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Biodegradation-driven Landfill Settlement Modelling

Committee

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Abstract

Eternal aftercare for landfills is the standard in Dutch waste management policy after a law came into effect in 1996, meaning eternal waste management from potentially hazardous substances. A prescription of this policy is the application of watertight barriers on top of the wastebody. The policy also prescribes the renewal of the packing materials every 75 years. The wastebody is dried out, and the degradation has stopped so the wastebody does not change. The 'dry tomb' stays hazardous, thus eternal aftercare is implied.

The project 'introductie Duurzaam Stortbeheer (iDS) aims to create aftercare with an ending, or finite aftercare. It is looking for possibilities to stabilise the landfill mass, i.e. to eliminate the threat of pollutants by treating the wastebodies.

The goal of the CURE project is to develop fundamental insight into landfill processes in order to research the feasibility of wastebody stabilisation. To predict behaviour of landfills, and to monitor the processes, as much information as possible needs to be gathered through measurements. These consist of measurement of gas concentration and production rates together with the variation in leachate quality and volumes, as well as many more. This research, as part of the CURE project, presents the applicability of settlement as and addition to these measurements.

The main goal of waste body stabilisation is to actively reduce the amount of organic matter in a landfill. Uncontrolled landfills produce considerable methane emissions as well as high concentrations of nitrogen and heavy metals in the leachate, leading to groundwater hazards in the environment.

McDougall (2007) introduced the fundamental conceptual model upon which this research is based. This model is not publicly available, so one of the goals of this research is to provide a fundamental conceptual model. The relation between degradation and settlement has been studied and implemented in a 1D model which allows for hydrological systems, oxygen penetration, degradation and cell strain. The outcome is a relation between mechanics, biochemistry and hydrology. A few assumptions and simplifications were made to make the model versatile and adjustible, but also easy to read. For instance, the model uses oxygen as absolute limiting factor in degradation, neglecting all processes concerning anaerobic degradation. The model also assumes that at the beginning of the simulation, each cell has the same composition, because there is no conclusive data about the distribution of waste types. The model has been created in one dimension, thereby neglecting all multi-dimensional processes and limitations.

In the final scenario, the main limitation to degradation is the availability of dissolved oxygen. As irrigation provides infiltration of 5 mm water per day with 10 mg dissolved oxygen per liter, the daily reduction of oxygen demand is 50 mg. The total modelled oxygen demand of the landfill is over 9600 kg, which concludes that a different tactic needs to happen in order to stabilise the wastebody. To increase the degradation rate, more oxygen needs to be applied. An approximation of the effect of applying a partial vacuum above the water table in the landfill to attract air from the environment is modelled, giving the oxygen more transfer area into unsaturated water. An increase by a factor 10^4 is applied to the effect of oxygen on organic matter to model this enhanced irrigation system. The results are modeled over 100 years, after which approximately 26.17% of the degradation has happened. This shows that aerobic degradation over a wastebody takes too long with conventional degradation, and the unsaturated voids might help the process.

The model shows credible results for an unspecified landfill with deterministic parameters. Settlement has been brought in relation to a simplified form of biodegradation. The need for further research, with a spatial fluctuation of these parameters and detailed multidimensional water flow is needed to predict landfill behaviour in more detail.

Contents

Chapter 1

Introduction

1.1 Relevance

A landfill is defined as a site where waste is buried underneath a layer of soil, with dimensions as shown in figure 1.1. As a result of a law instated in the Netherlands, every landfill that is closed after September 1st, 1996 needs obligatory eternal aftercare. All landfills that closed before the deadline are called former landfills, and do not require eternal aftercare according to these laws. Landfills contain vast amounts of poorly sorted waste, meaning anything could wind up in a landfill. This results for example in the presence of a toxic level of heavy metals, large amounts of organic matter and all sorts of plastic. Landfill aftercare management shortly entails do not let the wastebody contaminate the environment. This means the prevention of methane emissions, leaching of waste and especially transportation of toxic materials into the subsoil and groundwater.

Before closure, infiltration of water, for example rain, leads to water flow through the wastebody, resulting in leachate. Leachate is water that contains dissolved waste products, for example organic content (DOC) or heavy metals complexed with DOC (Mathlener et al. 2006). Modern landfills pump leachate from the bottom layer to prevent further infiltration of dissolved waste products. After closing the landfill by applying a watertight top cover layer, it takes up to five years before leachate stops flowing out of the landfill. This is pumped out of the bottom layer, making it harmless to the environment. However, the threat of toxicity remains as the landfill is essentially paused. Once water infiltrates the landfill for instance by breakage of the top cover, leachate production will recommence. Dutch law distinguishes the landfill and the subsoil, where the landfill falls under one law and the subsoil under another. The main goal of aftercare is to prevent pollution and contamination of subsoil and groundwater. As the threat, constisting of pollutants and toxic materials in the wastebody, continues to exist, so does the need for aftercare. Naturally, eternal aftercare is a temporary solution, until a permanent fix is found.

CURE is a multi-institutional project that focuses on the feasibility of a permanent solution for landfill aftercare. The project contributes to iDS, a programme created by the waste branche together with local and national governments to eliminate the eternal threat by waste stabilisation. Waste stabilisation consists of the stimulation of bioactivity resulting in degradation of organic matter. This leads to immobilisation of heavy metals and other toxic waste. CURE focuses on gathering information on the effectivity of different approaches on waste stabilisation. To assess the effectivity, the landfill needs to be monitored, and different types of measurements need to be carried out and compared.

To assess the stability of the wastebody in the landfill, data is needed about the developments of the wastebody. The most common ways of gathering data are leachate tests and air quality measurements. To increase the versatility of the assessment, settlement is suggested as an addition. However, the relation between settlement and biodegradation is not straightforward.

According to Hoekstra et al. (2010) the 80 km^2 of landfills in the Netherlands mostly lack liners or other protection measures. Leachate from these landfills can carry degradation products into the subsoil, from where they form a potential risk to both the nature and inhabitants of the area. A lot of basic information on these landfills may never have been documented, such as geometry and content. The current way of landfilling is placing a bottom (watertight) liner first,

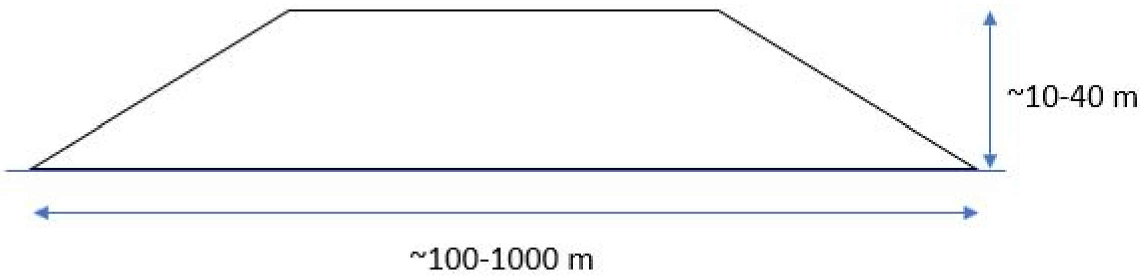

Figure 1.1. generic landfill dimensions.

filling the site, and covering it with another liner to pack the landfill. The wastebody will continue to discharge leachate for approximately 5 years, and after that the matter is considered dry and inert. This means no more degradation, but eternal pollution potential. According to Oonk (2012) The aim of conventional landfill management is to contain the risk and prevent processes that eventually pollute the environment. The new approach as described by Kattenberg et al. (2013) to substantially diminish the pollution potential of landfills in order to create a inert landfill that does not require eternal aftercare as a dry tomb does, means the eternal risk of damaging the environment with leachate from the wastebody can be eliminated.

In the light of climate change and the goal to cut greenhouse gases by 55% as set by the European Commission (2020), is essential in order to reduce the impact of waste on the environment. To reach these targets, every sector needs to reduce emissions. The waste sector is one of the more advanced sectors in this field, with a lot of improvement as can be seen in Table 1.1. In this table, every greenhouse gas is measured CO_2 equivalent. Methane, the by landfills most produced greenhouse gas, is 26 times as harmful for the environment as CO_2, meaning 1 kg methane equates to 26 kg of CO_2. The bottom row of the table shows the percentage that landfills contribute to the national emissions. As significant as the reduction that can be seen is, a lot is still to be gained.

Table 1.1. CO_2 equivalent emissions in the Netherlands for 1990 and 2018 as documented by Ruyssenaars et al. (2020).

	1990	2018
National emissions (Tg CO_2 eq.)	228.1	193.1
Waste emissions (Tg CO_2 eq.)	14.0	2.8
Landfill emissions (Tg CO_2 eq.)	13.7	2.5
Landfill emissions (% of total)	6.1	1.3

Scharff (2014) states that with Dutch law as it is, the aftercare timeframe for landfills is infinite. Aftercare comes with risk, thus waste from before 1990 will be the burden by generations to come. In order to truly put an end to aftercare, all organic matter in a landfill must have dissipated, and no pollutants find their way out of the landfill. The threshold that needs to be met in order for the landfill to be in post-aftercare needs to be defined, thus when a few million cubic meters of poorly sorted waste is treated sufficiently. As there is no feasible way to know the potential CO_2 equivalent emissions left, only a very course estimate can be given which might be a factor 10 off.

Therefore, Dutch policy is to wrap the potentially contaminating wastebody and protect the environment through containment in a dry tomb. This is a safe practice, provided that the cover gets replaced every 75 years. As nothing is to happen to the waste inside the dry tomb, the situation does not change and the cycle of 75 years is perpetual, meaning aftercare is perpetual. This also means the site is relatively useless, as the cover needs replacing and thus nothing that can last long should be placed on top.

1.2 Hydrology

Hydrology, or the study of behaviour of water finds applications in landfill dynamics as both transport of leachate contents and the activation and progress of biogeochemical degradation can be explained through hydrological processes as water flowand oxygen and degradation product solution and transport. With gathering as much information as possible, these processes need to be included in the model in order to create a reliable result.

To describe and model the hydrologic system within a landfill, the similarities and differences to conventional hydrology modelling are to be mapped, as well as the connection to settlement and degradation. McDougall (2007) describes simple models that are coupled to describe interdependency and the predictive relation of the three. As Zhan et al. (2017) state MSW can have a remarkably high leachate level, underneath which landfill gas (LFG) production can take place, confining a waterbody within the landfill. The hydrology of a landfill is complex and chaotic. In order to be able to make a fundamental model, simplifications need to be made.

1.3 Biodegradation

McDougall (2007) describes a fundamental conceptual model combining hydrology, biodegradation and deformation. Theoretically, these three are connected and dependent on each other. Part of the settlement is caused by degradation, called biochemical creep. The degradation is driven and limited by the water and air flows within the landfill. These flows are in return impacted by settlement of the landfill. The flows of biochemical products in the landfill are thus influenced by deformation, caused by biochemical reactions and these flows of biochemical products.

Different landfills need different approaches to aftercare, as the landfill can only be closed when authorities deem it safe for the environment. Laner et al. (2012) have proposed a way of defining these criteria. The most important criteria include quantity and nature of emissions, barrier performance and degradation product seepage into the surrounding environment. As landfills tend not to fulfil these criteria upon closure, a plan for active aftercare needs to be derived and implemented. Also, as these criteria are ongoing, a detection system needs to be in place to identify the autonomous activity of these processes after active aftercare.

According to Reinhart et al. (2002) possible advantages include a decrease in degradation time, a reduction of unwanted gas emissions, and reduced toxicity of landfill and subsoil. The disadvantages could include explosion or fire related hazards due to gas concentrations, additional costs, and the production of unknown other toxic gases as side products. Van Turnhout et al. (2016) created a toolbox to find the best model to describe the biochemical processes happening inside the landfill. One starts with the simplest model that could possibly work, and then adds one level of complexity at the time. The results of the model are then compared to the actual data. This is visualised in figure 1.2.

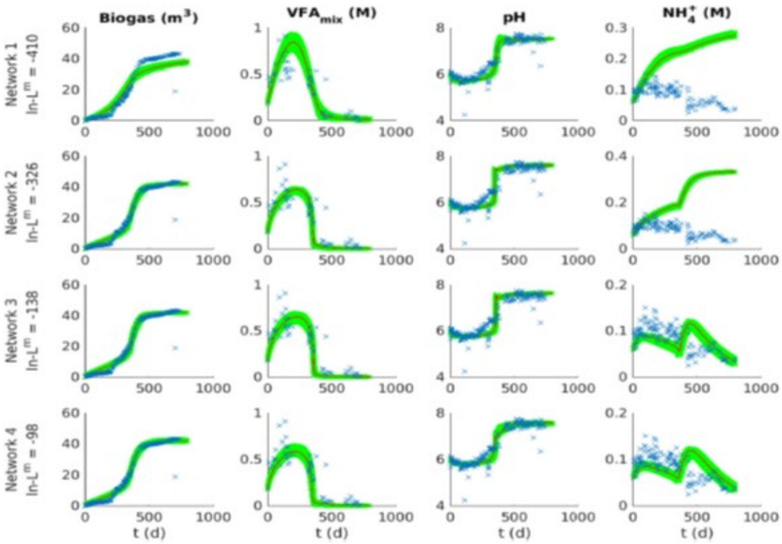

Figure 1.2. Van Turnhout et al. (2016) visualises the predictions of four model networks with increasing complexity, to find the simplest model that accurately fits the measured data.

Van Turnhout (2017) states that most researchers model a landfill as a black box, or an unknown system that produces a certain output, based on the inputs. In this case, examples of inputs are water and or leachate, air, thermic energy and dissolved chemicals. The relation between quantities of inputs and output quantities indicate certain processes happen at large scale within the landfill. Van Turnhout made an effort to open up the black box, describing the most relevant of these processes happening in these vast bodies consisting of highly heterogenous waste components. He then proceeded to create a model to predict the processes happening based on inputs, measured by the outputs. Figure 1.3 is an example of a process network as described by Van Turnhout.

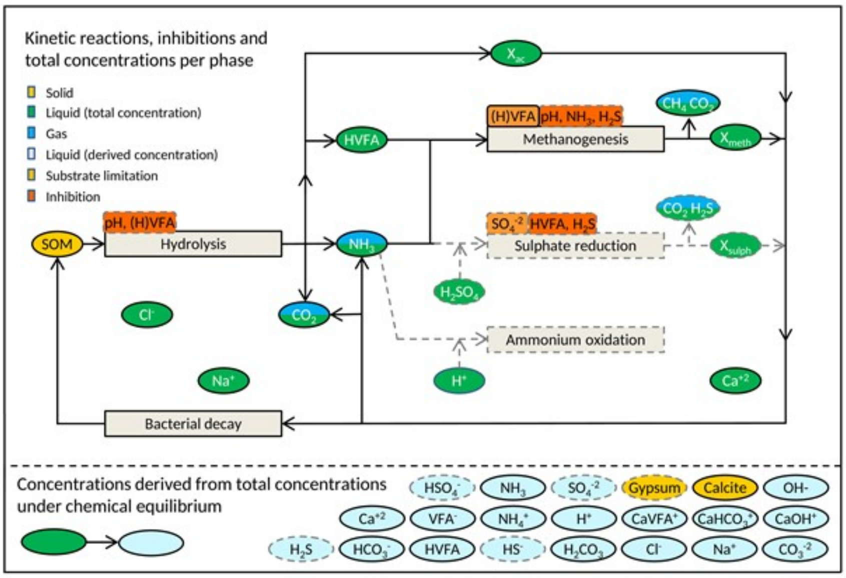

Figure 1.3. Van Turnhout (2017) describes a network of different anaerobic reactions and components, added one by one to increase the accuracy of the network model, approximating measured data.

1.4 Mechanics

According to N.D. Woodman et al. (2013), settlement of municipal solid waste (MSW) can be categorised in three different processes. The first is primary consolidation, where the load finds an equilibrium with the stiffness of the soil, depending on the rate of pore water pressure dissipation. The second part consists of two processes, namely the creep, a time-related process of continued deformation of the soil structure, and the biodegradation induced settlement, as described by Machado et al. (2009). As the first two processes can be compared to behaviour of comparable soil, biodegradation induced settlement is the most unpredictable part. The biodegradation settlement takes place as long as organic matter is degrading, and its products leached or emitted out of the landfill. Therefore, the quantity of biodegradation and its effect on settlement will need to be estimated in order to predict settlement behaviour.

McDougall (2007) claims the settlement of MSW could reach as much as 50% of the initial height of the landfill. As most landfills will continue to settle after closure, the negative effects on sealing and collection systems is considerable. If not designed accurately for these deformations, failure of the landfill and its containment will occur, leading to discharge of leachate and contamination of the subsoil and groundwater (Powrie, 2019). According to Powrie, on top of the regular mechanical deformation of soils, the pore fluid compressibility can influence the settlement of MSW. In contrast to regular soil mechanics, where the pore fluid is mostly incompressible, the landfill pore fluid consists of both gas and water, and will thus be considered as compressible. Also, the compressibility and discontinuous integrity of waste particles is mentioned as uconventional in regular soil mechanics, but relevant in landfill management and aftercare. As mentioned before, the degradation plays a role in settlement, specifically chemical and biological processes. This is mostly relevant on a longer timescale, as it is a long process.

With the notion that waste is a three phase system (Tahmoorian et al., 2020), where the solid phase consists of inert and organic matter, comes the alteration of the contents and portion of these three phases over time. Due to the variation of substances within unsorted waste in a landfill, and the range of compressibility and degradability of these different substances, no meaningful prediction can be given for waste settlement without knowledge of its composition and spatial variability.

1.5 Research Goal

Monitoring the bioreactor landfills in terms of the degradation of organic matter currently consists of measuring the quality of the leachate and the concentrations and production rates of landfill gas emissions in time. However, a lot of information could potentially be gained from measuring settlements. As part of the CURE Project, this research focuses on using one of the consequences of biodegradation in a landfill, namely settlement, as a monitor parameter, and estimates the effect of biodegradation on settlement to be able to back-engineer the biochemical activity of the landfill. To assess the applicability of this monitoring system, a model is to be introduced that can answer the following question:

> How to build a fundamental conceptual model that uses settlement data to estimate the biochemical activity inside a landfill?

In order to do that, the following subquestions need to be answered:

- What is the relation between settlement and biochemical activity?
- How to simulate the induction of volume change of the landfill?
- How can a model effectively couple hydrology with biochemical activity and mechanics?

The hypothesis is as follows: for every landfill, the approach is different, as the variables are different. Aside these differences, settlement indicates movement of the landfill volume that can only be explained by changes in hydrology and changes in terms of degradation. A fundamental conceptual model will need to be developed in order to begin to understand the impact of hydrology and biochemical activity on landfill settlement.

More specifically, pore water pressure combined with the total stress gives the net stress, and change in pore water pressure leads to a change in net stress. This leads to a strain. When, through biodegradation, part of the wastebody is removed, this may lead to weakening of the wastebody structure and, with previously found effective stress, this will lead to another strain. Together, these strains will lead to settlement of the landfill. These strains can be modelled both independently and combined to find the effect of the different processes on the landfill height.

McDougall (2007) created the hydro-bio-mechanical model to be able to do this, however it is not open source. The aim of this research is to develop a conceptual open source code in Python that is versatile and applicable to a wide range of applications, and that can be coupled with complex water flow and biodegradation modules.

1.6 Structure

This thesis is built up as to interpret the quantitative description of a model designed to assess settlement as a result of biochemical activity within a landfill. In Chapter 2, the theory upon which the model is based is laid out. Chapter 3 provides the structure and possibilities of the model. In chapter 4, the results are shown and interpreted. Most of the results for underlying models are visualised in the appendix. The discussion can be found in Chapter 4 as well. Chapter 5 goes on to conclude the hypothesis based on the previous chapters.

Chapter 2

Theory

Wastebodies in literature are mostly described as black boxes; the inputs and the outputs can be measured, but what happens inside is left undefined. The CURE project aims to stabilise the landfills by eliminating the pollution potential through the induction of degradation. Opening the black box and the gathering of knowledge of the processes within the black box are essential to enable oneself to optimise the degradation process, in order to reach landfill stabilisation. This research focuses on gathering knowledge from processes within. This chapter is built around the deterministic approach, or defining a representative value for each parameter and applying that value over the entire model, on a model based on the literature. To implement the literature in a model, first the variables and relations need to be derived. The model then uses these relations to quantify the effect of degradation and water flow on settlement of a one-dimensional virtual landfill that is 20 m deep.

2.1 Conceptual model

The model in this research consists of a landfill of 20 m depth. The landfill consists of an unsaturated and a saturated zone, of which the boundary is halfway. The landfill consists of a drainage layer underneath that is sealed at the bottom. The pressure head in the drainage layer is kept constant by pumps. The infiltration is simulated as if it were constant irrigation of 5 mm/d. In the process of degradation, an increase of air pressure is created by the landfill gas production, and as such there is no available oxygen in gas phase in the unsaturated zone. An assumption is made that two parts of solid matter exist; readily degradable organic matter and completely inert matter. No grades of organic matter are simulated. Oxygen is transported at 10 mg/L, which is the maximum concentration at 288 K. The decay rate for oxygen is slightly increased in relation to literature to increase the active degradation zone. This has little effect on the degradation quantities.

2.2 Hydraulic modelling

In soil mechanics it is good practice to normalize all volumes to the volume of solids, or in this case inert solids. In order to model the volume changes of the landfill, one starts with the mass balance equation for water in the waste body,

$$\frac{\partial \left(\rho_w \; n \; S_w\right)}{\partial t} = -\nabla \cdot \rho_w \boldsymbol{q_w} \tag{2.1}$$

where ρ_w is the density of water, n is the volume of pores, and S_w is the volume of water in these pores as a portion of the total volume of pores. $\boldsymbol{q_w}$ Represents the one-dimensional flow of water,

$$\boldsymbol{q_w} = -\boldsymbol{K}\nabla h = -K_{zz}(\frac{\partial h_w}{\partial z} + 1) \tag{2.2}$$

where K is the hydraulic conductivity, $i = \frac{dh_w}{dz}$ is the inclination where h is the total head in m, h_w is the pressure head in m and z is the height coordinate in the domain of 0 to -20 m. K is dependent on water content. Equation 2.1 gives the mass balance of water in a system that can be unsaturated and where the porosity can change. Following chapters 3 and 11 of Pinder and Celia (2006), one can expand the left hand side as follows in equation 2.3.

$$\frac{d(\rho_w\, n\, S_w)}{dt} = \rho_w\, n \frac{\partial S_w}{\partial t} + S_w\, n \frac{\partial \rho_w}{\partial t} + \rho_w\, S_w \frac{\partial n}{\partial t} \tag{2.3}$$

This enables the separation and detailed description of different processes in the landfill, leading to equation 2.4, 2.6 and 2.7.

$$\rho_w\, n \frac{\partial S_w}{\partial t} = \rho_w \frac{\partial \theta_w}{\partial t} = \rho_w C(h_w) \frac{\partial h_w}{\partial t} \tag{2.4}$$

where

$$C(h_w) = \frac{d\theta_w}{dh_w} \tag{2.5}$$

is the differential water capacity. The compressibility of water, β, is defined as the effect of pore pressure on water density. This means that the next term in the mass balance equation, the time derivative of the density of water can be written as follows in equation 2.6.

$$S_w\, n \frac{\partial \rho_w}{\partial t} = \rho_w^2\, g\, S_w\, n\, \beta \frac{\partial h_w}{\partial t} \tag{2.6}$$

The third term in equation 2.3 can be expanded as

$$\rho_w\, S_w \frac{\partial n}{\partial t} = \rho_w S_w \frac{\partial n}{\partial h_w} \frac{\partial h_w}{\partial t} \tag{2.7}$$

where $\frac{\partial n}{\partial h_w}$ is the change in porosity due to a change in pressure head which impacts the total effective stress on the soil. If we combine equations 2.4, 2.6 and 2.7 in the mass balance equation we obtain

$$\left(\rho_w C(h_w) + \rho_w^2\, g\, S_w\, n\, \beta + \rho_w S_w \frac{\partial n}{\partial h_w}\right) \frac{\partial h_w}{\partial t} = -\nabla \cdot (\rho_w \boldsymbol{q_w}) \tag{2.8}$$

If we now assume that the water flow multiplied by the gradient of water density is trivial compared to the water density multiplied by the divergence of the water flow as stated in 2.9, i.e. a virtually incompressible fluid that flows through the landfill, we can simplify the mass balance as written in equation 2.10, where ρ_w from both sides has been eliminated.

$$\boldsymbol{q_w} \cdot \nabla \rho_w << \rho_w \nabla \cdot \boldsymbol{q_w} \tag{2.9}$$

$$\left(C(h_w) + S_w \left(g\, n\, \rho_w\, \beta + \frac{\partial n}{\partial h_w}\right)\right) \frac{\partial h_w}{\partial t} = -\nabla \cdot \boldsymbol{q_w} \tag{2.10}$$

Equation 2.10 can be simplified by introducing the function S_s^w or specific storage capacity function, defined by equation 2.11. The mass balance equation then becomes as is shown in equation 2.12.

$$S_s^w(h_w) = \left(g\, n\, \rho_w\, \beta + \frac{\partial n}{\partial h_w}\right) \tag{2.11}$$

leading to

$$\left(C(h_w) + S_w\, S_s^w\right) \frac{\partial h_w}{\partial t} = -\nabla \cdot \boldsymbol{q_w} \tag{2.12}$$

2.3 Biodegradation modelling

This model is based on the assumption of first order degradation, with the same amount of degradation per day,

$$\frac{\partial M_{OM}}{\partial t} = -k_{OM;1} M_{OM} \tag{2.13}$$

where M_{OM} is the mass of organic matter and Δt is the time in days. $k_{OM;FO}$ is the organic matter consumption rate for the first order degradation, which is a constant.

An alternative link can be made to the aerobic degradation model that Van Turnhout (2017) has created. This means that the degradation is depending on the presence of organic matter and the concentration of oxygen,

$$\theta_w \frac{\partial C_{O_2}}{\partial t} = -\nabla \cdot (-D\nabla C_{O_2}) - \nabla \cdot (-\boldsymbol{q_w} C_{O_2}) - R_{O_2} - C_{O_2}\frac{\partial \theta_w}{\partial t} \tag{2.14}$$

where C_{O_2} is the concentration of oxygen and R_{O_2} is the sink term, defined by

$$R_{O_2} = \frac{\partial O_2}{\partial t} = -5.4\frac{\mu^{max}}{Y_{xs}} C_X \frac{C_{O_2}}{C_{O_2} + K_s} \frac{M_{OM}}{M_{OM} + K_D} \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2.15}$$

where the limiting factors are the amount of biologically degrading organisms (C_x), the present mass of organic matter (M_{OM}) and the amount of oxygen ($C_{O_2}\theta$) available. This forms the biological degradation variable,

$$\frac{\partial M_{OM}}{\partial t} = \frac{\partial M_{OM}}{\partial O_2} R_{O_2} = -k_{OM;O_2} M_{OM} \tag{2.16}$$

where k_{OM} is either the oxygen-related $k_{OM;O_2}$ or the first order $k_{OM;1}$, depending on the model. This is then translated to volume of solids where the total volume is defined as

$$V_{solids} = V_{OM} + V_{IM} = \frac{M_{OM}}{\rho_{OM}} + \frac{M_{IM}}{\rho_{IM}} \tag{2.17}$$

where M_{IM} is mass of inert matter (non-organic) and ρ is the volumetric mass.

2.4 Void change parameter

McDougall and Pyrah (2004) found a relation between the different phases in masses containing organics, i.e. the volume of voids changes proportionally to the volume of solids. The void change parameter (Λ) is assumed to be site-specific and a constant for constant conditions, where the volume of solids and the volume of voids together make up the entirety of mass. If one were to monitor the amount of organic matter exiting the system in a given time, and at the same time interval the volumetric change of the mass is monitored, one is able to find the value of the void change parameter as defined by McDougall and Pyrah (2004) in the form of

$$dV_v = \Lambda \cdot dV_s \tag{2.18}$$

Which can, due to the unchanging nature of the inert matter, be rewritten as

$$dV_v = \Lambda \cdot dV_{OM} = \frac{\Lambda}{\rho_{OM}} \cdot dM_{OM} \tag{2.19}$$

where $dV_s = dV_{IM} + dV_{OM}$, and $dV_{IM} = 0$. The value of the void change parameter generally is between -1 and the void ratio, and rarely higher than e. If it is -1, that means the decrease of solid volume is the same as the increase in void volume. If Λ is 0, the void volume does not change over changes in solid volume. If it is equal to the void ratio, the void volume decreases as the solid volume decreases, while the void ratio stays the same. The wastebody will reduce in volume at a rate of $(1 + e)\, dV_s$. If the Λ value is higher than e, the wastebody densifies and will likely increase in stiffness. As the amount of inert matter is constant in time, this results in

$$\frac{\partial V_{OM}}{\partial t} = \frac{1}{\rho_{OM}} \frac{\partial M_{OM}}{\partial t} = -k_{OM} \frac{1}{\rho_{OM}} M_{OM} \tag{2.20}$$

As $e = \frac{V_v}{V_s}$ where e is void ratio, and assuming that V_{OM} is given as a constant over each timestep, one can write

$$\frac{\partial e_\Lambda}{\partial t} = \frac{\partial \frac{V_v}{V_{OM}+V_{IM}}}{\partial t} + \frac{\Lambda}{\rho_{OM}\,(V_{OM} + V_{IM})} \cdot \frac{\partial M_{OM}}{\partial t} \tag{2.21}$$

where dV_v is the change in volume of voids and dV_s is the change in volume of solids. This is the dependency for void ratio on M_{OM}.

2.5 Stress modelling

To relate the stress balance to void ratio, the specific volume is introduced. This relates as

$$e_\sigma = \nu_\sigma - 1 \tag{2.22}$$

A structure in a 1D simulation can deform in two ways; heave and settlement. These both rely on the same mechanism of a spring model, combined with plastic deformation. In this model, the approach of Alonso can be introduced to equation 2.11.

$$\nu_\sigma = N(s) - \lambda(s) \ln \left(\frac{p'}{p^c} \right) \tag{2.23}$$

where N is the specific volume at reference stress p^c. λ Is the stiffness parameter for normally consolidated soils and p' is the net mean stress. Because we know that the effective mean stress at 'rest' can be calculated as

$$p' = \frac{\sigma'_v + 2\sigma'_h}{3} = \frac{1}{3} \left(\sigma'_v + 2 \left(1 - \sin \phi' \right) \sigma'_v \right) = \left(1 - \frac{2}{3} \sin \phi'\right) \sigma'_v \tag{2.24}$$

where σ'_v is the vertical effective stress, σ'_h is the horizontal effective stress and ϕ is the friction angle. Based on Reddy et al. (2008) the friction angle value is set as 15°. We calculate σ'_v using Bishop's effective stress approach

$$\sigma'_v = (\sigma_v - u_a) + \chi \left(u_a - u_w \right) \tag{2.25}$$

where χ in this case is the void saturation S_w. u_w is the water pressure defined as $u_w = h_w \rho_w g$, u_a represents the atmospheric pressure. This means The landfill is loaded only by its own weight, making the initial stress conditions linearly proportional to depth,

$$\sigma_v = \int_{z_d}^{z_{surf}} g \left(\rho_{IM} \theta_{IM} + \rho_{OM} \theta_{OM} + V_v \rho_w S_w \left(d \right) \right) dz \tag{2.26}$$

where θ is the specific content with $\theta_w = V_v S_w$, $S_w\left(d\right)$ is the depth-dependent void saturation, g is the gravity constant on the surface of the earth and ρ stands for specific gravity for inert (IM) or organic matter (OM). One can interpret the alteration of the void ratio due to a moving hydraulic head as

$$\frac{\partial e_\sigma}{\partial t} = \frac{\partial e_\sigma}{\partial h_w} \frac{\partial h_w}{\partial t} \tag{2.27}$$

This, combined with 2.21 gives

$$\frac{\partial e}{\partial t} = \frac{\partial e_\Lambda}{\partial t} + \frac{\partial e_\sigma}{\partial t} \tag{2.28}$$

2.6 Tracking the temporal change in volume

To track the volume change, total volume needs to be anchored to an indifferent volumetric parameter. As inert matter does not decay over time, the relation between the total volume and inert matter volume is unambiguous and reliable. Of course, volume in one dimension is height, making

$$V_{x;\rightarrow 1D} = z_x \tag{2.29}$$

where x can stand for inert matter, organic matter or voids, as well as any combination of these three.

In order to track how the volume of the soil is changing in time, the layer thickness of each cell is calculated as model variable $\Delta z_{i-\frac{1}{2}}$. In this case we are solving a 1D problem where all volumes become volume/surface area or height. This is normalized by inerts volume, $\Delta z_{i_{i-\frac{1}{2}}}$, which we assume to stay constant in time. Therefore, we obtain the relationship as described in equation 2.30.

$$\frac{d\Delta z_{i-\frac{1}{2}}}{dt} = \Delta z_{i_{i-\frac{1}{2}}} \left(\frac{\partial \nu}{\partial h_w} + \frac{\partial \nu}{\partial V_{OM}} \right) \tag{2.30}$$

2.7 Summary

In short, to obtain settlement based on h_w and V_b, one needs to compute equation 2.30 for every cell at each point in time. A few assumptions are made in this model. For instance, the inert matter is assumed to be incompressible, as is the organic matter. The void change parameter is site-specific, and constant. The The water properties do not differ from leachate properties. The equations to solve are

$$\frac{\partial M_{OM}}{\partial t} = f\left(t, hw, C_{O_2}, M_{OM}, e\right) \tag{2.31}$$

and

$$\frac{\partial h_w}{\partial t} = f\left(t, hw, M_{OM}, e\right) \tag{2.32}$$

and

$$\frac{\partial e}{\partial t} = f\left(t, hw, M_{OM}, e\right) \tag{2.33}$$

Chapter 3

Method

3.1 Toolbox Structure

The system as a whole introduces different sets of variables, of which an overview is shown in table 3.1. The class in the file combiclass.py calculates the equations that are presented in Chapter 2, whereas the variables are defined in different other files, e.g. lindegmodel2.py and oxydegmodel2.py for the first order model and aerobic degradation model, respectively. This model is created to be developed further, and therefore needs to be agile and adaptable. Modules may need to be altered, replaced or removed and it needs to work still. Figure 3.1 gives an overview of the modules in combiclass2.py as used for the results.

Table 3.1. parameters used in the Python model.

Name	primary state as in the model	meaning
pressure head	hw	water table in cells
temperature	T	temperature in cells (not used)
oxygen	O, Co2	oxygen concentration in cells
mass of organic matter	m, mOM	mass of organics in cells
void ratio	e	void ratio in cells, Vv/Vs

Name	derived state as in the model	meaning
landfill height	h	height of landfill
strain	eps	cell strain
wet bulk density	rhoBW	volumetric weight of mass
water content	th	water content per total volume
net stress	pEff	net stress
reference stress	p_c	reference stress
specific volume	nu	Vt/Vs
effective water content	Se	cell water content per volume of voids

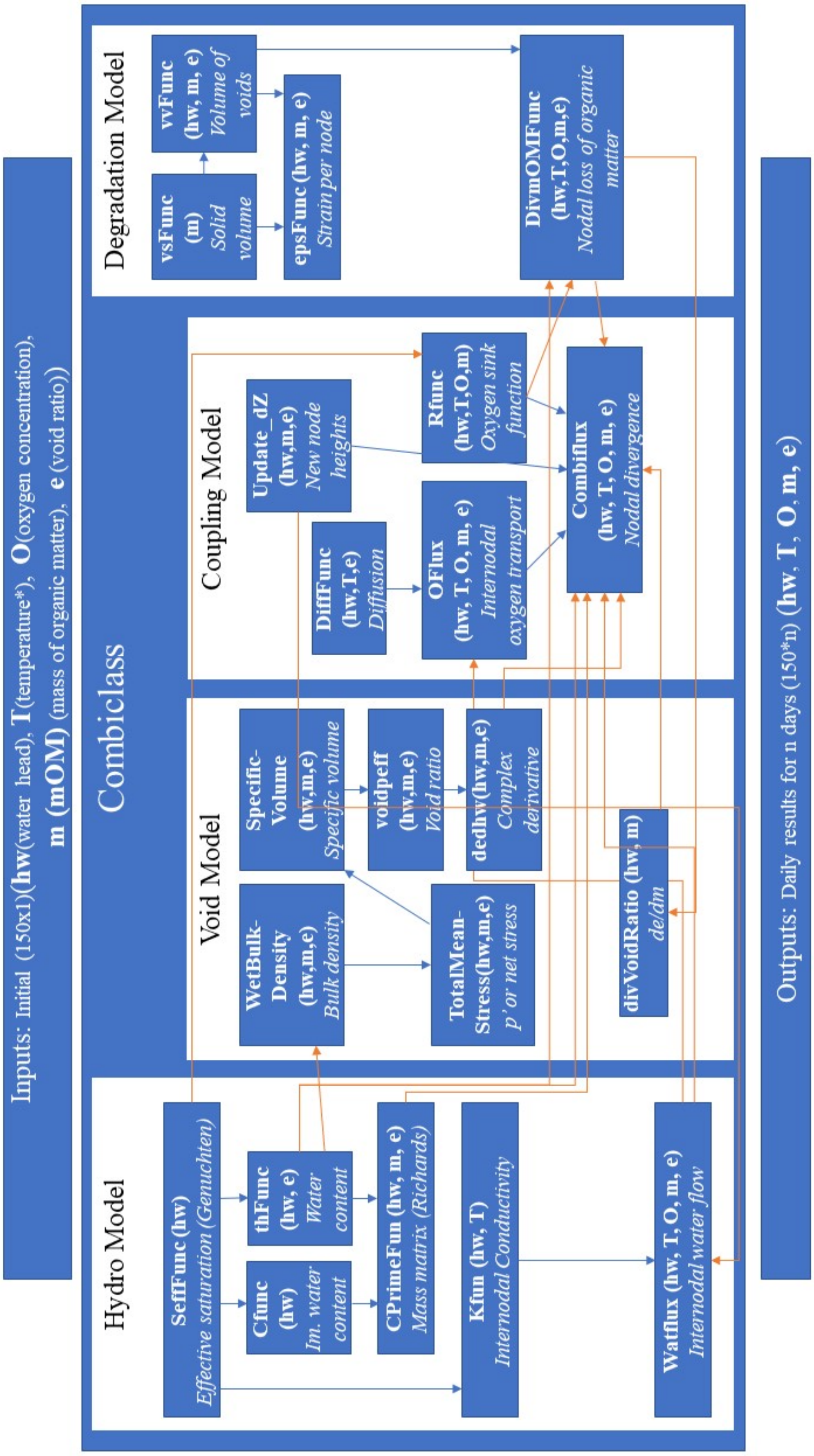

Figure 3.1. Flowchart of relevant modules in the model.

Table 3.2. parameters used in the Python model. (continuation)

Name	material property as in the model	meaning
node size	dzIN	vertical distance between internodes
node distance	dzN	vertical distance between nodes
internode height	zIN	height of internodes
node height	zN	height of nodes
initial void ratio	eIni	initial void ratio, Vv/Vs
initial pressure head	hwIni	Initial water table in cells
initial void volume	Vv	initial relative volume of voids
initial inert volume	VI	initial relative volume of inert solids
void change parameter	labda	relation dVs/dVv
specific organic weight	rhoB	mass density of organic matter
specific water weight	rhoW	mass density of water
specific inert weight	rhoI	mass density of inert solids
total time	ttot	time intervals
stiffness parameter Alonso	lamSS	stiffness for net stress changes
capillary scale	vg_alpha	Van Genuchten parameter alpha
pore size distribution	vg_n	Van Genuchten pore shape parameter
saturated conductivity	KSat	saturated conductivity

Name	flow parameters	meaning
hydraulic conductivity	kN	modal conductivity
internodal hydraulic conductivity	kIN	internodal conductivity
diffusion	DiffIN	internodal diffusion
water flux	qw	nodal net water flow

This script calculates settlement of landfills based on the height, volume of solid material present, water flow and degradation. This part of the script has parameters and variables as given in Table 3.1 per cell and calculates output values in the form of variables per cell. All strains combined will give the settlement of the entire landfill, all water pressures combined give an overview of water flow and content, and all degradation combined gives the total decrease of pollution potential for the landfill.

The equations whereupon this method is based are mentioned by McDougall and Pyrah (2004) and Alonso (1990). It is assumed that the degradation rate is lower than the transport rate of degraded waste, i.e. degradation equals removal of waste. McDougall and Pyrah (2004) then state that $dVv = \Lambda \cdot dVs$. This means that the volume of voids at any moment is related to the volume of solids, thus degradation drives volume reduction of voids, where Λcomes in, and of solids. The formula for degradation settlement is $dVv + dVs = (1 + \Lambda)\, dVs$, as stated by McDougall and Pyrah (2004).

Feng et al. (2016) state waste degradation and thus removal in a higher part of the modelled landfill will result in degradation settlement for this higher part of the landfill, but will have an adverse effect on the part underneath, resulting in a small, yet significant heave of the interface between these two parts. This counterreaction is one of the focus points of this toolbox. More detail about the formulation of driving equations behind the toolbox can be found in chapter 2.

3.2 Scenarios

To be able to understand what the model can do and what it produces, different simulations can be done as a dissection of the coupling of processes. These scenarios in themselves are simple theoretical situations that simulate a part of reality. These are used to validate the model as a whole, as the results from the simple scenarios need to follow logic. For instance, draining the waste should lead to settlement. the largest strain should be where the largest difference in effective stress is, and the biggest effective stress is where the water pressure difference is largest. By creating simple situations, the model can be validated step by step. If an error then occurs, and scenario that couples different processes does not resemble the simpler ones, the error can be found in the coupling.

The model domain for every scenario is the same, meaning 20 m below surface of one-dimensional landfill over 20 cells with 50% of volume being organic matter, 30% of volume being pores and 20% inert solids, which is the preferred ratio for bioreactors according to Luning et al. (2006) The drainage layer underneath is connected to the bottom cell through the bottom internode, which defines conditions above and below cells.

Focusing on the variables in a one-dimensional model of the actual situation, a reasonable estimate of the average is made and applied; e.g. initial volume percentage of organic matter, saturated hydraulic conductivity, soil stiffness and residual water content. Using these estimates, the waste response of the average waste column as defined can be found for different scenarios. When the model is accurate, the response will approximate the theory. in table 3.3 key aspects of the different models are presented.

Table 3.3. Differences in model parameters; defined in respective model file.

	Initital water table height (m)	Infiltration (mm)	Drainage layer head (m)	Degradation
Static model	10	0	10	No
Infiltration model	10	5	10	No
Draining model	15	0	0	No
Wetting model	0	10	-	No
First order Model	10	0	10	First order
Oxygen model	10	5	10	Aerobic

3.2.1 Static situation

The static simulation is to show the workings of a model without infiltration and without degradation, merely to show what the base case is. The water table is set at 10 m below the surface. The initial water pressure gradient is set approximately as the equilibrium situation. This case presents the possibilities and limitations of the model.

3.2.2 Infiltration to steady-state

The Infilitration model is made to show the workings of a model with infiltration but without degradation. The initial water table is set at 10 m below the surface, and the infiltration rate is set at 0.01 m/d. The initial water pressure gradient is set approximately as the equilibrium situation. This case presents the possibilities and limitations of the model.

3.2.3 Draining of a saturated wastebody

This scenario will need to prove that settlement in the model is related to the water pressure and saturation of the cells. The head will start near surface level (5 m below surface), with no prepicitation and the drain layer underneath is set to 0 kPa. The model will then drain and settle at the cells where the water pressure or saturation falls. This leads to the following graphs:

- time-dependent reduction of water pressure in cells, where water pressure is a function of depth and head level;
- time-dependent reduction of saturation in cells, where saturation is a function of depth and head level;
- time-dependent effective stress increase in cells, where effective stress is a function of water pressure and depth;
- time-dependent strain increase in cells, where strain is a function of effective stress.

3.2.4 Irrigation of a dry wastebody

This scenario is meant to prove that the model has the capability to simulate heave. In order to simulate heave, the initial conditions state that the landfill is dry, meaning in the cells only the residual water content is present. The conditions at the bottom boundary state that the head is at surface level, meaning groundwater will slowly flow into the landfill, saturating cell by cell. This all happens during fully anearobic conditions. The following graphs are to be drawn:

- time-dependent increase of water pressure in cells, where water pressure is a function of depth and head level;
- time-dependent increase of saturation in cells, where saturation is a function of depth and head level;
- time-dependent effective stress decrease in cells, where effective stress is a function of water pressure and depth;
- time-dependent strain decrease in cells, where strain is a function of effective stress.

3.2.5 Homogeneous degradation throughout the domain, steady-state water flow

The first model has a constant water head of 10 meters below the initial surface, with a constant degradation to see whether the degradation alone causes settlement, and how the voids are affected by the difference in depth for different cells. the void change parameter will be at -0.7, meaning the void volume will increase at 70% of the rate that the organic volume decreases. Stress on the mass will reduce due to the reduction of organic matter, which causes a slight but significant reduction in settlement. If oxygen can penetrate freely throughout the wastebody and reaches the entire mass, this means we can plot the following graphs:

- time-dependent reduction of organic matter due to degradation and removal, which have been modelled to happen at the same time;
- time dependent reduction of effective stress in the soil due to reduction of organic matter, where the stress reduction is proportionate to cell depth;
- time-dependent rise of strain (compression) throughout the model due to reduction of total matter in cells, reduced but not countered by the reduction of stress;
- time-dependent increase of void ratio as defined by the void change parameter Λ, combined with the influence of the stress-dependent strain component.

3.2.6 Aerobic degradation model, limited by oxygen transport

If we have water infiltration, saturated with oxygen, where the infiltration is set to 10 mm per day, the balance becomes more delicate and more graphs are needed:

- time-dependent reduction of organic matter due to degradation and removal, which have been modelled to happen at the same time, but limited by the quantity of oxygen infiltrating the soil;
- oxygen penetration depth defined by (rain)water infiltration, infiltration and the subsurface vertical flow of water. Oxygen is modelled to penetrate the soil at the same pace as the water flow, and decays proportionally to the degradation;
- time dependent reduction of effective stress in the soil due to reduction of organic matter, where the stress reduction is proportionate to the cumulative matter reduction of the higher situated cells;
- time-dependent increase of strain (compression) throughout the model due to reduction of total matter (if any) per cell. This is reduced and possibly countered by the reduction of stress;
- time-dependent increase of void ratio as defined by the void change parameter Λ when degradation occurs, combined with the stress-dependent strain component.

Chapter 4

Results and Discussion

After explaining the model and the validation process, this chapter shows and interprets the results of the different scenarios, with at the end the aerobic degradation model that couples the validated processes.

4.1 Model validation

As stated, different simulations can be done with the model, and the results and limitations of the simpler scenarios are outlined here. This is used to validate the model step by step. The scenarios are described in section 3.2, and the visualisations are shown in the Appendix.

4.1.1 Static situation

The static model is introduced as the base case; if no boundary conditions lead to change, then the primary states should remain at their initial values. The fact that no difference is calculated means that the balance is found in the model. Figures 4.1 and 4.2 show that the model simulates no height difference in a static situation. If the static model were to be exact, that means no other processes are affecting the model. The real effects of these processes fall outside the scope of this research. The model focuses on the mechanical consequences of water flow and degradation, of which none occur in the static situation. This corresponds with no mechanical consequences.

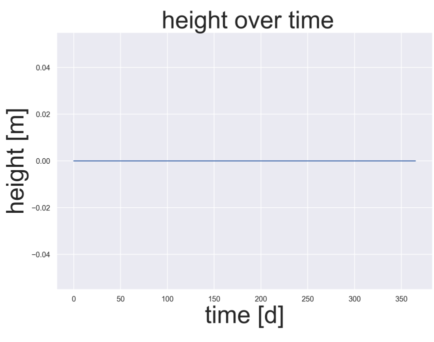

Figure 4.1. difference in effective stress for the draining model.

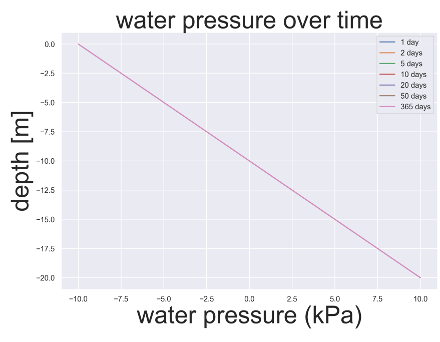

Figure 4.2. water pressure for the draining model.

4.1.2 Infiltration to steady-state

The infiltration model focuses on the transportation of dissolved oxygen. It takes the oxygen 200 days to reach the water table at 10 m below surface, as can be seen in figure 4.3. The oxygen does not react with the organic matter as the model is not activated for degradation. The 5 mm per day of infiltration water will at first have a disrupting effect on the water pressure in the model, as can be seen in Figure 4.4, but it stabilises as time progresses to a steady state flow. The water content will become as shown in Figure 4.5. The increase in water pressure, due to the increase in water content will lead to a small heave, which stabilises as the water flow does. The oxygen will continue to reach deeper parts of the model until the water in the landfill is saturated with oxygen. In reality, oxygen will not reach great depths until no degradable matter is left in the upper regions, which is the case for this model as no degradation is to be taking place.

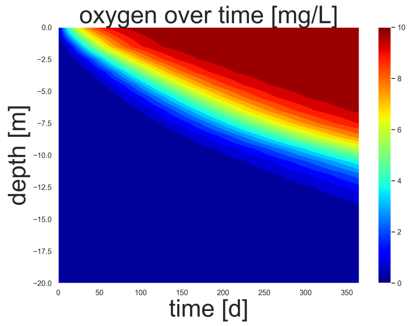

Figure 4.3. Oxygen concentration in the infiltration model.

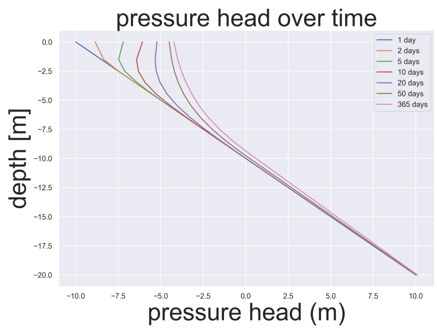

Figure 4.4. water pressure for the infiltration model.

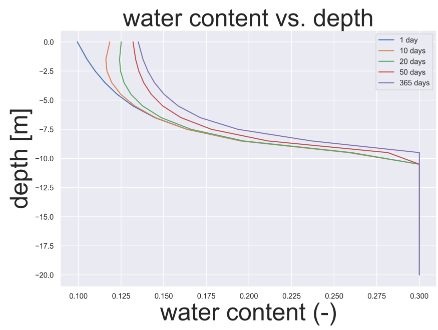

Figure 4.5. water content in the infiltration model.

4.1.3 Draining of a saturated wastebody

The Draining model shows what happens if the model is pumped dry after being saturated. No activity is assumed, and no water can infiltrate. The voids are filled with air, but no oxygen dissolves in the water present in the model. decreasing water pressure, causing a decrease in water content, will lead to a settlement reaction. After one year, 12 of the 15 meters of water have been pumped out of the model. This can be seen in Figure 4.6, and the settlement can be seen in Figure 4.7.

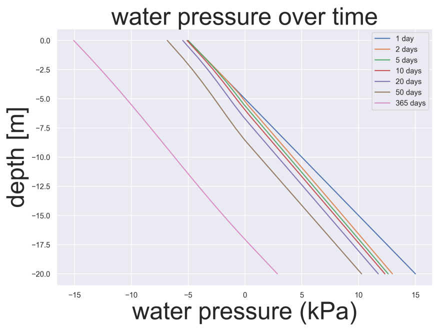

Figure 4.6. **water pressure development for the draining model.**

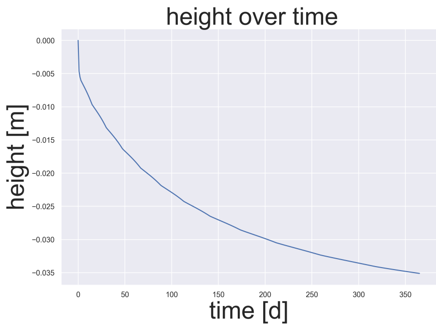

Figure 4.7. **time-dependent height of the draining model.**

4.1.4 Irrigation of a dry wastebody

The wetting model shows what happens if water is introduced to a virtually dry model. This is done via infiltration, which causes the negative pore pressure to dissipate slower in deeper parts of the dry model, but positive build-up of pressure will happen through saturation at the bottom first before moving upwards. This can be seen in Figure 4.9. The water content can be seen in Figure 4.8. This leads to heave of the model, as can be seen in Figure 4.10.

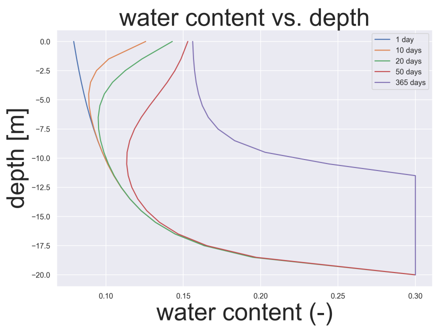

Figure 4.8. **water content for the wetting model.**

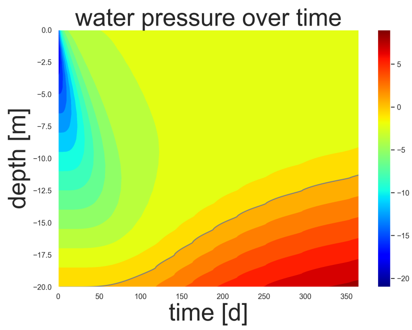

Figure 4.9. **water pressure for the wetting model.**

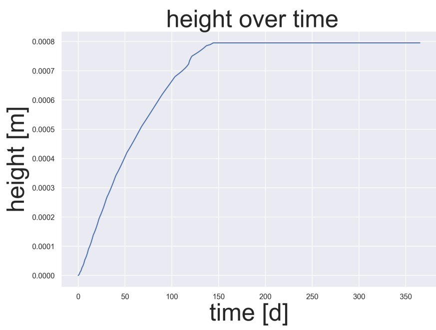

Figure 4.10. **time-dependent height of the wetting model.**

4.1.5 Homogeneous degradation throughout the domain, steady-state water flow

When taking a close look at what is simulated in the first order model, one can see that the model in the end has settled 55% of its total height in ten years, where this settlement is happening over the entire depth profile. The logical assumption would be that with a constant water table at 10 m above the base, and with 17 m of landfill left, the water table should be constant in height, as can be seen in figure 4.12. As the cells have not been defined with a fixed coordinate, the water pressure is calculated for a variable coordinate, with a small inaccuracy as the drop in the beginning would suggest. The model is not limited to small strains. A next model will need to refine the cell coordinate to assess the pressure balance more accurately still. In Figure 4.11 the organic matter over time is presented, and as can be seen, the first order relation of equation 2.13 creates a degradation reaction consistent with Λ. The water pressure distribution is constant over height and not over cells.

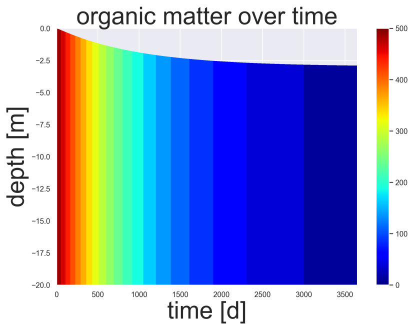

Figure 4.11. organic matter development in kg/m^3 for the first order model.

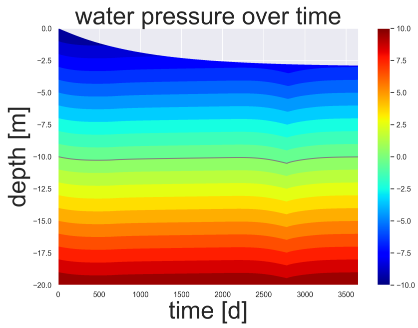

Figure 4.12. water pressure for the first order model.

4.2 Experiment Results

The focus of this research is to simulate the settlement of a landfill impacted by biodegradation. In order to activate biodegradation, different requirements need to be met. To be able to translate degradation into settlement, different processes of the model are combined to form a realistic virtual scenario. The results of the combination of these processes can be found in section 4.2 and the results of each individual process of the model can be found in the appendix.

Aerobic degradation model, limited by oxygen transport

The final model of this research is the oxygen-based model or Aerobic degradation model, limited by oxygen transport, where the volume share of organic matter develops as shown in Figure 4.13. In the left part, specific moments of the state of organic matter are shown, whereas the part on the right has all datapoints over depth and time. The initial organic matter is set as 50% of the total volume of a cell, as can be seen in the first day on the left. On the right, the first day is entirely red as no degradation has happened. The degradation happens fastest where the oxygen concentration is highest, as can be seen in Figure 4.13.

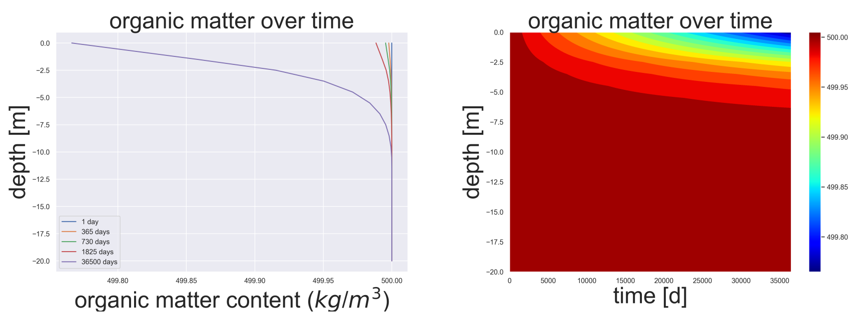

Figure 4.13. organic matter development for the oxygen-based model.

As shown, very little organic matter has been degraded yet. This is mainly due to the limited supply of oxygen. Every day, 5 L water is added to the top of the model, carrying 10 mg/L oxygen, so 50 mg/d. The ratio of oxygen versus organic matter in mol is 5.4:1. The modelled organic matter is virtually identical to glucose, minus the water production. This means 50 mg oxygen reacts with 52 mg organic matter. In the 100 years that have been modelled, the 10^7 g organic matter is reduced by 1898 g. The surface height development can be seen in figure 4.14. The rest of the figures are presented in the appendix.

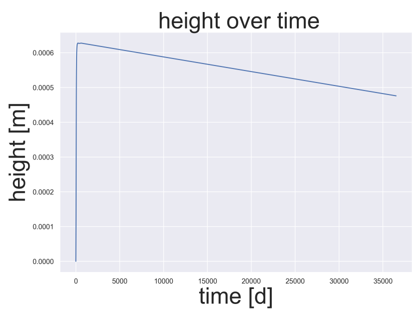

Figure 4.14. time-dependent height of the oxygen-based model.

In order to increase the degradation rate, one could introduce another solute that can dissolve in higher concentrations, while still stimulating the degradation process. One could also pump in oxygen at or below the water table to increase the oxygen concentration below the surface through increased oxygen transfer. One could also pump out gas of the unsaturated zone to create a partial vacuum in the void space, causing air to flow in and oxygen to dissolve inside the pores. An approximation of the latter is modelled by decreasing the ratio between oxygen and organic matter in a reaction. In this case, a decrease of that ratio by 10^4 is applied. The following figures are from the exaggerated aerobic degradation model.

As oxygen has an increased reaction ratio with organic matter, figure 4.15 now shows the progression of degradation into the landfill. After 100 years, the top 3 m of the landfill have very little organic matter left. The oxygen will continue to flow deeper into the landfill before reacting, which means the deeper organic matter will start to degrade as well as can be seen in the figure.

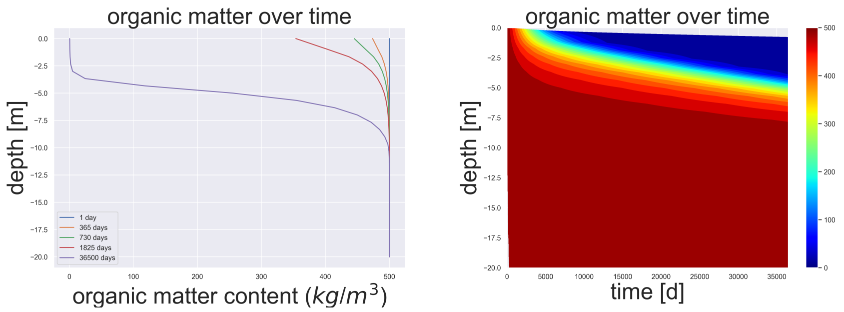

Figure 4.15. organic matter development for the oxygen-based model.

The water pressure in the cells develops as shown in Figure 4.16. Here, the effect of infiltrating water on the pore water pressure can be seen on the left. On day 1, there is no flow as the entire column is hydrostatic. As of day two, the infiltrating water causes the an overpressure in the top cells, causing water to flow. After 50 days, the flow has spread over the entire model, with slower flow rates in deeper parts. On the right visual, one can see the black line representing the water table, and the colours represent positive water pressures below the line, and negative pressures above the line. The right figure also shows the decreasing height of the model over time.

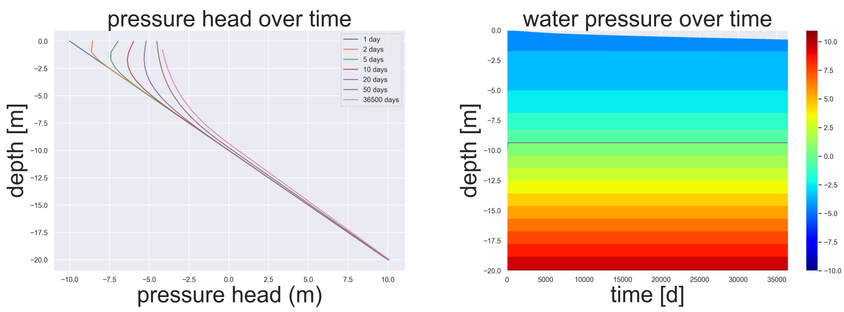

Figure 4.16. water pressure for the oxygen-based model.

The water pressure together with the total stress leads to the net stress, which can be seen in Figure 4.17. As one can see when comparing this figure to Figure 4.16, the stress path changes at the water table. The net stress decreases here because the water table rises slightly, and over time the organic matter decreases. The curve at the top in the right figure is caused by the increase in volumetric weight of the overlaying cells, causing an increase in effective stress due to an increase in total stress. this is due to the discretisation of cells, and can be solved by refining the model as well as a refined simulation of incremental net stress through a cell. Both options will greatly increase the computing time. Furthermore, the decrease in total stress due to loss of volume causes net stress to decrease in deeper regions.

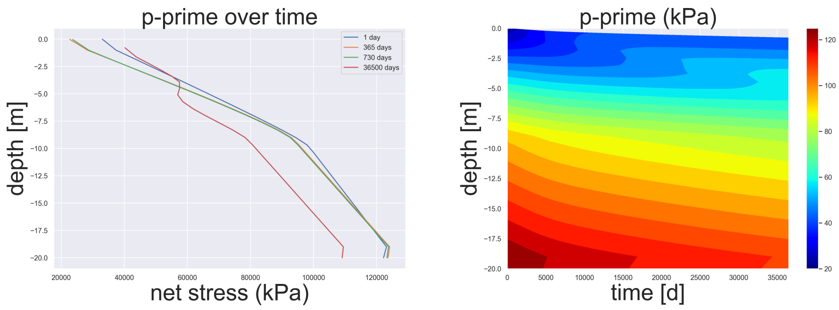

Figure 4.17. difference in net stress for the oxygen-based model.

The flow of affects the oxygen balance as shown in figure 4.18, where the oxygen concentrations are tracked through the depth of the model. over time, the oxygen reaches deeper regions, as can also be seen in figure 4.15. The oxygen level is limited with two monod equations based on the oxygen concentration and the presence of organic matter. The delay factor for the oxygen concentration is higher than usual to approximate the effect of internodal oxygen transfer.

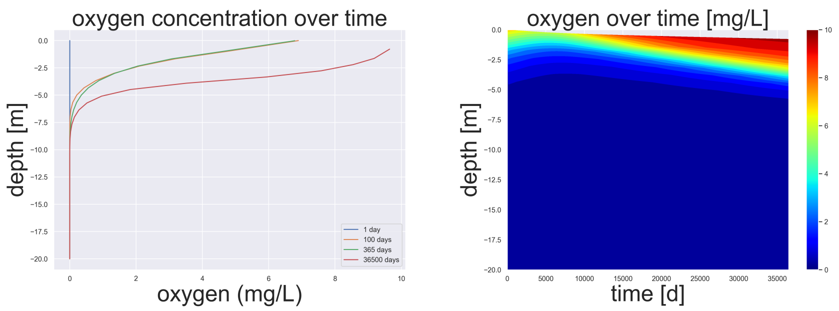

Figure 4.18. oxygen penetration for the oxygen-based model.

The strain in figure 4.19 is based on the degradation and the effective stress in the different cells. This is a visualisation of the connection between mechanics, hydrology and biochemistry in the model. This visual represents the relevance of this research in the study on landfill modelling. If the strain in this model and the height are combined, then the height of the model over time can be found. This is shown in figure 4.20.

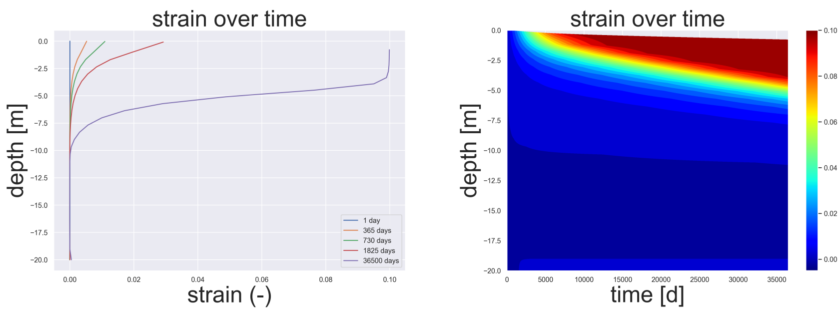

Figure 4.19. strain development for the oxygen-based model.

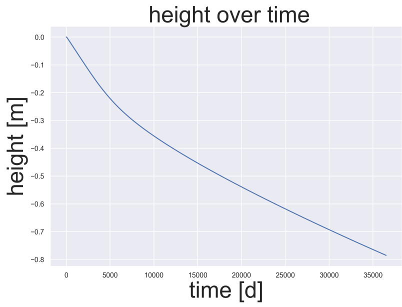

Figure 4.20. time-dependent height of the oxygen-based model.

As can be seen in the appendix, each individual process of the model creates results which are to be expected. Coupling these processes cause them to influence each other. Comparing the results in this chapter with the results in the appendix uncovers differences which can be explained by coupling another process.

4.3 Discussion

The aerobic degradation model, which combines every relevant possibility of the toolbox to simulate the outcome of using realistic parameters, shows a probable distribution of a specified landfill. Many landfills have unknowns and large inaccuracies on many parameters, so input data will need margins for further applications, and more detailed process focus in hydraulics and biodegradation as per the model of McDougall (2007), in order to allow for more detailed mechanical evaluation. For instance, the pore size distribution, the vertical position of cells and the transportation of degradation products are to be defined as values that change over time. Furthermore, the equilibrium of oxygen supply and consumption is reached in a few days after exposure to oxygen. In reality, growth of biodegradation cultures is a complicated process depending on a lot of variables. The horizontal lines in figure 4.18 will in reality not stay horizontal until another equilibrium is reached, and as this model takes into account a summation of a wide variety of biodegradation processes with all sorts of feedback loops, a steady state of oxygen supply and consumption will not be likely.

The model does not track failure of macroscopic mechanisms as it is one-dimensional, and failures happen due to weaknesses of multi-dimensional systems. A one-dimensional model can only strain in one dimension, but a two-dimensional model can bend and slide out of shape. A landfill is perfectly capable of failure due to differential settlements, or all kinds of slope failure, But what does landfill failure entail when failure is defined as loss of functionality? To track failure, one needs a definition of when failure is met. Possibilities are water or gas outbreaks in the cover layer, or landslides that incapacitate monitoring setups. The applicability of these examples are different per landfill. Therefore the definition of failure is different per landfill. Also, a one-dimensional model has little use when it comes to plastic deformation, but adding dimensions will need to take into account that differential settlement, pressure differences and soil weakening do cause plastic deformation on small scales. It might also implement a micro-failure criterion to indicate whether settlement in a certain column occurs. For macroscopic plastic deformation, isotach-like behaviour could be implemented in the model to simulate plastic behaviour as a comparison for waste structure weakening. The void change parameter as defined by McDougall and Pyrah (2004) is proposed as a simple solution to model the softening of the landfill, as it creates a linear relation between void volume and biodegradation. This research adds in a simple form of Alonso's nonlinear relation between stress and strain.

To tailor the model to a landfill, one needs to iterate the model with a range of different rate parameters concerning water flow and degradation until a fit on existing data (emissions and settlement) is created. The model can then estimate the pollution potential and settlement prediction of the landfill. The void change parameter is the result of a data analysis of a landfill, and will thus need to be based on landfill data. The information will need to encase data about failure and the time-dependence of void volume change.

Chapter 5

Conclusion

This thesis is created in order to answer the question 'How to build a fundamental conceptual model that uses settlement data to estimate the biochemical activity inside a landfill?'. Based on the literature in the introduction, a model has been formulated in chapter 2 that relates biodegradation to settlement. The details surrounding this model are stated in chapter 3. During development, the model needed to stay versatile and agile. With data on degradation and hydrology, settlement can be predicted, taking into account all the relevant processes and fitting the model into the available data. In other words, the model has built upon the understanding of landfill behaviour. It harbours information to create an approximate relation between settlement and biodegradation. In order to validate the model, each different scenario needs to be logical in and of itself. Combining these scenarios then would create a logical coupling of processes, where each process can still be isolated in order to distinguish the effect. This was the goal of the research, and a fundamental conceptual model has been created.

5.1 Consequences of the insights obtained

The model accounts for one-dimensional deviation of data, whereas a landfill is a three-dimensional system. While it is possible that in a landfill, a certain column behaves exactly like the one simulated in the model, it is virtually impossible to see uniform behaviour in the landfill as predicted by the model. As stated in Section 4.3, the model is one-dimensional and will need to be expanded both in relation to reliability and multi-dimensional hydro-bio-settlement processes. Then the model can take up micro and macro failure, as well as differential settlement.

5.2 Uncertainties leading to new research proposals

5.2.1 Dimensional reliability and uncertainty

The one-dimensional approach simplifies the coupling of processes. However, as the organic matter exits the landfill, the wastebody will most probably succumb to smaller and larger failures, with possibly cover breakage as a result. As this is related to the amount of degradation, only larger settlements are prune to failure. Therefore, focusing on the failure of soil weakening is only necessary for landfills that settle relatively quickly.

5.2.2 Hydrological system

The hydrology in this research is greatly simplified and homogeneous over the depth of the model profile. The flow rate is only dependent on pressure differences and water content. In reality, the wastebody is a heterogeneous system that is too complex for one-dimensional water flow modeling. A next step would be to implement preferential flow paths and differential hydraulic conductivity in general in a 3D model, to track where water can remain, and where it can flow, as this is of importance for the degradation process.

5.2.3 Scale of fluctuation

Different waste parameters such as organic content, organic volumetric weight, and wastebody stiffness are taken as constant in this model. To improve the existing model, it is advised to take into account the inconsistency of these calculate differential settlement, differential settlement rate, water pressure differences and degradation. In relation to preferential flow, this is the next step in calculating what the range of settlement is for a certain amount of degradation, based on water flow, oxygen supply and degradation product transport.

5.2.4 Bioactivity expansion

This research has a straightforward degradation process, where a certain amount of oxygen leads to a set amount of degradation and there is only one process, one degradation rate and one degradation product. This will disappear instantly when created, as dissolving of the degradation product does not have a negative effect on the degradation process. A next step could be expanding the degradation process, for a lot of different processes happen, as mentioned in Section 2.2.

Appendix

Model possibilities

Static model

These represent the figures for the static model, to show that the model is in balance in and of itself. Where the water pressure behaves as shown in figure 2, the effective stress can be seen in figure 1. This leads to a strain development as seen in figure 3 and leads to a settlement as shown in figure 4.

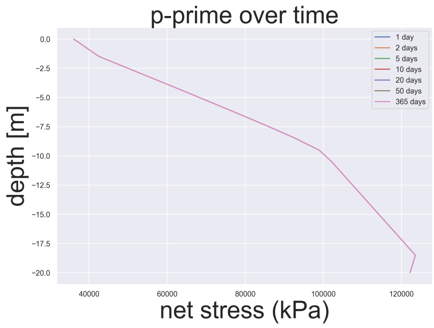

Figure 1. difference in effective stress for the static model.

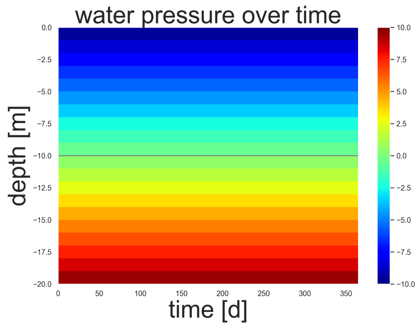

Figure 2. water pressure for the static model.

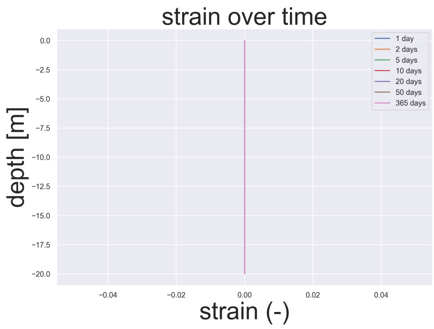

Figure 3. strain development for the static model.

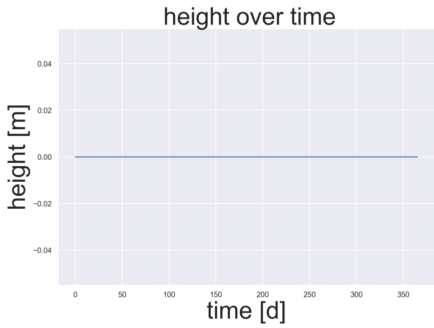

Figure 4. time-dependent height of the static model.

Infiltration model

For the case of infiltration without degradation and a constant drainage level, where the water pressure behaves as shown in figure 6, the effective stress can be seen in figure 5. This leads to a strain development as seen in figure 7 and leads to a settlement as shown in figure 9. Due to infiltration, the oxygen level rises in the model. This is shown in figure 8.

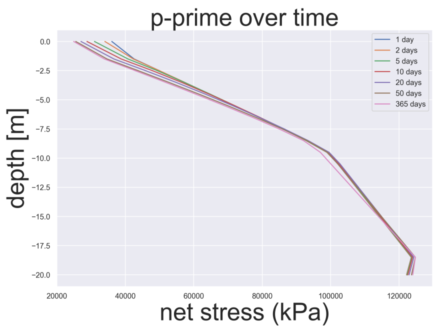

Figure 5. difference in effective stress for the infiltration model.

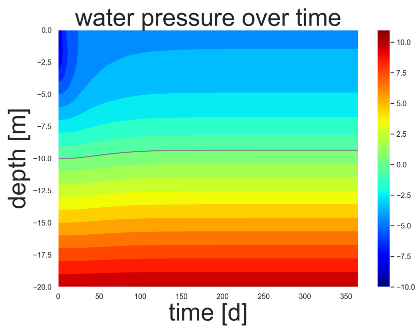

Figure 6. pressure head for the infiltration model.

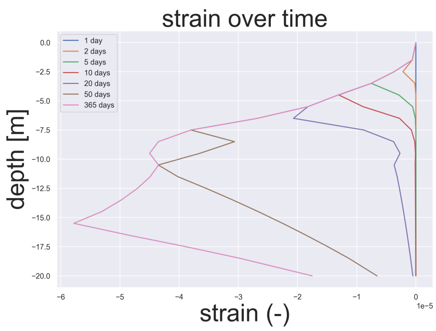

Figure 7. strain development for the infiltration model.

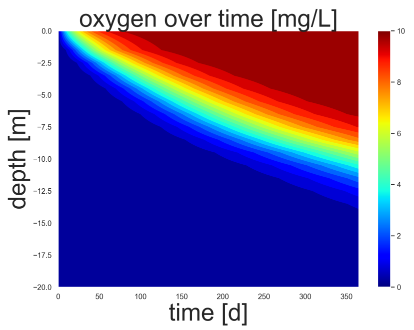

Figure 8. time-dependent oxygen concentration of the infiltration model.

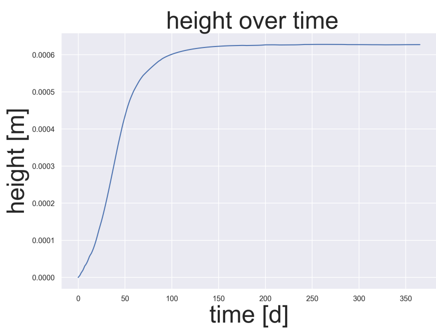

Figure 9. time-dependent height of the infiltration model.

Draining model

As one can see in figures 12 and 10 , the strain and stress development are greatly altered when the withdrawing water table reaches the cell, causing very little more stress change and strain to occur in the cell. The height of the model over time, as seen in figure 13 , follows the same curve as the water table, but at a different scale. This can be explained as the effect of an ever slower declining water pressure in the model, as seen in figure 11 .

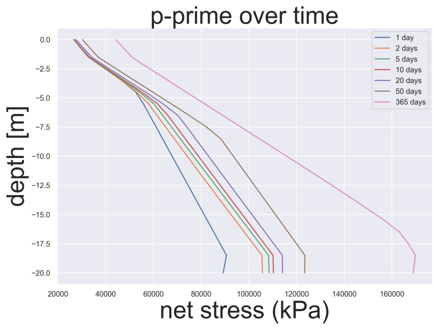

Figure 10. difference in effective stress for the draining model.

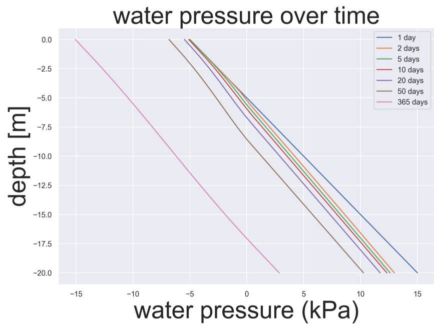

Figure 11. water pressure for the draining model.

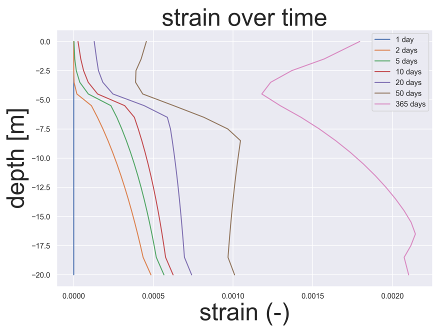

Figure 12. strain development for the draining model.

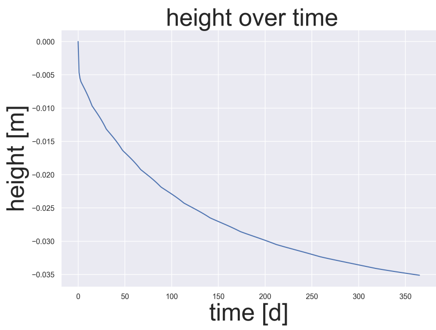

Figure 13. time-dependent height of the draining model.

Wetting model

For the case of drainage without degradation, where the water pressure behaves as shown in figure 15, the effective stress can be seen in figure 14. This leads to a strain development as seen in figure 16 and leads to the settlement shown in figure 17.

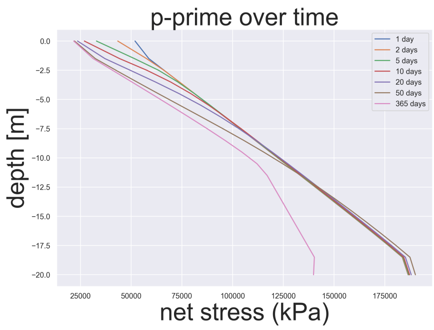

Figure 14. difference in effective stress for the wetting model.

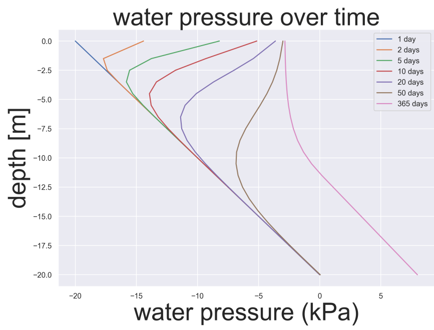

Figure 15. water pressure for the wetting model.

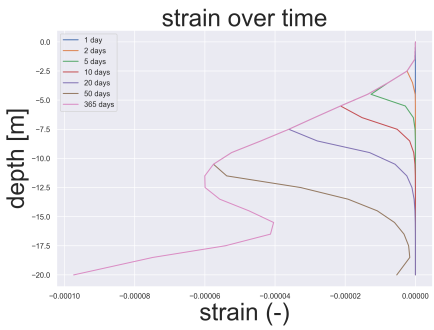

Figure 16. strain development for the wetting model.

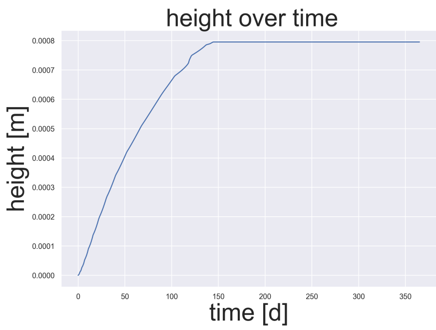

Figure 17. time-dependent height of the wetting model.

First order model

For the case of first order degradation, where the degradation process develops as shown in figure 20 and the water pressure behaves as shown in figure 21, the effective stress can be seen in figure 18. This leads to virtually depth-independent strain as seen in figure 19 and leads to a settlement as shown in figure 23. The contour plots show a change in height for $\Lambda = -0.7$. a higher value would create a greater decrease in depth. This is the only situation shown in the appendix where the decrease in height is visible in the contourplots, therefore the contourplots are shown.

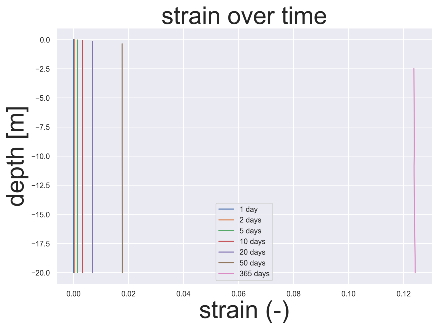

Figure 18. different strain levels for the first order model.

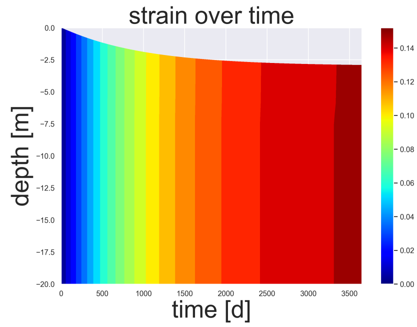

Figure 19. strain development for the first order model.

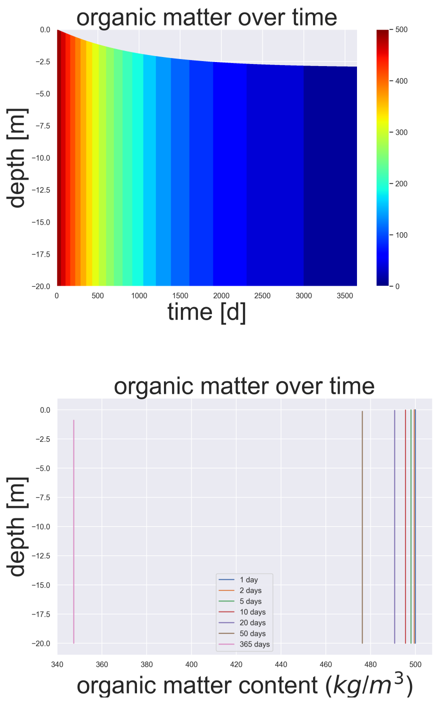

Figure 20. organic matter development in kg/m^3 for the first order model.

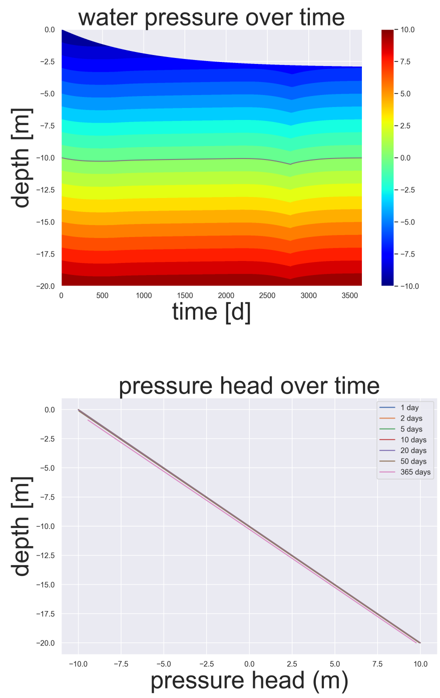

Figure 21. water pressure for the first order model.

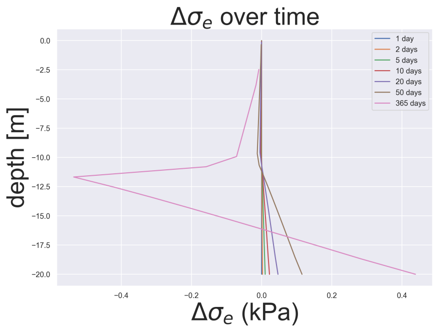

Figure 22. difference in effective stress for the first order model.

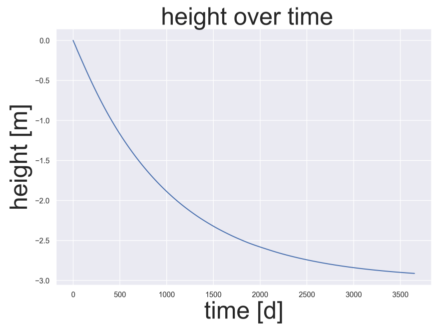

Figure 23. time-dependent height of the first order model.

Aerobic model

For the case of aerobic degradation without enhanced oxygen parameters, where the degradation process develops as shown in figure 28 and the water pressure behaves as shown in figure 25, the effective stress can be seen in figure 24. This leads to virtually depth-independent strain as seen in figure 26 and leads to a settlement as shown in figure 29. Due to infiltration, the oxygen level rises in the model. This is shown in figure 27.

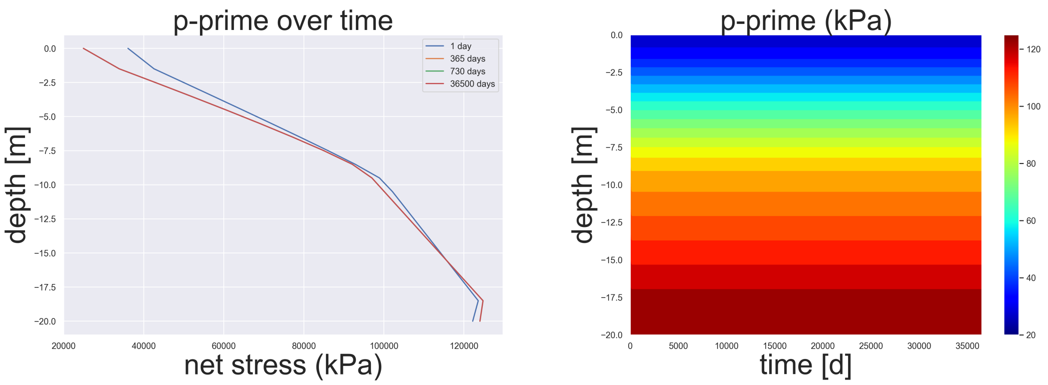

Figure 24. difference in effective stress for the oxygen-based model.

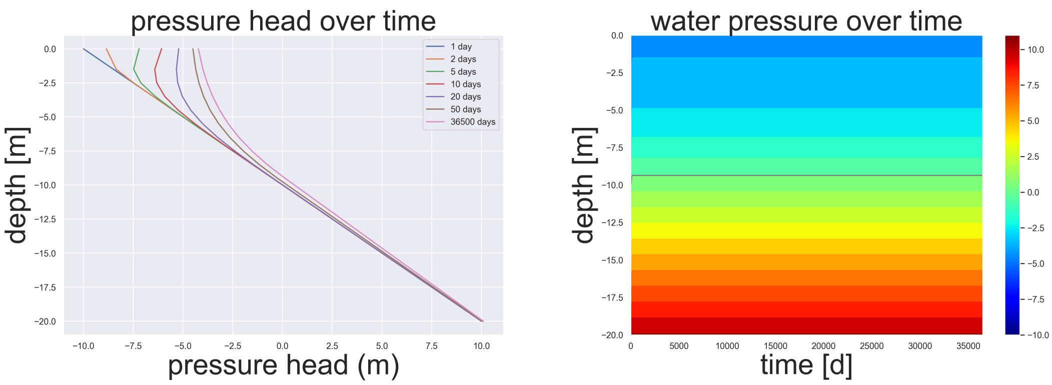

Figure 25. pressure head development for the oxygen-based model.

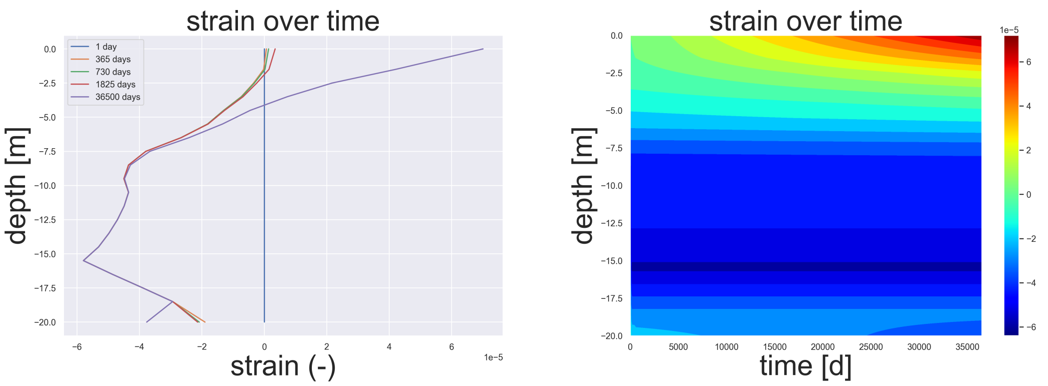

Figure 26. strain development for the oxygen-based model.

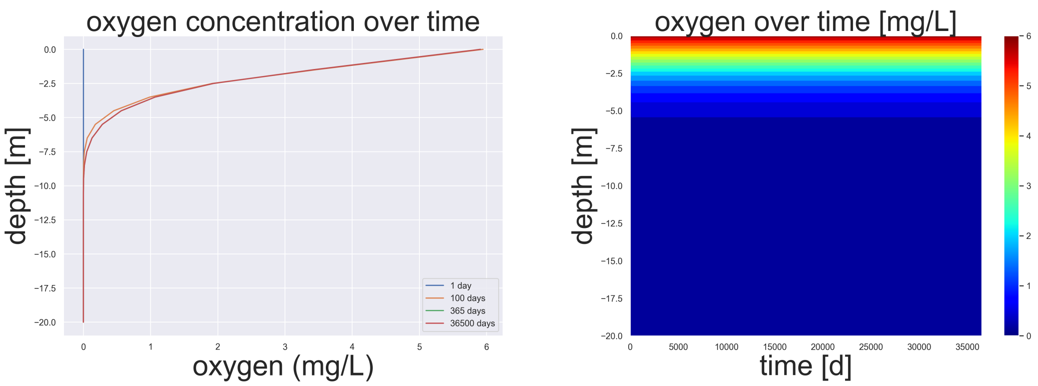

Figure 27. oxygen concentrations for the oxygen-based model.

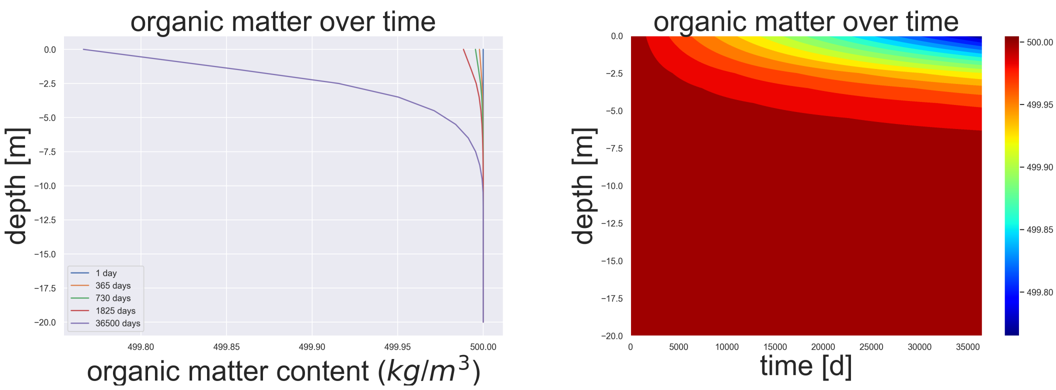

Figure 28. organic matter development for the oxygen-based model.

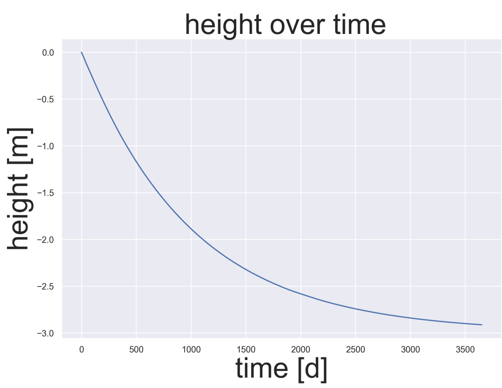

Figure 29. time-dependent height of the aerobic model.

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