in this program. However, as the amount of moisture content and MSW density varies according to waste composition, it is possible to calculate the desired property or settlement based on the available components of MSW and variable amount of moisture content and density for individual components of MSW. Therefore, according to available references (e.g. Tchobanoglous et al., 1993; Worrell and Vesilind, 2002), a typical range and value is considered for the moisture content of the waste components as presented in Table 5.3.

Table 5.3: Considered Ranges of Moisture Content for MSW Components in LTMT

Waste Component	Moisture Content (%)	
	Typical Range	Considered Value
Food waste	50-80	70
Paper	4-10	6
Cardboard	4-8	5
Plastics	1-4	2
Textiles	6-15	10
Rubber	1-4	2
Leather	8-12	10
Yard waste	30-80	60
Wood	15-40	20
Glass	1-4	2
Metal waste	2-4	3
Dirt, etc.	6-12	8

Moreover, based on available key references, it has been assumed that the total moisture content of municipal solid waste ranges from 15% to 60%.



Technical Management Tool for MSW Closed Landfills

Physical Properties Type: Moisture Content

Waste Component Amount [%]

Food Waste	15
Paper	40
Cardboard	4
Plastic	3
Textile	2
Rubber	0.5
Leather	0.5
Yard Waste	12
Wood	2
Glass	8
Metal Scrap	9
Dirt	4

Note: The input value for each of waste component must be between 0 and 100, considering that sum of waste component amounts should be 100%.

Waste Component Moisture Content [%]

Food Waste	70
Paper	6
Cardboard	5
Plastic	2
Textile	10
Rubber	2
Leather	10
Yard Waste	60
Wood	20
Glass	2
Metal Scrap	3
Dirt	8

Warning Message

Enter / modify input values
Then press "Calculate"

Waste Component Percentage

Correct! Total percentage of waste components is 100%.

Key Output

MSW Moisture Content [%] : 22

Figure 5.6: Graphical Interface for MSW Moisture Content

Figure 5.6 illustrates the graphical interface for moisture content of municipal solid waste. The calculated moisture content is in the range of MSW landfills moisture content recommended in key references as described in detail in Chapter Two.

5.2.2.2. MSW Density in LTMT

Knowledge of unit weight (density) is required for all aspects of landfill engineering. Many factors affect waste density. In this program, however, the main factors that are considered in calculating the initial density of waste are waste composition, the depth of burial or overburden stress, moisture content, the density of waste constituents, time under confinement, and the degree of compaction. Table 5.4 presents the typical range and values which are considered for the density of the waste components in LTMT. These values are adopted according to published values based on many researches (e.g. Tchobanoglous et al., 1993; US EPA, 1997; Worrell and Vesilind, 2002).

Table 5.4: Considered Ranges of Density for MSW Components in LTMT

Waste Component	**Density (kg/m^3)**	
	Typical Range	**Considered Value**
Food waste	130 – 1200	550
Paper	40 – 600	400
Cardboard	40 – 460	350
Plastics	40 – 300	230
Textiles	40 – 320	190
Rubber	100 – 400	150
Leather	100 – 400	180
Yard waste	150 - 900	450
Wood	130 – 800	700
Glass	160 – 1700	800
Metal waste	100 – 1800	550
Dirt, etc.	320 – 1000	870

In order to calculate the waste density, the following steps are incorporated into the program written in MATLAB:

- Read input parameters such as density of waste constituents, moisture content of waste components, percentage of individual components in waste, depth of burial, and time for settlement prediction.
- Check the total percentage of waste components. Obviously, the program continues running if the total percentage of waste components equals 100%.

- Check the compaction condition of waste in terms of uncompacted waste, moderately compacted waste, and well compacted waste.
- Calculate the initial density of waste according to the initial density of waste components in different compaction condition.
- Calculate the density of waste considering the depth of burial based on Equation (2.4).
- Calculate the density of waste considering the time under confinement based on Equation (2.5).
- Write the total density of waste which is calculated by taking into account the waste composition, the degree of compaction, the depth of burial (overburden stress), and the time under confinement.

The flowchart indicating density calculation sequence is shown in Figure 5.7.

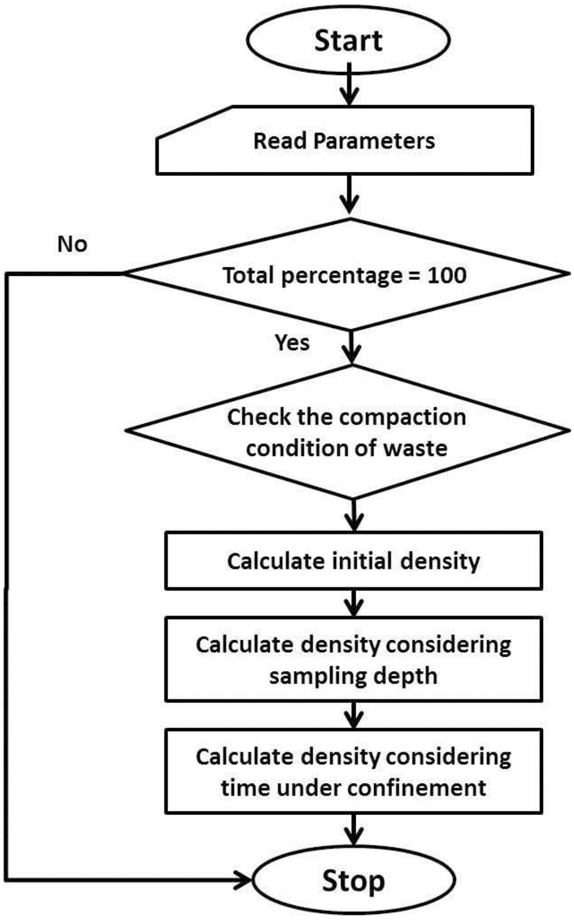
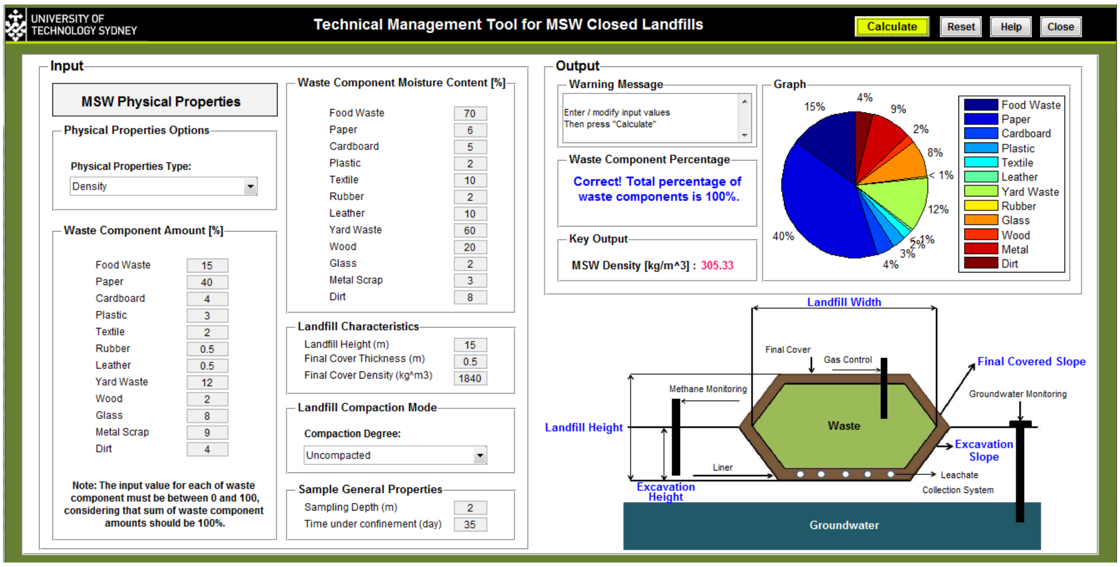


Figure 5.7: Flow Diagram for Waste Density Calculation

This program can calculate the density of solid wastes properly in the range of densities mentioned in literature reviews with different compaction effort, i.e. in the range of 305 kg/m^3 to 920 kg/m^3, 510 kg/m^3 to 800 kg/m^3, and 900 kg/m^3 to 1070 kg/m^3 for poor compaction, moderate compaction, and good compaction, respectively (Fassett et al., 1994). The graphical interface for MSW density is shown in Figure 5.8.



Physical Properties Options

Physical Properties Type: Density

Waste Component Amount [%]

Food Waste	15
Paper	40
Cardboard	4
Plastic	3
Textile	2
Rubber	0.5
Leather	0.5
Yard Waste	12
Wood	2
Glass	8
Metal Scrap	9
Dirt	4

Note: The input value for each of waste component must be between 0 and 100, considering that sum of waste component amounts should be 100%.

Waste Component Moisture Content [%]

Food Waste	70
Paper	6
Cardboard	5
Plastic	2
Textile	10
Rubber	2
Leather	10
Yard Waste	60
Wood	20
Glass	2
Metal Scrap	3
Dirt	8

Landfill Characteristics

Landfill Height (m)	15
Final Cover Thickness (m)	0.5
Final Cover Density (kg^m3)	1840

Landfill Compaction Mode

Compaction Degree: Uncompacted

Sample General Properties

Sampling Depth (m)	2
Time under confinement (day)	35

Warning Message

Enter / modify input values
Then press "Calculate"

Waste Component Percentage

Correct! Total percentage of waste components is 100%.

Key Output

MSW Density [kg/m^3] : 305.33

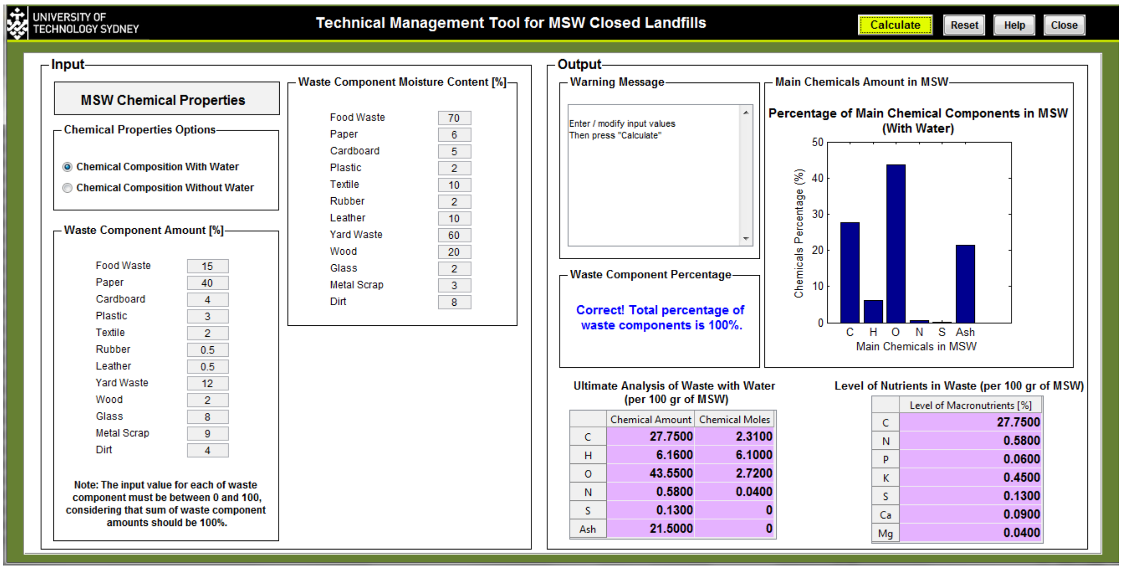
Figure 5.8: Graphical Interface of MSW Density

5.2.3. Chemical Properties Evaluation in LTMT

Information on the chemical properties of MSW is important in evaluating the potential of landfill gas production. As mentioned before, the amount of the carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and ash can be determined by the chemical analysis of a waste component. Subsequently, the results of this analysis can be used to characterize the chemical composition of the MSW. Since the landfill gas generation potential depends on the nature and the components of the MSW, this program enables users to identify the chemical composition of the municipal solid waste in order to evaluate the landfill gas production rate as well as other aspects in landfill engineering.

On the other hand, although municipal solid wastes are rich in organic sources, biological reactions and microbial activities need all required nutrients particularly nitrogen and phosphorous. Moreover, the landfill gas generation rate is highly affected by the quantity and quality of nutrients in addition to other influencing factors. Therefore, this program is suited to estimate the amount of available nutrients in the MSW.

Figures 5.9 to 5.10 illustrate graphical interfaces for chemical Properties of MSW including chemical composition of MSW with water and without water, respectively, indicating navigation, input, and output sections.



Chemical Properties Options

● Chemical Composition With Water
○ Chemical Composition Without Water

Waste Component Amount [%]	
Food Waste	15
Paper	40
Cardboard	4
Plastic	3
Textile	2
Rubber	0.5
Leather	0.5
Yard Waste	12
Wood	2
Glass	8
Metal Scrap	9
Dirt	4

Note: The input value for each of waste component must be between 0 and 100, considering that sum of waste component amounts should be 100%.

Waste Component Moisture Content [%]	
Food Waste	70
Paper	6
Cardboard	5
Plastic	2
Textile	10
Rubber	2
Leather	10
Yard Waste	60
Wood	20
Glass	2
Metal Scrap	3
Dirt	8

Warning Message

Enter / modify input values
Then press "Calculate"

Waste Component Percentage

Correct! Total percentage of waste components is 100%.

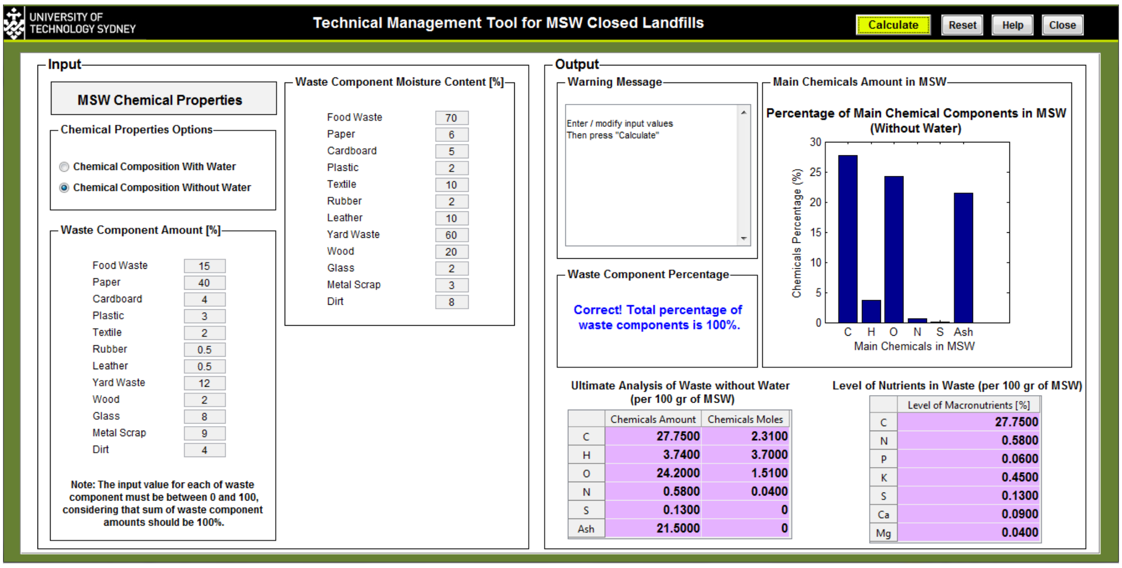
Ultimate Analysis of Waste with Water
(per 100 gr of MSW)

	Chemical Amount	Chemical Moles
C	27.7500	2.3100
H	6.1600	6.1000
O	43.5500	2.7200
N	0.5800	0.0400
S	0.1300	0
Ash	21.5000	0

Level of Nutrients in Waste (per 100 gr of MSW)

	Level of Macronutrients [%]
C	27.7500
N	0.5800
P	0.0600
K	0.4500
S	0.1300
Ca	0.0900
Mg	0.0400

Figure 5.9: Graphical Interface of Chemical Composition of MSW with Water



Chemical Properties Options

○ Chemical Composition With Water
● Chemical Composition Without Water

Waste Component Amount [%]	
Food Waste	15
Paper	40
Cardboard	4
Plastic	3
Textile	2
Rubber	0.5
Leather	0.5
Yard Waste	12
Wood	2
Glass	8
Metal Scrap	9
Dirt	4

Note: The input value for each of waste component must be between 0 and 100, considering that sum of waste component amounts should be 100%.

Waste Component Moisture Content [%]	
Food Waste	70
Paper	6
Cardboard	5
Plastic	2
Textile	10
Rubber	2
Leather	10
Yard Waste	60
Wood	20
Glass	2
Metal Scrap	3
Dirt	8

Warning Message

Enter / modify input values
Then press "Calculate"

Waste Component Percentage

Correct! Total percentage of waste components is 100%.

Ultimate Analysis of Waste without Water
(per 100 gr of MSW)

	Chemicals Amount	Chemicals Moles
C	27.7500	2.3100
H	3.7400	3.7000
O	24.2000	1.5100
N	0.5800	0.0400
S	0.1300	0
Ash	21.5000	0

Level of Nutrients in Waste (per 100 gr of MSW)

	Level of Macronutrients [%]
C	27.7500
N	0.5800
P	0.0600
K	0.4500
S	0.1300
Ca	0.0900
Mg	0.0400

Figure 5.10: Graphical Interface of Chemical Composition of MSW without Water

5.2.4. Biological Properties Evaluation in LTMT

As it was discussed in chapter two, there are many factors affecting the biodegradation rate in the landfill such as moisture, oxygen, pH, temperature, nutrients, inhibitors, and organic compounds. By far, the most critical factor is the optimum level of moisture for the microorganisms to perform the waste degradation effectively. As it is assumed that the landfill gas is generated as a result of decomposition processes in the landfill, all these factors influence the gas generation rate in landfills. In general, the main factors affecting the gas production rate in landfills are illustrated in Figure 5.11.

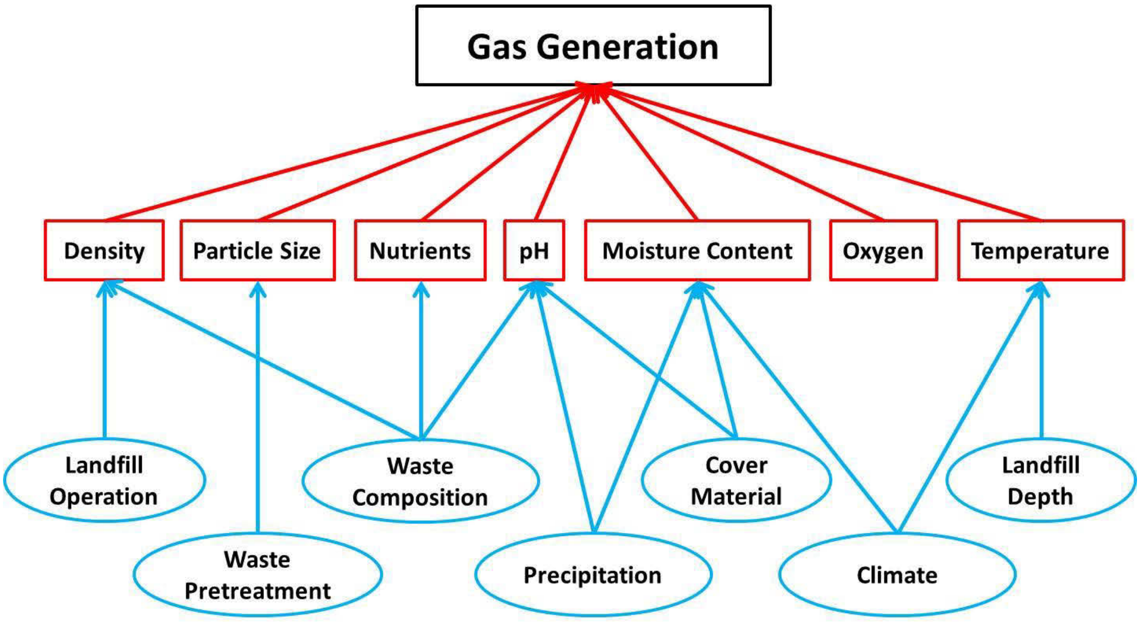


Figure 5.11: Main Factors Affecting Gas Production Rate in MSW Landfills

The landfill gas generation influences the gas and liquid pore pressures in addition to various landfill parameters such as porosity, total stress, permeability, etc., and consequently it affects the deformation in landfills. Therefore, the evaluation of landfill gas generation is extremely critical in landfill redevelopment and engineering so that it has attracted the attention of many researchers to develop different models and methods to estimate the potential of gas generation as well as gas generation rate in landfills.

In general, the landfill gas generation can be quantified either experimentally or theoretically. In experimental estimation, the actual amount of gas production is measured based on laboratory experiments and approaches. However, as gas generation is highly dependent on waste decomposition and microbial activities, many environmental factors such as pH, temperature, moisture, etc. must be considered during the laboratory experiments in order to avoid misleading results. On the other hand, theoretical estimation is mainly based on some assumptions and follows relevant formulas and existing models.

In this technical management tool, the upper boundary for gas generation potential is calculated based on the methods stoichiometric method.

As shown in Equation (5.1), stoichiometric method considers a global formula to estimate the maximum volume of the gases released during anaerobic decomposition of waste in landfills. In this method, MSW is represented by a generalized formula based on chemical composition of waste (Ham and Barlaz, 1987; Tchobanoglous et al., 1993).

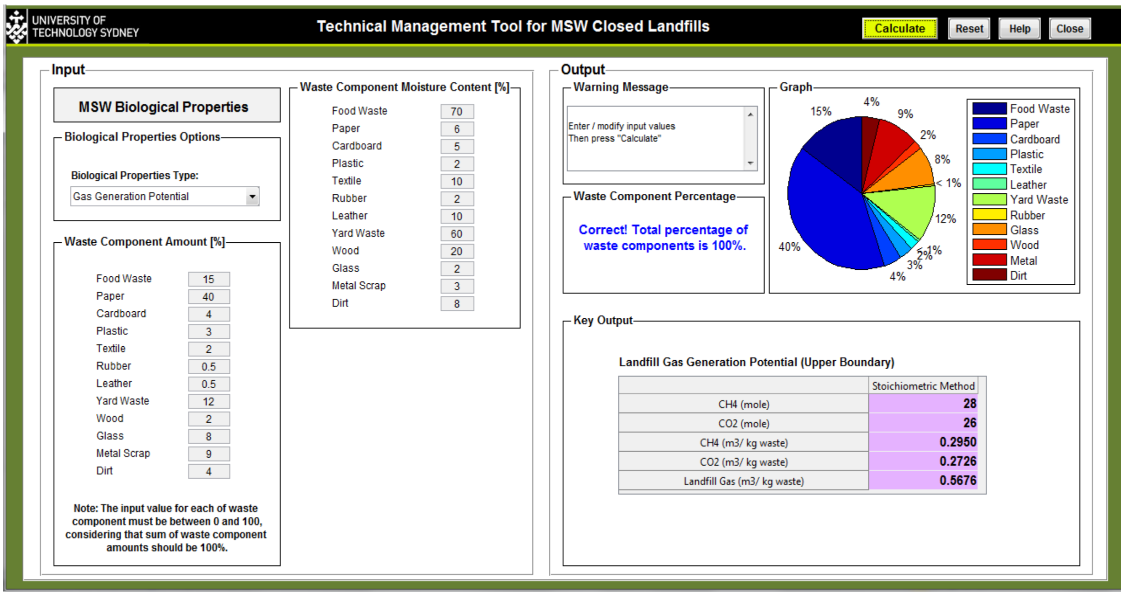
$$\mathbf{C_aH_bO_cN_d} + \left(\frac{\mathbf{4a - b - 2c + 3d}}{\mathbf{4}}\right)\mathbf{H_2O} \rightarrow \left(\frac{\mathbf{4a + b - 2c - 3d}}{\mathbf{8}}\right)\mathbf{CH_4} + \left(\frac{\mathbf{4a - b + 2c + 3d}}{\mathbf{8}}\right)\mathbf{CO_2} + \mathbf{dNH_3} \qquad (5.1)$$

The stoichiometric method assumes that complete conversion of biodegradable fraction of waste occurs in landfills to generate gas comprised of methane (CH_4) and carbon dioxide (CO_2) with the properties presented in Table 5.5. In other words, biodegradable organic wastes are not consumed in bacterial cell production. Moreover, all required nutrients are available for microbial activity. However, the complete bioconversion takes a long time and it cannot be attained in reality due to many reasons and limitations. Following the general assumption accepted in this method, this method overestimates the landfill gas yield. Therefore, it can be considered as an upper boundary on the amount of gas generation that could be achieved at landfills.

Table 5.5: Properties of Major Landfill Gases Considered in LTMT

Parameter	Unit	Methane	Carbon dioxide
Formula	-	CH_4	CO_2
Molecular Weight	g/mole	16.04	44.01
Volumetric Weight	kg/m^3	0.621	1.709
Dynamic Viscosity	Pa s	11.755×10^{-6}	15.746×10^{-6}
Pressure	kPa	101.325	101.325
Temperature	◦Celsius	42	42

For the waste composition considered in this technical management tool (Figure 5.2), the above equation gives the 27.7 and 25.6 moles methane (CH_4) and carbon dioxide (CO_2) per mole solid waste, respectively. Considering the data presented in Table 5.5, the capacity of gas production for CH_4 and CO_2 would be 295 lit/kg waste and 273 lit/kg waste, respectively. This corresponds to a production of 52% of CH_4 and 48% of CO_2 by volume. Moreover, total gas generation potential from this typical waste was estimated as 568 lit per kg waste using stoichiometric method, which is in the range of typical theoretical potential of gas generation published in literatures, i.e. 500 lit gas/ kg waste to 800 lit gas/kg waste.



Technical Management Tool for MSW Closed Landfills

Input

MSW Biological Properties

Biological Properties Options

Biological Properties Type: Gas Generation Potential

Waste Component Amount [%]

Food Waste	15
Paper	40
Cardboard	4
Plastic	3
Textile	2
Rubber	0.5
Leather	0.5
Yard Waste	12
Wood	2
Glass	8
Metal Scrap	9
Dirt	4

Note: The input value for each of waste component must be between 0 and 100, considering that sum of waste component amounts should be 100%.

Waste Component Moisture Content [%]

Food Waste	70
Paper	6
Cardboard	5
Plastic	2
Textile	10
Rubber	2
Leather	10
Yard Waste	60
Wood	20
Glass	2
Metal Scrap	3
Dirt	8

Output

Warning Message

Enter / modify input values
Then press "Calculate"

Waste Component Percentage

Correct! Total percentage of waste components is 100%.

Key Output

Landfill Gas Generation Potential (Upper Boundary)

	Stoichiometric Method
CH4 (mole)	28
CO2 (mole)	26
CH4 (m3/ kg waste)	0.2950
CO2 (m3/ kg waste)	0.2726
Landfill Gas (m3/ kg waste)	0.5676

Figure 5.12: Graphical Interface of MSW Landfill Gas Generation Potential Estimation

Based on these calculations as shown in Figure 5.12, it can be concluded that as the stoichiometric method oversimplifies the complex waste decomposition processes in landfills, it can be used to estimate the maximum amount of gas generated in proportion to the degraded wastes.

The issue of biodegradability of waste is broad. Since having knowledge about the biodegradable fraction of MSW will be useful in evaluation of waste bioconversion in landfills as well as the potential of landfill gas generation, this technical management tool enables user to calculate the biodegradable fraction of municipal solid wastes in terms of the lignin content of a waste according to previous discussion in chapter two. Obviously, as various factors, in practice, affect the biodegradation processes in landfills and because the right conditions may not exist in most landfills, the values obtained from the analytical methods usually overestimates the real conditions that occur in landfills.

5.2.5. Landfill Settlement in LTMT

According to existing researches, several factors influence the MSW settlement process including waste composition, organic content, moisture content, waste density, biodegradation rate, porosity, and etc. These influencing factors, in fact, affect different mechanisms in landfills which consequently result in landfill primary and secondary settlement.

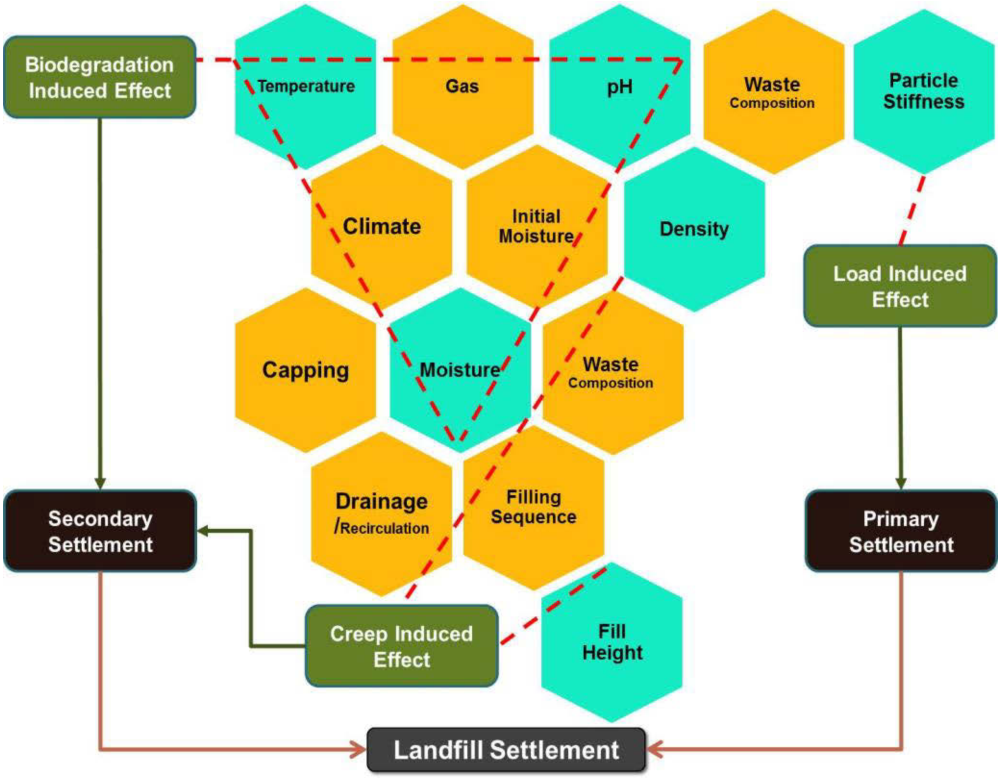
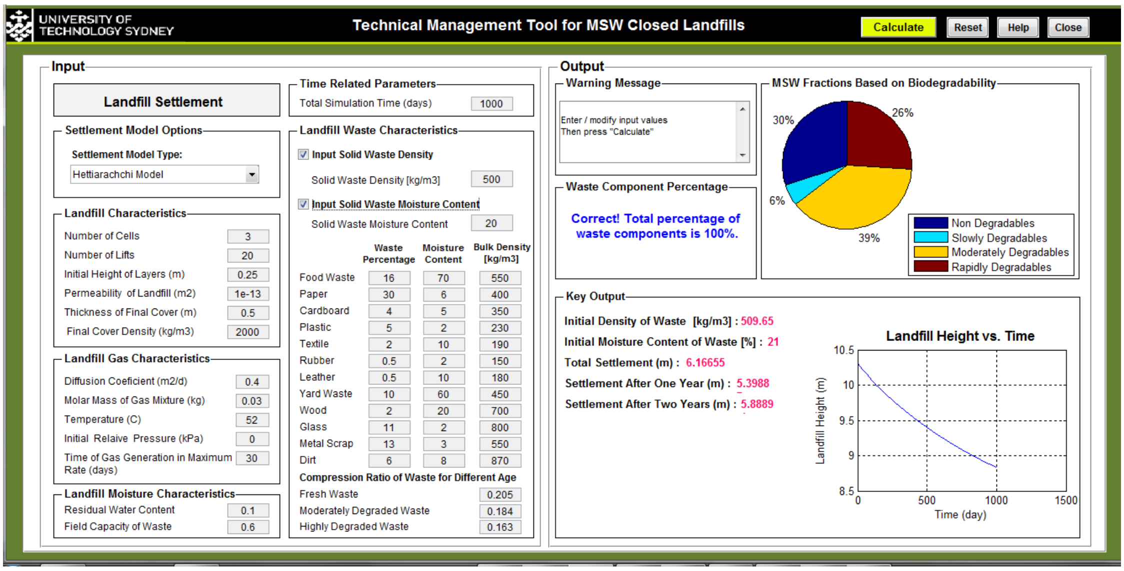


Figure 5.13: Main Factors Influencing MSW Landfill Settlement

The first group of factors involve some factors such as waste density, moisture, fill height, temperature, and pH which define the condition of waste within the landfill, while the second group of influencing factors are some factors like compaction, waste composition, filling sequence, climate, initial moisture, which affect the internal condition of landfill as well as the first group of influencing factors. These main factors are illustrated in Figure 5.13.

As shown in this figure, the second group of factors influence the first group of influencing factors, which subsequently this group affect the settlement mechanisms and hence lead to primary and secondary settlement of landfills. For example, waste composition influence the particle stiffness, which in turn, it affects the load-induced effect, and finally landfill primary settlement. On the other hand, biodegradation-induced effect which is the most significant constituent of secondary compression in MSW landfills is influenced by three kinds of factors related to the first group of factors including temperature, pH, and moisture. Meanwhile, waste composition, initial moisture, and gas affect pH; gas and climate affect temperature; and initial moisture, waste composition, filling sequence, drainage or recirculation, capping, and climate have an effect on moisture.



Time Related Parameters

Total Simulation Time (days): 1000

Settlement Model Options

Settlement Model Type: Hettiarachchi Model

Landfill Characteristics

Number of Cells: 3
Number of Lifts: 20
Initial Height of Layers (m): 0.25
Permeability of Landfill (m2): 1e-13
Thickness of Final Cover (m): 0.5
Final Cover Density (kg/m3): 2000

Landfill Gas Characteristics

Diffusion Coeficient (m2/d): 0.4
Molar Mass of Gas Mixture (kg): 0.03
Temperature (C): 52
Initial Relaive Pressure (kPa): 0
Time of Gas Generation in Maximum Rate (days): 30

Landfill Moisture Characteristics

Residual Water Content: 0.1
Field Capacity of Waste: 0.6

Landfill Waste Characteristics

☑ Input Solid Waste Density

Solid Waste Density [kg/m3]: 500

☑ Input Solid Waste Moisture Content

Solid Waste Moisture Content: 20

	Waste Percentage	Moisture Content	Bulk Density [kg/m3]
Food Waste	16	70	550
Paper	30	6	400
Cardboard	4	5	350
Plastic	5	2	230
Textile	2	10	190
Rubber	0.5	2	150
Leather	0.5	10	180
Yard Waste	10	60	450
Wood	2	20	700
Glass	11	2	800
Metal Scrap	13	3	550
Dirt	6	8	870

Compression Ratio of Waste for Different Age

Fresh Waste: 0.205
Moderately Degraded Waste: 0.184
Highly Degraded Waste: 0.163

Warning Message

Enter / modify input values
Then press "Calculate"

Waste Component Percentage

Correct! Total percentage of waste components is 100%.

Key Output

Initial Density of Waste [kg/m3] : 509.65
Initial Moisture Content of Waste [%] : 21
Total Settlement (m) : 6.16655
Settlement After One Year (m) : 5.3988
Settlement After Two Years (m) : 5.8889

Figure 5.14: Graphical Interface of MSW Landfill Settlement Estimation

According to previous discussions, although the wastes are also composed of three phases including solids, liquid, and gas, the soil mechanics concepts cannot be simply employed for landfill settlement evaluation because of the waste nature, biodegradability characteristics of MSW, liquid and gas pressures in landfill, etc. therefore, it is essential to study the landfill settlement considering all physical, chemical, and biological processes as all of them have a substantial influence on each other and also on total settlement which must not be neglected.

This technical management tool has been developed based on a settlement models which consider different phases including solid, liquid and gas phases in MSW landfills as well as mechanical, hydraulic and biological processes. Assuming parameters play a vital role in predicting settlements, this technical management tool as a user interface program enables users to estimate the MSW landfill settlement according to their specified conditions and parameters such as the landfill geometry, landfill characteristics, the waste composition, the waste moisture content, the waste density, the simulation time, the landfill gas and moisture characteristics, etc.

Based on the input data for the landfill settlement estimation, the settlement of landfill will be calculated and the results will be displayed as a graph in terms of the landfill final height versus the simulation time.

Table 5.6: Parameter Identification for Calculation of Landfill Settlement in LTMT

Input Parameter	Value	Unit
Landfill Height	15	m
Simulation Time	1000	day
Intrinsic Permeability	10^{-13}	m^2
Moisture Content	20	%
Field Capacity	60	As a percentage of porosity
Residual Moisture Content	0.1	-
Van Genuchten parameter (α)	26	-
Van Genuchten parameter (n)	1.6	-
Van Genuchten parameter (p)	0.5	-
Gas Diffusion Coefficient	0.4	m^2/day
Molar Mass of Gas Mixture	0.03	kg (50% CH_4 and 50% CO_2)
Temperature	42	Celsius Degree
Atmospheric Pressure	101	kPa
Initial Relative Pressure	0	kPa
Gas Generation Potential	0.28	m^3/kg waste
Time for the Peak Rate of Gas Generation	30	day
Waste Density	500	kg/m^3
Compression Ratio	0.205 0.184 0.174 0.163	time < 200 days time: 200 days - 2000 days time: 2000 days - 20000 days time > 20000 days
Swell Ratio	0.069 0.067 0.064 0.043	time < 200 days time: 200 days - 2000 days time: 2000 days - 20000 days time > 20000 days
Waste Mass Fractions	35 0.25 0.25 0.15	% (Non-degradable wastes) % (Slowly degradable wastes) % (Moderately degradable wastes) % (Rapidly degradable wastes)
Waste Specific Gravity	3 2 1.2 1	Non-degradable wastes Slowly degradable wastes Moderately degradable wastes Rapidly degradable wastes
Waste Decay Constant	0 0.00001 0.0001 0.001	day^{-1} (Non-degradable wastes) day^{-1} (Slowly degradable wastes) day^{-}1 (Moderately degradable wastes) day^{-}1 (Rapidly degradable wastes)

Moreover, the total landfill settlement as well as the settlement at the end of each year will be displayed at the output panel, as presented in Figure 5.14. The main input parameters in this technical management tools as well as the default values considered for them are summarized in Table 5.6.

Furthermore, the fundamentals of the model adopted for this technical management tool is described in detail in Chapter Three.

5.2.6. Landfill Slope Stability in LTMT

Stability is one of the most significant issues in landfill engineering. Slope failure of landfill can occur during the construction of landfill, filling operations or after closure of the landfill. Therefore, many parameters including geotechnical aspects, landfill geometry, and loading conditions should be considered in the landfill engineering in order to prevent landfill failures and increase the safety factor of landfill slope stability. In this study, the slope stability analysis of the landfill was performed for different landfills in terms of their total heights and slope inclinations with PLAXIS 2D program to evaluate the influence of the slope geometry and landfill height on the safety factor (SF) of landfill slope stability. The procedure of this numerical analysis as well as its results is described in detail in Chapter Four.

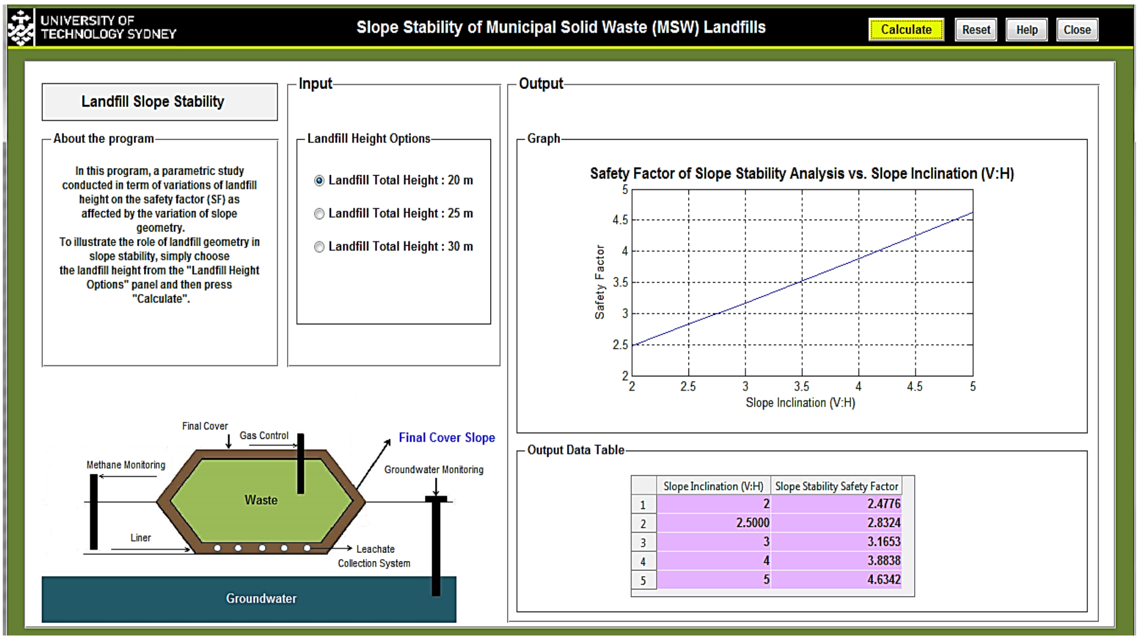
Furthermore, as the numerical study of landfill slope stability is based on the engineering properties of municipal solid wastes, extensive knowledge on the mechanical properties of waste materials including friction angle, cohesion, etc. are of utmost importance. Thus, the concepts of these waste properties are discussed in Chapter Two. However, the geotechnical properties of MSW which are considered in this numerical analysis and the typical values for these properties are presented in Table 5.7.

Table 5.7: Typical Geotechnical Properties of MSW

Parameter (Unit)	Typical range	Considered value
Cohesion (kN/m^2)	0 – 30	11
Elastic Modulus (MPa)	40 – 120	-
Poisson’s ratio	0.2 – 0.5	-
Friction angle (Degree)	20 – 35	29

It should be noted that the Soft Soil Creep Model has been chosen for modelling waste material in this numerical analysis, as detailed in Chapter Four. Therefore, some of geotechnical properties of the waste such as elastic modulus and Poisson's ratio were not considered in this model.

Eventually, the result of this numerical analysis regarding landfill slope stability safety factor as affected by the variations of the slope geometry and landfill height is demonstrated in Slope Stability part of Landfill Technical Management Tool (LTMT) in order to illustrate the role of the landfill height and the slope inclination in landfill slope stability (Figure 5.15).



In this program, a parametric study conducted in term of variations of landfill height on the safety factor (SF) as affected by the variation of slope geometry.
To illustrate the role of landfill geometry in slope stability, simply choose the landfill height from the "Landfill Height Options" panel and then press "Calculate".

● Landfill Total Height : 20 m
○ Landfill Total Height : 25 m
○ Landfill Total Height : 30 m

	Slope Inclination (V:H)	Slope Stability Safety Factor
1	2	2.4776
2	2.5000	2.8324
3	3	3.1653
4	4	3.8838
5	5	4.6342

Figure 5.15: Graphical Interface of MSW Landfill Slope Stability

5.3. Summary

As land becomes more valuable, reuse of abandoned land including former landfills is becoming more widespread. Landfills provide unique opportunities for reuse, although significant development limitations and many relevant considerations must be addressed. Among various factors and conditions that should be considered in landfill redevelopment, settlement of waste can be the most important one and needs to be considered in this regard.

Prediction of MSW landfill settlement is not only critical to design cover systems but also to ensure the safety of appurtenant structures placed within the waste (e.g., gas extraction wells/drains) and structures constructed over the landfill.

MSW settles due to physical, chemical, and biological processes. Several models have been developed based on different assumptions. These models can be used in advanced numerical methods to predict the settlement behaviour of MSW landfills. According to review of the models and studies on landfill settlement, it has been concluded that there are limited number of models that consider all three processes for the settlement. Moreover, the predicted settlement can vary significantly depending on the model selected and the specific values of model parameters used. Therefore, it is essential to study the landfill settlement estimation considering all physical, chemical, and biological processes is of critical importance in landfill engineering as all of these processes have a substantial influence on each other and also on total settlement which must not be neglected. In this study, a technical management tool is developed to predict the time dependent settlement of MSW landfills coupled with landfill gas pressure and leachate flow while this technical management tool is able to measure MSW physical, chemical and biological properties.

Moreover as discussed in this chapter, this landfill technical management tool (LTMT) is comprised of different parts which enable the user to investigate the role of various parameters and conditions on landfill settlement and slope stability. Some software packages such as MATLAB and PLAXIS are employed in the development of this technical management tool.

Chapter 6

Parametric Study and Sensitivity Analysis

6.1. Introduction

Large amount of wastes are being generated annually in all over the world. Landfilling is still the most common method for disposal of municipal solid waste (MSW) worldwide. In recent times, MSW landfilling and even more development on top of landfills have significantly improved. Generally, evaluation of settlement is one of the critical components in landfill redevelopment and engineering management. This evaluation requires extensive knowledge of the different processes, which occurs simultaneously in MSW during settlement as well as various parameters such as waste composition, landfill characteristics, waste compression ratio, etc., which affect the landfill settlement behaviour.

All these parameters are highly variable due to heterogeneity of MSW and the landfill condition. The literature review indicates that the variability of these parameters plays a vital role in landfill behaviour and influences the waste settlement in landfills. Therefore, the purpose of this chapter is to illustrate the role of these parameters in landfill settlement through conducting a detailed parametric study considering variations of different parameters in term of variations of the settlement with time. In addition, the results of a sensitivity analysis, performed to study the sensitivity of a designated model to variation of input parameters such as unit weight, landfill height and waste properties, are presented in this chapter. It can be noted that all analyses have been carried out using the developed model as a code written in MATLAB software.

6.2. Parametric Study on Input Parameters

To investigate the performance of the MSW landfill with respect to changes in input parameters, the parametric study has been performed for the main parameters over a reasonable range. In this study, several parameters have been selected for the aforementioned purpose of investigating the influence of the different parameters on the landfill settlement behaviour during a period of approximately 50 years (i.e.18250 days). The landfill height, the waste density, the elapsed time, the gas diffusion coefficient, the waste moisture content, the compression ratio, the amount of rapidly degradable wastes, the decay constant, the landfill permeability, the Van Genuchten parameter (α) , and the lift thickness have been the variable parameters selected for the parametric study. The investigated parameters and the range of their values used in this parametric study are presented in Table 6.1. Moreover, this section and the subsequent sections provide more information on this parametric study and discuss on the generated results.

Table 6.1: Investigated Parameters in the Parametric Study

Parameter	Unit	Range of Value	Base Value
Landfill Height	m	5 – 55	15
Waste Density	kg/m^3	500 – 1500	500
Time	day	100 – 9500	1000
Gas Diffusion Coefficient	m^2/day	0.4 – 2	0.4
Waste Moisture Content	%	15 – 60	20
Compression Ratio	-	0.155 – 0.358	0.205
Amount of Rapidly Degradable Wastes	%	15 – 90	15
Waste Decay Constant	day^{-1}	0.0001 – 0.002	0.001
Landfill Permeability	m^2	$10^{-14} – 10^{-12}$	10^{-13}
Van Genuchten Parameter (α)	m^{-1}	22 - 30	26
Lift Thickness	m	0.20 – 5	0.25

6.2.1. Parametric Study on Landfill Height

In order to demonstrate the effect of varying the landfill height to the variation of landfill settlement, a number of different value of landfill height but the same values in all the other parameters, have been taken into account to reveal the trend therein. Table 6.2 lists the results of this analysis.

Table 6.2: The Influence of Initial Height of Landfill on Settlement

Landfill Height (m)	Initial Settlement (m)	Final Settlement (m)
5	1.28	2.12
10	2.90	4.58
15	4.71	7.24
20	6.65	10.04
25	8.69	12.94
30	10.82	15.93
35	13.01	18.99

As previously mentioned, the waste decomposition in landfills generates gas, which causes a change in gas and liquid pressures in the landfill. These pressure changes will influence the porosity, stress, degree of liquid and gas saturations, which consequently affect the landfill settlement. Since the overburden pressure at the landfill bottom reaches to its maximum value, the stresses and the pressures would be at their highest value. As the landfill height increases, this condition would be worse. Therefore the amount of landfill settlement in the longest landfill is the highest. This can be described due to the overburden pressure. Referring to available references (e.g. Stearns, 1987; Tchobanoglous et al., 1993), the estimates of the total settlement of a landfill ranges from 20% to 50% of the landfill initial thickness. This estimation as well as the above mentioned description can be seen in the obtained results of the parametric study on landfill height.

Thus, it is reasonable to assume that the longest landfills would lead to a higher landfill settlement, as more overburden pressure provides the opportunity for more compression and increases the waste density. Figure 6.1 clearly illustrates the trend of variation of landfill settlement when the parameter, landfill height, changes. As shown in this figure and the above table, the settlement increases if the landfill height increases. In other words, the final settlement value increased from 2.12 m to 18.99 m in 50 years by increasing the landfill height from 5 m to 35 m, whereas the initial settlement (after 1 day) varied from 1.28 m to 13.01 m.

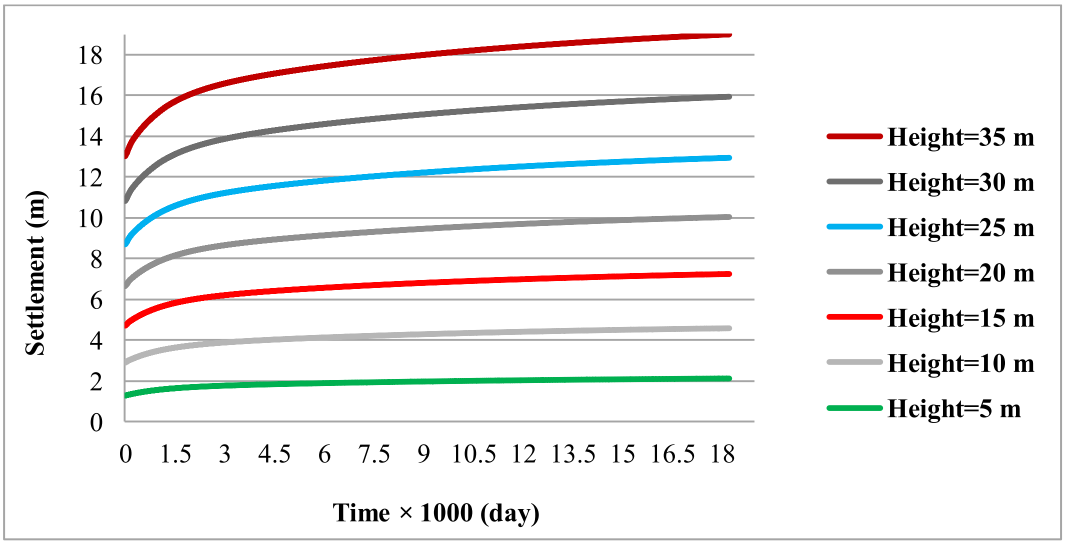


Figure 6.1: Time versus Landfill Settlement for Different Height of Landfill

6.2.2. Parametric Study on Waste Density

Generally, the waste density is one of the most significant factors, affecting the MSW landfill settlement. A contributing characteristic, which influences the landfill density and hence settlement over the time is the decomposition of the organic portions of the waste materials. As organic wastes decompose, void spaces are created in the waste matrix, which then compresses under the weight of overlying layers to attempt to fill the void spaces. This compression results in the density increase and is reflected by settlement at the landfill surface. Therefore, the waste density can be considered as one of the most important parameters, which should be taken into account in the parametric study. Accordingly, the same approach, as explained in the previous section, is applied to analyse the effect of the waste density on the landfill settlement. The results of this study are listed in Table 6.3.

Table 6.3: The Influence of Waste Density on Landfill Settlement

Waste Density (kg/m^3)	Initial Settlement (m)	Final Settlement (m)
500	4.71	7.24
600	4.64	7.66
700	4.59	8.12
800	4.56	8.58
900	4.52	9.48
1000	4.50	10
1100	4.48	10.68

Figure 6.2 illustrates the variation of waste density versus the landfill settlement. As can be seen in this figure, the settlement increases with an increase of waste density within the range of density considered herein.

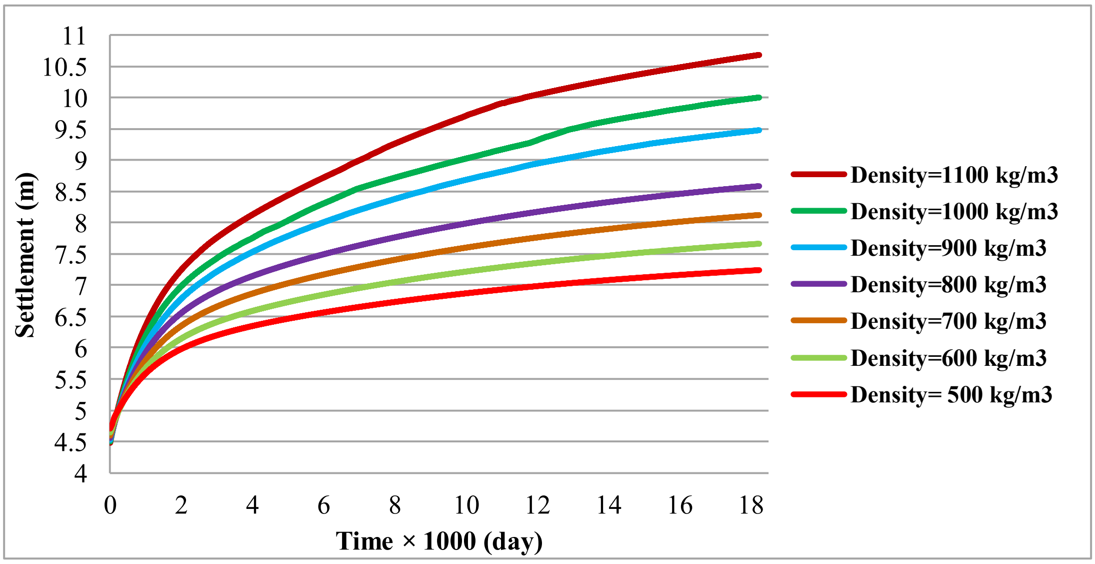


Figure 6.2: Time versus Landfill Settlement for Different Waste Densities

Table 6.4: The Influence of Time on Landfill Settlement

Time (day)	Settlement (m)	Time (day)	Settlement (m)	Time (day)	Settlement (m)
1	4.7055	**5400**	6.5059	**18500**	7.2494
100	4.8584	**5600**	6.5258	**19000**	7.2644
200	4.9767	**5800**	6.5451	**19500**	7.2789
300	5.0773	**6000**	6.5640	**20000**	7.2928
400	5.1697	**6200**	6.5824	**20500**	7.3065
500	5.2546	**6400**	6.6004	**21000**	7.3196
600	5.3327	**6600**	6.6181	**21500**	7.3323
700	5.4046	**6800**	6.6353	**22000**	7.3445
800	5.4710	**7000**	6.6522	**22500**	7.3562
900	5.5323	**7200**	6.6688	**23000**	7.3676
1000	5.5890	**7400**	6.6850	**23500**	7.3785
1100	5.6415	**7600**	6.7009	**24000**	7.3891
1200	5.6903	**7800**	6.7165	**24500**	7.3993
1300	5.7357	**8000**	6.7318	**25000**	7.4091
1400	5.7779	**8100**	6.7393	**25500**	7.4186
1500	5.8174	**8400**	6.7615	**26000**	7.4278
1600	5.8542	**8700**	6.7831	**26500**	7.4368
1700	5.8887	**9000**	6.8041	**27000**	7.4454
1800	5.9211	**9300**	6.8245	**27500**	7.4537
1900	5.9516	**9600**	6.8444	**28000**	7.4618
2000	5.9803	**10000**	6.87	**28500**	7.4697
2200	6.0331	**10500**	6.9009	**29000**	7.4773
2400	6.0806	**11000**	6.9303	**29500**	7.4847
2600	6.1237	**11500**	6.9585	**30000**	7.4918
2800	6.1630	**12000**	6.9855	**30500**	7.4988
3000	6.1992	**12500**	7.0114	**31000**	7.5056
3200	6.2328	**13000**	7.0361	**31500**	7.5122
3400	6.2641	**13500**	7.0598	**32000**	7.5186
3600	6.2935	**14000**	7.0825	**32500**	7.5248
3800	6.3214	**14500**	7.1043	**33000**	7.5309
4000	6.3478	**15000**	7.1251	**33500**	7.5368
4200	6.3730	**15500**	7.1451	**34000**	7.5425
4400	6.3972	**16000**	7.1643	**34500**	7.5482
4600	6.4204	**16500**	7.1827	**35000**	7.5536
4800	6.4428	**17000**	7.2004	**35500**	7.559
5000	6.4645	**17500**	7.2174	**36000**	7.5642
5200	6.4855	**18000**	7.2337	**36500**	7.5693

However, the calculated data indicated that the final settlement value increases from 7.24 m to 10.68 m over a period of 50 years as the waste density increases from 500 kg/m^3 to 1100 kg/m^3, whereas the initial settlement decreases from 4.71 m to 4.48 m, as presented in both Table 6.3 and Figure 6.2.

6.2.3. Parametric Study on Time

The MSW landfill settlement is highly affected by time as all processes and mechanisms such as mechanical creep and biodegradation occurring in landfills are time dependent processes. Therefore, another parameter which was considered in this parametric study was the elapsed time and the results of parametric study for investigating the influence of time are listed in Table 6.4. Based on these results, the amount of settlement at the end of 10,000 days is found to be 6.87 m for a 15 m depth landfill, which is well within the range for MSW landfills as proposed by many researchers as discussed previously.

Figure 6.3 demonstrates the variation of landfill settlement due to the variation of time. As shown in this figure, the majority of settlement takes place after landfill closure over a number of years. After that the rate of settlement gradually slowed down until it achieves a steady state. It can be noted that considerable amount of settlement also occurs during the filling and construction stages of the landfill.

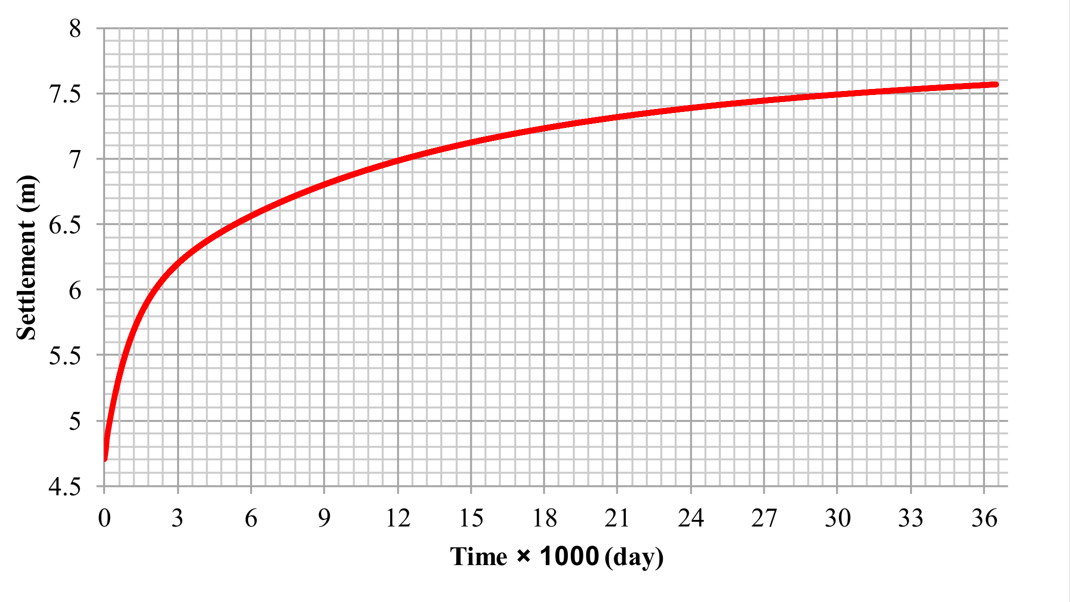


Figure 6.3: Time versus Landfill Settlement

As depicted in Figure 6.3, there is a high rate of settlement for the first 2,000 days (approximately 5 years). This rate of settlement increases within the first 5 years and at the end of 22,000 days (approximately 60 years). However, this rate slows down thereafter until the end of 100 years. The results of this parametric study (as specified in Table 6.4) express that the settlement value varies from 4.71 m to 5.92 m (approximately 26%) over 1800 days (5 years), while this value increases to 7.34 m at the end of 60th year or over a period of 21,900 days (approximately 24% with respect to the settlement after 5 years). Finally, the settlement value increases with lower rate until the end of 36,500 days (100 years) so that it reaches to 7.57 m, which means approximately 3% increase with respect to the settlement after 60 years.

6.2.4. Parametric Study on Gas Diffusion Coefficient

Gas diffusion coefficients are constant rates that determine the mode of landfill gas transport and quantify the rate of diffusion. Different diffusion coefficients are published for landfill gases based on their compounds. As the gas diffusion coefficient is a function of temperature and porosity, it has been considered as one of the influencing parameters in parametric study for a landfill depth of 15 m over a period of 18250 days. The results of parametric study of landfill settlement for different values of gas diffusion coefficient are given in Table 6.5.

Table 6.5: The Influence of Gas Diffusion Coefficient on Landfill Settlement

Gas Diffusion Coefficient (m^2/day)	Final Settlement (m)	Final Settlement with more precision (m)
0.4	7.240	7.2403142
0.6	7.240	7.2403116
0.8	7.240	7.2403103
1	7.240	7.2403095
1.2	7.240	7.2403090
1.4	7.240	7.2403085
1.6	7.240	7.2403083
1.8	7.240	7.2403080
2	7.240	7.2403079

The obtained values of final settlement for different gas diffusion coefficients show a negligible decrease (approximately 0.00009%) as the gas diffusion coefficient increases from 0.4 m^2/day to 2 m^2/day over a period of 18250 days. This is reflected in Figure 6.4, in which all the graphs plotted to illustrate the trend of variation of landfill settlement when the gas diffusion coefficient changes, are completely overlapped.

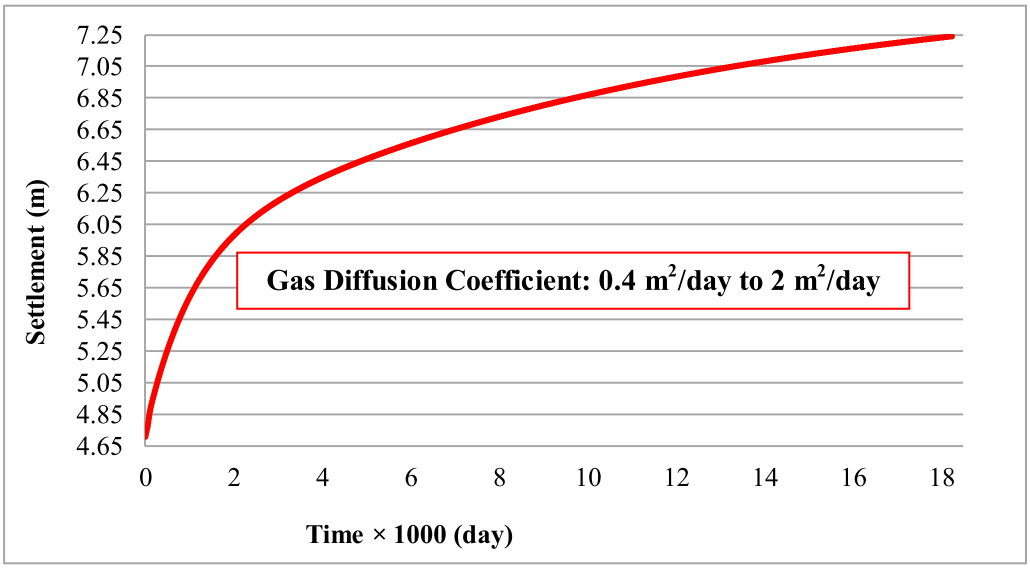


Figure 6.4: Time versus Landfill Settlement for Different Gas Diffusion Coefficients (all graphs are overlapping due to negligible effect of gas diffusion coefficient on settlement)

Table 6.6: The Influence of Moisture Content on Landfill Settlement

Moisture Content (%)	Final Settlement (m)
15	7.302
17	7.270
20	7.240
25	7.228
27	7.227
29	7.228
31	7.239
32	7.246
33	7.264
34	7.264
35	7.229
37	7.209
40	7.2
42	7.2
45	7.2
47	7.2
50	7.2

6.2.5. Parametric Study on Waste Moisture Content

As Moisture content provides an aqueous environment that facilitates the transport of nutrients and microbes within the landfill, it is a variable that has the greatest effect on the biodegradation process, and hence the landfill settlement.

Therefore, it has been considered as one of parameters in the parametric study and the results of parametric study of landfill settlement at different values of the waste moisture content are given in Table 6.6.

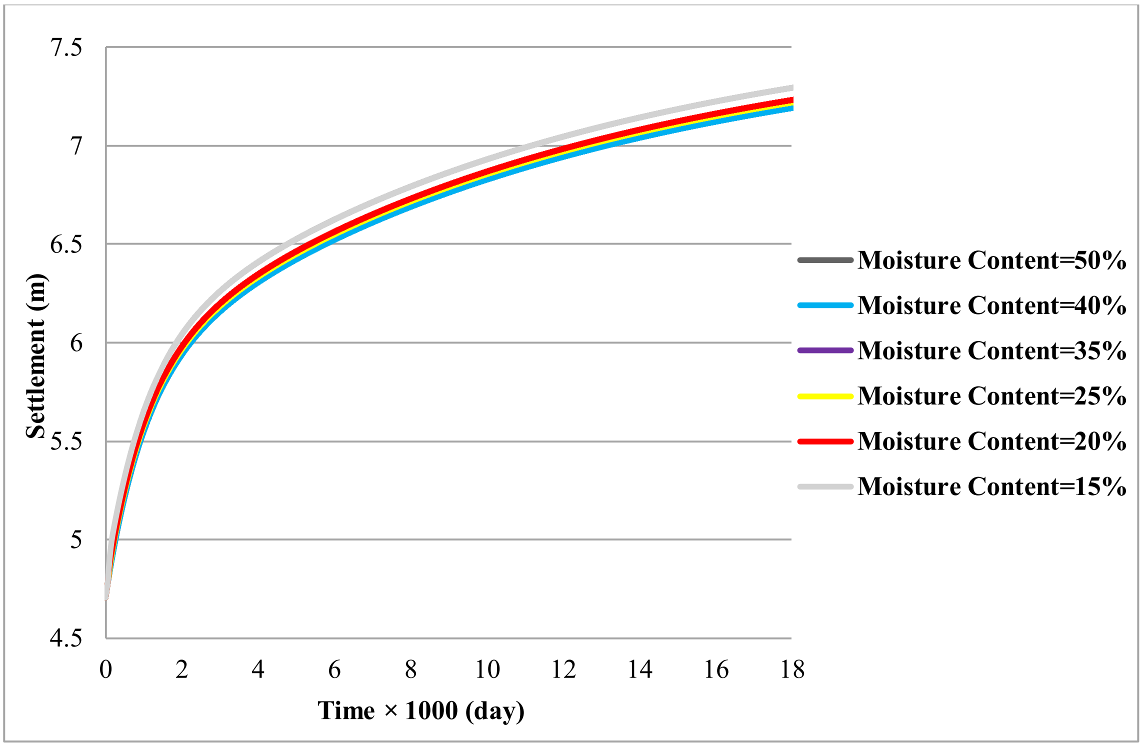


Figure 6.5: Time versus Landfill Settlement for Different Waste Moisture Content

Figure 6.5 shows the variation of landfill settlement due to the variation of waste moisture content.

6.2.6. Parametric Study on Compression Ratio

The compression ratio is an important factor, which imposes a significant influence on the behaviour of the landfill settlement. In order to demonstrate the effect of varying the compression ratio to the variation of landfill settlement over a period of 50 years, a number of different values of the compression ratio at different ages of waste as well as different swelling ratios have been taken into account to reveal the trend of variation of landfill settlement due to the variation of compression ratio as presented in Table 6.7. Subsequently, Table 6.8 specifies the data regarding the influence of the variation of compression ratio on the variation of landfill settlement. The data provided in this table shows the comparison of time-settlement response for the different values of compression ratio. It can be noted that the higher values of compression ratio are associated with larger settlements. It can also be noted that by increasing the compression ratio from 0.154 to 0.363, the differences in the settlement at the initial stage would be from 3.535m to 8.336m (approximately 136%), while the final settlement at the end of 50 years will be from 6.106m to 10.887m (about 78%).

Table 6.7: The Assumed Values for Parametric Study of Compression Ratio

Compression Ratio for Different Waste Age				Swelling Ratio for Different Waste Age			
< 200 days	200 – 2000 days	2000 – 20000 days	> 20000 days	< 200 days	200 – 2000 days	2000 – 20000 days	> 20000 days
0.1540	0.1382	0.1307	0.1225	0.0518	0.0503	0.0481	0.0323
0.1694	0.1521	0.1438	0.1347	0.0570	0.0554	0.0529	0.0355
0.1864	0.1673	0.1582	0.1482	0.0627	0.0609	0.0582	0.0391
0.205	0.184	0.174	0.163	0.0690	0.0670	0.0640	0.0430
0.2255	0.2024	0.1914	0.1793	0.0759	0.0737	0.0704	0.0473
0.2480	0.2226	0.2105	0.1972	0.0835	0.0811	0.0774	0.0520
0.2729	0.2449	0.2316	0.2170	0.0918	0.0892	0.0852	0.0572
0.3001	0.2694	0.2548	0.2385	0.1010	0.0981	0.0937	0.0630
0.3301	0.2963	0.2802	0.2625	0.1111	0.1079	0.1031	0.0693
0.3632	0.3260	0.3082	0.2888	0.1222	0.1187	0.1134	0.0762

Table 6.8: The Influence of Compression Ratio on Landfill Settlement

Compression Ratio	Initial Settlement (m)	Final Settlement (m)
0.1540	3.535	6.106
0.1694	3.889	6.450
0.1864	4.279	6.828
0.205	4.705	7.240
0.2255	5.176	7.693
0.2480	5.692	8.194
0.2729	6.264	8.752
0.3001	6.888	9.353
0.3301	7.576	10.020
0.3632	8.336	10.887

Figure 6.6 clearly illustrates the increasing trend of variation of landfill settlement when the compression ratio changes. Referring to this figure, MSW with low compressibility undergoes less settlement with time. Therefore, the compressibility parameter plays a significant role in the time compression response of waste.

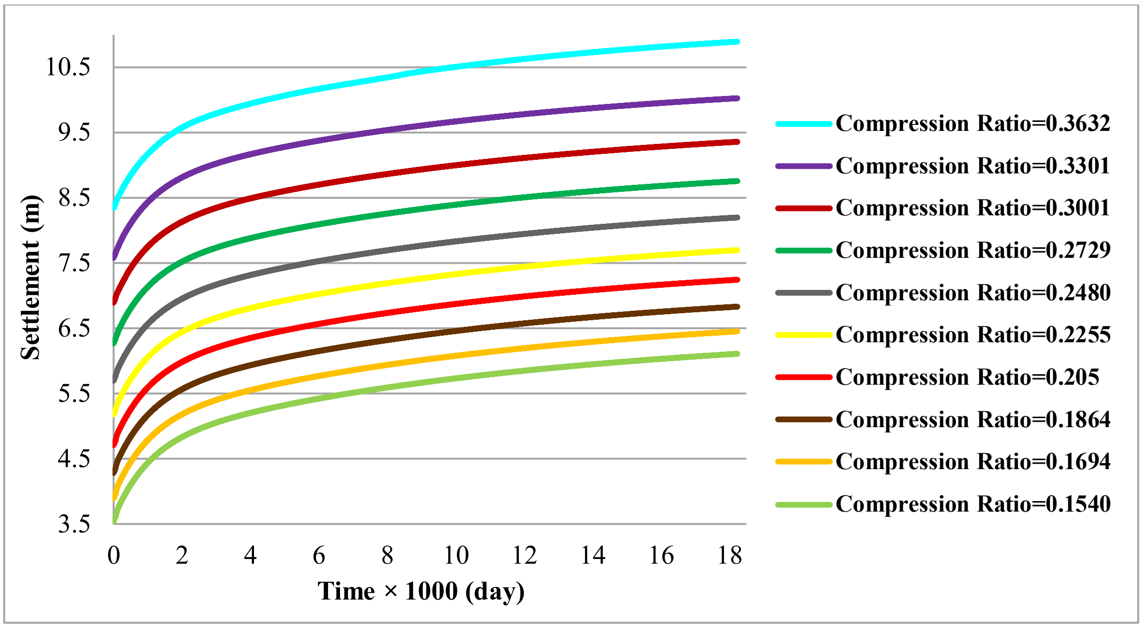


Figure 6.6: Time versus Landfill Settlement for Different Compression Ratios

6.2.7. Parametric Study on the Amount of Rapidly Degradable Wastes

The amount of degradable materials, particularly rapidly degradable materials, in waste have a substantial effect on landfill settlement due to explicit relationship between waste degradation and landfill settlement. Referring to Al-Khafaji and Andersland (1981), the settlement due to decomposition of organics might be more significant than settlement induced by applied loadings. Therefore, there is a need to study the effect of biodegradation on time-settlement response. Since the total biodegradation settlement can be related to the total biodegradable matter present in the MSW, to assess the settlement behaviour of MSW with respect to biodegradation effect, different values of the biodegradable materials are used, while keeping the waste decay coefficient constant and the other parameters the same.

The correlation between the amount of rapidly degradable wastes and the landfill settlement can be observed in the results of parametric study concerning the influence of waste composition in terms of the amount of rapidly degradable wastes on landfill settlement as specified in Table 6.9.

As the data presented in Table 6.9 clearly show, there are minor differences in the settlement at the initial stage (approximately 0.09%). However, as time increases the biodegradation settlement increases from 7.240 m to 9.771 m (about 35%) reaching a final value corresponding to the total biodegradation settlement at the end of 50 years.

Table 6.9: The Influence of Degradable Wastes Amount on Landfill Settlement

Rapidly Degaradable Waste (%)	Initial Settlement (m)	Final Settlement (m)
15	4.705	7.240
21	4.706	7.554
27	4.706	7.868
33	4.707	8.183
39	4.707	8.497
45	4.708	8.821
51	4.708	9.139
57	4.709	9.449
63	4.709	9.771

The increasing trend of the curve by increasing the amount of rapidly degradable wastes is obviously demonstrated in Figure 6.7.

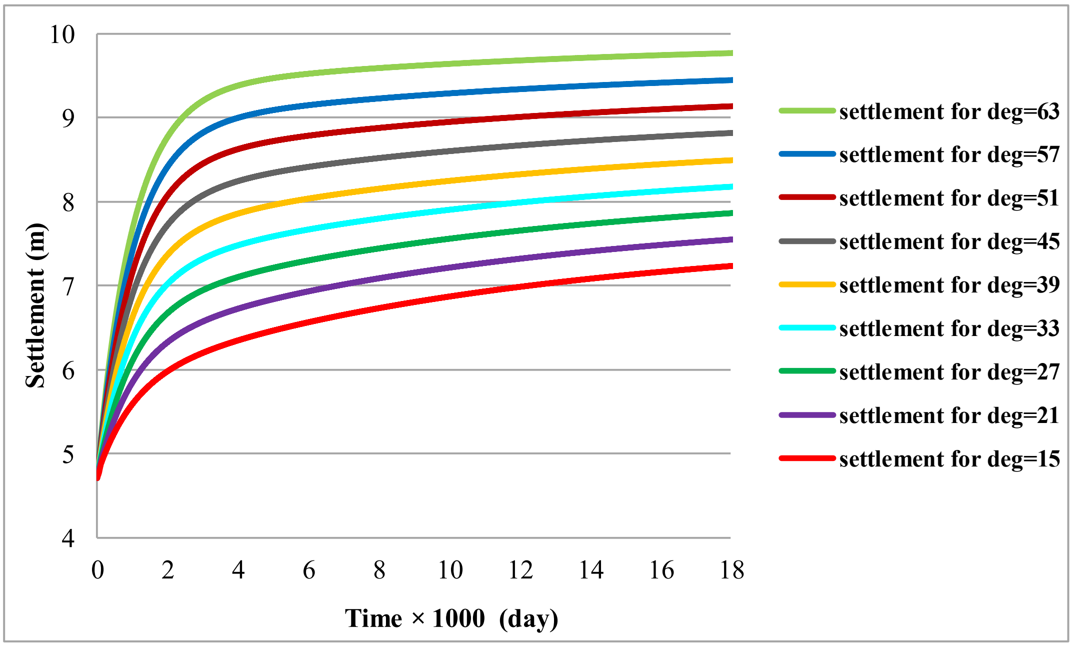


Figure 6.7: Time versus Landfill Settlement for Different Amount of Rapidly Degradable Wastes

From the plotted results, it is observed that the waste settlements are highly influenced by the values of total biodegradable materials presented in landfills. The predicted results show that biodegradation effect is more pronounced causing higher settlements in the case of waste materials having higher values of biodegradable content. Thus, the degree of settlement depends on the quantity of biodegradable waste present in MSW.

6.2.8. Parametric Study on Waste Decay Constant

The landfill settlement is highly related to the waste decomposition as waste decay increases the waste porosity due to mass loss, and hence leads to the landfill settlement. Solid wastes are heterogeneous material including different components of waste with specific biodegradability. Since the first order kinetics is used to estimate decomposition in landfills, a better understanding of the waste decay constant parameter as the first order kinetic constant in related equation would increase the understanding of waste decomposition and consequently landfill settlement. Therefore, this parameter is considered as one of the most important parameter in this parametric study.

Table 6.10: The Influence of Waste Decay Constant on Landfill Settlement

Decay Constant (day^{-1})	Initial Settlement (m)	Final Settlement (m)
0.0001	4.704	5.929
0.0002	4.704	6.301
0.0003	4.705	6.513
0.0004	4.705	6.676
0.0005	4.705	6.812
0.0006	4.705	6.927
0.0007	4.705	7.024
0.0008	4.705	7.107
0.0009	4.705	7.179
0.0010	4.705	7.240
0.0011	4.706	7.294
0.0012	4.706	7.340
0.0013	4.706	7.380
0.0014	4.706	7.416
0.0015	4.706	7.447

To conduct this study, the values for this parameter have been selected in the range of 0.0001 day^{-1} and 0.0015 day^{-1} for rapidly degradable wastes. Subsequently, the time-settlement response is calculated for these different values of waste decay constant, while keeping the other parameters the same. The results for investigating the effect of waste decay constant on landfill settlement are listed in Table 6.10. The results show that the rate of degradation affects settlement. For smaller values of waste decay constant, the smaller settlement observed while for higher values of waste decay constant, higher settlement resulted. Based on these calculations, the increase in settlement at early stages is insignificant. However, the final settlement changes from 5.93 m to 7.45 m (approximately 26%) as waste decay constant of rapidly degradable wastes increases from 0.0001 day^{-1} to 0.0015 day^{-1}.

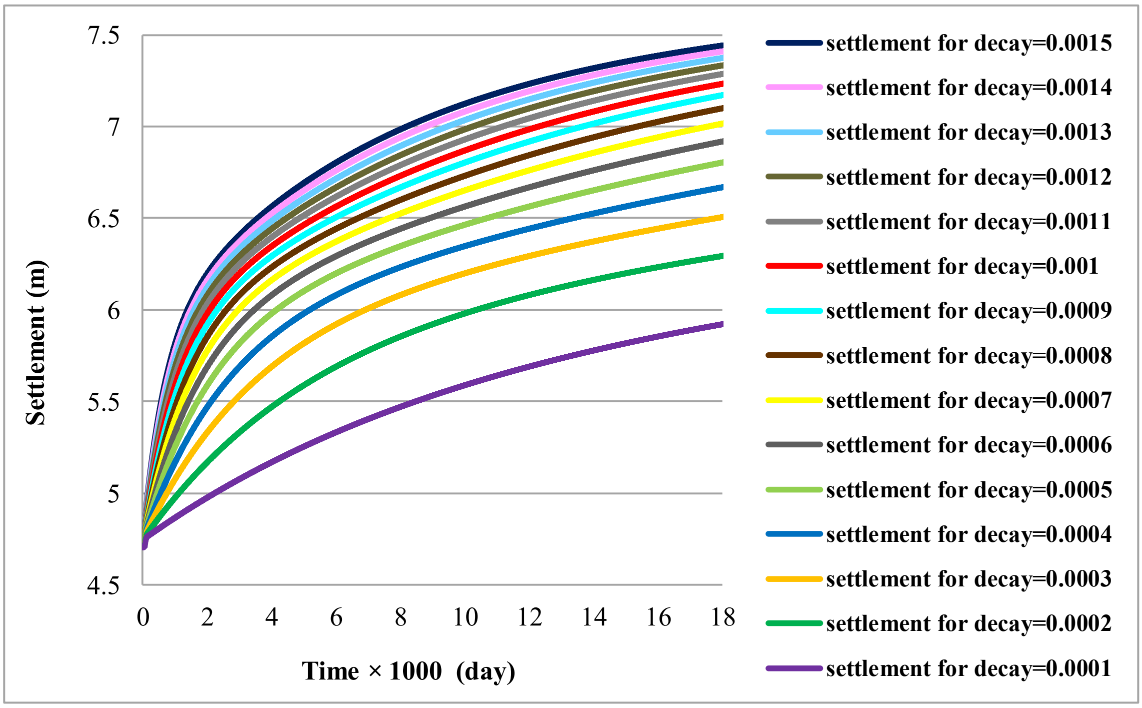


Figure 6.8: Time versus Landfill Settlement for Different Values of Decay Constant

Comparison of time-settlement response for different values of waste decay constant is shown in Figure 6.8. This figure depicts that the settlement clearly increases by increasing the waste decay constant. Therefore, as expected, it can be concluded that the rate of biodegradation significantly influence the landfill settlement response. Hence, enhancement of biodegradation rates through different methods such as leachate recirculation can lead to acceleration in landfill settlement.

6.2.9. Parametric Study on Landfill Permeability

In general, the permeability of waste is an important parameter which governs the movement of liquid and gases in MSW landfills, and hence influences the landfill behaviour. Therefore, in order to investigate the effect of permeability on landfill settlement, a parametric study was conducted on landfill settlement assuming different values of the intrinsic permeability ranging from 10^{-14} m^2 to 10^{-12} m^2. The results of this parametric study are given in Table 6.11. The results indicate that for permeability of 10^{-14} m^2, the final settlement was estimated as 7.31 m, whereas for permeability of 10^{-12} m^2, the final settlement was decreased trivially to 7.28 m.

Table 6.11: The Influence of Landfill Permeability on Landfill Settlement

Landfill Permeability (m^2)	Final Settlement (m)
10^{-14}	7.308
0.5×10^{-13}	7.277
10^{-13}	7.240
0.5×10^{-12}	7.287
10^{-12}	7.279

Figure 6.9 demonstrates the variation of landfill settlement with respect to different values of landfill permeability. From this figure, it is observed that the settlement decreases with increase in permeability.

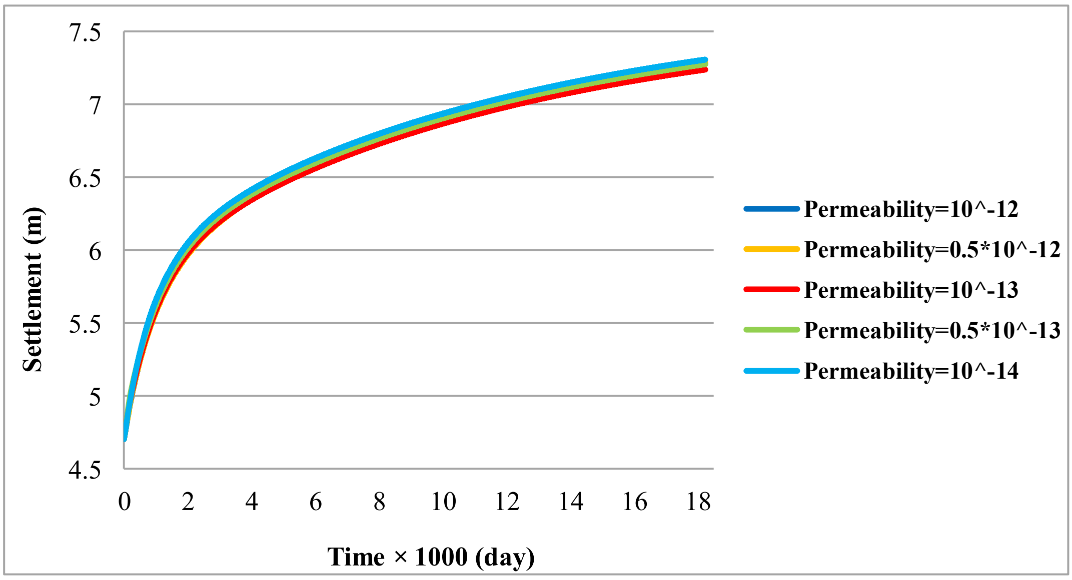


Figure 6.9: Time versus Landfill Settlement for Different Values of Landfill Permeability

6.2.10. Parametric Study on van Genuchten Parameter

As previously mentioned, the Richards equation was used to simulate the distribution of moisture in landfill while the van Genuchten (1980) formula has been selected for describing the water retention and hydraulic conductivity functions. Therefore, the role of van Genuchten Parameter (α) has been investigated in this parametric study. The influence of van Genuchten Parameter (α) can be counted on by varying this parameter and evaluation of landfill settlement by LTMT.

Table 6.12: The Influence of van Genuchten Parameter (α) on Landfill Settlement

van Genuchten Parameter - α (m^{-1})	Settlement (m)
22	7.239
23	7.240
24	7.240
25	7.240
26	7.240
27	7.240
28	7.241
29	7.241
30	7.242

The results of parametric study on landfill settlement for varying values of van Genuchten Parameter (α) over a period of 50 years are summarized in Table 6.12. As it can be observed, the final settlement will increase from 7.239 m to 7.242 m (approximately 0.04%) due to increase of parameter α of van Genuchten from 22 m^{-1} to 30 m^{-1}. This indicates that this parameter cannot be considered as an important parameter from landfill design viewpoint. The variation of this parameter has not any influence on the landfill settlement at early stages.

Figure 6.10 displays the variation of landfill settlement due to the variation of Van Genuchten Parameter (α). This figure also shows that the landfill settlement is not substantially influenced by this parameter as all curves illustrating the landfill settlement during the considered time are almost overlapped.

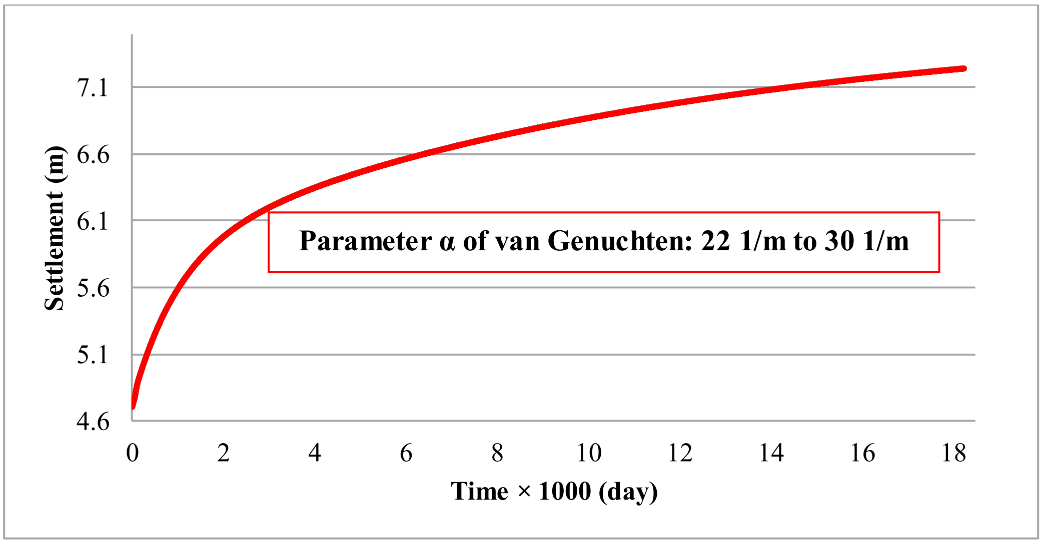


Figure 6.10: Time versus Landfill Settlement for Different Values Parameter (α) of van Genuchten

6.2.11. Parametric Study on Lift Thickness

The lift thickness is also an important aspect in landfilling. Therefore, the lift thickness has been chosen as another parameter for parametric study in which the effect of different thicknesses of lift is studied by varying it from 0.2 to 5 m while considering the same landfill height of 15 m over a period of 50 years (18250 days). The results of this study are presented in Table 6.13 and Figure 6.11.

Table 6.13: The Influence of Lift Thickness on Landfill Settlement

Lift Thickness (m)	Initial Settlement (m)	Final Settlement (m)
0.20	5	7.53
0.25	4.70	7.27
0.50	3.80	6.39
1	2.92	5.62
1.25	2.65	5.36
2.5	1.83	4.53
5	1.09	3.81

According to the results, it can be noted that the lift thickness has significant influence on the landfill settlement behaviour from initial stage to final settlement since the final settlement value in 50 years varied from 7.53 to 3.81 m as the lift thickness is changed from 0.2 to 5.0 m, whereas initial settlement (after 100 days) varied from 5 to 1.09 m. This shows that the waste lift thickness should be properly selected in order to provide the better compaction effort and hence to achieve an accurate prediction of settlement.

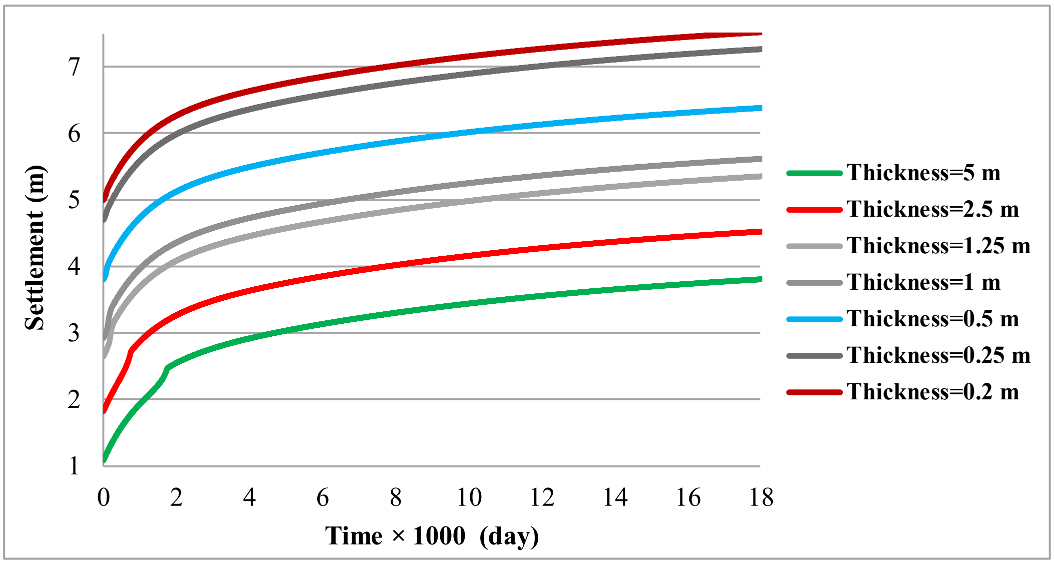


Figure 6.11: Time versus Landfill Settlement for Different Lift Thicknesses

6.3. Sensitivity Analysis of Input Parameters

In this research, the sensitivity analysis has been conducted on key parameters in order to investigate the influential and non-influential parameters. The sensitivity analysis facilitates to understand the landfill settlement behaviour as well as to determine the significant parameters.

Table 6.14: Investigated Parameters in the Sensitivity Analysis

Parameter	Unit	NOP	Range
Landfill Height	m	15	6 – 27
Waste Density	kg/m^3	500	450 – 550
Time	day	1000	200 – 1800
Gas Diffusion Coefficient	m^2/day	0.4	0.3 – 0.5
Waste Moisture Content	%	20	15 – 24 38 – 42
Compression Ratio	-	0.205	0.1701 – 0.2713
Amount of Rapidly Degradable Wastes	%	15	9 – 21
Waste Decay Constant	day^{-1}	0.001	0.00052 – 0.00148
Landfill Permeability	m^2	10^{-13}	$10^{-14} – 1.8\times10^{-13}$
Van Genuchten Parameter (α)	m^{-1}	26	25 – 27
Lift Thickness	m	0.25	0.2 – 0.5

Identifying influential parameters will be extremely crucial to predict the long term behaviour accurately resulting in reduced construction and maintenance cost in landfill redevelopment projects. For the purpose of conducing sensitivity analysis, different parameters with specific normal operating points (NOP) are selected and analysed, as presented in Table 6.14.

In order to conduct this sensitivity analysis, NOP values and its associated parameters are kept constant except for the particular value which is of interest for each analysis. In addition, the following mathematical expression is used for each of the input parameters with respect to their relevant NOP and within the range given in Table 6.14 to determine relative sensitivity:

$$\mathbf{S_j} = \frac{\partial \mathbf{Y} / \mathbf{Y_{NOP}}}{\partial \mathbf{X} / \mathbf{X_{NOP}}} \qquad (\mathbf{6.1})$$

where S_j is the relative sensitivity number, ∂Y is change in output with respect to NOP, ∂X is the change in input with respect to NOP, Y_{NOP} is the output at NOP, and X_{NOP} is the input at NOP.

The subsequent sections provide relevant information regarding the sensitivity analysis of different parameters to determine their significance in landfill settlement.

6.3.1. Sensitivity Analysis on Landfill Height

As previously discussed, the landfill height influences the landfill settlement behaviour due to the overburden pressure and stresses. Therefore, a series of 15 calculations has been undertaken to determine the sensitivity of landfill height in terms of settlement. The range between 6m and 27m has been selected for this study.

As shown in Figure 6.12, the results indicate a great variation in the calculated landfill settlements with respect to the initial landfill height, since the initial landfill height is directly proportional to the superimposed loads and overburden pressures. As presented in Table 6.15, the difference in landfill settlement between initial height of 6m and 27m is approximately 9.245 m (11.165 m – 1.920 m). Since this appears to have a large variance, landfill height is considered highly significant. This is reflected in the sensitivity number, where $S_1 = 1.175$, indicating that overall MSW landfill settlement is highly sensitive to initial landfill height.

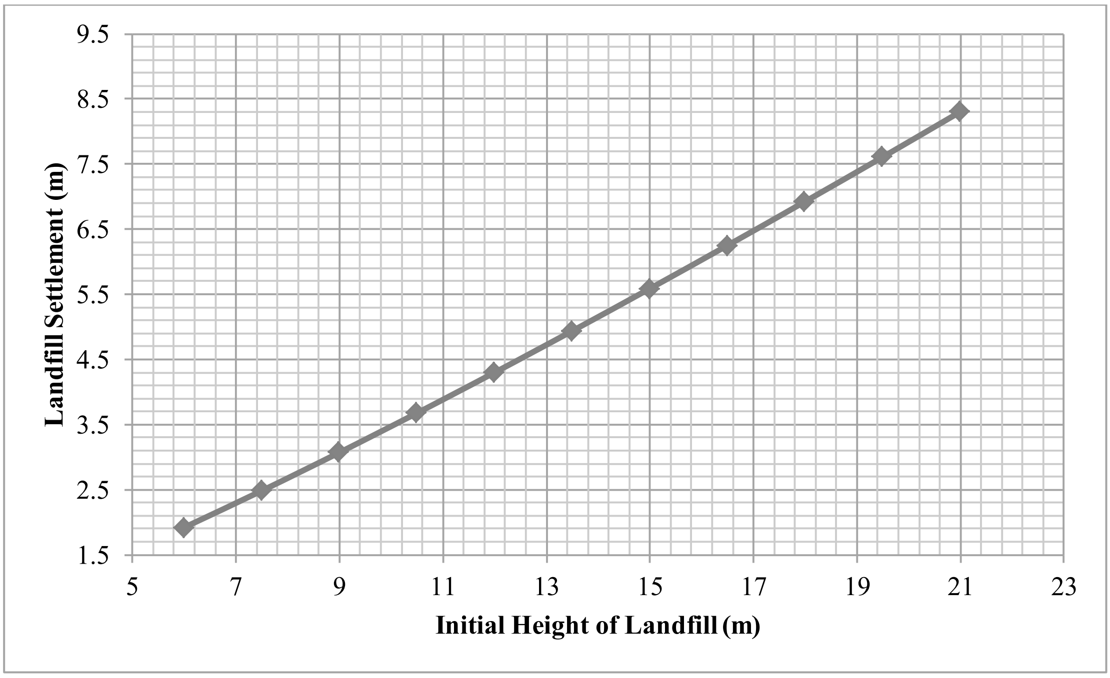


Figure 6.12: Impact on Landfill Settlement due to Change in Landfill Height

Table 6.15: Sensitivity Analysis of Initial Height of Landfill

Landfill Height (m)	Settlement (m)	Sensitivity Analysis
6	1.920	$S_1 = \frac{\delta S_H / S_{NoP}}{\delta H / H_{NoP}}$ $S_1 = \frac{(6.252 - 4.938)/5.589}{(16.5 - 13.5)/15}$ $\boldsymbol{S_1 = 1.175}$
7.5	2.484	
9	3.071	
10.5	3.677	
12	4.300	
13.5	4.938	
15	5.589	
16.5	6.252	
18	6.926	
19.5	7.610	
21	8.304	
22.5	9.009	
24	9.720	
25.5	10.443	
27	11.165	

6.3.2. Sensitivity Analysis on Waste Density

Similar to the analysis for the initial height of landfill, a series of 11 calculations have been undertaken to investigate the sensitivity of landfill settlement with respect to waste density.

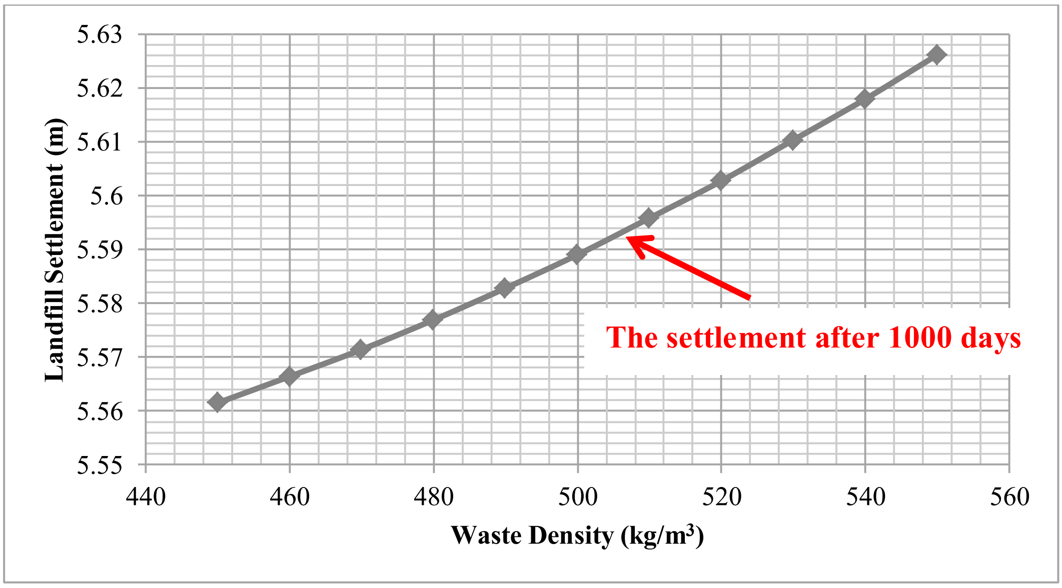


Figure 6.13: Impact on Landfill Settlement due to Change in Waste Density

This sensitivity analysis indicates that the overall landfill settlement increases with respect to waste density as illustrated in Figure 6.13 and Table 6.16. This equates to 64.6 mm of total change in landfill settlement due to approximately 100 kg/m^3 increase in waste density (550 kg/m^3 – 450 kg/m^3).

Table 6.16: Sensitivity Analysis of Waste Density

Waste Density (kg/m^3)	Settlement (m)	Sensitivity Analysis
450	5.562	$S_2 = \dfrac{\delta S_D / S_{NoP}}{\delta D / D_{NoP}}$ $S_2 = \dfrac{(5.596 - 5.583)/5.589}{(510 - 490)/500}$ $\boldsymbol{S_2 = 0.0581}$
460	5.566	
470	5.571	
480	5.577	
490	5.583	
500	5.589	
510	5.596	
520	5.603	
530	5.610	
540	5.618	
550	5.626	

The sensitivity analysis has been calculated based on waste density of 490 kg/m^3 and 510 kg/m^3, where the NOP of waste density is 500 kg/m^3. The landfill settlement varied significantly between the two control points (490 kg/m^3 and 510 kg/m^3), by 13 mm. Hence, the calculated sensitivity number is $S_2 = 0.0581$, shown in Table 6.16.

6.3.3. Sensitivity Analysis on Elapsed Time

In order to demonstrate the variance in landfill settlement with respect to time, 33 calculations have been undertaken while all parameters, with the exception of time, are constant.

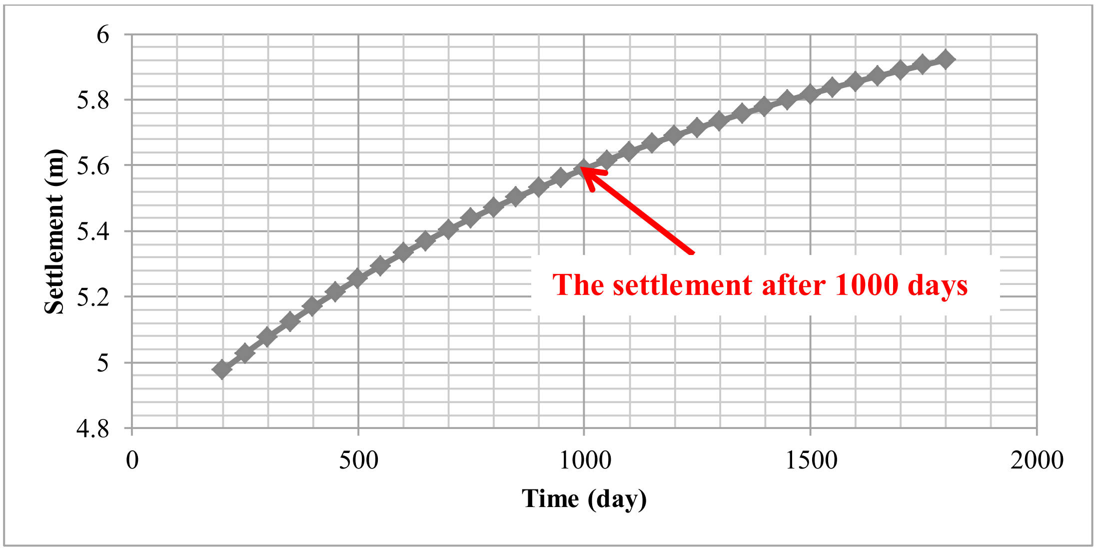


Figure 6.14: Impact on Landfill Settlement due to Change in Time

As illustrated in Figure 6.14, the relative sensitivity of the time is considered to be sensitive. It yields a significant impact on the landfill settlement. The sensitivity number calculated is, $S_3 = 0.0984$, shown in Table 6.17. The change in landfill final height for considered range (200 days to 1800 days) of sensitivity analysis equates to 944.4 mm.

6.3.4. Sensitivity Analysis on Gas Diffusion Coefficient

Intent of this sensitivity analysis is to determine the influence of the gas diffusion coefficient on the landfill settlement. A range between 0.30 and 0.50 has been selected to demonstrate the overall impact of gas diffusion coefficient on the landfill settlement. A series of 11 analyses at 0.02 increments has been undertaken.

Table 6.17: Sensitivity Analysis of Time

Time (day)	Settlement (m)	Sensitivity Analysis
200	4.977	$S_3 = \frac{\delta S_T / S_{NoP}}{\delta T / T_{NoP}}$ $S_3 = \frac{(5.616 - 5.561) / 5.589}{(1050 - 950) / 1000}$ $\boldsymbol{S_3 = 0.0984}$
250	5.028	
300	5.077	
350	5.125	
400	5.170	
450	5.213	
500	5.255	
550	5.294	
600	5.333	
650	5.369	
700	5.405	
750	5.438	
800	5.471	
850	5.502	
900	5.532	
950	5.561	
1000	5.589	
1050	5.616	
1100	5.642	
1150	5.666	
1200	5.690	
1250	5.713	
1300	5.736	
1350	5.757	
1400	5.778	
1450	5.798	
1500	5.817	
1550	5.836	
1600	5.854	
1650	5.872	
1700	5.889	
1750	5.905	
1800	5.921	

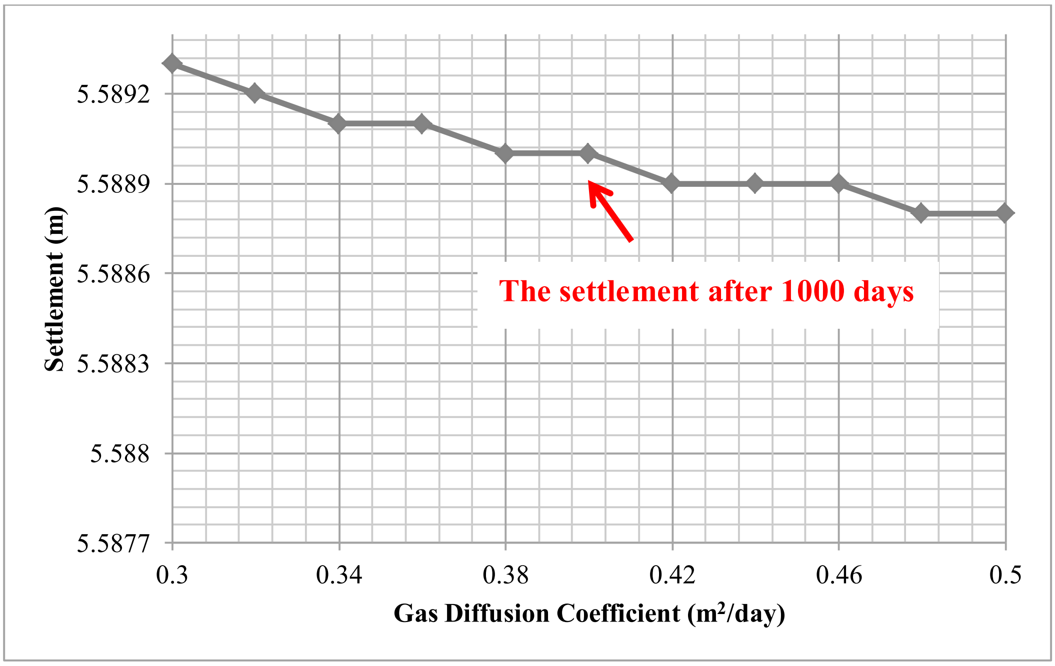


Figure 6.15: Impact on Landfill Settlement due to Change in Diffusion Coefficient

As shown in Figure 6.15, the change in landfill settlement was fairly consistent throughout the testing phase.

Table 6.18: Sensitivity Analysis of Gas Diffusion Coefficient

Diffusion Coefficient (m^2/day)	Settlement (m)	Sensitivity Analysis
0.30	5.5893	$S_4 = \frac{\delta S_{GD} / S_{NoP}}{\delta GD / GD_{NoP}}$
0.32	5.5892	
0.34	5.5891	
0.36	5.5891	
0.38	5.5890	$S_4 = \frac{(5.5890 - 5.5889) / 5.5890}{(0.42 - 0.38) / 0.40}$
0.40	5.5890	
0.42	5.5889	
0.44	5.5889	
0.46	5.5889	$\boldsymbol{S_4 = 0.0002}$
0.48	5.5888	
0.50	5.5888	

The total change in landfill final height within the range of the analysis is 0.5 mm. Calculations in Table 6.18 yields a sensitivity number of, $S_4 = 0.0002$. This parameter is considered to be insensitive.

6.3.5. Sensitivity Analysis on Waste Moisture Content

A total of 15 analyses including two series of calculations between a range of 15% to 24% and range of 38% to 42% have been undertaken in order to access the influence of moisture content on landfill settlement. The results of the calculations for both series are summarized in Table 6.19 and Table 6.20.

Table 6.19: Sensitivity Analysis of Moisture Content (Series 1)

Moisture Content (%)	Settlement (m)	Sensitivity Analysis
15	5.651	$S_5 = \frac{\delta S_{MC}/S_{NoP}}{\delta MC/MC_{NoP}}$ $S_5 = \frac{(5.597 - 5.582)/5.589}{(21 - 19)/20}$ $\boldsymbol{S_5 = 0.0268}$
16	5.632	
17	5.618	
18	5.607	
19	5.597	
20	5.589	
21	5.582	
22	5.576	
23	5.573	
24	5.572	

Table 6.20: Sensitivity Analysis of Moisture Content (Series 2)

Moisture Content (%)	Settlement (m)	Sensitivity Analysis
38	5.5482	$\boldsymbol{S_5 = 0.0000}$
39	5.5482	
40	5.5482	
41	5.5482	
42	5.5482	

Based on the calculations, the total change in landfill settlement between moisture content of 15% and 24% is approximately 80 mm (about 1.5%), whereas the total landfill settlement for the moisture content between 38% and 42% is almost negligible. These results are reflected in sensitivity numbers calculated in Table 6.19 and Table 6.20.

6.3.6. Sensitivity Analysis on Compression Ratio

Voids compression in landfills due to the weight of the overlying waste will lead to mechanical compression. As the mechanical compression is controlled by compressibility parameters, 11 analyses are specifically assessing the impact of change in compressibility parameters on the landfill settlement with respect to NOP of compression ratio for waste with less than 200 days age (as presented in Table 6.14).

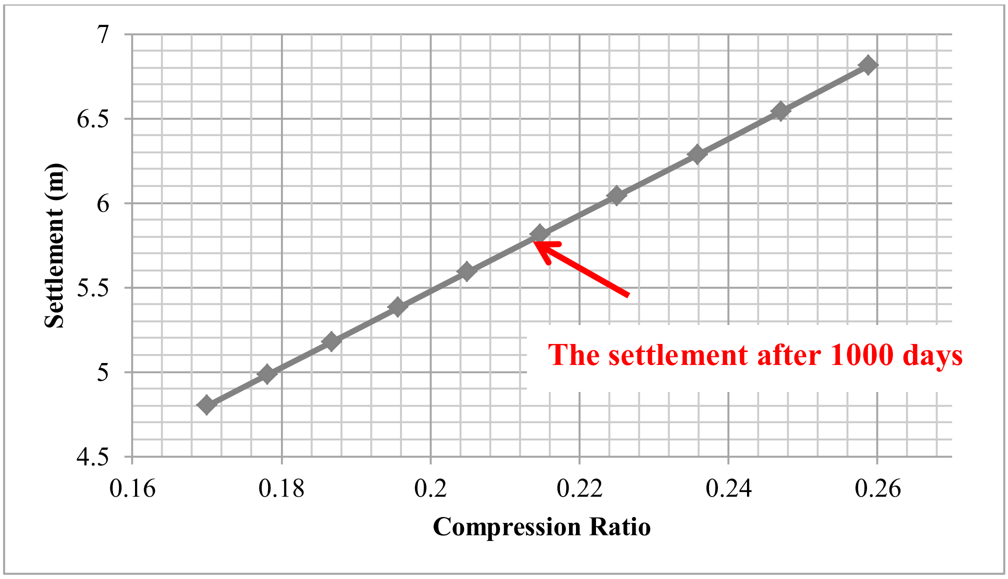


Figure 6.17: Impact on Landfill Settlement due to Change in Compression Ratio

The results indicate that the change in landfill settlement appears to be linear with respect to the change in compressibility parameters, as shown in Figure 6.17 and Table 6.21.

Table 6.21: Sensitivity Analysis of Compression Ratio

Compression Ratio	Settlement (m)	Sensitivity Analysis
0.1701	4.800	$S_6 = \frac{\delta S_C / S_{NoP}}{\delta C / C_{NoP}}$ $S_6 = \frac{(5.811 - 5.379)/5.589}{(0.2148 - 0.1957)/0.2050}$ $\boldsymbol{S_6 = 0.830}$
0.1782	4.984	
0.1868	5.177	
0.1957	5.379	
0.2050	5.589	
0.2148	5.811	
0.2251	6.042	
0.2359	6.284	
0.2471	6.541	
0.2589	6.813	
0.2713	7.095	

Considering the respective data, the total change of 2.295 m in landfill settlement occurs over a variable range between 0.1701 and 0.2713 for compression ratio. This change states that compressibility parameters can be considered as significant factors in landfill settlement, reflected in the calculated sensitivity number, $S_6 = 0.830$.

6.3.7. Sensitivity Analysis on the Amount of Rapidly Degradable Wastes

Total settlement occurs as the wastes undergo the mechanical compression and biodegradation in landfills. Since the waste decomposition is essentially a function of waste type and waste component biodegradability, the settlement at a given time also remains a function of waste biodegradability. Therefore, a series of 9 analyses have been conducted to determine the impact of the amount of rapidly degradable wastes on the overall landfill settlement with respect to NOP presented in Table 6.14. It can be expected that the amount of rapidly degradable wastes has a substantial impact on the landfill settlement. The results of these analyses are provided in Figure 6.18.

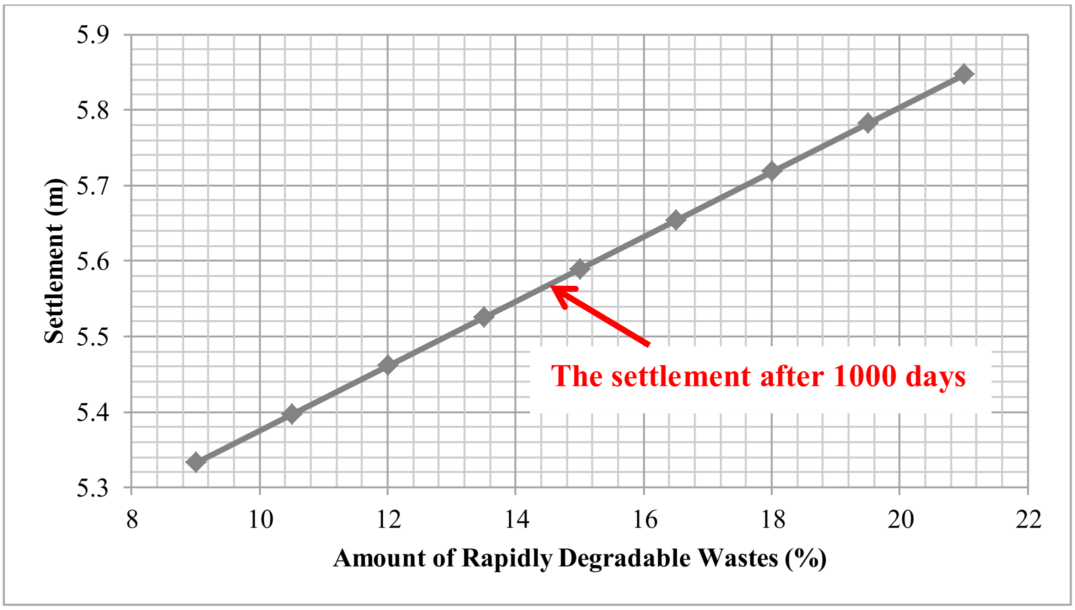


Figure 6.18: Impact on Landfill Settlement due to Change in the Amount of Rapidly Degradable wastes

The total change in landfill settlement between 9% and 21% of rapidly degradable wastes is calculated to be 513.9 mm, thus fluctuated approximately 10%. This is reflected in the calculated sensitivity number of 0.1145, shown in Table 6.22.

Table 6.22: Sensitivity Analysis of the amount of Rapidly Degradable Wastes

Rapidly Degradable Wastes (%)	Settlement (m)	Sensitivity Analysis
9	5.332	$S_7 = \frac{\delta S_{RD}/S_{NoP}}{\delta RD/RD_{NoP}}$ $S_7 = \frac{(5.653 - 5.525)/5.589}{(16.5 - 13.5)/15}$ $\boldsymbol{S_7 = 0.1145}$
10.5	5.397	
12	5.461	
13.5	5.525	
15	5.589	
16.5	5.653	
18	5.718	
19.5	5.782	
21	5.846	

6.3.8. Sensitivity Analysis on Waste Decay Constant

The settlement rate due to biological decomposition is expressed by the rate of biodegradation. In general, it can be said that the biodegradation induced settlement is influenced by the waste decay constant, whereas mechanical compression is generally affected by the compressibility parameters. Therefore, a series of 33 calculations has been undertaken to analytically review the impact of waste decay constant on the landfill settlement. The results of analyses are illustrated in Figure 6.19.

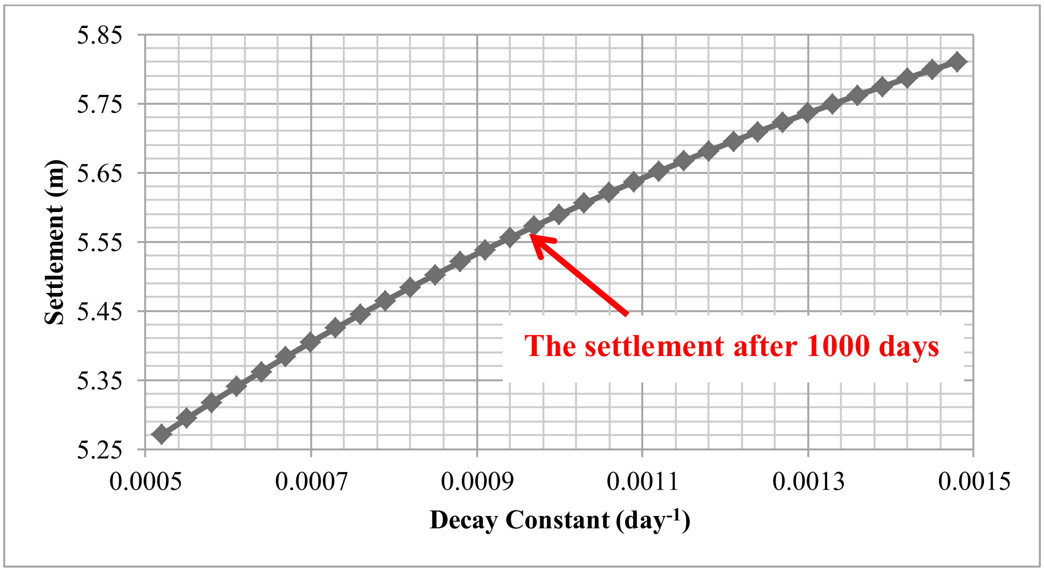


Figure 6.19: Impact on Landfill Settlement due to Change in the Waste Decay Constant

Table 6.23: Sensitivity Analysis of the amount of Waste Decay Constant

Waste Decay Constant (1/day)	Settlement (m)	Sensitivity Analysis
0.00052	5.271	$S_8 = \frac{\delta S_{DC}/S_{NoP}}{\delta DC/DC_{NoP}}$ $S_8 = \frac{(5.605-5.572)/5.589}{(0.00103-0.00097)/0.001}$ $\boldsymbol{S_8 = 0.0984}$
0.00055	5.294	
0.00058	5.317	
0.00061	5.340	
0.00064	5.362	
0.00067	5.383	
0.00070	5.404	
0.00073	5.425	
0.00076	5.445	
0.00079	5.464	
0.00082	5.485	
0.00085	5.502	
0.00088	5.520	
0.00091	5.538	
0.00094	5.555	
0.00097	5.572	
0.001	5.589	
0.00103	5.605	
0.00106	5.621	
0.00109	5.637	
0.00112	5.652	
0.00115	5.667	
0.00118	5.681	
0.00121	5.695	
0.00124	5.709	
0.00127	5.723	
0.00130	5.736	
0.00133	5.749	
0.00136	5.762	
0.00139	5.774	
0.00142	5.787	
0.00145	5.799	
0.00148	5.810	

Sensitivity analysis is carried out between 0.00052 day^{-1} and 0.00148 day^{-1} with respect to the selected NOP value of 0.001 day^{-1} for rapidly degradable wastes. Total change in landfill settlement is found to be 534 mm, approximately 10% in change. As calculated in Table 6.23, the calculated sensitivity number equates to 0.0984.

6.3.9. Sensitivity Analysis on Landfill Permeability

In order to show the impact of permeability on the landfill settlement, a series of 35 calculations have been documented based on the range of the intrinsic permeability between 10^{-14} m^2 and 1.8×10^{-13} m^2. The behaviour of landfill at different values of permeability is the same as curve which is demonstrated in Figure 6.20.

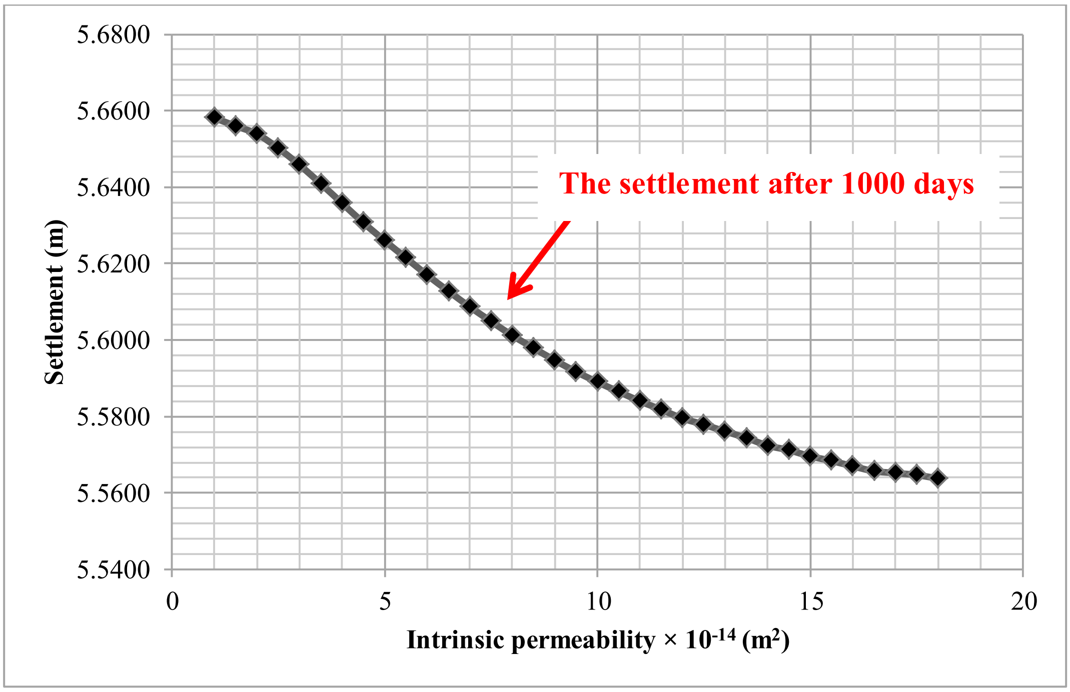


Figure 6.20: Impact on Landfill Settlement due to Change in Permeability

The total landfill settlement in the considered range for permeability appeared to converge to 94.3 mm, approximately 2% in change. However, sensitivity analyse on permeability between the considered range with respect to the selected NOP value of 10^{-13} m^2 results in approximately 5.2 mm change in landfill settlement. As calculated in Table 6.24, the calculated sensitivity number equates to 0.0089. This indicates that the landfill permeability affects the gas pressure and moisture distribution, however, a substantial impact of permeability on landfill settlement cannot be observed through these calculations. Thus, this parameter can be considered to be insensitive.

Table 6.24: Sensitivity Analysis of the Permeability

Intrinsic Permeability (m^2)	Settlement (m)	Sensitivity Analysis
10^{-14}	5.658	$S_9 = \frac{\delta S_P / S_{NoP}}{\delta P / P_{NoP}}$ $S_9 = \frac{(5.592 - 5.587) / 5.589}{(1.05 \times 10^{-13} - 9.5 \times 10^{-14}) / 10^{-13}}$ $\boldsymbol{S_9 = 0.0089}$
1.5×10^{-14}	5.656	
2×10^{-14}	5.654	
2.5×10^{-14}	5.650	
3×10^{-14}	5.646	
3.5×10^{-14}	5.641	
4×10^{-14}	5.636	
4.5×10^{-14}	5.631	
5×10^{-14}	5.626	
5.5×10^{-14}	5.622	
6×10^{-14}	5.617	
6.5×10^{-14}	5.613	
7×10^{-14}	5.609	
7.5×10^{-14}	5.605	
8×10^{-14}	5.601	
8.5×10^{-14}	5.598	
9×10^{-14}	5.595	
9.5×10^{-14}	5.592	
10^{-13}	5.589	
1.05×10^{-13}	5.587	
1.1×10^{-13}	5.584	
1.15×10^{-13}	5.582	
1.2×10^{-13}	5.580	
1.25×10^{-13}	5.578	
1.3×10^{-13}	5.576	
1.35×10^{-13}	5.574	
1.4×10^{-13}	5.572	
1.45×10^{-13}	5.571	
1.5×10^{-13}	5.570	
1.55×10^{-13}	5.568	
1.6×10^{-13}	5.567	
1.65×10^{-13}	5.566	
1.7×10^{-13}	5.565	
1.75×10^{-13}	5.565	
1.8×10^{-13}	5.564	

6.3.10. Sensitivity Analysis on Van Genuchten Parameter

Based on laboratory experiments by Benson and Wang (1998), a range between 25 and 27 has been selected for the evaluation of an overall impact of Van Genuchten parameter (α) on landfill settlement in this sensitivity analysis.

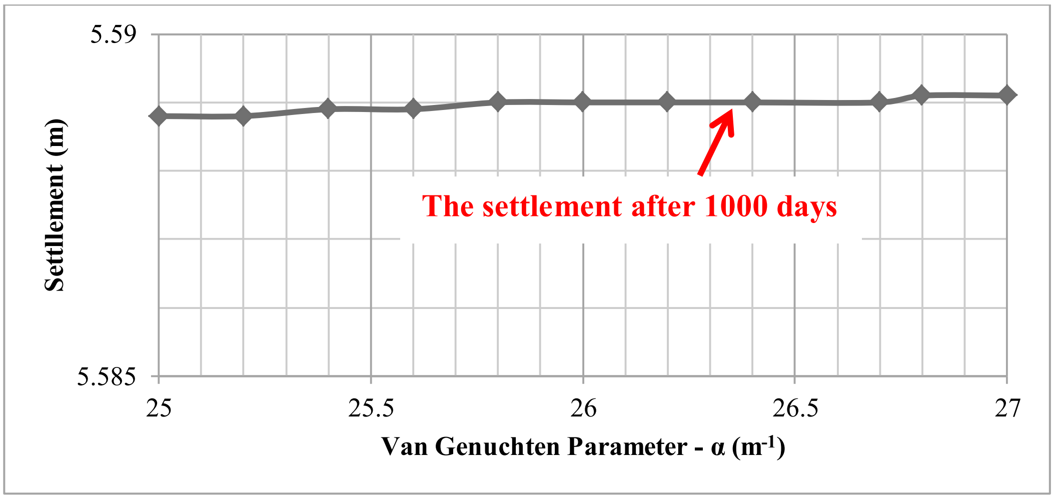


Figure 6.21: Impact on Landfill Settlement due to Change in Van Genuchten Parameter (α)

As shown in Figure 6.21 and Table 6.25, a series of 11 calculations in the considered range indicated a total change in landfill settlement of 0.3 mm, approximately 0.01% in change.

Table 6.25: Sensitivity Analysis of the Van Genuchten Parameter (α)

Van Genuchten Parameter α (1/m)	Settlement (m)	Sensitivity Analysis
25	5.5888	$S_{10} = \frac{\delta S_{VG}/S_{NoP}}{\delta VG/VG_{NoP}}$ $S_{10} = \frac{(5.5890 - 5.5889)/5.5890}{(26.4 - 25.6)/26}$ $\boldsymbol{S_{10} = 0.0006}$
25.2	5.5888	
25.4	5.5889	
25.6	5.5889	
25.8	5.5890	
26	5.5890	
26.2	5.5890	
26.4	5.5890	
26.7	5.5890	
26.8	5.5891	
27	5.5891	

The sensitivity analyses conducted based on 25.6 to 26.4 for parameter α Van Genuchten formula also indicated that the change in landfill settlement between these values is 1 mm. This is reflected on the sensitivity number, where $S_{10} = 0.0006$, which is again considered as insensitive from a design point of view.

6.3.11. Sensitivity Analysis on Lift Thickness

In order to quantify the importance of the lift thickness in landfill settlement behaviour, a series of 3 calculations were done by varying the range of lift thickness from 0.25 m to 0.5 m.

The results of this sensitivity analysis showed that the ultimate settlement of landfill depends on the waste lift thickness used while filling operations and this parameter can be sensitive from the design point of view as reflected in sensitivity number obtained in Table 6.26.

Table 6.26: Sensitivity Analysis of the Lift Thickness

Lift Thickness (m)	Settlement (m)	Sensitivity Analysis
0.20	5.876	$S_{11} = \frac{\delta S_{LT} / S_{NoP}}{\delta LT / LT_{NoP}}$ $S_{11} = \frac{(5.876 - 4.735) / 5.588}{(0.5 - 0.2) / 0.25}$ $\boldsymbol{S_{11} = 0.1702}$
0.25	5.588	
0.50	4.735	

6.4. Summary

This chapter evaluates the importance of all the input parameters used in technical management tool (LTMT) for MSW landfill settlement estimation. To do this, a holistic screening process was initially performed in which all the non-influential parameters and those which are outside the scope of this study were eliminated. Eventually, a total of ten key parameters were chosen for parametric study and sensitivity analysis.

The parameters investigated in parametric study include landfill height, waste density, time, gas diffusion coefficient, waste moisture content, compression ratio, amount of rapidly degradable wastes, waste decay constant landfill permeability, parameter α of van Genuchten model, and lift thickness. The objective of this parametric study was to examine the effect of the variations of different ranges of parameters over 50 years (18,250 days) on landfill settlement as well as to draw inferences with regard to time-settlement response of MSW.

Table 6.27: Summary of the Sensitivity Analysis

Item	Description	Unit	NOP	Range	Sensitivity Number
S_1	**Landfill Height**	m	15	6 – 27	1.175
S_2	**Waste Density**	kg/m^3	500	450 – 550	0.0581
S_3	**Time**	day	1000	200 – 1800	0.0984
S_4	**Gas Diffusion Coefficient**	m^2/day	0.4	0.3 – 0.5	0.0002
S_5	**Waste Moisture Content**	%	20	15 – 24 38 – 42	0.0268 0.0000
S_6	**Compression Ratio**	-	0.205	0.1701 – 0.2713	0.830
S_7	**Amount of Rapidly Degradable Wastes**	%	15	9 – 21	0.1145
S_8	**Waste Decay Constant**	day^{-1}	0.001	0.00052 – 0.00148	0.0984
S_9	**Landfill Permeability**	m^2	10^{-13}	10^{-14} – 1.8×10^{-13}	0.0089
S_{10}	**Van Genuchten Parameter (α)**	m^{-1}	26	25 – 27	0.0006
S_{11}	**Lift Thickness**	m	0.25	0.2 – 0.5	0.1702

In overall, this parametric study shows that the different parameters can significantly affect the landfill settlement. Hence, the values of these parameters must be selected carefully for accurate prediction of landfill settlements.

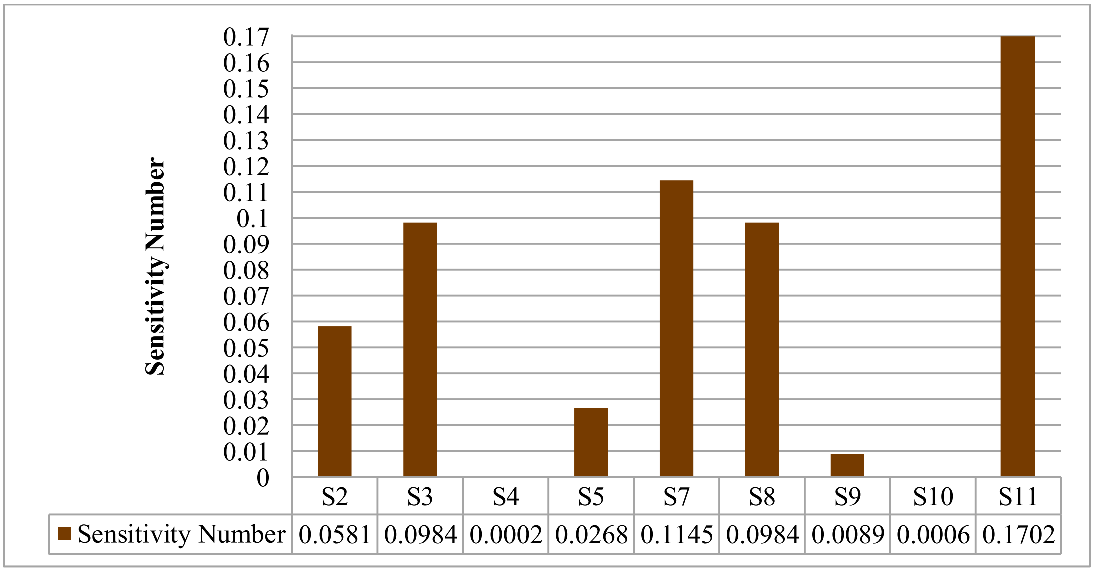


Figure 6.22: Summary of the Sensitivity Analysis

In addition, the sensitivity analysis consists of a total of 179 calculations over ten parameters which have been undertaken to determine the importance of selected parameters on the overall settlement of landfill. The sensitivity analysis was completed based on Normal Operating Point (NOP) of each parameter. All data and the results of sensitivity analysis with respect to the relevant NOP are presented in Table 6.27 and Figure 6.22.

Based on the calculations and the data given in Table 6.23, as the calculated sensitivity number for two parameters of landfill height and compression ratio are much higher than the others, these parameters are not shown in Figure 6.22 and can be considered as highly sensitive parameters.

Chapter 7

Validation of Landfill Technical Management Tool (LTMT)

7.1. Introduction

In recent years, a growing number of redevelopment projects have been carried out on the municipal solid waste (MSW) landfills or adjacent to them. To perform this kind of projects, many studies have been carried out regarding waste settlement prediction and monitoring. In this study, a landfill technical management tool (LTMT) has been developed in order to investigate the settlement characteristics of MSW landfills as well as the solid waste properties. As verification of a model is crucial to develop an accurate and credible model, the main objective of this chapter is to verify the validation of this technical management tool. Therefore, Tehran landfill has been selected as a case study and its relevant field study data has been collected for this purpose. To achieve this goal, this chapter discusses the verification of LTMT based on the gathered data related to the mentioned case study, while general relevant information about Tehran solid waste management system, its waste characteristics and Tehran landfills are provided in this chapter.

7.2. General Information

The rate of generation of solid waste in the society is increasing with the increase of population, technological development, and the changes in the life style of the people. The management of municipal solid waste has become an acute problem due to enhanced economic activities and rapid urbanisation. For example in a metropolitan like Tehran as capital of Iran, which has been divided into 22 administrative districts, the large amount of waste are daily generated in different points of this large city ,as presented in Figure 7.1. Generally, Tehran Covers an area of 1500 square Kilometres and is situated in the north-central part of Iran, on the slope of the Alborz Mountain. As the national capital, Tehran is the most populated city in Iran which is a mountainside city with an altitude of 1200 m to 1700 m above the sea level and enjoys a mild climate. In the south of Tehran and its suburbs, the desert begins which has dry and very hot weather in summer and sometimes very cold in winter.

In general, the climate of Tehran province in the desert and southern territories is warm and dry, in the skirts of the mountains cold and semi humid, and in the higher regions cold, experiencing long winters. The average annual rainfall of Tehran is approximately 400 mm. and the maximum rainfall happens during the winter season.

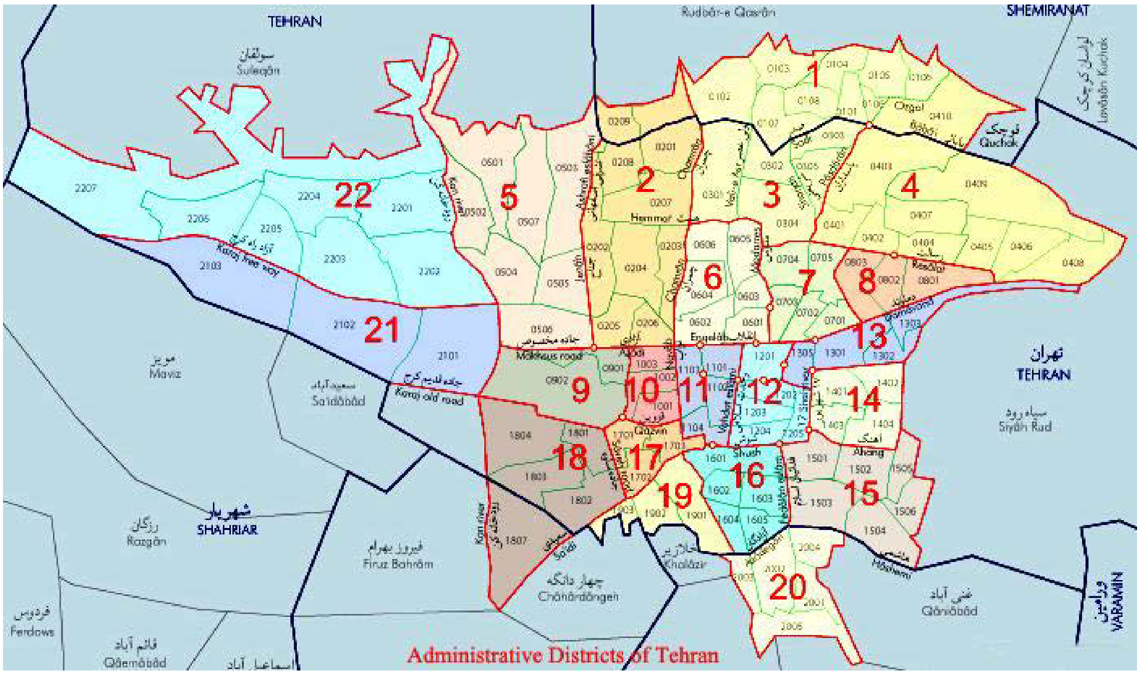


Figure 7.1: The Expansion of Tehran and its Administrative Districts

(courtesy of Tehran Municipality)

The condition of this city in terms of population, the values of land, geographical and environmental issues will necessitate the selection of proper systems for waste disposal, and hence the landfill redevelopment.

7.2.1. MSW Characteristics in Tehran

It is obvious that MSW is a complex and heterogeneous mixture, made of various components that their origin can be very diverse. This results in generation of materials with very different properties.

The proportion of municipal solid waste that is generated from households varies quite widely from city to city and from country to country. Consequently, the composition of the municipal solid wastes can vary depending on regional and seasonal factors. Based on measurements made on the municipal solid waste of this city in 2001, 2004, and 2007 by picking samples from different districts of Tehran, the average MSW composition for Tehran was determined as presented in Table 7.1.

Table 7.1: MSW Composition in Tehran (courtesy of Tehran Municipality)

Waste Component	Waste Composition (%)		
	2001	2004	2007
Food waste	71.4	68.9	68.3
Paper	4.9	4.4	4.2
Cardboard	4.5	3.7	4.8
Plastics	6.4	9.6	11.1
Textiles	2.9	3.4	2.7
Rubber	0.3	0.7	0.2
Leather	0.3	0.6	0.6
Yard waste	1.3	1.7	2.9
Wood	0.8	0.7	0.2
Glass	1.9	2.4	1.8
Metal waste	2.5	2.6	2.5
Dirt, etc.	2.8	1.3	0.7

Moreover, the solid waste composition as well as the variation in Tehran MSW composition is illustrated in Figure 7.2.

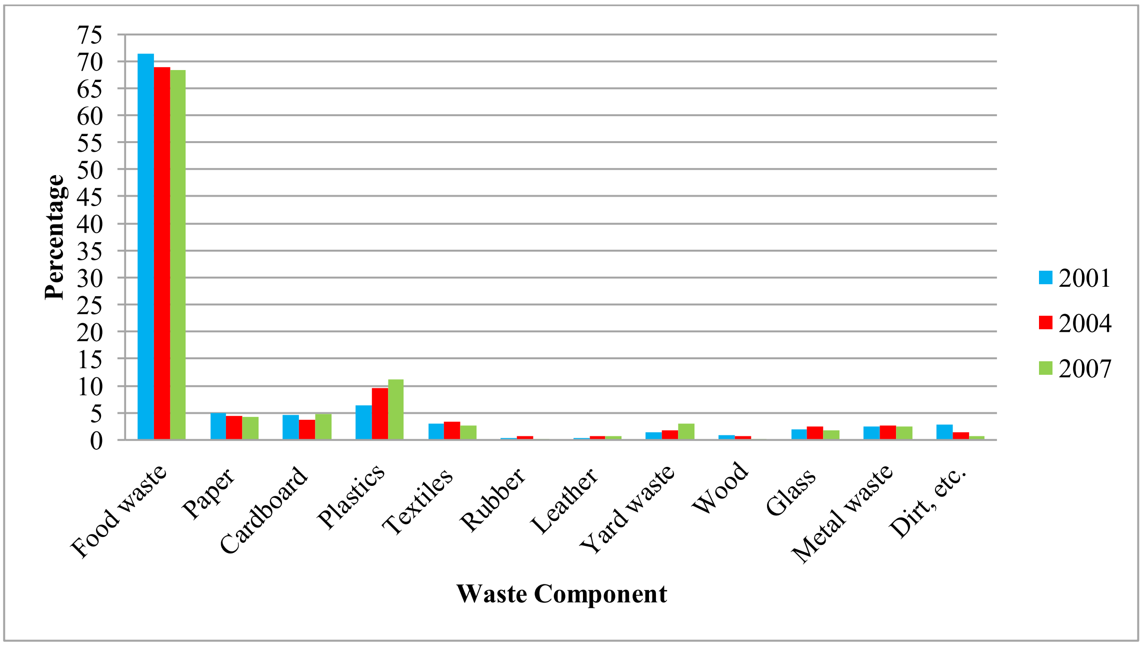


Figure 7.2: The Measured Waste Composition for Tehran

As it can be observed in Figure 7.2, the most significant component of Tehran wastes is food waste, which accounts for about 70% of total weight. The rest of the portions consist of plastics, paper and cardboard, textiles, metal scraps, glass, yard waste and wood, rubber, leather, and miscellaneous materials including dirt, etc.

Based on the results of experiments conducted on Tehran wastes, the unit weight of MSW in Tehran landfill is about 10 kN/m^3. This value ranges between 12 kN/m^3 and 14 kN/m^3 after consolidation. Moreover, the average moisture content of fresh waste samples is approximately 75%. This value, however, increases to 105% for the samples with age of 6 month (Karimpour Fard et al., 2010)

7.2.2. MSW Landfills in Tehran

It has been estimated that 7,500 tonnes of waste are generated daily in Tehran with a population of 12 million. Municipal solid waste is the main category of waste generated in Tehran. The main compositional categories of municipal solid waste are organic waste, paper and cardboard, yard waste, plastics, metals, glass, textiles and other minor fractions of waste. The majority of municipal solid wastes in Tehran is landfilled, recycled or converted to compost. However, the first incinerator as well as the first digester has being built for Tehran wastes in 2014.

Previous method for treating Tehran wastes was disposing of the wastes from different districts of Tehran in open landfills called dumps. Historically, no engineered sanitary landfills consisting of base liners, leachate collection and removal system, and gas collection systems were considered for waste disposal in this city. Therefore, major threats were posed to air, water, and soil due to lack of gas and leachate collection systems, improper cover systems, inadequate landfill bottom liners, insufficient compaction, poor landfill design, and so forth. Furthermore, insufficient compaction and lack of source separation necessitated the allocation of large lands for waste disposal. In such circumstances, the problems such as odour and fire causing by the build-up of methane gases at dumps were unavoidable. However, a growing realization of the negative impacts that wastes can have on the environment including air, water, soil, human health, etc. led to increased attention given by the governments in recent years to handle these problems in a safe and hygienic manner. Therefore, a sanitary MSW landfill with the total capacity of 700,000 tonnes is recently constructed in Aradkooh disposal centre in a region, located about 20 km away from Tehran to prevent the observation of some problems regarding air pollution and water and soil contamination. This sanitary landfill has an area of 5 hectares with an average height of

15 m, which has been constructed for the placement of some fractions of Tehran municipal solid wastes.

Based on the gathered information, there are generally three kinds of landfills in Tehran which are briefly described in the subsequent sections. These landfills including:

- traditional landfills (dumps)
- a pilot scale landfill
- an instrumented sanitary landfill

7.2.2.1. Traditional Landfills (Dumps)

As mentioned previously, the traditional landfills are dumps which are filled with the waste of Tehran for over 50 years without any instrument to prevent the pollution to air and soil. Tehran dumps are located in three sections as illustrated in Figures 7.3 to 7.4.

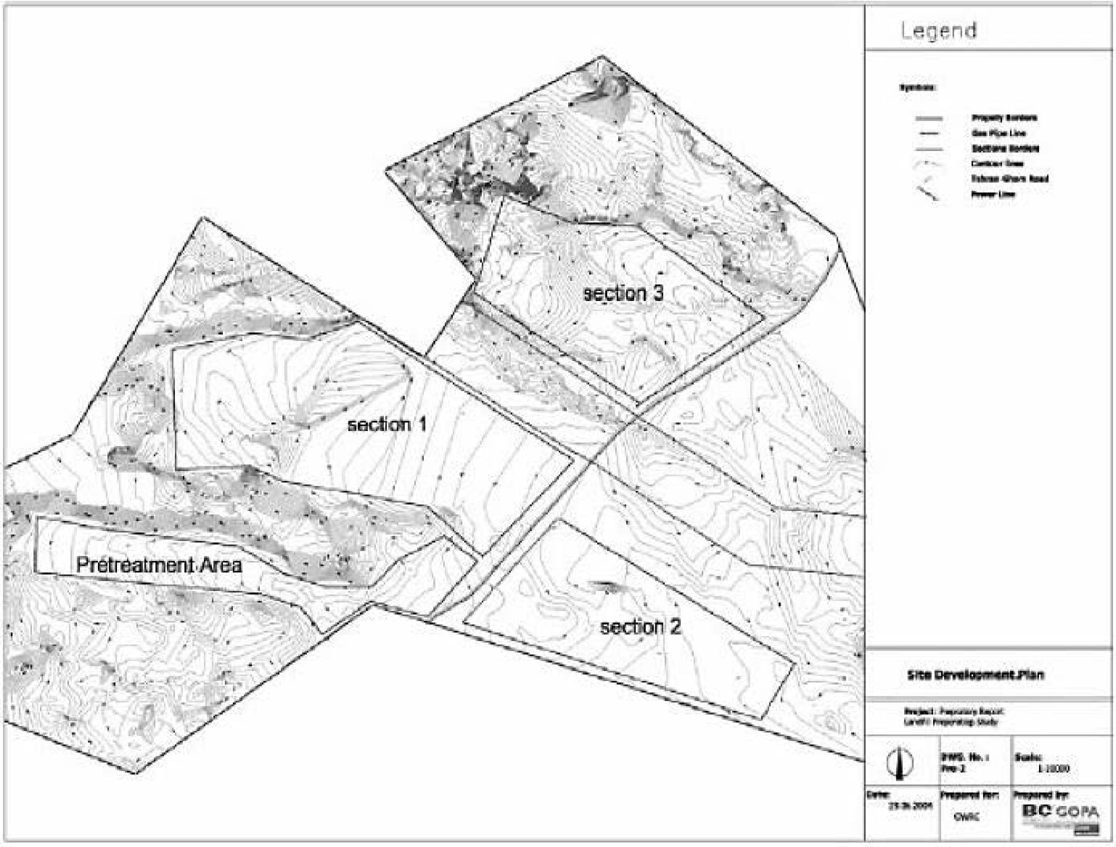


Figure 7.3: A typical Tehran Traditional Landfill (Dump) [Jahanfar, 2011]

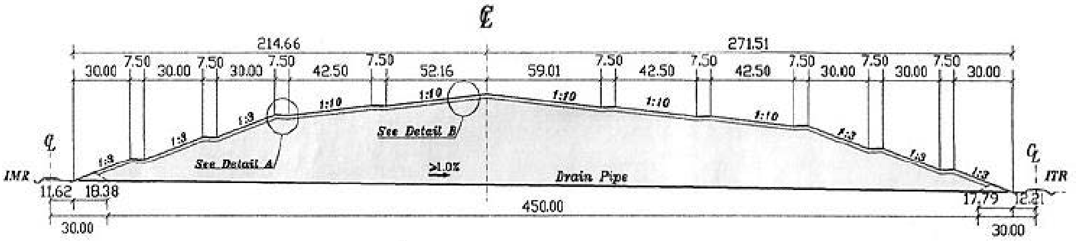


Figure 7.4: Cross Section of a Cell in Section 1 [Jahanfar, 2011]

Furthermore, the general information about this kind of landfills is presented in Table 7.2.

Table 7.2: Data related to Tehran MSW Landfills (Dumps) [Jahanfar, 2011]

Section	Area (ha)	Capacity ($m^3 \times 10^6$)
1	370	56.1
2	209	31.7
3	227	34.4

7.2.2.2. Pilot Scale Landfill

The pilot scale landfill is an instrumented landfill containing two separate cells ,cell A and cell B, which is constructed for monitoring landfill behaviour in Aradkooh disposal centre located 20 km south-east of Tehran. In one of the cells (cell B), leachate is recirculated on the landfill. During the research, which was conducted by Iran University of Science and Technology (IUST), the settlement of the landfill monitored for about 30 months since final capping in 2nd November 2006. Moreover, various characteristics of the landfill including its waste composition, as-placed moisture content, density, porosity, and daily covers were studied during this research. In addition, to reflect the progress of biodegradation, landfill gas generation, leachate composition, and in-situ temperature were also investigated in this study. The settlement measurements from this project are used to verify the validation of Landfill technical management tool (LTMT).

7.2.2.3. Instrumented Sanitary Landfill

The instrumented sanitary landfill was constructed in south of Tehran in 2008 with the total capacity of 700,000 tonnes. The landfill has an area of 5 hectares with an average height of 15 m and it has not been closed yet. Figures 7.5 to 7.8 illustrate the different construction stages of the project.

Figure 7.5: Excavation Phase of Tehran Sanitary Landfill (Photo Taken by the Author)

Figure 7.6: Excavation for Leachate Collection System of Tehran Sanitary Landfill (Photo Taken by the Author)

This landfill is an engineered structure consisting of bottom liners, gas and leachate collection and removal systems, and final covers.

Figure 7.7: Covering Tehran Sanitary Landfill with Geosynthetic Base Liners (Photo Taken by the Author)

Figure 7.8: Tehran Sanitary Landfill Covered with Geosynthetic Base Liners

The base liner of the sanitary landfill is composed of three geosynthetic liners including geosynthetic clay liner (GCL), geomembrane and geotextile layers to prevent leachate infiltration and soil contamination.

Figure 7.9: Drainage Layer Implementation and Waste Disposal in Tehran Sanitary Landfill (Photo Taken by the Author)

7.3. LTMT Validation

As mentioned previously, the settlement data regarding a pilot scale landfill in Tehran was selected for the verification of validation of LTMT. This section provides further information about this case study specification.

7.3.1. Pilot Scale Landfill Data

The selected case study involves two cells which were designed and constructed in pilot scale within Aradkooh region located approximately 20 km Southeast of Tehran, Iran. This project which was performed by Iran University of Science and Technology (IUST) places municipal solid wastes from Tehran in two cells with a height of about 5.2 m and the dimensions of 35 m × 57 m, as presented in Figure 7.10. The wastes were deposited in these test cells in three layers since 15th July 2006 to 2nd November 2006. The data related to each test cell is summarized in Table 7.3.

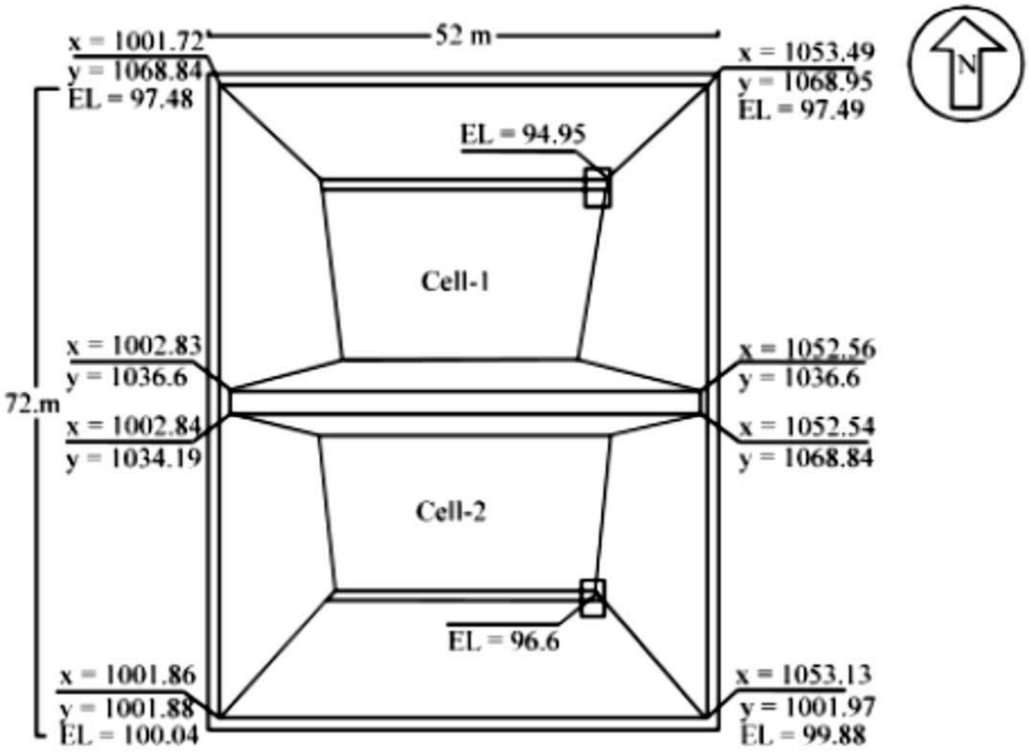


Figure 7.10: The Plan of Two Cells of Tehran Pilot Scale Landfill

The base liner of these two test cells comprise of 0.60 m of compacted clay with a specified hydraulic conductivity of less than 1.56 $\times 10^{-8}$ m/s and geomembrane liner with 1.5 mm thickness which was protected by a 500 gr/m^2 geotextile liner and a layer of fine sand with 0.15 m thickness, whereas the final cover consists of two layers of compacted clay with the thickness of 150 mm. Integrated into all liner systems is a leachate collection system. This leachate collection system is composed of a drainage layer with thickness of 0.45 m, and leachate collection pipes which drain leachate into a header pipe, and subsequently into the leachate collection sump. However, leachate recirculation system has been practiced in the south cell (Cell 2) and circulates the leachate after 3 months of construction of final cover. In addition, both cells are equipped with gas collection system.

These cells were constructed in approximately 4 months and they placed about 4600 tonnes of Tehran wastes during 3 months. A landfill compactor CAT 826C was employed to compact the deposited wastes to achieve the waste density of about 900 kg/m^3. In order to obtain this density, six passes of the Caterpillar was considered over the waste layer with the thickness of 0.3 m.

Table 7.3: Data related to Tehran Pilot Scale Landfills

Layer	Characteristic	Cell 1	Cell 2
1st Layer	Capacity (tonne)	1755	1555
	Thickness (m)	1.6	1.5
	Fill Duration (day)	30	30
	Final Cover Construction and Instrument Installation (day)	13	13
2nd Layer	Capacity (tonne)	1505	1460
	Thickness (m)	1.9	2
	Fill Duration (day)	19	19
	Final Cover Construction and Instrument Installation (day)	6	6
3rd Layer	Capacity (tonne)	1490	1545
	Thickness (m)	1.8	1.7
	Fill Duration (day)	17	17
	Final Cover Construction and Instrument Installation (day)	16	16
General Description	Area (m2)	1980	1990
	Capacity (tonne)	4750	4560
	Thickness (m)	5.3	5.2

Different phases of this pilot scale project are illustrated in Figures 7.11 to 7.13.

Figure 7.11: Construction of Tehran Pilot Scale Landfill

The landfill settlement behaviour was investigated in this research over a period of 872 days.

Figure 7.12: MSW Disposal in Tehran Pilot Scale Landfill

Figure 7.13: Implementation of Final Cover for Tehran Pilot Scale Landfill

The field data for this case study indicate that the total amount of 94.9 m^3 leachate was produced in Cell 1 during the modelling period of one year since covering the landfill with final cap in January 2007. During this period, 164 m^3 leachate was recirculated over the Cell 2.

Moreover, the maximum monthly value for leachate discharge in Cell 1 was recorded 12.1 m^3 while the corresponding value for Cell 2 has been reported to be 12.7 m^3. In additions, the total generated methane from Cell 1 and Cell 2 was measured to be 113.39 tonnes and 156.59 tonnes, respectively. In comparison, the amount of generated dioxide carbon from Cell 1 and Cell 2 was 496.53 tonnes and 677.31 tonnes, respectively.

Table 7.4: Simulation Required Data for Tehran Pilot Scale Landfill

Input Parameter	Value	Unit
Landfill Height	5.4	m
Layer Thickness	0.3	m
Number of Lifts	3	-
Simulation Time	872	day
Moisture Content	75	%
Field Capacity	27	As a percentage of porosity
Waste Porosity	35	%
Waste Void Ratio	0.54	-
Waste Density	870	kg/m^3
Initial Waste Dry Density	500	kg/m^3
Waste Mass Fractions	6 (Non-degradable wastes) 10 (Slowly degradable wastes) 13 (Moderately degradable wastes) 71 (Rapidly degradable wastes)	%
Final Cover Thickness	0.3	m
Final Cover Density	2000	kg/m^3
Residual Moisture Content	0.17	-
Maximum Value of Leachate Discharge	12.1 (cell 1) 12.7 (cell 2)	m^3/month
Temperature	45	Celsius Degree
Gas Generation Potential	0.165	m^3/kg waste
Molar Mass of Gas Mixture	0.035	kg (34% CH_4 and 66% CO_2)

The information required for this validation which were available in this field study, are presented in Table 7.4. It should be noted that the best possible assumptions were made for the missing data, as presented in Table 7.5.

As the final cover has been provided from the local soil which is made up of ML soil type (compacted low plasticity sandy silt) with low permeability, the density of 2000 kg/m^3 is assumed for this layer. Moreover, the adopted approach for this technical management tool classifies the waste into four groups in terms of their biodegradability, as explained in previous chapters. All these groups are defined with specific characteristics including waste decay constant and waste specific gravity. Therefore, it is essential to consider the proper values for these different waste fractions. Referring to the available values of waste decay constant in literatures (e.g. Hettiarachchi et al., 2006; Babu et al., 2010) and based on the nature of Tehran's waste materials in terms of high moisture content and large organic fraction, as discussed in the following and shown in Figures 7.14 and 7.15, the assumed values for waste decay constant and waste specific gravity are presented in Table 7.5.

Table 7.5: Selected Data for Simulation of the Tehran Pilot Scale Landfill

Input Parameter	Value	Unit
Gas Diffusion Coefficient	0.4	m^2/day
Intrinsic Permeability	10^{-13}	m^2
Atmospheric Pressure	101	kPa
Initial Relative Pressure	0	kPa
Time for the Peak Rate of Gas Generation	30	day
Compression Ratio	0.10 0.08 0.07 0.06	time < 200 days time: 200 days - 2000 days time: 2000 days - 20000 days time > 20000 days
Swelling Ratio	0.020 0.016 0.014 0.012	time < 200 days time: 200 days - 2000 days time: 2000 days - 20000 days time > 20000 days
Waste Specific Gravity	3 (Non-degradable wastes) 2.2 (Slowly degradable wastes) 2 (Moderately degradable wastes) 1.8 (Rapidly degradable wastes)	-
Waste Decay Constant	0 (Non-degradable wastes) 0.00001 (Slowly degradable wastes) 0.0001 (Moderately degradable wastes) 0.001 (Rapidly degradable wastes)	day^{-1}

In addition, the survey of literature (e.g. Machado et al., 2009) indicates that the swelling ratio is usually between 10% and 20% of the value of compression ratio. Based on the published values for compression ratio and in accordance with the void ratio of Tehran waste (Table 7.4), the compressibility parameters are selected and specified in

Table 7.5. Furthermore, the initial dry density of waste is calculated from the given data on Tehran waste density and initial moisture content, as 497 kg/m^3 which was approximated to 500 kg/m^3. Additionally, the measured values for gas generation in test cells as discussed before and will be described further in the following sections and the Table 7.7, indicate that the generated gas in cell 1 comprises 39% methane and 61% carbon dioxide, whereas the produced gas in cell 2 consists of 34% methane and 66% carbon dioxide. Therefore, the molar mass of gas mixture has been calculated as presented in Table 7.4.

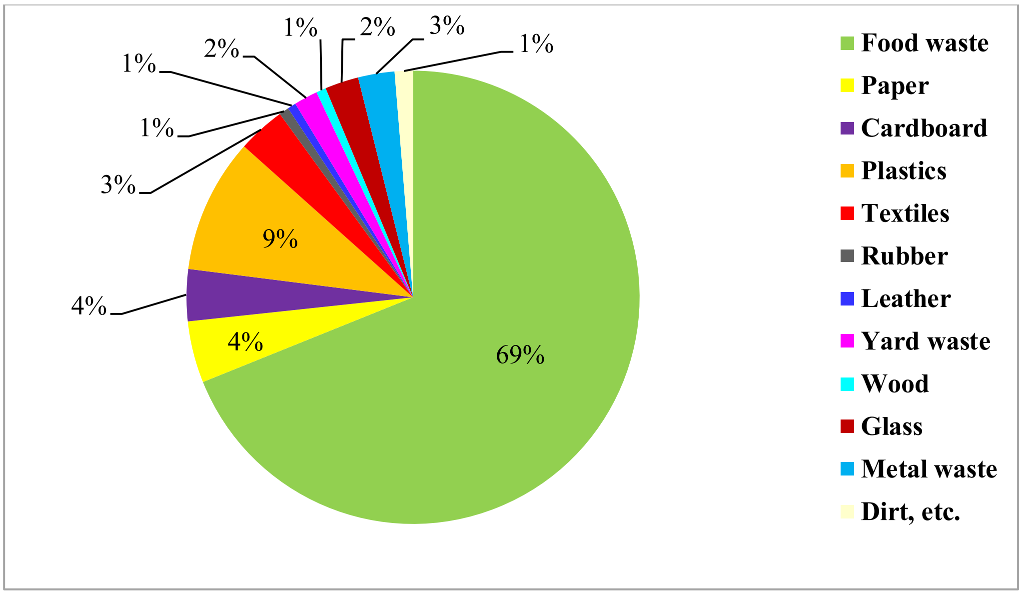


Figure 7.14: Waste Composition in Tehran Pilot Scale Landfill

Based on Zekkos (2005) research, the rate and magnitude of landfill settlement primarily depends on refuse composition and operational management practices, especially waste compaction. Thus, any data associated with waste composition and its characteristics play an important role in the settlement prediction. It should be noted that in the above mentioned projects, the wastes from 22 districts of Tehran were disposed in landfills with the composition similar to the waste composition shown in Figure 7.14. Referring to this Figure, the largest component of the Tehran waste stream is the food waste, which has high moisture content.

Moreover, Figure 7.15 illustrates Tehran waste composition divided into four groups in terms of their biodegradability based on the theory and the model adopted in this technical management tool.

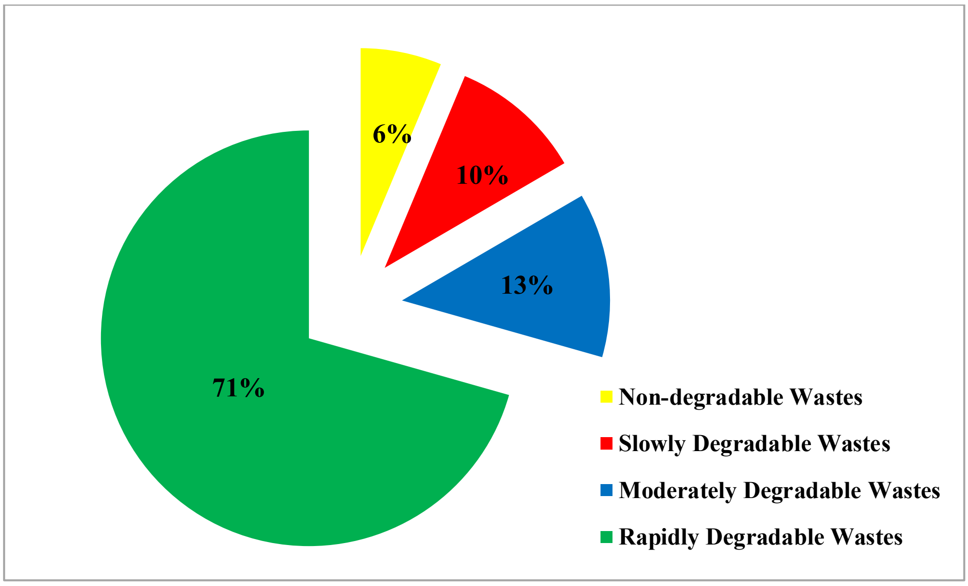


Figure 7.15: Waste Groups of Tehran Pilot Scale Landfill Based on Adopted Model

It should be noted that there are some conditions that can affect the waste properties in Tehran landfill which can be summarized as follows:

- The evaporation rate in Tehran is higher than typical values and it exceeds the value of precipitation. Therefore, the precipitation role in leachate production would be minimized in this city.
- The moisture content of Tehran municipal solid waste is around 60% to 75%, which is higher than the typical values for this parameter.

7.3.2. Tehran Landfill Data on Gas and Leachate Production

Since landfill settlement is highly associated with gas generation and leachate production, the amount of produced leachate and generated gas has also been investigated in these test cells. As mentioned previously, the test cells were filled with Tehran municipal solid wastes in three lifts since 15 July 2006 until 2 November 2006.

The data regarding the amount of produced leachate in both cells as well as leachate recirculation in Cell 2 are presented in Table 7.6. According to the data given in this table, the total amount of produced leachate in cell 1 during monitoring time has been recorded as 375.17 m^3, whereas the leachate production in cell 2 during the same time has been 395.86 m^3. In addition, the amount of recirculated leachate in cell 2 was about 481.69 m^3.

Table 7.6: Amount of Produced Leachate in Tehran Pilot Scale Landfill

Time	Produced Leachate (Litre)		Recirculated Leachate (Litre)
	Cell 1	Cell 2	
August 2006	7290	7282	0
September 2006	16744	9026	0
October 2006	31518	31990	0
November 2006	37358	30217	0
December 2006	16937	11531	0
January 2007	9551	8172	0
February 2007	7555	7608	0
March 2007	6039	5130	7369
April 2007	4455	5006	11096
May 2007	5523	7475	22292
June 2007	5611	7899	29397
July 2007	7555	10488	23210
August 2007	8473	10424	18622
September 2007	6406	8581	11626
October 2007	10278	10929	14967
November 2007	11300	12511	22393
December 2007	12159	11137	13060
January 2008	10154	10513	12415
February 2008	14252	14062	14064
March 2008	9645	11853	18121
April 2008	8232	8764	17404
May 2008	8456	10163	16257
June 2008	7351	7968	17633
July 2008	10232	10894	22966
August 2008	10333	11970	26507
September 2008	11455	17516	23927
October 2008	14224	21598	27367
November 2008	13004	14104	22608
December 2008	14417	16471	26364
January 2009	14506	15183	25002
February 2009	12453	14739	21576
March 2009	11972	14652	25447

Moreover, the amounts of generated gas from both test cells were studied after covering the cells with final cover. The results of this investigation are summarized in Table 7.7. Based on the measured data provided in this table for the monitoring time of 872 days, the amount of methane generation per kg waste is 39 lit and 56 lit for test cell

1 and test cell 2, respectively. Moreover, the corresponding values for carbon dioxide are 62 lit and 109 lit.

Table 7.7: Amount of Generated Gas in Tehran Pilot Scale Landfill

Time (day)	Generated Gas in Cell 1 (m^3/day)			Generated Gas in Cell 2 (m^3/day)		
	CO_2	CH_4	O_2	CO_2	CH_4	O_2
1	217.38	106.61	44.45	167.03	76.40	57.99
21	234.71	169.08	28.13	364.41	260.65	1.25
95	177.36	146.11	0	145.59	120.53	0
127	172.52	125.43	0	118.80	97.02	0
199	302.69	262.40	0	445.90	433.19	0
217	324.15	276.38	0	460.99	419.84	0
232	258.56	274.64	0	460.88	427.82	0
248	261.92	253.72	0	459.89	413.48	0
270	301.94	253.12	0	504.53	404.33	0
286	328.60	238.02	0	512.34	390.58	0
309	325.71	256.33	0	479.43	455.95	0
321	360.80	264.96	0	553.70	416.94	0
338	355.67	243.48	0	541.36	408.25	0
344	351.43	264.26	0	527.50	387.46	0
351	311.70	232.89	0	514.14	384.99	0
366	324.43	246.05	0	528.70	385.46	0
375	368.27	256.69	0	485.12	382.46	0
399	366.71	257.32	0	510.12	377.79	0
426	358.89	246.15	0	469.49	365.66	0
444	335.50	255.67	0	507.51	359.35	0
476	351.34	228.95	0	487.47	356.42	0
501	325.35	214.96	0	521.41	345.70	0
747	117.41	192.06	0	314.07	222.70	0
782	117.41	190.50	0	280.79	208.60	0
839	266.26	187.42	0	314.83	180.60	0
872	264.07	186.01	0	305.98	175.45	0

7.3.3. Tehran Landfill Settlement Data

To investigate the settlement behaviour of Tehran pilot scale landfill, three monitoring systems were employed in two test cells to measure the settlement in both landfill body and landfill surface. These systems included as following:

- Profiler which is a long tube with a sensor at its end. To employ this device, it is required to provide some HDPE pipes, fixed on every layer, in order to send the sensors through them. These sensors can provide the profile of the pipe (i.e. layer) with respect to a fixed point. Subsequently, the settlement of pipes can be measured in an interval of one month by this system. In this project, four pipes have been considered for landfill settlement measurement in each cell. Figure 7.16 and Figure 7.17 illustrate the position of these pipes in plan and section, respectively.

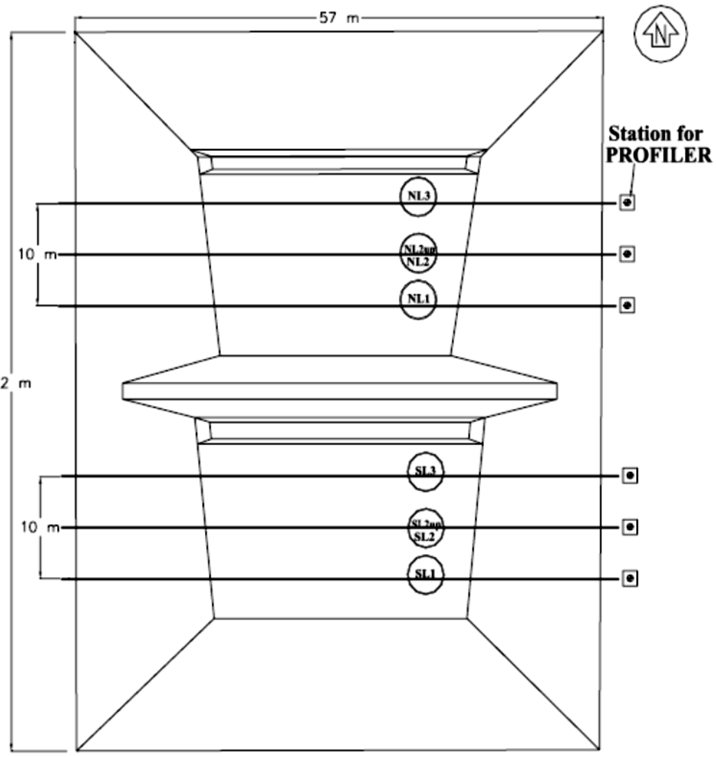


Figure 7.16: Plan of Tehran Pilot Scale Landfill Illustrating the Position of HDPE Pipes for Profilers

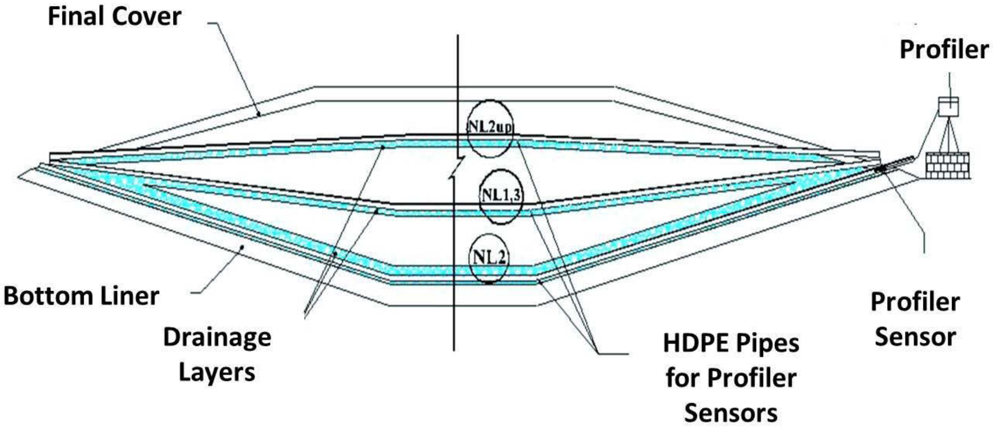


Figure 7.17: Section of Tehran Pilot Scale Landfill Illustrating the Position of HDPE Pipes for Profilers

The results of settlement measurement in both test cells by this settlement monitoring device are summarized in Tables 7.8 to 7.9.

Table 7.8: Average Settlement Measured by Profiler in Cell 1

Time (day)	Average Settlement (mm)	
	Layer 1 (level +2 m)	Layer 2 (level +3.8 m)
34	23	37
60	61	82
92	69	127
124	81	161
168	60	154
203	78	174
262	150	244
530	189	-
952	200	498

It should be noted that the settlement values of first layer is subtracted from the settlement values of second layer to provide the settlement values of layer 2.

Table 7.9: Average Settlement Measured by Profiler in Cell 2

Time (day)	Average Settlement (mm)	
	Layer 1 (level +2 m)	Layer 2 (level +3.8 m)
34	18	41
60	35	80
92	46	102
124	67	145
168	85	166
203	112	203
262	175	269
530	212	397
952	241	552

- In this project, 16 extensometers, which consists of a metal platform and a vertical rod, are installed in each test cell at different layers with levels of 0, 2 m, and 3.8 m, as shown in Figure 7.18.

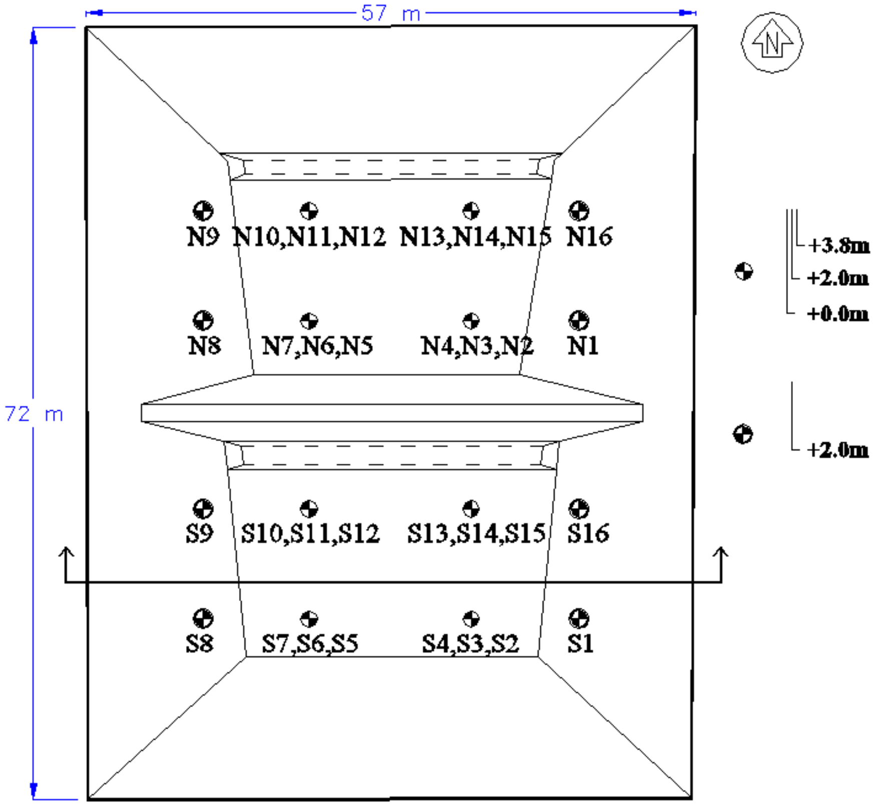


Figure 7.18: Plan of Tehran Pilot Scale Landfill Illustrating the Position of Fixed Extensometers

As shown in Figure 7.19, the HDPE pipes for profilers and the extensometers placed over the intermediate cover of each lift of test cells.

Figure 7.19: Placement of HDPE Pipes for Profiler and the Fixed Extensometers in Tehran Pilot Scale Landfill

Tables 7.10 and 7.11 present the results of settlement measurement in both test cells by employing this settlement monitoring device. It should be noted that the fixed extensometers installed on the bottom of landfill (level 0.0) show no significant settlement may be due to the excavation height of landfill which is very small in comparison with the height of real landfills.

Moreover, the settlement values for each layer is calculated based on averaging the measurement values for a group of extensometers installed in that layer. As data presented in Tables 7.10 and 7.11 shows, the fixed extensometers installed in second layer introduced greater values in comparison with the first layer due to the larger height of waste in that layer. It should be noted that the settlement values given for layer 2 are net settlement, i.e. the settlement values of first layer is subtracted from the settlement values of second layer.

Table 7.10: Average Settlement Measured by Fixed Extensometers in Cell 1

Time (day)	**Average Settlement (mm)**	
	Layer 1 (level +2 m)	**Layer 2 (level +3.8 m)**
0	0	0
22	6	35
39	16	57
64	29	85
100	42	114
127	56	140
166	86	192
205	101	228
234	115	259
263	130	292
298	151	334
349	172	379
390	187	412
419	198	431
475	214	468
511	226	488
538	233	501
566	240	513
598	243	521
641	254	541
691	258	555
756	268	574
815	277	591
872	282	604

Table 7.11: Average Settlement Measured by Fixed Extensometers in Cell 2

Time (day)	Average Settlement (mm)	
	Layer 1 (level +2 m)	Layer 2 (level +3.8 m)
0	0	0
22	54	111
39	56	121
64	72	154
100	100	208
127	112	235
166	138	286
205	156	328
234	165	357
263	177	390
298	188	423
349	203	461
390	210	492
419	217	508
475	229	548
511	238	568
538	243	581
566	248	595
598	250	604
641	260	629
691	265	640
756	271	644
815	278	645
872	284	657

- The surface settlement can be considered as the landfill settlement in many studies. Therefore, surface measurement was taken into account in this project in order to investigate the landfill surface settlement and hence, 84 benchmarks were considered on each test cell and the settlement of them was measured with respect to a fixed point in an interval of one month. The approximate positions of these benchmarks are illustrated in Figure 7.20.

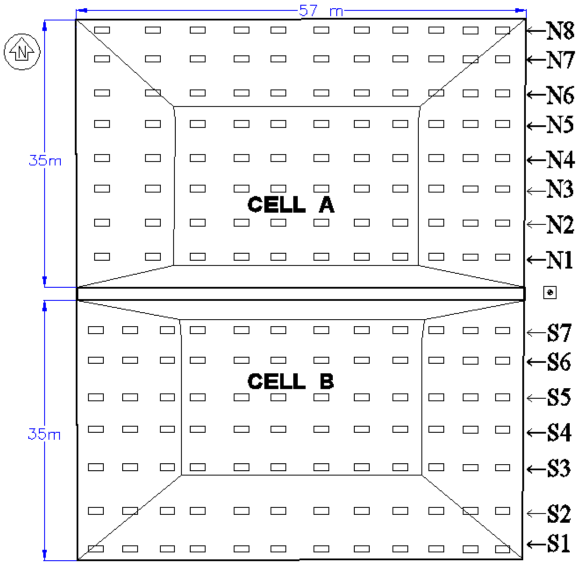


Figure 7.20: Plan of Tehran Pilot Scale Landfill Illustrating the Position of Surface Benchmarks

Table 7.13: Average Settlement Measured in Tehran Pilot Scale Landfill

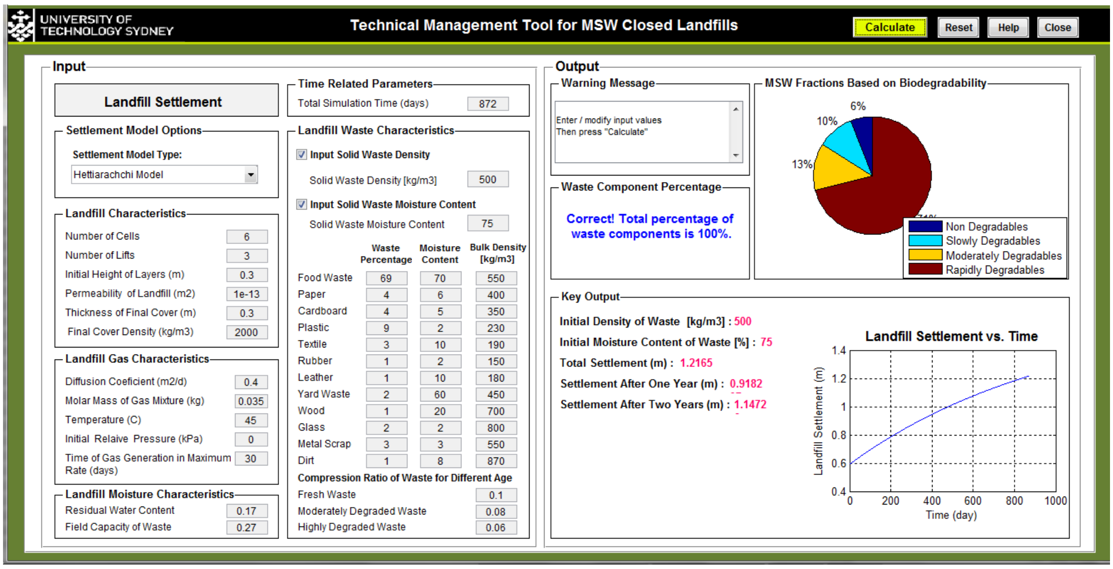
Time (day)	Average Settlement (mm)	
	Cell 1	Cell 2
22	25.9	35
39	34.5	46.7
64	62.2	81.3
100	94.1	124.7
127	113.3	150.5
166	145.3	188.8
205	173.1	228
234	198.1	257.7
263	225.1	288.2
298	262.9	325.2
349	307	366.6
390	337.1	393.4
419	351.3	409.3
475	367.3	430.8
511	387.7	453.2
538	402.9	470.1
566	418.1	486.9
598	428.7	500.3
641	459.1	535.4
691	482	559.9
756	512.2	588.1
815	532.1	604.3
872	549.5	622.5

In general, the measured surface settlement in both test cells of Tehran pilot scale landfill can be summarized as the values presented in Table 7.13. It could be noted that the values given in this table are obtained by averaging the settlement value in points with maximum height (i.e. the central part of cells).

7.3.4. Comparison of Measured and Estimated Settlement Data

As leachate recirculation was practiced in one of the test cells (Cell 2) in Tehran pilot scale landfill, settlement data from this cell was taken to validate this management tool. The collected and assumed data provided in Tables 7.4 to 7.5 is used for this verification. The results of the comparison between measured data and the data obtained from LTMT are discussed in the following.

As it was discussed previously, the settlement of landfill was estimated by measuring the benchmark settlement over Tehran pilot scale landfill caps. This measurement showed the total settlement of about 620 mm in Cell 2 with leachate recirculation. Using the available data for Tehran waste and its landfill, the settlement was estimated by LTMT, which the result of settlement estimation by this technical management tool is illustrated in Figures 7.21 to 7.22.



Technical Management Tool for MSW Closed Landfills

Input

Landfill Settlement

Settlement Model Options

Settlement Model Type: Hettiarachchi Model

Landfill Characteristics

Number of Cells	6
Number of Lifts	3
Initial Height of Layers (m)	0.3
Permeability of Landfill (m2)	1e-13
Thickness of Final Cover (m)	0.3
Final Cover Density (kg/m3)	2000

Landfill Gas Characteristics

Diffusion Coeficient (m2/d)	0.4
Molar Mass of Gas Mixture (kg)	0.035
Temperature (C)	45
Initial Relaive Pressure (kPa)	0
Time of Gas Generation in Maximum Rate (days)	30

Landfill Moisture Characteristics

Residual Water Content	0.17
Field Capacity of Waste	0.27

Time Related Parameters

Total Simulation Time (days): 872

Landfill Waste Characteristics

☑ Input Solid Waste Density

Solid Waste Density [kg/m3]: 500

☑ Input Solid Waste Moisture Content

Solid Waste Moisture Content: 75

	Waste Percentage	Moisture Content	Bulk Density [kg/m3]
Food Waste	69	70	550
Paper	4	6	400
Cardboard	4	5	350
Plastic	9	2	230
Textile	3	10	190
Rubber	1	2	150
Leather	1	10	180
Yard Waste	2	60	450
Wood	1	20	700
Glass	2	2	800
Metal Scrap	3	3	550
Dirt	1	8	870

Compression Ratio of Waste for Different Age

Fresh Waste	0.1
Moderately Degraded Waste	0.08
Highly Degraded Waste	0.06

Output

Warning Message

Enter / modify input values
Then press "Calculate"

Waste Component Percentage

Correct! Total percentage of waste components is 100%.

MSW Fractions Based on Biodegradability

Key Output

Initial Density of Waste [kg/m3] : 500
Initial Moisture Content of Waste [%] : 75
Total Settlement (m) : 1.2165
Settlement After One Year (m) : 0.9182
Settlement After Two Years (m) : 1.1472

Figure 7.21: Graphical Interface of Settlement Estimation in Tehran Pilot Scale Landfill

As it can be observed in the settlement profile presented in Figure 7.22, there is an initial settlement of about 0.60 m due to the philosophy adopted in this technical management tool. In fact, the model considered in this technical management tool estimates the settlement for each layer of waste. However, the landfill closure and the final cover placement are usually assumed as the starting time of the settlement process in field studies.

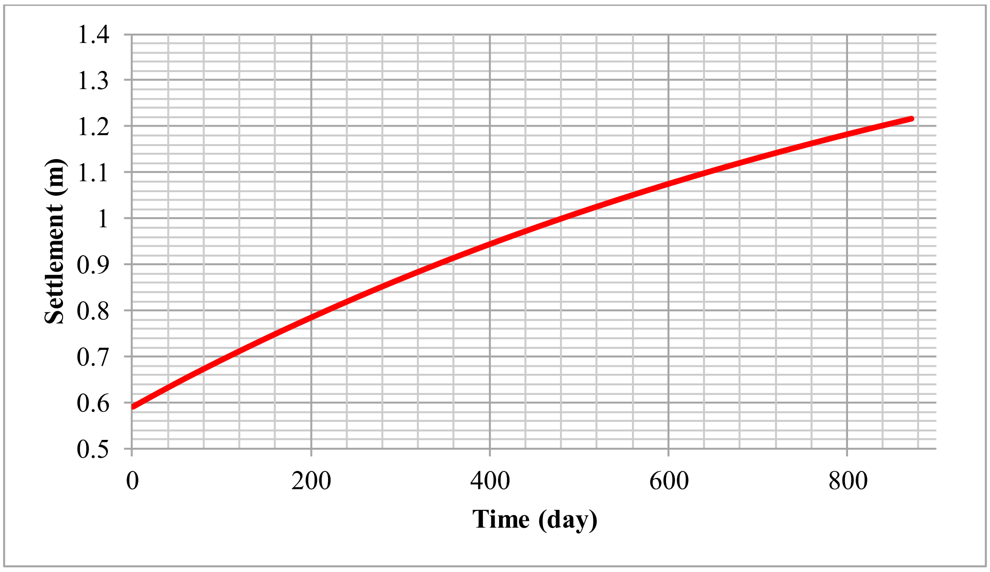


Figure 7.22: Settlement Profile Predicted by LTMT for Tehran Pilot Scale Landfill

The settlement profiles obtained from the LTMT and the measured values, disregarding the initial settlement are compared in Figure 7.23. As it can be clearly observed in this figure, both settlement profiles have the same trend and the same difference in settlement.

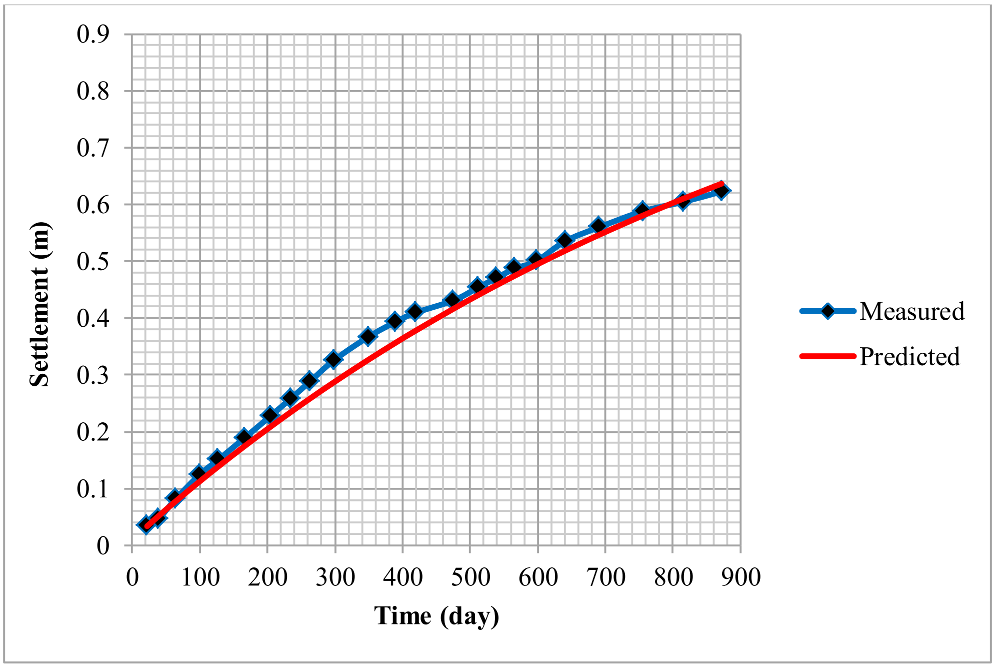


Figure 7.23: Comparison of Measured and Predicted Settlement

The results and settlement profiles illustrated in Figure 7.23 indicate that this landfill technical management tool (LTMT) can be effectively used for MSW landfill settlement estimation.

7.4. Summary

In fact, Waste is a pressure on the environment in terms of the loss of land and other resources necessary for its disposal or treatment, and of the environmental contamination that may potentially result from its treatment, storage, disposal and other handling. In this regard, municipal solid waste management systems have been arisen and different countries have adopted various policies for proper management of their solid wastes. In Tehran as a capital of Iran with a total population of about 12 millions, different approaches have been considered for waste management, among them disposal in landfills have been chosen for depositing some fraction of solid wastes in them. The results of the field study undertaken in a pilot scale landfill in Tehran has been selected as a case study to validate the landfill technical management tool (LTMT) developed during this research. The predicted results by the developed model have been in very good agreement with the measured filed settlement data collected from Tehran landfill.

Chapter 8

Conclusions

8.1. Summary

Landfills remain an attractive disposal route for municipal solid waste because in most cases it is more economical than other alternatives such as incineration and composting. The post-closure development of landfilled areas becomes essential as urban growth reaches landfill boundaries. One of the most awkward technical post-closure considerations is the large amount of settlement that can take place for many years after abandonment. Predicting settlement is difficult analytically, as municipal fill undergoes large amounts of secondary consolidation, not easily incorporated into traditional settlement calculations. Therefore, the ability to predict settlement becomes a key issue in the design and construction of landfills.

In this study, a landfill technical management tool (LTMT) is developed to estimate the landfill settlement considering various parameters and conditions. A geotechnical software (PLAXIS) and a programming language (MATLAB) is employed for the development of LTMT. The technical management tool is comprised of different parts including the following parts:

- Municipal Solid Waste Physical Properties
- Municipal Solid Waste Chemical Properties
- Municipal Solid Waste Biological Properties
- Landfill Settlement
- Landfill Slope Stability
- Parametric Study

All these parts can estimate different properties of municipal solid wastes while they enable the user to investigate the role of various parameters and conditions on landfill settlement and slope stability.

For development of this technical management tool, a comprehensive study has been carried out on different proposed models associated with MSW landfill settlement. Among these models, a model incorporating gas generation and leachate movement has been considered as a basis for the development of the landfill technical management tool. As the selected model considers constant parameters for the moisture content, the waste component, the landfill height, the density etc., some modifications have been made in order to predict more precise long term settlements of MSW landfills with more effective parameters.

Furthermore, this study involves a detailed parametric study considering variations of different parameters, which is conducted in term of variations of the settlement with time as affected by parameters. Additionally, a sensitivity analysis is also performed to study the sensitivity of the models to variation of input parameters such as unit weight, landfill height, waste properties, and factors, affecting the biodegradation process of landfills.

This research also covers a numerical study on the stability of MSW Landfill by employing PLAXIS 2D as well as a detailed parametric study for investigation of the influence of the slope geometry on the safety factor (SF) of landfill slope stability considering the variation of the landfill height, and the slope inclinations.

The verification of any model play an important role in making engineering predictions with quantified confidence and quantifying the confidence and predictive accuracy of model calculations provides the decision-maker with the information necessary for making high-consequence decisions. Accordingly the model verification has been carried out in this study to validate the landfill technical management tool (LTMT) results. In order to conduct the verification process, a comprehensive data was gathered regarding different kinds of landfills in Tehran and the waste characteristics of this city, and subsequently the Tehran landfill has been modelled based on the relevant collected information to predict the settlement incorporating this technical management tool. Finally, the results obtained from the landfill settlement prediction by LTMT have been compared with the field study data.

8.2. Conclusions

As mentioned previously, a technical management tool has been developed during this research to estimate the landfill settlement considering various parameters and conditions. The landfill technical management tool (LTMT) works as a User Interface Program in order to enable researchers in this area to use it much more efficient. Moreover, as many factors such as waste composition, moisture content, waste density, so forth, which have significant effects on analysing waste settlement are considered as constant parameters in almost all existing landfill settlement models, this program has the advantage of enabling users to change these parameters in order to evaluate the effect of their variations on the landfill settlement.

In this study, by employing the landfill technical management tool, a detailed parametric study has also been conducted on the influence of some of the relevant parameters on the time settlement response of municipal solid waste based on the selected model. Overall, the parametric study shows that the variation of parameters can lead to significantly different results. Therefore, it is necessary that the parameter values be carefully selected for accurate prediction of landfill settlements.

Moreover, in order to increase the understanding the landfill behaviour and to quantify the significance of different parameters, sensitivity analysis has been performed. The results of this sensitivity analysis indicate that there were two prominent characteristics which have significant impacts on the overall landfill settlement. These characteristics are landfill height (S_1) and compressibility parameters (S_6), while two other parameters including gas diffusion coefficient (S_4) and Van Genuchten parameter (S_{10}) have trivial effects when compared to their relevant NOP. However, some other parameters have different degree of impact on the landfill settlement, as discussed in Chapter 6. Furthermore, the sensitivity of landfill settlement to moisture content has been investigated for two normal operating points. Based on the relevant calculations, the landfill settlement is influenced by moisture content of around 20%. However, the moisture content is non-influential for the study of landfill settlement where moisture content is about 40%.

In addition, a numerical study on the slope stability of MSW landfill has been conducted using PLAXIS. A detailed parametric study has been carried out to investigate the influence of variations of landfill height on the safety factor (SF) as affected by the variation of slope geometry. The results show that the safety factor of landfill slope stability increases by increasing the slope inclination. Moreover, the safety factor decreases by increasing the landfill height at the same slope inclination.

The verification process, as mentioned earlier, has been performed to verify the technical management tool developed during this research with available results obtained from the experimental study on Tehran Landfill settlement. Subsequently, the final outcomes have been compared and verified with the estimated data from the considered case study to obtain accurate practical results. The verification process indicate that the results predicted by the technical management tool are in very good agreement with the measured filed settlement data collected from Tehran landfill.

8.3. Recommendations for Future Investigations

Numerous models have been developed to simulate the landfill behaviour and study its settlement. The existing predicting models still have deficiencies and weakness to integrate all mechanical, physical, and biological parameters as well as to incorporate the gas generation and moisture distribution. Moreover, the total settlement is commonly assumed to consist of mechanical compression, mechanical creep, and biodegradation-induced compression. Several models have been developed based on different assumptions. According to review of the models and studies on landfill settlement, it has been concluded that there are limited number of models that consider all three components of the settlement. Therefore, the main areas considered for future studies are listed as follows:

- Estimating the settlement of MSW landfills incorporating the digestibility and the solid degradable fraction, as the amount of degradable material and the rate at which a waste mass degrades are fundamental factors in controlling the landfill settlement rate and its magnitude
- Estimating the settlement of MSW landfills incorporating unsaturated condition due to the unsaturated nature of landfilled waste, as the saturated state might misrepresent field conditions because under the saturated conditions, the landfill is considered to be completely liquid saturated by preventing gas generation at all times
- Estimating the settlement of MSW landfills incorporating the generation and dissipation of landfill gases and moisture distribution coupling of the 2D Richards equations
- Studying the effect of the decomposition induced void change parameter on the MSW landfill settlement to understand the link between biodegradation induced solid phase loss and the final landfill settlement. This parameter has a direct controlling influence on the biodegradation which subsequently can affect the settlement magnitude and rate
- Studying the creep settlement properties under the co-effect of stress, biodegradation and temperature for predicting the total settlement of waste in landfills, as the variations of the physiochemical reactions and biodegradation

as well as the temperature in the landfills can affect the creep settlement, and hence the total settlement in MSW landfills.

- Estimating the MSW landfill settlement by considering a combined settlement of soil underneath of landfill and waste material inside the landfill.
- Studying municipal solid waste landfill settlement integrating the settlement due to the surcharge (such as traffic load), the landfill settlement due to the waste self weight (which have been considered in this research), and the settlement of subgrade below the landfill.
- Studying the MSW landfill settlement incorporating the leachate and gas generation while modifying the landfill technical management tool in order to predict the amount of leachate and gas generated over the simulation time.

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