

UNIVERSITY OF PADOVA

DEPARTMENT ICEA



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MSc LEVEL DEGREE IN
ENVIRONMENTAL ENGINEERING

THESIS

BIOGAS PRESSURE EFFECTS ON COVER SYSTEM
STABILITY OF THE GRUMOLO DELLE ABBADESSE
MSW LANDFILL

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A. A. 2013-2014

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Introduction

The degradation of MSW organic compounds, stored in the landfill, lead to the production of biogas: a mixture between methane (50-70%), carbon dioxide and trace components.

According to the D.Lgs 36/2003 law, it's mandatory to arrange a biogas extraction plant. The purpose of the plant is to maintain a vacuum around each aspiration shaft's head, in order to suction the biogas and to forward to the energy recovery plant.

Moreover the above mentioned law decrees that it must be placed over the solid waste a capillary and drainage layer.

The purpose of this layer is to collect biogas emissions released by the below MSW into a homogeneous drainage media. The drainage is particularly useful whenever it may occur a temporary interruption between the convey shaft and extraction system.

In this condition if the drainage media's porosity (and the conductivity as well) is not sufficient to guarantee an adequate biogas flux towards the exit holes, it may happen an increase of pressure, lowering the normal resisting forces of the final cover and leading itself to instability.

The thesis's purpose is to evaluate biogas pressure effects on cover system stability whenever the extraction system is temporary off. The case study is that of the Comune di Grumolo delle Abbadesse(VI) 's landfill.

Actually the D.Lgs. 36/2003 law doesn't provide design patterns for the biogas drainage layer. It just define the minimum thickness of the layer itself, being of 50 cm.

The thesis considers the case of a inert media layer having a permeability enough to provide an adequate biogas diffusion without the chance of overpressures.

In order to analyze the behavior of the final cover system under the biogas driving pressure it has been necessary to adopt models based on the limit equilibrium methods, such as the infinite slope.

Chapter 1

Site location

The thesis's area lies entirely in the Grumolo of Abbesses municipality (Province of Vicenza) and is 500 m east from the territorial limits of the City of Grisignano di Zocco, 1,000 m to the west from the border territory of the City of Longare and 500 m to the south, the boundaries of the City of Montegalda.

The nearest town of a certain size is to the north, the city of Sarmego where the dwellings are approximately 800 m from the plant.

Other settlements are: Vancimuglio north-east (1,800 m), Barbano east (about 2,000 m), Colzè southwest (about 3.000 m). The center of Grumolo of Abbesses is located approximately 3,000 m to the north.

In the range of 200 m perimeter around the area affected by the project, there are no houses, while in the range of 400 m there are occasional isolated dwellings. At about 200 m is placed a small manufacturing business.

Runs along the north side of the area, to 233 m (at the closest point), the A4 Torino - Trieste, while almost parallel to the highway, 300 m (at the closest point to the area), there's the SS n. 11 ex Padana Superiore, farther and farther away to the landfill. In the area (but within a radius of 1000 m from the perimeter of the area) there are no lakes or waterways used for drinking water use and in a radius of 2000 m are not taken or wells operated by companies aqueduct or private wells used for drinking water, being the area in question served by the public waterworks.

Chapter 2

Landfill description

Below, through the major projects that have followed, the type of the landfill is described.

2.1. Project of march 1992

The project of 1992 provided only the first category's landfill¹ without the pretreatment and stabilization plants. The site in question had certain characteristics that made it suitable to host a landfill; in particular:

- the presence in the system of a plastic clay layer, with very low permeability, a relatively small depth from the ground level (on average 11.5 m);
- the position out of urban centers.

The coincidence of these two elements in an area in which the above mentioned layer of clay presented sufficient thickness and continuity, suggested designers the realization of perimeter diaphragms included into the impermeable layer of clay, in this way, from the aquifers present, the landfill is isolate.

¹ The decision of July 27, 1984, classified as a first class landfill simple storage facilities in which to be disposed of municipal solid waste, special waste similar to urban waste, not toxic and harmful sludge is.

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The plastic diaphragm perimeter has therefore enabled the realization of a waterproof "bowl" inside which allocate the landfill.

The design approach adopted in the formation of the basins host the landfill is summarized in the following points:

1. Realization of a plastic diaphragm perimeter having the purpose to isolate the area of the landfill from the surrounding ground, obtaining a closed cylinder, confined by the walls of the plastic diaphragm and the lens conspicuous clay of good quality background. All feedback regarding the prediction of the behavior of groundwater, particularly from the surface in the area of the excavation, have moved to the narrow scope of the cylinder confined in which the only external inputs are related to those meteoric. In order to cope evacuation of rain water within the cylinder to allow the dry digging of the tanks, has been proposed a system of drainage Well-point having the purpose of depressing the water within the cylinder, the below the level of the excavation (about -6 m);
2. Realisation dry, for subsequent batches, the waterproofing barrier of the bottom of the tanks, consisting, according to the design predictions, by a layer of 16 cm of bentonite;
3. Realization dry for subsequent batches, the barrier to water escarpments; they are coated with bentonite quilted mattresses, of a thickness of 10 cm and 70 cm overlapped longitudinally and transversely.
4. Management System lowering of the water with respect to issues related to the management of the landfill and the completion of subsequent batches;
5. Paving a drainage bed;
6. Waste disposal;
7. Realisation of the waterproof cover consists of a layer of compacted clay of at least 30 cm surmounted by fine soil from the excavation (40 cm) and from vegetable soil (40 cm) with a gradient of 5% declared and drainage ditches.

In project of 1992 the realization was scheduled for subsequent batches; the preparation of a lot happened in the course of the management of the previous batch, thus limiting the exposed surfaces of the yard.

LANDFILL DESCRIPTION

- The project of 1992 provided the biogas extraction and combustion plant.

2.2. Adjustment of August 1993

In compliance with the requirement of the Regional Council, dated July 30, 1993, which provided for the establishment in the main dump of a plant for the wet-dry mechanical sorting of MSW, the consortium of municipalities client has prepared a project, started in August 1993, in fact, introduced a structured pre-treatment plant. The new project involved the landfilling of the only "dry" fraction of MSW, previously compacted into a baler, while the "wet" had to undergo an aerobic stabilization at a purpose built shed in the topic area, and then return in the landfill.

According to the designers, it was changed the nature of the waste landfilled that, "tal quale" passed "dry", so you no longer have a significant production of biogas; the variant is then:

- Total elimination of the biogas extraction and combustion system present in the original project.

The landfill, thus, essentially maintained the characteristics of the project in 1992.



Fig. 2.1 – Packing of MSW stored in landfill

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The plant began its operations on July 13, 1999.

2.3. 2001-2002 Arrangement Project

In 2000, partly as a result of comments made by the Province and the City of Grumolo of Abbesses, initiatives have been launched to improve the characteristics of the landfill, resulting first in the “Progetto di captazione del biogas” (dicember 2000) and in the “Progetto di Adeguamento” November 2001 / May 2002.

These two projects have introduced a number of technological innovations that have made the landfill complies with modern design standards.

Some of the key improvements to the landfill with the Plan of Adjustment are as follows:

1. Reshape of the top covera with the realization, in the long term, grades suitable for evacuation of rainwater (more than 7%);
 2. Construction of a new package of coverage, including a drainage layer above the barrier in clay mineral;
- Biogas extraction and combustion system.

F for the new biogas collection and incineration plant, the first experimental phase has started, whose purpose is to verify the design assumptions; this phase, which ended in May 2003, was conducted in the first two sectors allowing you to proceed to the final design of the biogas plant.

2.4. Adjustment Project related to D.Lgs. 36/2003

With the enactment of the legislative decree of 13 January 2003 n.36, the transposition of Directive 1999/31/EC of 26 April 1999 on the landfill of waste, have been introduced into national law specific provisions relating to the management of landfills. Before the entry into force of this Decree. the planning framework of reference for the landfill, as seen, was formed by the projects of 1992 and 1993 with the modifications introduced by the “Progetto di Adeguamento of the 2001-2002” ; they should be added to the “Progetto dell’impianto di captazione del biogas (2000)”, adapted with the guidelines provided by the tests conducted in the experimental phase.

LANDFILL DESCRIPTION

For what concerns the biogas, the abovementioned experimental phase has highlighted the need, among other things, provide for the energy recovery of the gas. In accordance with the provisions contained in Legislative Decree 36/2003 proved necessary to establish a biogas collection system, which, through a system of forced extraction maintains a negative pressure (vacuum) at the head of each collection well, it ensures' aspiration of the biogas produced and, as a rule, sends it to the system of energy recovery.

The above-mentioned Legislative Decree 36/2003 also introduced the obligation to implement, over the storage of waste stored, a "layer of capillary rupture and drainage of biogas", with the main function to collect the fumes of biogas from underlying waste in half draining sufficiently homogeneous.

2.5. Final cover's stratigraphy and MSW's landfill storage

On the coverage end surface of the landfill, Legislative Decree 36/2003, defines the rules of implementation by providing a multilayer structure formed, from the top downwards, by: a surface layer of cover with thickness greater than or equal to 1 m that favor the development of the plant species, a draining layer with a thickness greater than or equal to 0,5 m, capable of preventing the formation of a hydraulic head above the underlying barriers, a layer of compacted mineral thickness greater than or equal to 0,5m of low conductivity 'hydraulic, a layer of uptake of biogas thickness of at least 0.5m act gathering the fumes of biogas from waste underlying and finally, a layer of regularization.

About the drainage layer, the object of study of the present thesis, the decree merely indicates a layer whose height must be at least 50cm, without providing any further information or technical rules about the type of material to be used.

The table below shows graphically the stratigraphy of surface coverage imposed by legislation.

CHAPTER 2

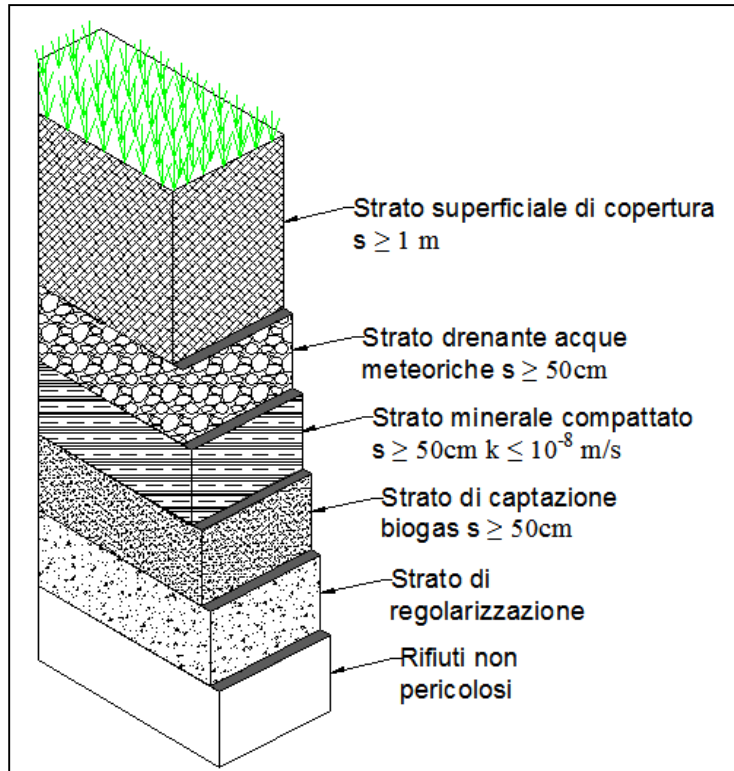


Fig. 2.2 – Top cover stratigraphy according to the D. Lgs. 36/2003

The landfill object of study hosts, for the most part, MSW packaged after compaction with a percentage of biowaste less than 15%; from a technical point of view, the waste is loose laid on the sloping banks of the landfill in order to create a surface for the refusal packed.

As shown in the figure 2.3, the loose waste are also positioned above the packed in order to achieve the necessary slope to the runoff of rainwater that would otherwise be to infiltrate within the landfill itself.

In this regard, it is designed for short-term slope of 7.6%, which evolves to 7% in the long term.

LANDFILL DESCRIPTION

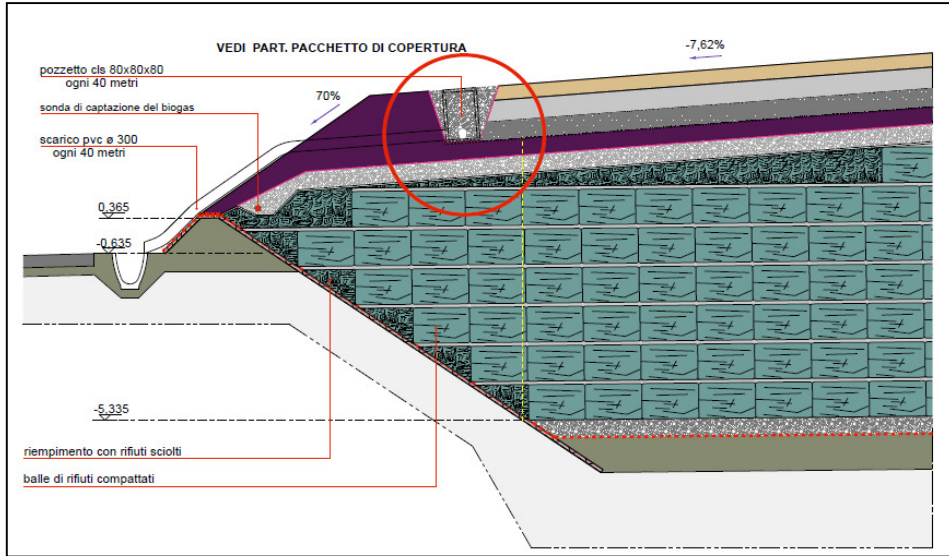


Fig. 2.3 – MSW deposition and the geometry of the final slope

The table below shows, in compliance with current legislation, the stratigraphy of the landfill final cover adopted.

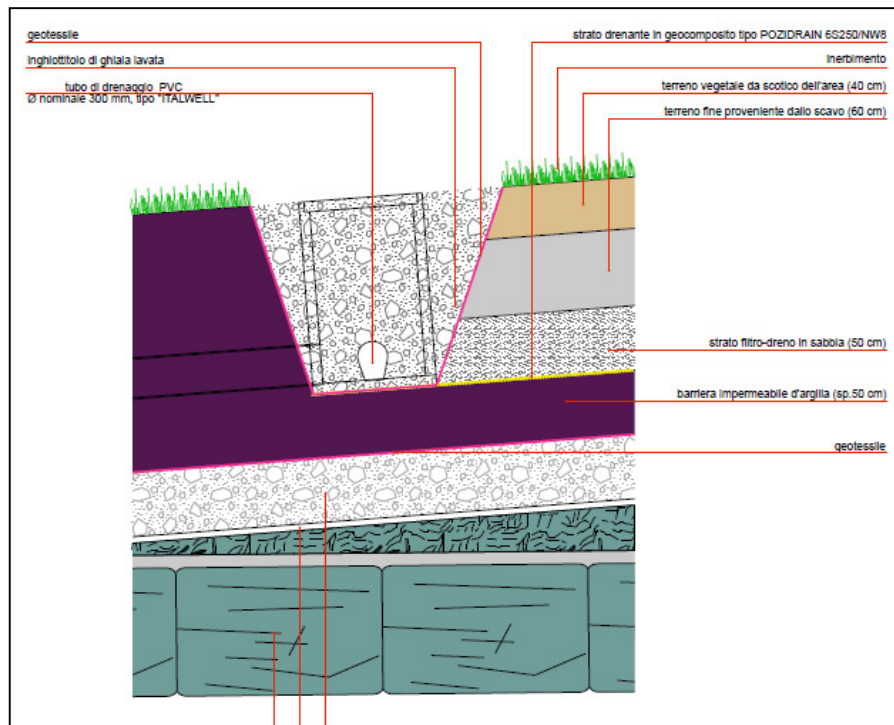


Fig. 2.4 – Detail of the top cover

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Starting from the top:

- *Finish vegetable layer*

Outer layer, consists of covering soil carryover thick 100cm, such as to guarantee both the growth and development of vegetation, that protection against climatic actions.

- *Sandy filter layer*

Layer made with sand from the excavation of the tanks, the transition between the layer of finishing plant (in silt-sandy soil) and the underlying carpet in geocomposite drainage;

- *Geocomposite drainage*

Its purpose is to intercept rainwater to keep the soil layer in unsaturated conditions. The intercepted water are drained into the sinkhole perimeter.

- *Low permeability mineral layer*

Waterproofing, constituted by a layer of clay, has the aim to avoid limiting the passage of water in the underlying layers.

- *Geotextile*

Used in order to separate adjacent layers and to avoid a possible inclusion of low-permeability material within the layer below.

- *Capillary rupture and biogas layer*

As previously mentioned, the layer, composed of materials draining has the purpose of intercepting the gas and direct it at the appropriate pipes which convey it outside.

- *Regularization soil*

Which functions to regulate the laying surface for the proper implementation of the higher elements.

The correct management of landfill includes a layer of daily coverage of MSW discharged and compacted on a daily basis in the areas of landfill. This daily capping, is carried out with a dual purpose: to contain or reduce the spread of odors (due to the fermentation of the organic fraction contained in MSW) and avoid: whether the light fraction is dispersed into the surrounding environment due to the wind

LANDFILL DESCRIPTION

and to prevent contact of the front of the dump with unwanted animals (seagulls, rats, flies, etc..).

The following figure shows how, at the end of the workday, are used as a solution equivalent to the spread of a layer of soil, tarpaulins over of their waste.



Fig. 2.5 – Daily coverage on the active edge

Chapter 3

Degradation process of MSW's Organic fraction in landfill

3.1. Biogas production description

The waste stored in landfills are degraded through a combination of chemical, physical and biological process. These processes, acting simultaneously, degrade the organic component of the waste resulting in the production of leachate and biogas. The MSW landfill may be likened to a large biological reactor in which the organic matter forms the substrate for bacteria able to demolish it completely up to the achievement of the simplest products of metabolism.

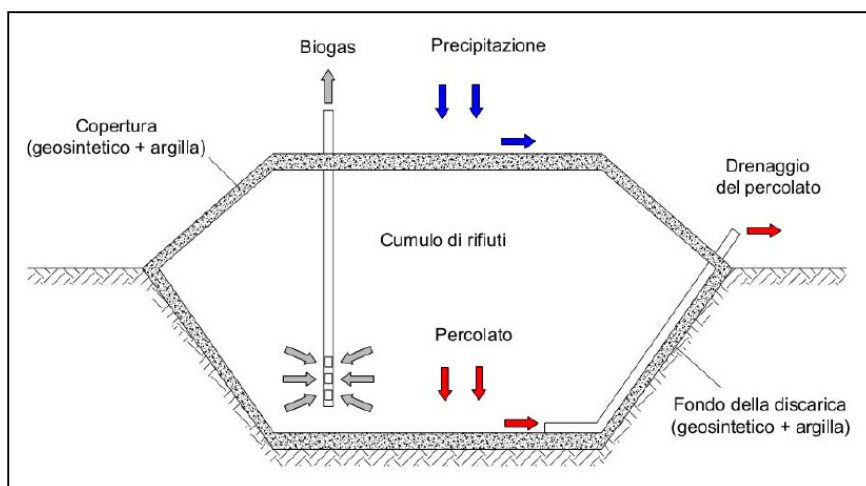
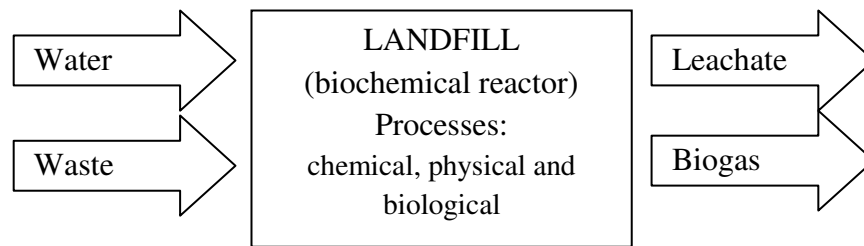


Fig. 3.1 - Operating diagram of a plant for waste storage

DEGRADATION PROCESS OF MSW'S ORGANIC FRACTION IN LANDFILL



Within the same are created processes: chemical, physical and biological with the degradation of the organic substance.

a. Physical processes

The physical processes occurring in landfills consist in the breakage and in the handling of waste, in the variation of humidity in the same, in the transport of particles with the water and in the diffusion of substances due to concentration gradients.

b. Chemical processes

The chemical processes that contribute to the degradation of the waste include hydrolysis, dissolution / precipitation, adsorption / desorption, ion exchange. The chemical degradation produces an alteration of the waste characteristics and the increased mobility of constituents in the waste, tending to greater uniformity of the chemical characteristics of the landfill.

c. Biological processes

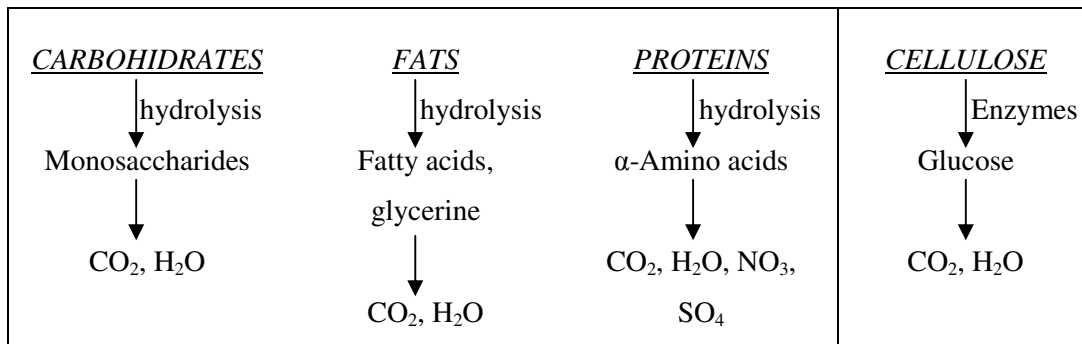
These processes can be considered as the main mechanisms of degradation, beginning when the waste is deposited in landfill going to act on the organic part. The biological degradation of organic matter of the waste occurs in a process consisting of several stages with aerobic metabolism and (mostly) anaerobic.

Being the landfill managed in a ways to prevent the circulation air, there is still a limited despite the presence of oxygen due to both air aggregated in the fresh waste, which in the upper layers due to dissolved oxygen conveyed from rainwater . Aerobic degradation ceases when the oxygen is consumed, the same, is in fact used by microorganisms for aerobic respiration.

3.1.1. Aerobic degradation

This phase appears to be the first stage of degradation, requires the presence of oxygen as produced by bacteria that for breathing using free oxygen as electron acceptor. Considering that the main organic components of the waste involved in the degradation are: carbohydrates, fats and proteins; microorganisms, using them as a source of energy to convert them

Tab. 3.1. - Conversion processes of the main organic components.



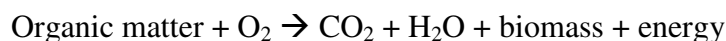
This implies hydrolysis during which the complex organic substances are transformed into simple organic compounds: Carbohydrates are converted to carbon dioxide and water after hydrolysis to monosaccharides; hydrolyse fats to fatty acids and glycerine to carbon dioxide and water then pass through the intermediate formation of volatile acids and alkalis; proteins are degraded first in amino acids, and then to carbon dioxide, water, nitrates and sulphates.

The cellulose, which constitutes the main part of the organic fraction of the waste is degraded by extracellular enzymes into glucose, which is then converted by bacteria into carbon dioxide and water.

The hydrolysis reaction is highly exothermic and can be observed, usually after the commissioning of the waste in situ, the temperature rises to 60-70 ° C.

This initial phase lasts from a few hours to 1-2 weeks at the most superficial layer of waste, there is the consumption of the oxygen (O₂) and production, almost exclusively, of carbon dioxide (CO₂).

The aerobic degradation can be represented as follows:



Unless there is a supply of air due to, for example, by the high vacuum applied to the well head of uptake with consequent aspiration of outside air (such that it has the progress of the aerobic phase), the concentration of nitrogen (N₂) decreases and oxygen (O₂) is consumed reduced to zero.

3.1.2. Anaerobic degradation

The degradation in anaerobic condition begins when the waste is to be in terms of silting deeper and after it has been consumed all the oxygen initially available. During this phase, we have the decomposition of organic matter with production of methane (CH₄) and carbon dioxide (CO₂), the primary constituents of biogas (LFG, "landfill gas" in Anglo-Saxon terminology).

In reference intake exhibited in the variation of August 1993, which provided the total elimination of the extraction and combustion of biogas, justifying the claim by arguing that the landfill was designed to accommodate the only dry waste; then, assuming the total lack of carbon (main nutrient of microorganisms) there could be production of biogas.

Above assumption turns out to be inappropriate due to the presence, within the dry fraction of cellulosic material.

Cellulose, being a polysaccharide (formed by long chains of monomers of beta-D-Glucose C₆H₁₂O₆) so that it can be degraded by extracellular organisms, long lead times are required; This implies that, unlike the quickly degradable material, remains in the landfill for more time prolonging the production of biogas.

In this regard, as can be seen from Figure 3.2., Dwelling in the analysis of the fourth phase as stable methanogenic, is reached that the percentage of cellulose are not yet degraded is of the order of 80% (compared to the total stored in landfills).

During this phase the extracellular organisms degrade about 70%, as a result there is not only the production of carbon dioxide, but, being in an anaerobic environment, methane, both as aforesaid primary constituents of biogas.

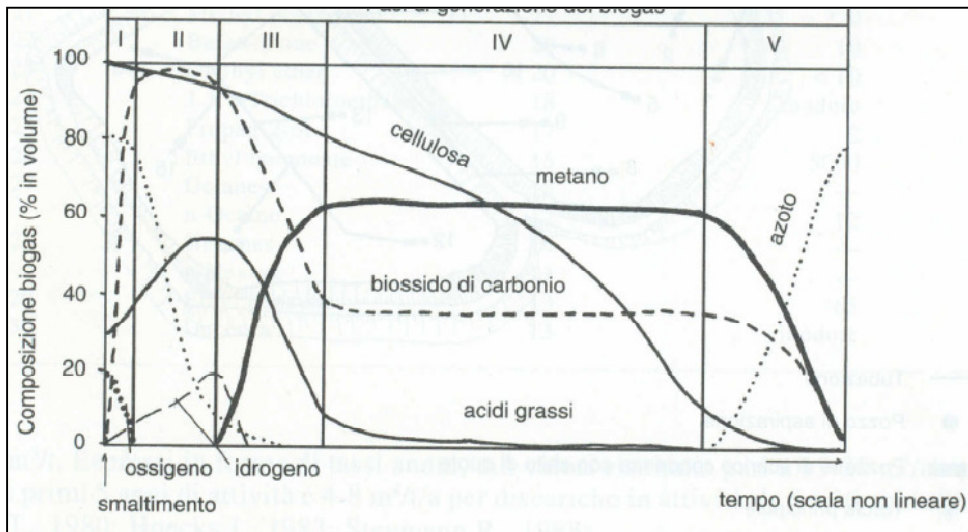


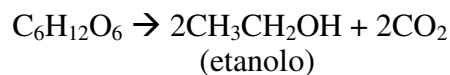
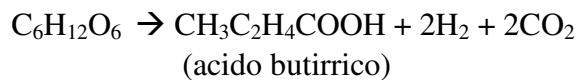
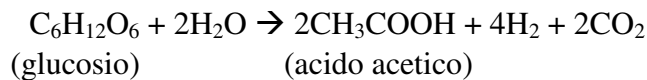
Fig. 3.2. - Phases of cellulose degradation (Rarquar G.J. e Rovers, 1973)

The steps of anaerobic degradation are shown in Figure 3.3 and articulated as follows:

3.1.2.1. Acidogenic and acetogenic phase:

The organic substance complex (carbohydrates, fats, proteins), in the form which is dissolved particulate, is hydrolysed to simpler compounds dissolved able to be able to permeate cell membranes of bacteria; these compounds are degraded by bacteria of the fermentation to volatile fatty acids, alcohols, hydrogen and carbon dioxide.

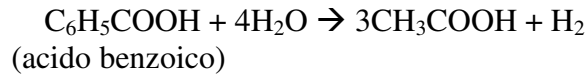
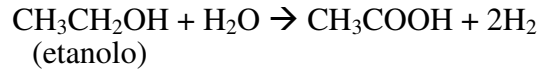
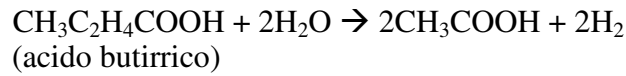
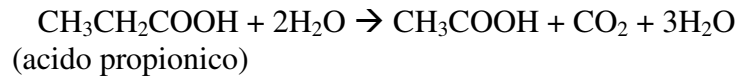
During this phase, there is a net production of gases such as CO₂ and H₂



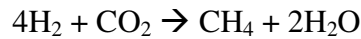
3.1.2.2. Unstable methanogenic phase

The acetogenic bacterial groups converted to acetic acid, hydrogen and carbon dioxide products by the I stage of degradation.

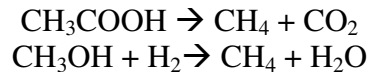
DEGRADATION PROCESS OF MSW'S ORGANIC FRACTION IN LANDFILL



It has also biogas production, both by idrogenofila (CO₂ and H₂):



and by acetofila (from acetic acid):



3.1.2.3. Stable methanogenic phase

Continues the production of methane and carbon dioxide by methanogenic bacteria which use as the substrate is acetic acid (bacteria acetofili) both the hydrogen and carbon dioxide (bacteria idrogenofili).

Degraded all the biodegradable organic substance, methane production ceases. Theoretically, the completion of the methanogenic fermentation, the interstices of the landfill alveolar tend to be pervaded by air again, which would allow aerobic fermentation residues phenomena.

Below is a chart indicating the fermentation of waste, with the composition, in volume percentages of biogas

CHAPTER 3

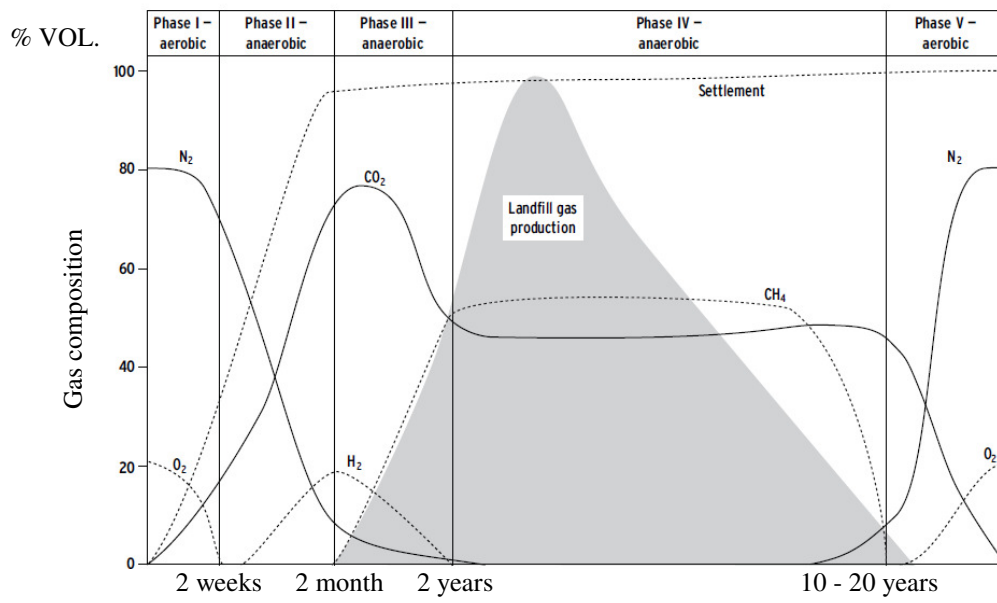


Fig. 3.3 - Idealised representation of landfill gas generation (Guidance on the management of landfill gas, Environment Agency 2004)

Chapter 4

Biogas production predictive Models

This section describes the models adopted in order to predict the amount of biogas produced from the degradation of the waste stored in the Grumolo delle Abbadesse landfill in the various projects that have occurred over time.

Recalling the projects described in the second paragraph, through the figure 4.1 are shown the points of greatest relevance useful in order to describe the type of waste to landfill.

According to the implementation or not of the pre-treatment step upstream, the rejection is dry or tal quale is; based on these assumptions are derived the data useful for the implementation of the models suitable for the prediction of biogas production.

CHAPTER 4

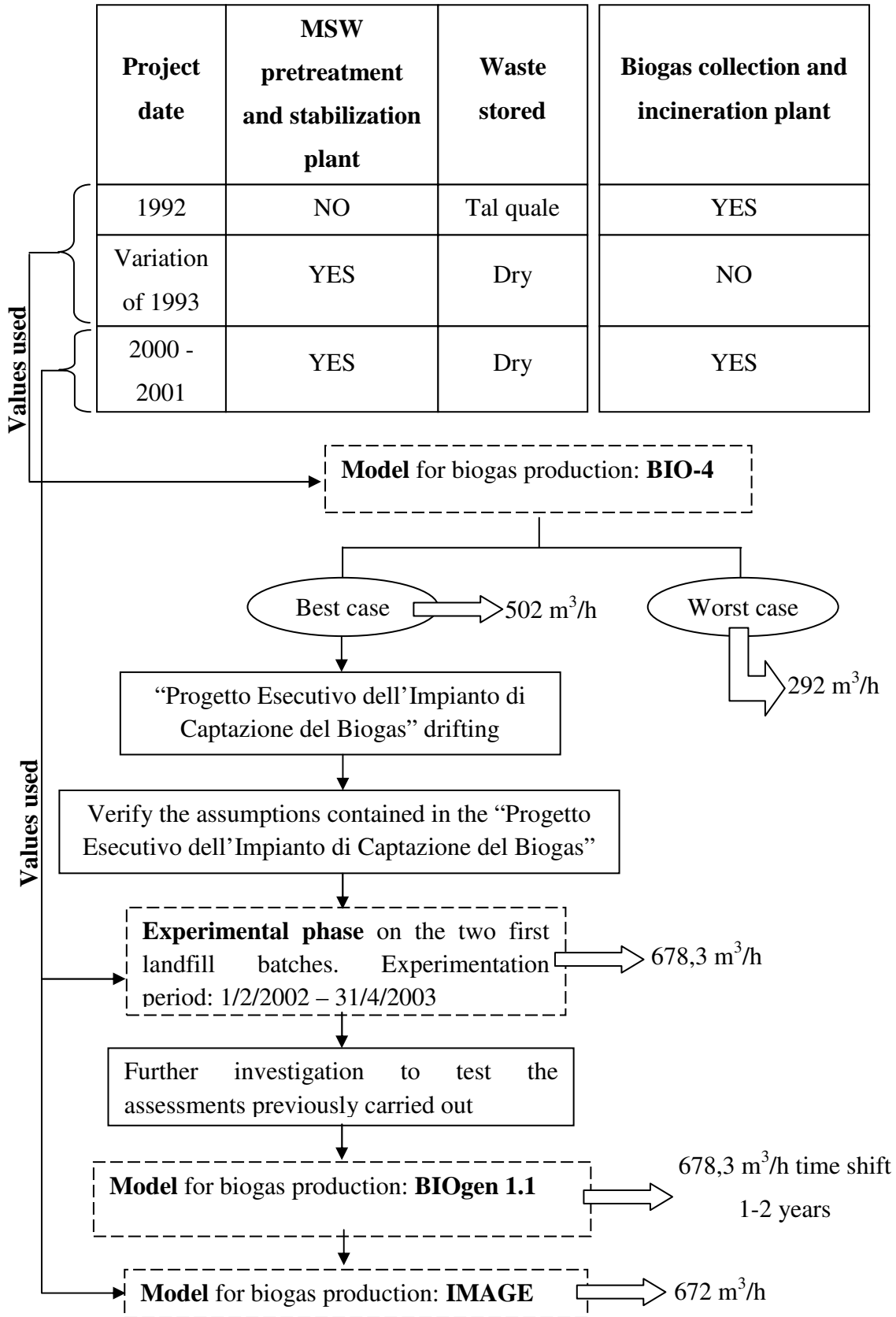


Fig. 4.1 – Diagram of the biogas prediction models adopted

4.1. BIO-4 | Biogas production Model

The first model adopted for the determination of biogas production in the dump object of study is called BIO-4.

BIO-4 uses an algorithm derived from biochemical model, that considers the biodegradability of the different components of rejection on the basis of equations of removal of the biodegradable substrate.

The input data to the model refer to two methods of disposal of waste in landfill different from each other: in 1992, the waste is stored in an "as is" implying a high rate of biodegradable component, subsequently, with the variant in 1993, the waste are classified as dry preparing a pre-treatment plant through which the waste has been disposed of "preset" and compacted going to subtract good part of the biodegradable component.

One of the major difficulties associated with the aforementioned model is given by the lack of precision of the input data due to the different modes of delivery of waste have just enunciated. In this regard, the values assigned are matters of judgment, with the result that may fade the reliability of estimates provided by the model does not exist in the literature to refer to specific cases.

For this reason, the input data is associated with a value of "probabilistic": instead of inserting a specific value for a given, they are placed at both ends with two corresponding probabilistic: in this way, there are two extreme scenarios defined as *best* and *worst* case.

- **Best case:** the input data is associated with a value "optimistic" in the sense of the maximum biogas production.

The refusal is considered "tal quale", with high biodegradable fraction as it does not pre-treated.

- **Worst case:** the input data is associated with a value "pessimistic" in the sense of minimum production of biogas.

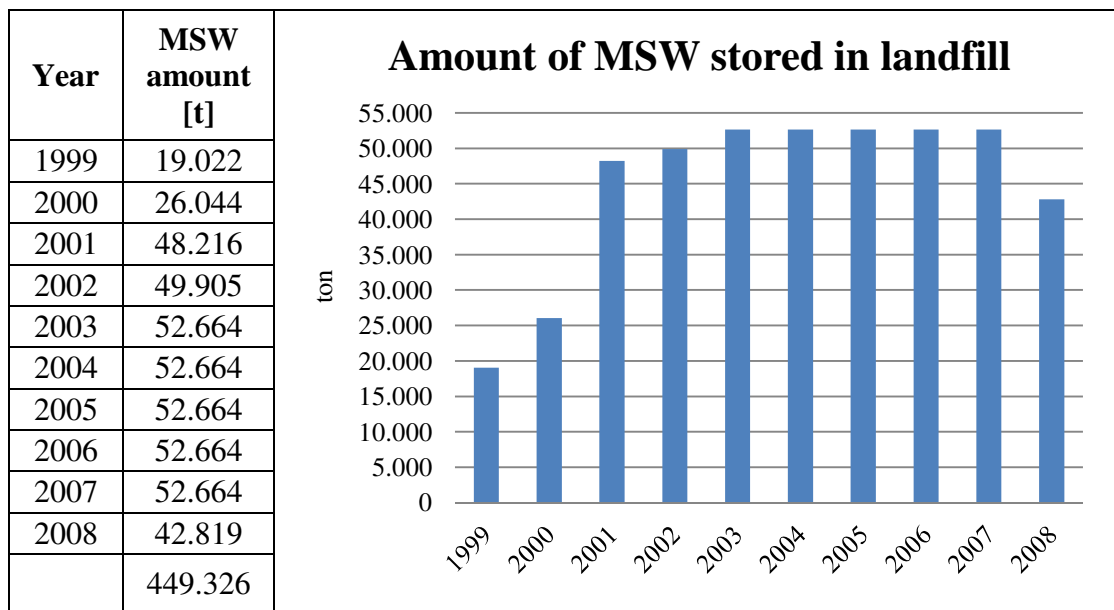
The refusal is considered "dry" because, being subjected to pre-treatment, the biodegradable fraction (MSW) is less than 15%.

CHAPTER 4

The first step is to evaluate the breakdown of the waste disposed of in landfills by dividing it into three fractions differentiated by fermentation kinetics:

- **RVP:** Rapidly putrescibile fraction;
- **RLP:** Slowly putrescibile fraction;
- **RNP:** Non putrescibile fraction.

Tab. 4.1 – Amount of MSW stored in landfill



BIOGAS PRODUCTION PREDICTIVE MODELS

Tab. 4.2 – Merceological valuation of MSW entering the landfill and separation efficiency in the worst case and best case

CATEGORIA MERCEOLOGICA RIFIUTI IN INGRESSO ALL'IMPIANTO		VALUTAZIONE MERCEOLOGICA DEI RIFIUTI IN INGRESSO ALLA DISCARICA	VALUTAZIONE PROBABILISTICA DI MASSIMA EFFICIENZA DELLA SEPARAZIONE (Worst case)	VALUTAZIONE PROBABILISTICA DI MINIMA EFFICIENZA DELLA SEPARAZIONE (Best case)
RVP	velocemente putrescibile	7,11%	7,00%	15,00%
	1/2 pannolini			
	1/3 incernibile			
RLP	carta	45,57%	45,62%	41,70%
	cartone			
	legno - ramaglia			
	cuoio			
	tessuti - cuoio			
	1/2 pannolini			
	1/3 incernibile			
RNP	metalli	47,32%	47,38%	43,30%
	pericolosi			
	polistirolo			
	plastica dura			
	plastica film			
	poliaccoppiati			
	inerte			
	vetro			
	1/3 incernibile			

The calculation model has been calibrated so that the production of biogas is estimated for a period of 40 years against the transfer of waste to landfill than 9 years (1999-2008).

Below are the graphs representing the two scenarios for the production of biogas.

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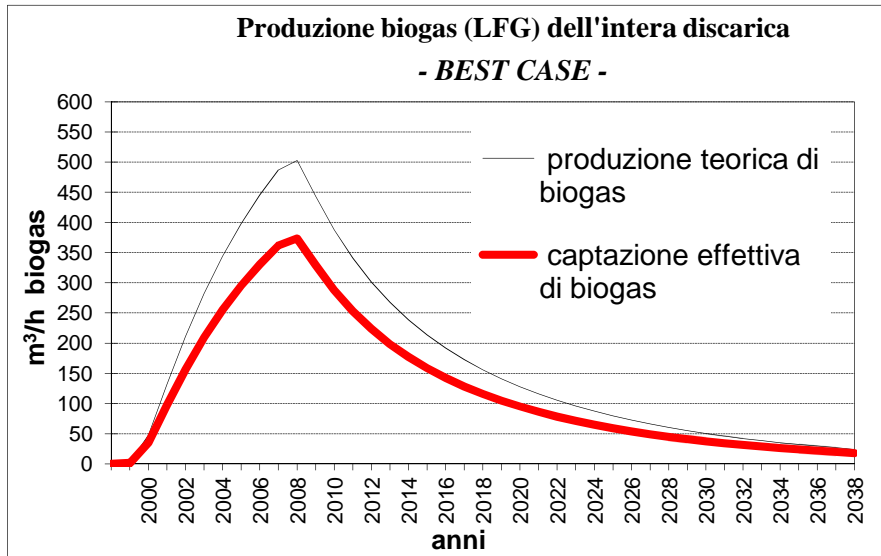


Fig. 4.2. – Biogas production trend: Best case

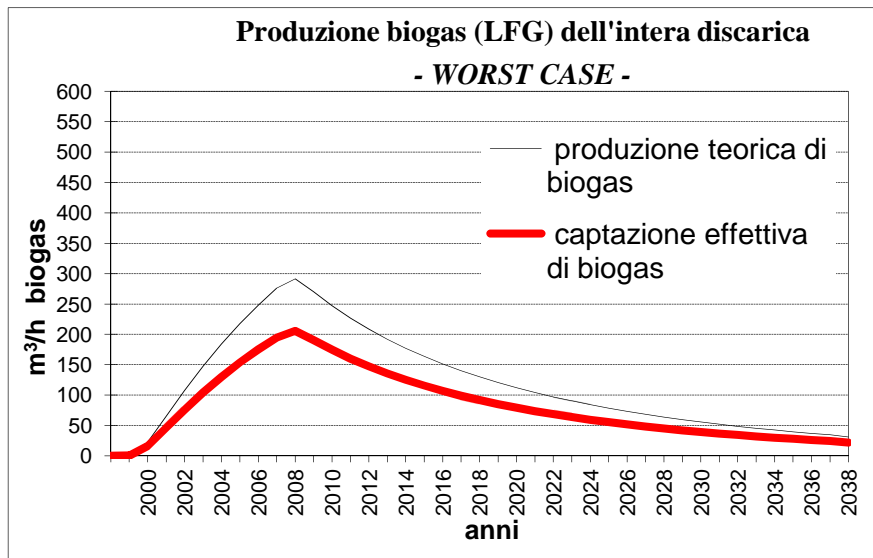


Fig. 4.3. –Biogas production trend: worst case

As can be seen from the graphs, the biogas production follows a time course bell, this is due to the superposition of the curves of biogas production progressively relating to the waste stored in the landfill.

For both scenarios, the peak of production of biogas in 2008, near the completion of deliveries of waste; the maximum values of biogas production are defined in the following table.

BIOGAS PRODUCTION PREDICTIVE MODELS

Tab. 4.3 - Maximum theoretical production of biogas in the worst and best case

	Maximum theoretical production of biogas
<i>Best case</i>	502 m ³ /h
<i>Worst case</i>	292 m ³ /h

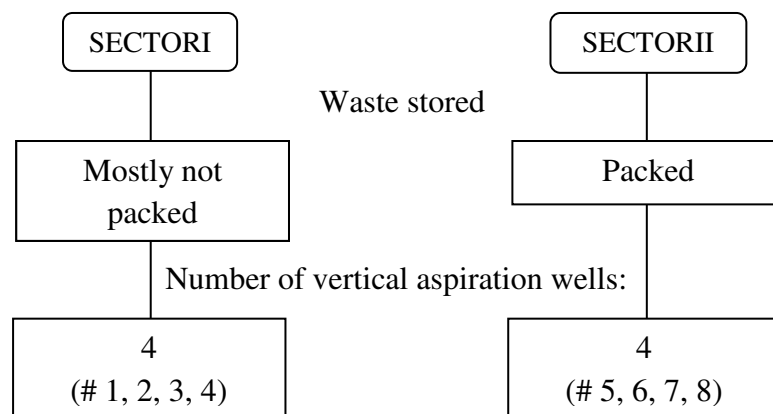
The trends of the curves (theoretical production of biogas) resulting from the application of the best and worst case scenarios, are used for two purposes:

- Best case: regardless of the quality of the gas and its methane content, the dimensions of the "environmental safeguards"; with the aim of safeguarding and protecting the area surrounding the landfill, it is then necessary to capture the maximum amount of biogas produced, as is the case in the process of reclamation;
- Worst case: it is usually adopted in projects for energy recovery, where it is important to aim for the uptake of gas suitable for incineration, for which the concentration of methane in the biogas must be high.

Part of the biogas produced by the degradation of the waste is picked up for the purpose of energy recovery, having a methane content in the neighborhood of 50%.

4.2. Experimental Phase | Target and development

The phase of verification and monitoring test, performed in the period 1/2/2002 - 4/31/2003, on the installation of biogas collection that insists on the first two batches of the landfill, is aimed at finding the forecasts of the production of biogas and design hypotheses expressed in the "Executive Plan of the Plant uptake of Biogas", and proceed in the light of the results obtained, the possible revision of the project. The two areas used for the reception of waste are managed as follows:



In order to perform the estimation of the specific curve of biogas production, it is necessary to know both the quantity of stored waste that the timing of the filling of the tanks under investigation.

The storage of waste in a landfill is via filling in series.

The following lists represents the times and the quantities of MSW stored.

Tab. 4.4 Filling times and amount of MSW stored in the sector

Sector	Filling time [month]	MSW stored [t]
First	10,5	27.891
Second	9,5	25.447
Total	20	53.338

With an average monthly filling of 2.668 t / month.

BIOGAS PRODUCTION PREDICTIVE MODELS

Once the filling phase of the tanks, it is to the insertion of the wells through the drilling waste through the auger dry from 600 mm diameter to a depth of 1.5 m above the portion of the waterproof layer of the bottom.

The wells in the respective tanks were linked through two lines of horizontal tubes (DE 120 mm): the first line joins the wells from 1 to 4 while the second combines the wells 5-8; the two lines are merged and become a single line, over the east side of the landfill, to be connected to the Central Mining and Combustion (CEC).

It then calculated the average flow of biogas assessed during the year of experimentation, bringing in the figure below, the curve of the cumulative biogas extracted.

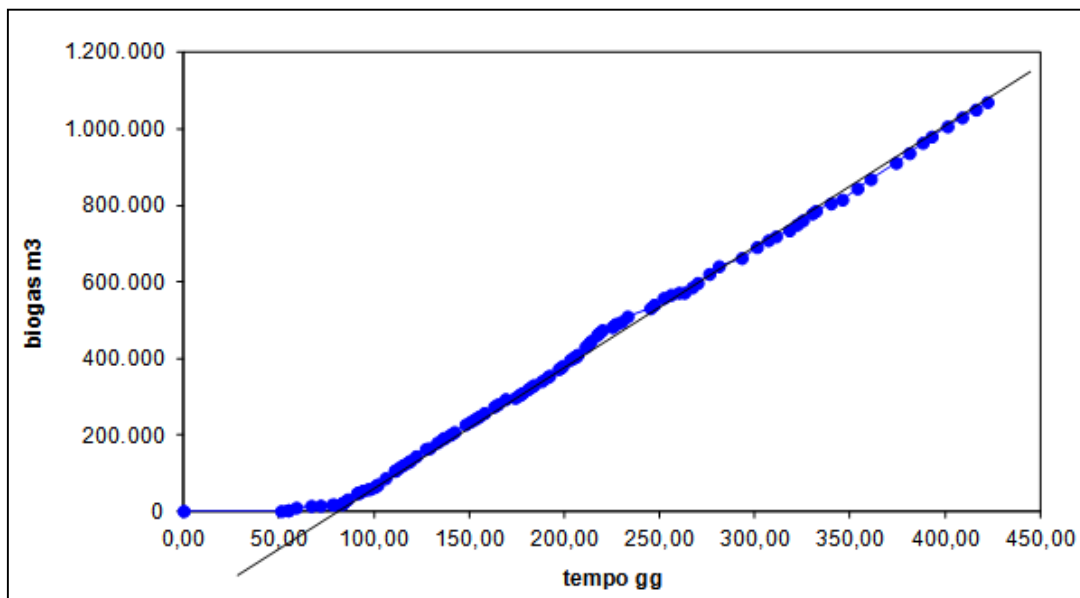


Fig. 4.4. – Cumulated curve of biogas extracted during the experimental phase

In the model BIO4 the term "production" refers to the production of biogas generated by the degradation processes; in the experimental phase, such term acquires a different phrase Whereas the production from the point of view of plant i.e. the biogas extracted. With this condition, the average flow extracted total sum as extracted from the two tanks was 123 Nm³ / h on an annual basis.

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Tab. 4.5 – Type of incoming waste and biogas production in the two respective tanks

Sector	Type of incoming waste	Biogas production
First	Mostly not packed	33,64 Nm ³ /h
Second	Packed	89,35 Nm ³ /h
		123 Nm ³ /h

As deduced from the values obtained, the first sector produces about 38% of the biogas produced by the second; this may be accounted to the fact that the waste stored in the second sector being in bales, and then compacted, favor the onset of phenomena anaerobes due to the negligible presence of air, with greater advance compared to waste "loose" stored in the first tank.

The air, in fact, is extracted in the pressing step and thus the little remaining capacity is consumed quickly by aerobic micro-organisms that characterize the early stages of fermentation of waste in a landfill.

The rejection packed tends to produce faster biogas compared to that stored in a landfill with traditional methods, the consequence of this is the mineralization in short times of the same waste.

Using the values thus obtained is checked for goodness of prediction of the model used in the "Executive Plan of the Plant Uptake of Biogas", that compares the yield curve (and not the collection), as estimated in a greater amount of biogas, the model "LFG best case" with the results obtained in the testing phase.

The table below shows the values of biogas produced annually by the degradation of one ton of MSW obtained with the model "LFG Best Case":

BIOGAS PRODUCTION PREDICTIVE MODELS

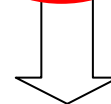
Tab. 4.6 – Biogas produced from the breakdown of one ton of MSW in case "LFG best case"

Year	Productivity [Nm ³ /t•y]
1999	0,94
2000	11,69
2001	15,82
2002	14,98
2003	12,84

Considering the quantities of waste that are landfilled annually, we come to the value of biogas produced per unit of time:

Tab. 4.7 – Biogas produced per unit of time in the case of "LFG Best Case"

Year	Waste stored in landfill [t]			Biogas production [Nm ³ /h]
1999	32.016		32.016	3,4
2000	32.016	21.352	53.368	45,0
2001	32.016	21.352	53.368	86,3
2002	32.016	21.352	53.368	93,3
2003	32.016	21.352	53.368	83,4



Being the year of the survey between 2002 and 2003, the above-mentioned model estimates a production of biogas between 93.3 and 83.4 Nm³ / h, compared with an experimental measurement of extraction of 123 Nm³ / h; from these values shows that the model generates an estimate of the production of biogas at fault:

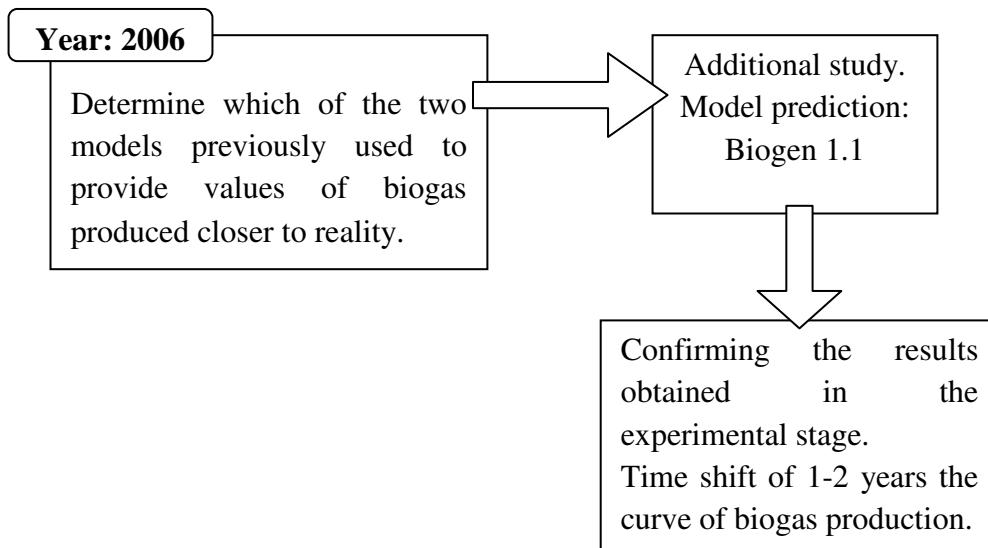
Tab. 4.8 – Comparison of the quantities of biogas evaluated during the experimental phase and in the "LFG Best case"

Year	Biogas production		
	Experimental phase [Nm ³ /h]	LFG Best Case [Nm ³ /h]	“LFG Best Case” vs “Experimental phase”
2002	123	93,3	- 24%
2003	123	83,4	- 33%

BIOGAS PRODUCTION PREDICTIVE MODELS

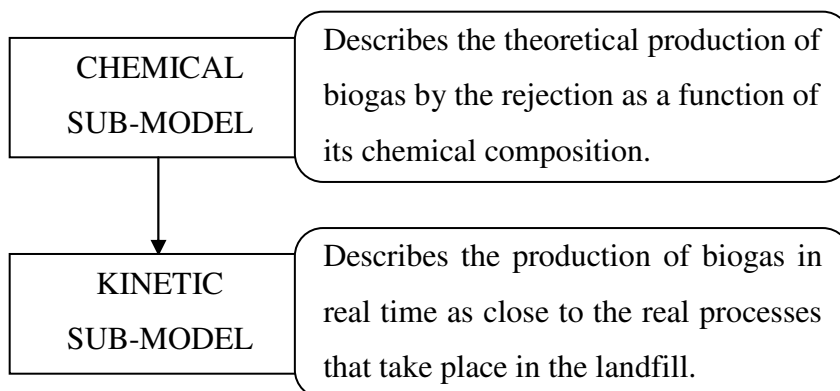
Reasonably conservative in the sense it can be said that the estimate of biogas in default of 35%, at least for the period tested.

4.3. BIOgen 1.1 | Biogas production Model



The model adopted as a tool for assessing the potential production of biogas from Grumolo d. A. landfill, is BIOgen 1.1; this model has confirmed the values of the curve of increased production obtained in the experimental phase, with the only variant of a temporal translation of 1-2 years.

The adopted model is developed in the following components:



Sub-kinetic model takes into account the contentions of the experimental phase: the packed waste, with respect loose waste, has a more rapid degradation.

BIOGAS PRODUCTION PREDICTIVE MODELS

In this regard, the simulation produced by the model will consider intervals of half-life (t_{1/2}) below the bibliographic data, considering a faster degradability of the packed waste.

Tab. 4.9 – Half-life time for the two different reactions: fast and slow

	half – life time t_{1/2}		
	[years]		
	RVP	RMP	RLP
Fast reaction (MSW packed)	2	5	10
Slow reaction (RSU loose)	5	10	20

Starting from a given quantity of MSW deposited in landfill and a breakdown note, you get the performance of biogas production over time.

The following assessment of the evolution of biogas production considering the two types of reaction: slow and fast.

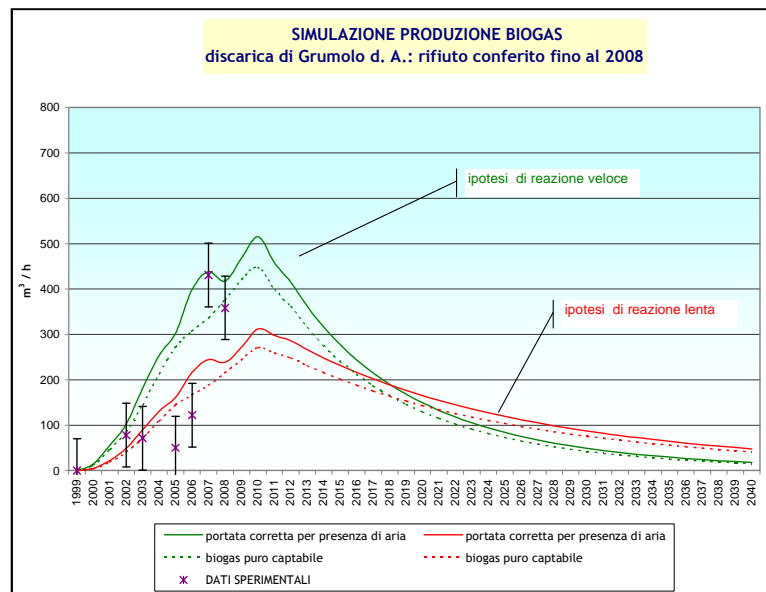


Fig. 4.5 – Trend of biogas production using the method Biogen 1.1.

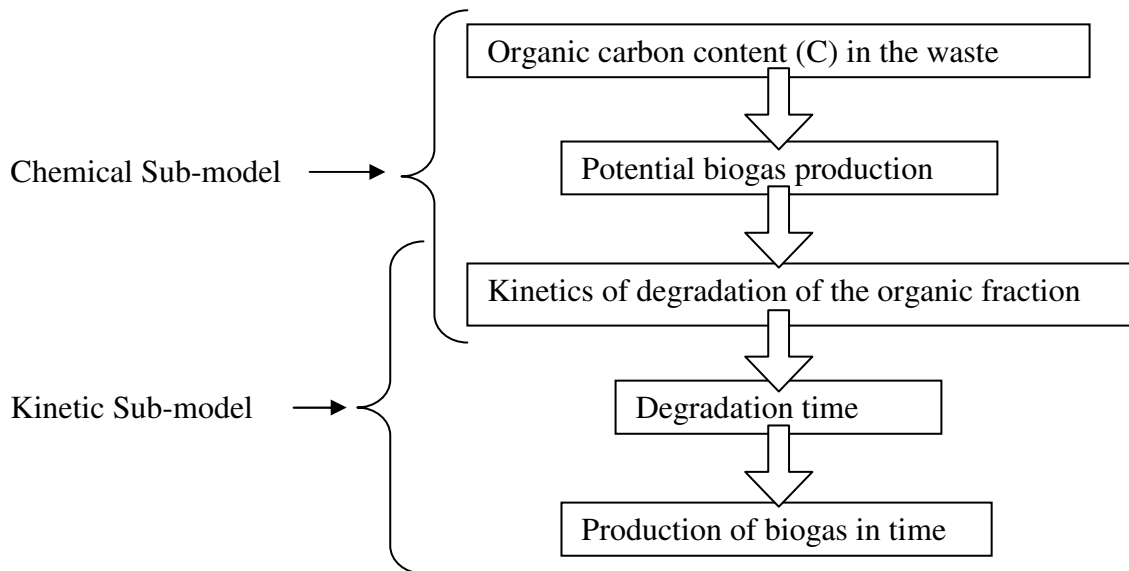
The slow reaction must be regarded as protective condition, in the sense that considers a duration of longer productive phenomenon, but with lower tips.

The biogas is considered to be broadcast on the basis of numerous experimental experiences in the bibliography, equal to 70% of the biogas produced by the landfill. The graph in Figure 4.5 shows the trend of the two curves obtained by considering the assumptions previously discussed:

- Green trend: hypothesis of fast reaction. Expresses the condition of more rapid biodegradation of the waste, i.e. shorter $t_{1/2}$;
- Red trend: slow reaction hypothesis. Expresses the condition of slow biodegradation of the waste, i.e. longer $t_{1/2}$.

4.4. IMAGE | Biogas production Model

The model used is composed of two sub-models: chemical and kinetic. The first, provides the maximum theoretical yield of biogas from the anaerobic degradation of the organic fraction, while the second, being a dynamic model, provides the rate of biogas production in time.



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This part of the model interprets the biodegradation of waste in a landfill, considering the amount of organic substrate that will be converted into biogas during the anaerobic degradation processes.

The landfill Grumolo d. A. during the operational phase, between 1999 - 2008, has stored a total of 449,326 tons of waste with an average of 52 664 t / y of MSW per year. Below is a breakdown by type of waste deposited in the landfill under study.

Tab. 4.10 – Merceological analysis of the MSW stored in landfill.

		Putres. fraction	Paper and cardboard	Plastic and rubber	Textile and leather	Wood	Glass and inert	Metals	Undersieve
1999	[%]	10,7	35,6	31,3	4,5	1,5	0,9	3,6	11,9
	[t]	2.035	6.772	5.954	856	285	171	685	2.264
2000	[%]	10,7	35,5	31,4	4,5	1,5	0,9	3,6	11,9
	[t]	2.787	9.246	8.178	1.172	391	234	938	3.099
2001	[%]	4,7	34,0	26,5	7,2	11,3	5,3	5,3	5,7
	[t]	2.266	16.394	12.777	3.472	5.448	2.555	2.555	2.748
2002	[%]	6,4	39,6	30,4	8,3	2,3	2,3	4,7	6,0
	[t]	3.194	19.762	15.171	4.142	1.148	1.148	2.346	2.994
2003	[%]	7,5	34,7	32,4	7,6	3,6	0,7	2,8	10,7
	[t]	3.950	18.274	17.063	4.002	1.896	369	1.475	5.635
2004	[%]	6,9	29,7	43,5	7,0	1,9	0,7	4,1	6,2
	[t]	3.634	15.641	22.909	3.686	1.001	369	2.159	3.265
2005	[%]	7,7	28,8	44,6	8,3	2,4	1,1	2,0	5,1
	[t]	4.055	15.167	23.488	4.371	1.264	579	1.053	2.686
2006	[%]	5,9	32,4	45,2	7,5	1,8	0,8	1,6	4,8
	[t]	3.107	17.063	23.804	3.950	948	421	843	2.528
2007	[%]	5,2	28,9	36,6	12,6	2,4	4,7	5,2	4,4
	[t]	2.739	15.220	19.275	6.636	1.264	2.475	2.739	2.317
2008	[%]	6,9	32,4	38,9	14,7	1,4	1,6	1,0	3,1
	[t]	2.955	13.873	16.657	6.294	599	685	428	1.327

For a total waste useful for the biogas production:

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Tab. 4.11 – Amount of LFG’s waste stored in landfill

Year	Amount of LFG waste [t]
1999 (da luglio)	19.022,00
2000	26.043,74
2001	48.216,20
2002	49.904,93
2003	52.664,00
2004	52.664,00
2005	52.664,00
2006	52.664,00
2007	52.664,00
2008 (for 9 month)	42.819,00
	449.326

Inflows are divided into 4 categories according to the degree of waste’s putrescence

- RVP: rapidly putrescibile fraction (putrescibile fraction + 1/3 underscreen);
- RMP: medium putrescibile fraction (paper, cardboard and wood + 1/3 underscreen);
- RLP: slowly putrescibile fraction (textile and leather + 1/3 underscreen);
- RNP: non putrescibile fraction. (plastic, rubber, glass, inert and metall).

Tab. 4.12 – Subdivision of waste stored in landfill according to their degree of putrescence.

Fraction of MSW stored		t	t/y
RVP	Putrescibile fraction	30.721	3.601
RMP	Paper and cardboard	147.412	17.278
	Wood	14.244	1.669
	Underscreen	28.864	3.383
RLP	Textile and leather	38.582	4.522
RNP	Plastic and rubber	165.276	19.371
	Glass and inert	9.007	1.056
	Metals	15.220	1.784
		449.326	52.664

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The criterion adopted for this distribution was to evaluate the quantity of organic carbon present in the waste and then the biodegradable fraction of the same. The annual quantities of waste entering the landfill are differentiated as follows:

Tab. 4.13 - Annual quantities of waste entering the landfill

Fraction of MSW stored	MSW [t/y]	MSW [%]
RVP	3.601	6,8%
RMP	22.330	42,2%
RLP	4.522	8,6%
RNP	22.211	42,2%
	52.664	100%

For the purposes of the implementation of the model, in the absence of direct experimental data for the various product fractions, reference is made to the average values of some significant parameters summarized in the table below.

Tab. 4.14 - Average values of some parameters related to different merceological components (Andreottola and Cossu, 1988, modified).

Fraction of MSW stored		RSU t/y	C [kgC/ kg dry]	f _b [kgC _b / kgC]	u [kgH ₂ O/ kg wet]	(1-u) [kgss/ kgtot]	p [kg _i / kgMSW]
RVP	Putrescibile fraction	3.600,72	0,48	0,80	0,60	0,40	0,07
RMP	Paper and cardboard	18.969,25	0,44	0,50	0,08	0,92	0,36
	Wood	3.361,02	0,50	0,50	0,20	0,80	0,06
RLP	Textile and leather	4.522,02	0,55	0,20	0,10	0,90	0,09
RNP	Plastic and rubber	19.371,44	0,7	0	0,02	0,98	0,37
	Glass and inert	1.055,69	0	0	0,03	0,97	0,02
	Metals	1.783,86	0	0	0,03	0,97	0,03
		52.664,00					

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where:

C_i = organic carbon content of the i -th component of the waste on a dry basis

[kgC/kg_{componente i}];

f_b = biodegradable fraction of organic carbon C_i [kgC_b/kgC];

u_i = water content of the i component [kgH₂O/ kg_{i_umido}];

p_i = wet weight of component i [kg_{i_umido}/kgRSU]

The stoichiometric model has the characteristic of being static, that is, does not describe the production of biogas in time, it is still used in order to predict the amount of biogas that is produced by a unit mass of substrate (ie of biodegradable waste) disposed in landfill.

It is based on the following reaction of anaerobic biodegradation, called biochemical model:

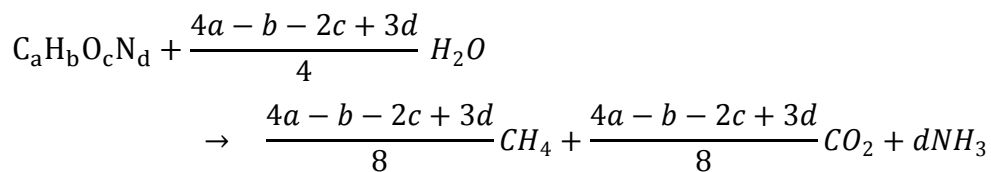


Where the term $C_aH_bO_cN_d$ represents the biodegradable fraction of the waste (ie the substrate) while $C_5H_7O_2N$ la biomass produced.

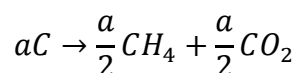
The biodegradable organic carbon is transformed during anaerobic degradation, methane (CH₄) and carbon dioxide (CO₂).

The substrate converted into biomass, whereas a residence time infinity, appears to be of the order of 4% (EMCON, 1980); In this regard it is convenient, for the purposes of the evaluation of the maximum theoretical yield of biogas produced by the landfill, neglecting the conversion of the substrate into biomass.

Balancing the reaction will determine the stoichiometric coefficients n , x , y , w , z as a function of the parameters a , b , c , d obtaining:



The relationship between carbon (C) and biogas (CH₄ + CO₂) is given by:



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Which shows that 1 mole of carbon is converted to 1 mole of biogas. Whereas the volume occupied by 1 mole of carbon, at temperature $T = 0^\circ \text{C}$ and at pressure $P = 1 \text{ atm}$ is:

$$PV = nRT \rightarrow V = \frac{nRT}{P} = \frac{1 \text{ mol} \cdot 8,205 \cdot 10^{-5} \frac{\text{m}^3 \text{ atm}}{\text{mol K}} \cdot 273 \text{ K}}{1 \text{ atm}} = 0,0224 \text{ m}^3$$

$$= 22,4 \text{ l}$$

$$1 \text{ mol C (content in the substrate)} = 22,4 \text{ l gas (CH}_4 + \text{CO}_2)$$

In terms of mass:

$$1 \text{ g C (content in the substrate)} = 1,87 \text{ l gas (CH}_4 + \text{CO}_2)$$

The substrate for the microorganisms, as mentioned above, is represented by biodegradable organic carbon (C_{ob}), the same, constitutes the initial data input of the model adopted.

The biodegradable organic carbon (C_{ob}) (potentially biogassificabile) is given for each component of the rejection, by the expression:

$$(C_{ob})_i = C_i \cdot f_s \cdot (1 - u_i) \cdot p_i \quad [\text{kg C}_b/\text{kg RSU}]$$

The amount of organic carbon that actually gasifies however, is only a fraction of the biodegradable organic carbon (C_{ob}), this is because, some of the carbon is used by the bacterial population for cell synthesis.

The quantity of organic carbon actually biogassificabile is calculated by the multiplication factor dependent on the temperature according to the equation Tabasaran (1981):

$$(C_{oeb})_i = (C_{ob})_i \cdot (0,014 T + 0,28) \quad [\text{kg C}_b/\text{kg RSU}]$$

In which the temperature was considered to be of 38°C .

The values of the individual waste fractions are listed in the table below.

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Tab. 4.15 – Values of organic carbon biogassificabile (C_{ob}) and actually biogassificabile (C_{oeb}) for the respective fraction of stored waste.

Fraction of MSW stored		RSU t/y	P [kgi/kgMSW]	C _{ob} [kg C _b /kg MSW]	C _{oeb} [kg C _b /kg MSW]
RVP	Putrescibile fraction	3.600,72	0,07	0,011	0,009
RMP	Paper and cardboard	18.969,25	0,36	0,073	0,063
	Wood	3.361,02	0,06	0,013	0,011
RLP	Textile and leather	4.522,02	0,09	0,009	0,007
RNP	Plastic and rubber	19.371,44	0,37	0	0
	Glass and inert	1.055,69	0,02	0	0
	Metals	1.783,86	0,03	0	0
		52.664,00		0,105	0,091

The total organic carbon, and organic carbon actually biogassificabile total:

$$C_{ob} = \sum(C_{ob})_i = 0,105 \quad [\text{kg } C_b/\text{kg RSU}]$$

$$C_{oeb} = \sum(C_{oeb})_i = 0,091 \quad [\text{kg } C_b/\text{kg RSU}]$$

The stoichiometric model used to estimate the production of biogas through the formulation

$$y_{biogas} = 1,867 \cdot C_{oeb} \quad [\text{m}^3/\text{kg RSU}]$$

therefore, the biogas produced by the storage of 52,664 t / year of waste is:

Tab. 4.16 – Biogas produced for each fraction of stored waste

Fraction of MSW stored	y _{biogas} [m ³ /t MSW]	y _{biogas} [%]
RVP	17,05	10%
RMP	139,05	82%
RLP	13,80	8%
	169,90	

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With a production of biogas per ton of waste in the landfill of about 170 m³ / t MSW Through the kinetic model is made a prediction of biogas production over time, being, as a dynamic model mentioned above.

To assess the expected production of biogas from the landfill, is applied a mathematical model that simulates the activity of degradation of the substrate carried by the bacteria based on a first order kinetics, for which the rate of degradation is proportional to the residual substrate (in this way other factors such as moisture and nutrient availability are not considered as limiting.)

$$\frac{d(C_{og})_i}{(C_{oeb})_i - (C_{og})_i} = k_i dt$$

where:

$(C_{og})_i$ = organic carbon from the gasified component at time t [kgC/kgMSW wet];

$(C_{oeb})_i$ = amount of organic carbon effectively biogasifiable of [kgC/kgMSWwet];

k_i = biodegradation constant of the i-th component [anni⁻¹];

t = time [years].

As done previously, the components of the waste entering the landfill, were divided into 3 categories according to the degree of putrescibility: fast, medium and slow putrescible.

Tab. 4.17 – Annual quantities of MSW subdivide in the three different categories according to the putrescibility degree.

Fraction of MSW stored	MSW t/y
RVP	3.600,72
RMP	22.330,28
RLP	4.522,02
	30.453,01

The amount of waste in landfills considered for the production of biogas turns out to be about 58% of all waste placed; This is because, as can be seen from the Table 4.15 the putrescible fraction, irrelevant to the production of biogas, is 22.211 t/y.

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RNP

$$52.664 - \overbrace{(19.371,44 + 1.055,69 + 1.783,86)} = 52.664 - 22.211 = 30.453 \text{ t/year}$$

Each of the fractions is characterized by a different value of the rate of generation "k"; this coefficient expresses the velocity of biogas production from the mass of waste to landfill: the higher is the value assumed by k, the more quickly it will reach the maximum of biogas production in time and, in the same way, much more rapidly that production will begin to decline.

For the calculation of k will be used to the following empirical relationship:

$$k = \frac{\ln 2}{t_{50}} \quad [\text{years}^{-1}]$$

where t_{50} is the time required to reduce by 50% the biodegradable organic substance.

Through literature data (Damiano et al., Gestione del biogas da discariche controllate) for the coefficients k_i of the individual organic fractions of different degradability can take the following values of the time t_{50} :

Tab. 4.18 – Values of half-life t_{50} and biodegradation constant k for each fraction of incoming waste.

Fraction of MSW stored	t_{50} [y]	k_i [1/y]
RVP	1	0,693
RMP	4	0,173
RLP	10	0,069

The coefficient of the reaction is in fact influenced by: humidity, size and density of the waste; for these reasons the effective biodegradation constant of the i-th component is considered:

$$k_{ie} = \alpha_i \cdot \beta_i \cdot k_i \quad [\text{anni}^{-1}]$$

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- Humidity:

The moisture content of the waste at the time of deposit in the controlled waste depends on the composition of the waste, the weather conditions and the techniques of collection or pre-treatment.

It turns out that kitchen waste and garden ones have the highest moisture content, while paper and paperboard have values much lower. Most of the moisture found in the fractions cellulosic derived from absorption of water from the other components of the mixture of waste, during the process of formation of solid waste. The function of moisture in the process of methanogenesis is threefold:

- allow the activity of micro-organisms;
- creation of a solid-liquid interface;
optimal distribution in the cluster of microorganisms and nutrients in the substrate hydrolyzate..

During fermentation, has a high consumption of water until almost completely deplete the availability and therefore severely inhibit the anaerobic fermentation of waste; if an area of the landfill is put into operation in the dry season and completed in short times, there is the real possibility that the humidity of the waste is not sufficient for a complete development of the phenomenon of production of biogas.

Several experiences, laboratory and field, showed a significant increase in biogas production with increasing humidity.

At the time of landfilling the waste normally found in unsaturated conditions, and are therefore able to absorb water to reach saturation capillary, beyond which there is the formation of leachate.

The parameters

$$\alpha_i = \frac{(u)_i}{(u_s)_i} \quad \beta_i = \frac{(SR)_i}{(SR_{max})_i}$$

take into account humidity and density respectively. Considering:

- $(u)_i$ = effective moisture of the waste;
- $(u_s)_i$ = humidity of capillary saturation;

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- $(SR)_i$ = reactive surface of the component under actual storage conditions [m^2];
- $(SR_{max})_i$ = maximum reactive surface of the component [m^2].

The value of the coefficient β_i , determined during calibration of the model, varies between 0 and 1.

The table below shows the values of the calculated parameters.

Tab. 4.19 – Values of the parameters useful for the implementation of the model

Fraction of MSW stored	MSW t/y	C_{oeb} [kgC/kgMSW]	t_{50} [y]	k_i [1/y]	α_i	β_i	k_{ie} [1/y]
RVP	3.600,72	0,009	1	0,693	0,820	0,930	0,529
RMP	22.330,28	0,074	4	0,173	0,790	0,940	0,129
RLP	4.522,02	0,007	10	0,069	0,770	0,790	0,042

The analysis of biogas production is being conducted since 1999, the year of commencement of the landfill activities until 2038; in 2008, after 9 years of operation, post operative phase begins.

The specific production of biogas, supposed consists of only methane and carbon dioxide, is $1,87 m^3/kg$ of biogassificabile carbon.

The cumulative production of biogas, G_t ($m^3/tRSU$) is obtained by summing the contributions for the three organic fractions:

$$G_t = \sum_{i=1}^3 1,87 \cdot (C_{oeb})_i \cdot (1 - e^{-k_{ie} \cdot t}) \quad [m^3_{biogas} / tMSW]$$

The specific production of biogas in time, is estimated using the derivative of the cumulated production of biogas in time through the following expression:

$$g = \frac{dG_t}{dt} = \sum_{i=1}^3 1,87 \cdot (C_{oeb})_i \cdot k_{ie} \cdot e^{-k_{ie} \cdot t} \quad [m^3_{biogas} / tRSU \cdot anno]$$

Useful in order to predict the annual production of biogas.

BIOGAS PRODUCTION PREDICTIVE MODELS

$$B(t) = \sum_{i=1}^3 \sum_{t=0}^{31} g_{i,t} d_t \quad [m^3_{biogas}/ year]$$

For which:

- $g_{i,t}$ is specific biogas production of the i -th component at time t ;
- d_t is annual deposition: i.e. 52664 t/y.

Di seguito viene riportato l'andamento della portata di biogas nel tempo.

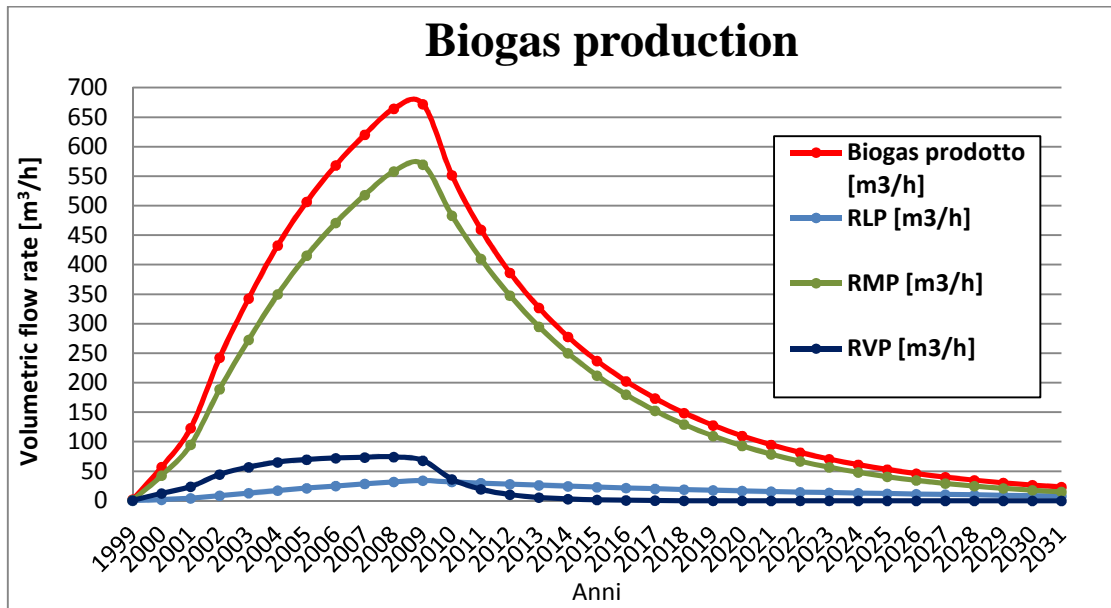


Fig. 4.6 – Annual production of biogas for each category of waste

As can be seen, the fraction of MSW that contributes most relevant to the production of biogas is the average biodegradable component (RMP), with a peak of about 570 m³/h. The village quickly putrescible (RVP) is assimilated by the bacteria in a short time, so that, after 2009, the production of biogas supplied by such fraction is almost nothing. The trend estimate of the total annual production of biogas, obtained by adding the three components of refusal, evaluates a maximum production of about 672 m³/h.

4.5. Predictive biogas models comparison

In order to compare the values of the flow rates of biogas obtained through the predictive models used, is bringing in the following graph the results. The chart shows that: the model BIO-4, in the "best case", shows a peak production of biogas in the order of 502 m³/h, the value increased by 35% ie 678 m³ / h in the experimental phase. The models BIOgen 1.1 and IMAGE confirm this prediction, respectively, with a production of about 678 m³/h and 672 m³/h less than a time shift.

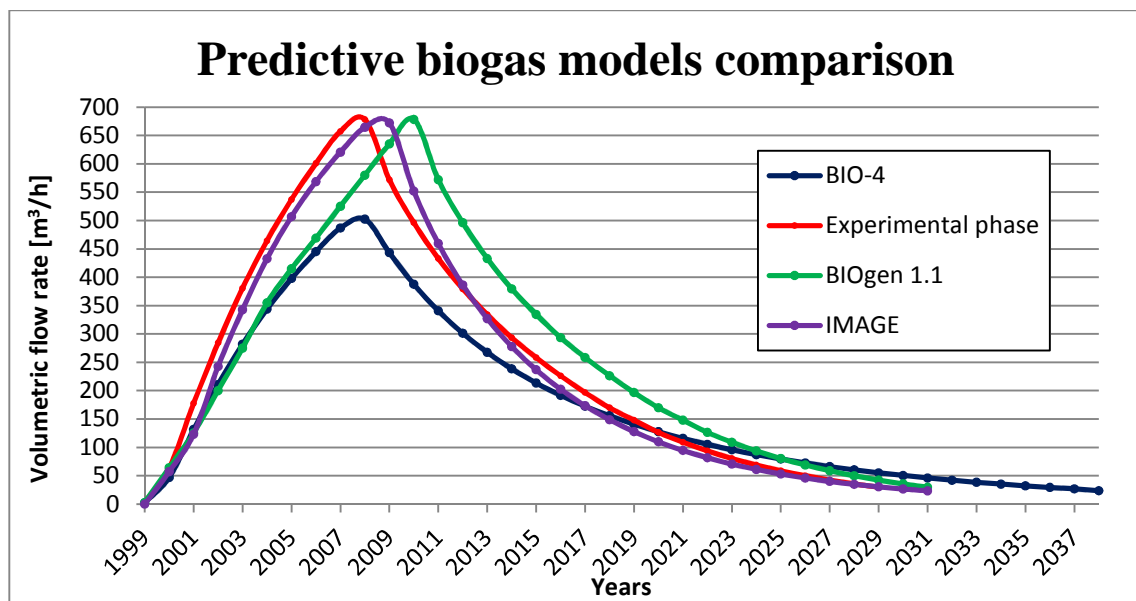


Fig. 4.7 – Evolution of production of biogas for different models adopted

Chapter 5

Characteristics of biogas plant

In this chapter will be provided the technical description of the works that make up the network of uptake and transport of biogas related to the surface of the landfill.

5.1. Extraction system and biogas convey description

1. Biogas extraction section, consists of:

- The plant for the capture and recovery consists of three different sections:
wells for the extraction of biogas drilled in the mass of waste, that is made after the completion of each sector of the landfill and the laying of the mineral layer of the cover (temporary top cover). Particular importance should be given to the wellhead as the constituent element of connection between the vertical shaft and the secondary line of transport of biogas.



Fig. 5.1 – Pozzo di captazione verticale collegato alla linea secondaria

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- Biogas transport network, consisting of: lines throughout the collection wells and the “principals of management” (located on the main collector), these transmission lines have parallel configuration ie to each well corresponds to a line to “principals of management”; while, the primary lines connecting the “principals of management” to the central extraction.

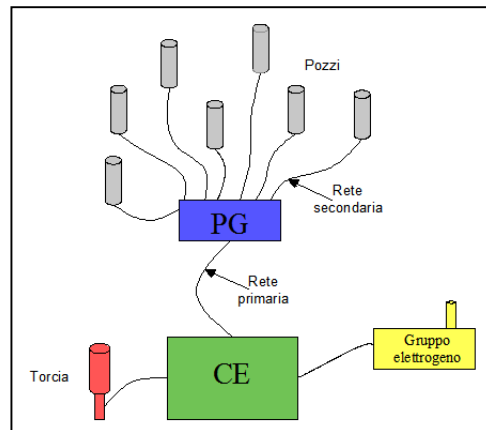


Fig. 5.2 – Wiring diagram of the biogas plant

- “principals of management”, whose objective is the simplifying the tasks of network management. For each “principals of management” are connected the terminals of biogas transmission lines, are located the condensate traps and the control valves through which is possible to share the depression.



Fig. 5.3 – “principals of management”,

CHARACTERISTIC OF BIOGAS PLANT

2. Aspiration section, consist of:

- Extraction plant (CE), consisting of multistage centrifugal fans that allow to suck the biogas from the landfill through the primary lines connected to the “principals of management” and compress it to send it to generator sets;

3. Producing Energy section, consist of:

- Generator sets;
- Equipment transformation and elevation that transform the voltage of electricity produced from low to medium to connect to the electricity grid;
- Emergency torch and "vent" at high temperature.



Fig. 5.4 – High temperature emergency torch

Any surplus production of gas are conveyed in the torch of high-temperature combustion or used as an emergency system in the event of arrest of the generator. Another use of the torch is to burn the biogas at low methane content as not usable for the purpose of energy recovery.

The following figure shows the network diagram for the capture and transport of biogas.

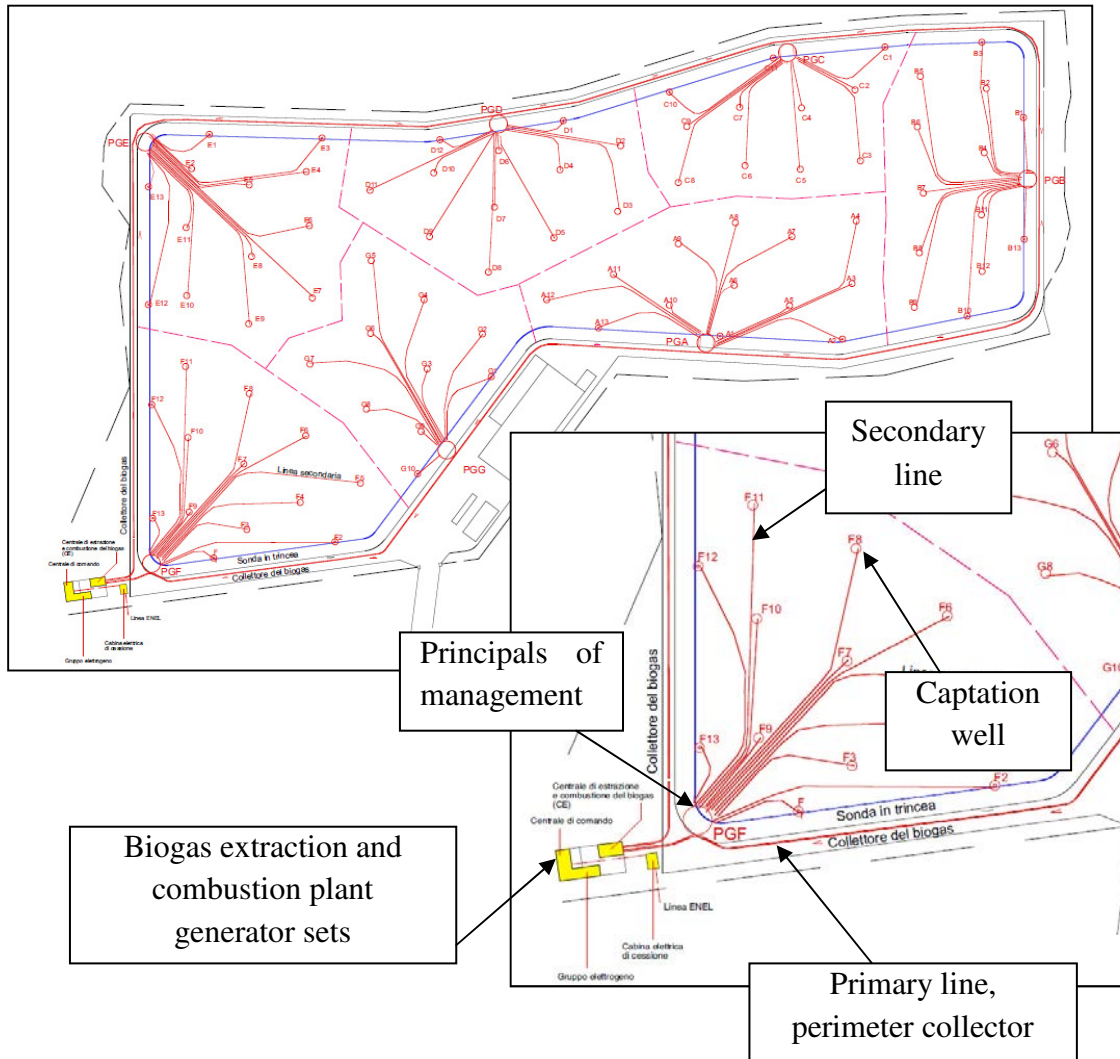


Fig. 5.5 – Biogas capture and transport schema

5.2. Radius of Influence and extraction wells' number

The experimental phase, in the manner of storage of the waste described in section 4.2, has allowed us to evaluate the radius of influence useful in order to ensure, as far as possible, that the biogas produced is conveyed by force and not be lost by diffusion to the upper layers.

The analysis of depression applied to the two tanks has allowed us to estimate the value of the radius of influence of the collection wells equal to 20m.

CHARACTERISTIC OF BIOGAS PLANT

Tab. 5.1 – Average values of the depressions applied to the wells for the two modes of storage waste

Average values of the depressions applied to the wells							
Sector1: storage waste “loose”				Vasca 2: storage waste “packed”			
Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8
[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]
6,21	5,99	5,2	5,4	3,57	3,48	3,37	2,85

The entire surface of the landfill is equipped with 84 elements of collection. The following is the outline of the arrangement of the collection wells and its radius of influence.

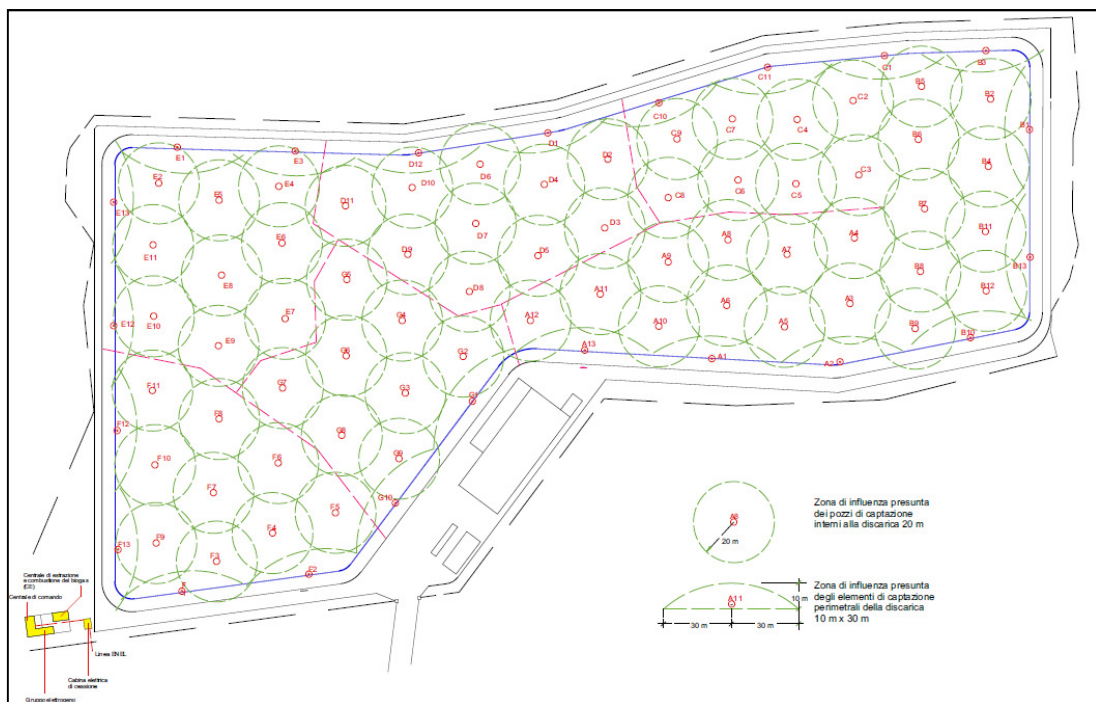


Fig. 5.6 – Schematic layout of the 84 collection wells elements and its radius of influence.

Chapter 6

Biogas diffusion in passive conditions

The biogas generated as a result of the decomposition of waste in the landfill, ideally, should be fully collected by the network of collection; in this way it should be to avoid a multiplicity of adverse effects such as: the migration of gases through the more superficial layers of the soil, the escape into the atmosphere with repercussions on the vegetation adjacent the landfill and the diffusion of odors.

In reality, the efficiency of a system of aspiration of the biogas is not 100%, but oscillates on values that vary in the range of 23% ÷ 56%, with average values of approximately 40% (A. Esposito, 1984) . This assumption implies that a percentage of the biogas produced is not picked up, remaining within the waste mass and then circulated within the drainage layer of biogas required by law.

Both during the landfill operating phase that in the post operative, extraction system appears to be working. During this period, may be necessary operations that require a temporary disconnection of collection wells to extraction system, such as the implementation of the final top cover normally realized by sectors. As can be seen from Figure 6.1. the mineral layer compromise by settling needs to be restored, for these maintenance operations it is necessary a localized biogas wells disconnection neighboring areas of processing.

BIOGAS DIFFUSION IN PASSIVE CONDITION



Fig. 6.1 – Collection wells unplugged for restoring the mineral layer deteriorated

By the following images is known as, during the phase of installation of the waterproof sheet (green) and the drainage layer in the geocomposite (white) on top of the layer mineral in its final configuration, a loss of the connection between the vertical shaft and the secondary line for the collection of biogas.



Fig. 6.2 – Disconnection between the vertical shaft and the secondary line

CHAPTER 6

In the passivity condition of the collection system, the biogas need to be collected within the drainage layer; This layer should be designed with adequate permeability so that the entire flow of biogas produced can diffuse through it without giving rise to excessive pressure.

6.1. Purpose of the biogas drainage layer

The D.Lgs 36/2003 not provides, if not for the minimum thickness of 50cm, particular elements of detail aimed at the design of the drainage layer of biogas as: the type of material, the particle size of the porous medium or the hydraulic conductivity necessary to an adequate gas diffusion.

The purpose of the drainage layer is to convey the biogas towards the collection wells. If the permeability of this layer does not ensure an adequate spread of biogas overpressure are generated, with consequent negative effects on the stability of the overlying impermeable layer: excessive pressure can reduce the stabilizer normal load on the same area by introducing stability problems.

A possible break of the waterproof layer of coverage would favor the passage of meteoric water within the mass of waste, doing so would be to promote not only a greater production of leachate but, because the generation of biogas depends strongly on the quantity of moisture of refusal itself, there would be an increase in the rate of production causing further subsidence.

It is necessary that the permeability of the material forming the drainage layer is such as to allow adequate diffusion of biogas excluding the possibility of increases in interstitial pressures.

6.2. Biogas dynamic inside the drainage layer

Initially, the biogas produced from the degradation of MSW, it expands within the mass of waste and, assuming that the extraction wells are passive (ie collection system off), diffuses into the drainage layer in the ways that offer lower resistance.

BIOGAS DIFFUSION IN PASSIVE CONDITION

Within the landfill, the factors that influence the migration of biogas are:

- Characteristics of the biogas: concentration gradient, fluid viscosity, pressure gradient;
- Construction techniques and management: waste compaction, real porosity, presence of daily and final cover layers, presence of waterproof sheets on the walls and bottom.

The gas flow inside the porous medium can be compared to the flow of a liquid in laminar condition; this consideration allows the use of Darcy's law which rewritten in terms of the pressure gradient becomes:

$$Q_{b_x} = k_w \cdot A \cdot \left(\frac{dh}{dx} \right) \rightarrow Q_{b_x} = k_g \cdot A \cdot \frac{1}{\gamma_g} \cdot \left(\frac{du_g}{dx} \right) \left[\frac{m^3}{s} \right]$$

The term du_g/dx , is the pressure gradient, it's the driving force that allows gas to move, along the path of the x coordinate, from areas of high pressure towards areas of low pressure within the drainage layer overcoming the resistance from the material forming the same layer.

Pressure differences that can set in motion the biogas occur both within the drainage layer within which the mass of waste as a result of:

- higher concentration of organic matter in decomposition;
- higher density of stored waste;
- increased water content.

On the other hand zones occur at low pressure in the presence of the opening of trenches, drainage and suction systems.

Chapter 7

Biogas drainage layer design

As mentioned in section 6.1, it is necessary to design the drainage layer of biogas with a permeability to allow proper diffusion of biogas excluding the possibility of giving rise to overpressure.

The following describes the steps necessary in order to size the drainage layer of biogas:

1. Estimates of the maximum flow of biogas generated from the degradation of the waste, ie biogas production unit of time on the whole surface of the landfill (Section 7.1);
2. Through the slope stability analysis, the factor of safety (FS) is evaluate, which is a function of the pressure generated by biogas (Section 8.2);
3. Determination of the biogas conductivity value;
4. Evaluation of the hydraulic permeability starting from the value of the biogas permeability.

7.1. Estimation of Biogas flux emissions released by MSW

In order to size the drainage layer is convenient to consider the volume of biogas diffuses in a square meter of surface drainage (A_i) i.e. the flow of biogas.

In the following section evaluates, through the use of two methods, the flow of biogas (Φ_g) generated by the degradation of the underlying MSW and consequently diffused within the drainage layer (Figure 7.1.).

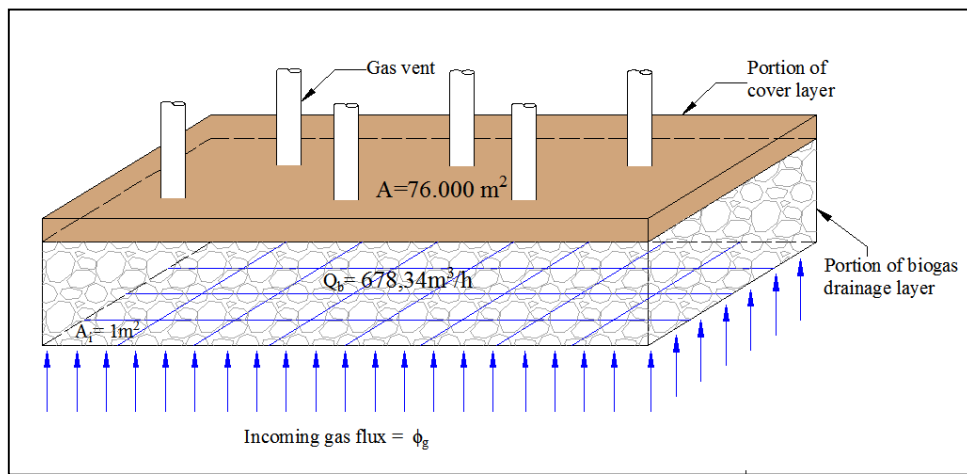


Fig. 7.1. - Schematization of the biogas drainage layer

- A. This method involves the use of predictive models that allow to determine the extent of biogas (Q_b) generated by the degradation of MSW in time. The biogas flow is then estimated as the ratio between the said flow of biogas and the surface coverage of the landfill:

$$\Phi_g = \frac{Q_b}{A} \left[\frac{m^3}{m^2 \cdot y} \right]$$

where,

Q_b = biogas flow rate [m^3/y];

A = landfill surface [m^2].

B. This method involves the use of experimental formulas. Known, the average thickness of the layer of waste and the specific weight of the same, the biogas flow is obtained through the following relation:

$$\Phi_g = r_g \cdot \frac{V_{waste}}{A_{cover}} \cdot \gamma_{waste} = r_g \cdot \bar{H}_{waste} \cdot \gamma_{waste} \quad \left[\frac{m^3}{s \cdot m^2} \right]$$

Where,

Φ_g = biogas flux [$m^3/s \cdot m^2$];

r_g = biogas generation rate [$m^3/kg \cdot y$];

\bar{H}_{waste} = average height of the waste [m];

γ_{waste} = unit weight of waste [kg/m^3].

7.1.1. Predictive model analysis

In chapter 3 have been described models used in order to predict the amount of biogas produced from the degradation of the waste; with the experimental phase was assessed an hourly production of 678,34 m^3/h , value confirmed by the models Biogen 1.1 and IMAGE.

Analyzing figure 7.1., Schematizing a portion of the drainage layer, within which there are fixtures the collection wells, for a covering surface of the landfill (A) of about 76.000 m^2 , the biogas flow is equal to :

$$\Phi_g = \frac{Q_b}{A} = \frac{678,34 \left[\frac{m^3}{h} \right]}{76.000 [m^2]} = 78,2 \frac{m^3}{y \cdot m^2}$$

Which indicates that, within the layer of biogas is conveyed a flow rate of 678,34 m^3/h then, for each square meter of coverage (represented in Figure 7.1. from two blue lines), the flow of biogas is around 78,2 m^3/y .

Given an average height of the waste stored and a unit weight of waste, respectively:

$\bar{H}_{waste} = 11m$ e $\gamma_{waste} = 800 \frac{kg}{m^3}$ the biogas production rate is around: order:

$$r_g = \frac{\Phi_g}{\bar{H}_{waste} \cdot \gamma_{waste}} = 8,9 \cdot 10^{-3} \frac{m^3}{kg \cdot y}$$

BIOGAS DRAINAGE LAYER DESIGN

Which indicates that annually, the degradation of one kilogram of MSW produces $8,9 \cdot 10^{-3} \text{ m}^3$ of biogas.

7.1.2. Experimental formula analysis

Studies carried out by Thiel (1998) on MSW closed landfill of the northwestern United States have allowed to estimate the biogas generation rate of:

$$r_g = 6,24 \cdot 10^{-3} \left[\frac{\text{m}^3}{\text{kg} \cdot \text{y}} \right]$$

This parameter, measured at atmospheric pressure and room temperature, indicates that the volume of $6,24 \cdot 10^{-3} \text{ m}^3$ of biogas is generated in a year by one kilogram of waste. The flow of the biogas produced is determined as follows:

$$\Phi_g = r_g \cdot \bar{H}_{\text{waste}} \cdot \gamma_{\text{waste}} = 6,24 \cdot 10^{-3} \frac{\text{m}^3}{\text{kg} \cdot \text{y}} \cdot 11\text{m} \cdot 800 \frac{\text{kg}}{\text{m}^3} = 55 \frac{\text{m}^3}{\text{y} \cdot \text{m}^2}$$

That is, a flow rate of $55 \text{ m}^3/\text{y}$ for every square meter of covered area.

7.1.3. Evaluation results

By comparing the values obtained by the two methods adopted both the flow rate of the respective biogas production, the following assessments are made:

Tab. 7.1. – Confronto dei risultati di flusso e tasso di biogas prodotto ottenuti attraverso l'applicazione delle due metodologie

	Analysis based on:	
	Predictive models	Experimental formula
Biogas flux (Φ_g)	78,2 m ³ /y·m ²	55 m ³ /y·m ²
Biogas generation rate (r_g)	8,9·10 ⁻³ m ³ /kg·y	6,24·10 ⁻³ m ³ /kg·y
	+ 42% with respect the experimental formula	

CHAPTER 7

In the absence of an experimental phase which allows to evaluate in situ the rate of biogas produced, we propose a production ratio of $6,24 \cdot 10^{-3} \text{m}^3/\text{kg} \cdot \text{y}$.

This parameter is strongly influenced by factors such as the composition of the waste, compaction, moisture, temperature; as well as the design of the landfill and its management. This parameter cannot be generalized to different realities than that for which it has been assessed; is unreliable relates a value obtained for landfill site in the northwestern part of the United States with the corresponding value measured experimentally in a landfill located in an Italian site.

To which, the value of biogas flux that better approximates the reality of Grumolo landfill is $\phi_b=78,2 \text{m}^3/\text{y} \cdot \text{m}^2$, for two reasons: either because it has been obtained starting from an actual flow values of biogas (i.e. $678 \text{m}^3/\text{h}$), and because, being between the two the greater, it is preferable to opt for his choice as a precautionary measure.

7.2. Estimation of biogas discharge diffused in the drainage layer

Derived the value of the biogas flow you want to evaluate the trend of the flow rate of biogas within the same layer.

In reference to Figure 7.3. for a specific position x between two consecutive collection wells placed at a distance $D = 20\text{m}$ and, considering for simplicity that the drainage layer has unitary width, the volume of gas (Q_{b_x}) is written in terms of flow of gas transported through the drainage layer:

$$Q_{b_x} = \Phi_g \cdot A = \Phi_g \cdot (L - x) \cdot 1 \quad \left[\frac{\text{m}^3}{\text{s}} \right]$$

In the above equation, instead of considering the distance D , we consider the semi-distance $L = D / 2 = 10\text{m}$ assuming that the diffusion of biogas is symmetric with respect to the centerline; this formula allows to derive the following values of the biogas flow:

BIOGAS DRAINAGE LAYER DESIGN

Tab. 7.2. – Valori della portata di biogas ad una determinata distanza x

Relative distance x [m]	Biogas flow rate at a distance x	
	$Q_{b,x}$ [m ³ /s]	$Q_{b,x}$ [m ³ /y]
0	2,48E-05	781,88
1	2,23E-05	703,69
2	1,98E-05	625,50
3	1,74E-05	547,31
4	1,49E-05	469,13
5	1,24E-05	390,94
6	9,92E-06	312,75
7	7,44E-06	234,56
8	4,96E-06	156,38
9	2,48E-06	78,19
10	0	0

These values are represented in the following graph depicting the distribution of the flow of biogas ($Q_{b,x}$) in function of the distance x.

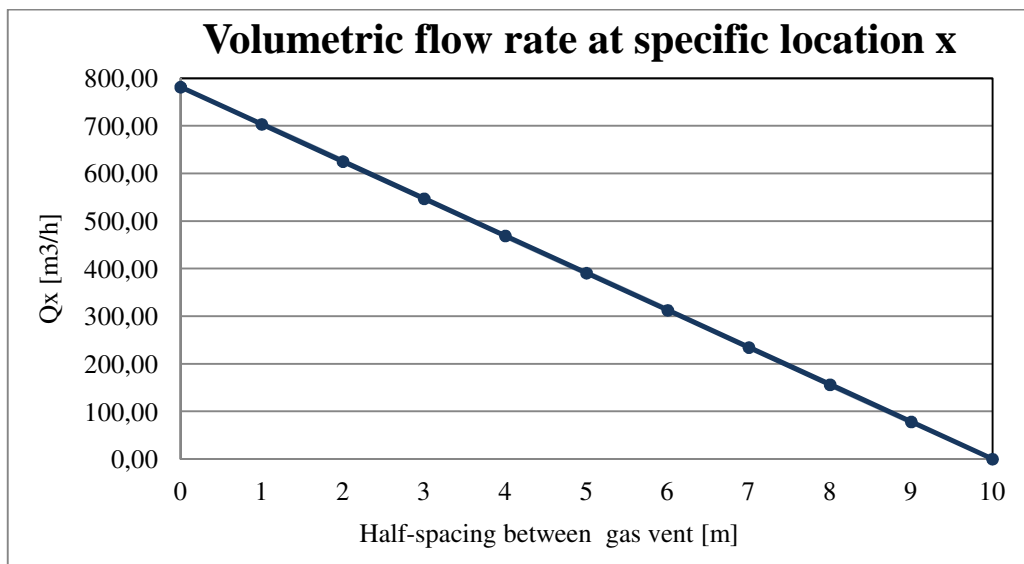


Fig. 7.2. – Volumetric flow rate ($Q_{b,x}$) at a specific position x

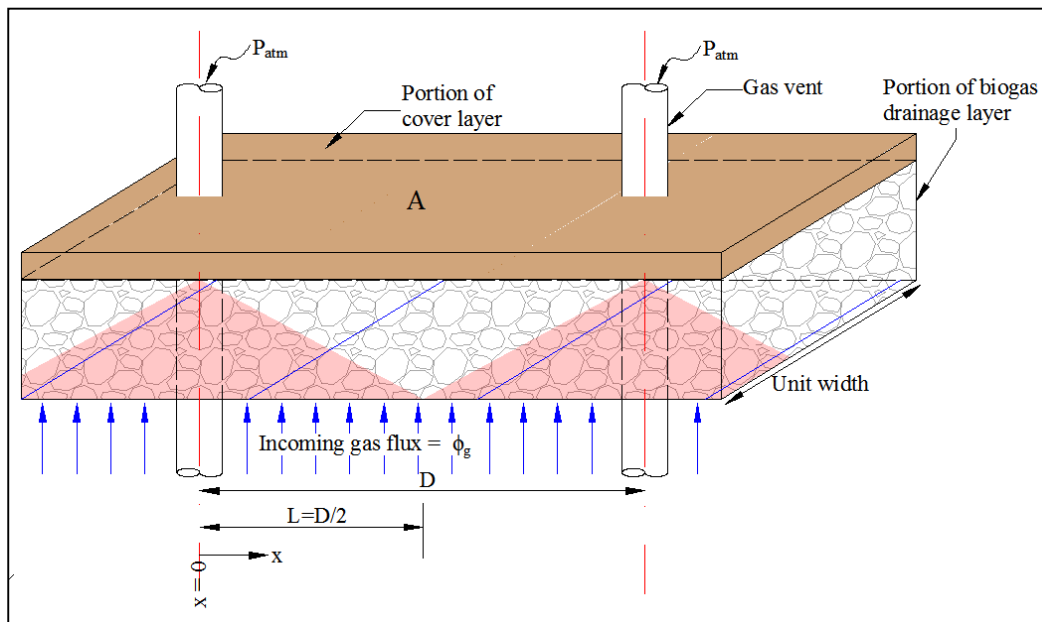


Fig. 7.3. – Distribution of the biogas flow within the drainage layer

As can be seen from the graph shown in Figure 7.2, the trend of the flow of biogas within the drainage layer varies linearly from a maximum value for $x = 0$ to a null value for $x = L$.

- $x = 0 \rightarrow Q_{b_x} = Q_{b_{max}}$;
- $x = L \rightarrow Q_{b_x} = 0$

Chapter 8

Cover system stability analysis | biogas pressure driving effects

As mentioned, the stability of the final cover system of MSW landfill may be compromised due to the overpressure induced by the biogas into the drainage layer. The study of the behavior of the cover system provides for the adoption of models based on the slope stability analysis of limit equilibrium. The method is based on a comparison of resistant forces and driving forces and the establishment of a factor of safety given by their relationship.

As the case in a slip plane, the limit equilibrium analysis can be carried out by adopting the simplifications of the infinite slope.

8.1. Criteria to evaluate final cover's stability

The limit equilibrium method assumed for the soil a rigid perfectly plastic behavior. One imagines that is that the soil is not deformed until the failure condition, and that, in conditions of failure, the shear resistance is constant and independent of the deformations accumulated.

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From this hypothesis, strongly simplifying, it follows that:

- the failure occurs along the interface between the moving mass and the stable layer;
- the moving mass is an undeformed block with a rigid roto-translation movement;
- mobilized resistance along the sliding surface in conditions of equilibrium limit is constant in time, independent of the deformations and then by the movements of the landslide, and everywhere equal to the shear strength;
- is not possible to determine neither the deformation preceding the break, nor the extent of the movements of the block in landslide, nor the speed of the phenomenon.

The easiest and most versatile way to analyze stability conditions is to adopt the infinite slope scheme.

The conditions which must be observed for this hypothesis to be valid are:

- the sliding surface must be sub-parallel to the plane countryside;
- the mass potentially unstable should have a length much greater than the thickness, and therefore it is assumed as infinite;
- is neglected the contribution of the resistance mobilized in the endings of the head and of the foot (because the level surface of breakage is assumed as infinite);
- the mechanical characteristics and the hydraulic conditions are constant along the entire section of interest.

It is assumed, as a simplifying assumption and cautionary, as well as very often realistic, zero cohesion.

The analysis is shown schematically through the following criteria:

1. select the potential failure surface: in the case in question, this surface is defined by the interface of biogas drainage layer and the layer immediately above i.e. of compacted material, as shown in Figure 8.1;

COVER SYSTEM STABILITY ANALYSIS | BIOGAS PRESSURE DRIVING EFFECTS

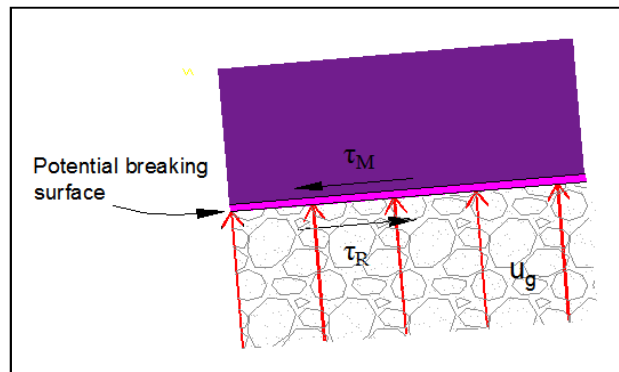


Fig. 8.1. – potential failure surface between the biogas drainage layer and the compacted mineral layer

The shear stresses that develop in the interface between the two layers are resistant (τ_R) opposite to the direction of motion and mobilizing (τ_M) in the direction of motion.

2. Is use the Mohr – Coulomb criterion. The resistance of a material is defined by the last stress that it can endure before get the "break".

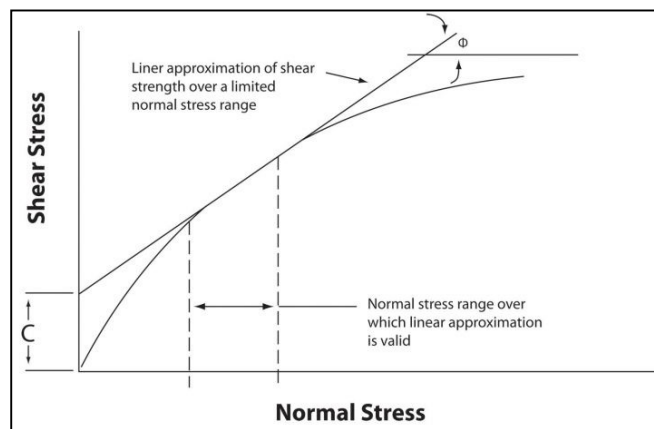


Fig. 8.2 – Criterio di rottura di Mohr - Coulomb

This criterion states that the strength of the material increases linearly with the effective normal stress (σ') and that the material comes to failure when the Mohr circle touches the envelope of the efforts expressed by:

$$\tau_R = c' + \sigma' \tan \phi' \quad [Pa]$$

where:

τ_R = resistant shear stress, opposite to the direction of motion [Pa];

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c' = material cohesion, intercept of the line limit [Pa];

φ' = internal friction angle, slope of the line limit [°];

$\tan\varphi'$ = internal friction coefficient [°];

σ' = effective normal stress, linked to the solid matrix [Pa].

The shear strength (τ_R) on the interface can be reduced by the pore pressure (u), this is because, these pressures reduce the effective normal force acting at the interface. This means that the presence of a pressurized fluid, liquid or gaseous, within the porous matrix, it can lead to destabilization of the final cover. It is necessary to establish an interaction law between the phases, i.e. between the two continuous solid and fluid occupying the same volume of soil; this law is described by the principle of effective stress (Terzaghi K., 1923):

$$\sigma' = \sigma - u \quad [\text{Pa}]$$

For which the difference is an increase compared to the neutral pressure (or pore pressure) and is based exclusively on the solid phase of the soil; this fraction of the total tension (σ) is defined as the effective stress (σ').

The pore pressure (u) derives from the presence of biogas within the porous medium.

3. The value of the factor of safety is determined. This value is derived from the ratio between the resisting forces, in opposition to the sliding of the mass placed on the inclined plane and the driving forces in the sense of motion:

$$FS = \frac{\text{resisting forces}}{\text{driving forces}} = \frac{\tau_R \cdot A}{\tau_M \cdot A} \quad [/]$$

The analysis of this factor will allow to assess the degree of stability of the cover layer.

8.2. Factor of safety definition and evaluation

The limit equilibrium methodology provides to calculate, along a specified failure surface, the relationship between the resisting forces and the driving one i.e. the factor of safety (FS).

Once evaluated the FS surface assumed, it is necessary to analyze other failure surfaces (kinematically possible) until find the one with the lower factor of safety, that area is considered as the potential failure surface.

As mentioned above, this failure surface is represented by the interface between biogas layer and the layer immediately above.

In order to assess the degree of stability of the cover surface, the value of the factor of safety, obtained using the relationship shown earlier, with the following criteria is compared:

- $FS > 1$ stability condition. D.M 11/03/1988 decree that $FS \geq 1,3$.
- In precautionary conditions, as will be seen later, this value will be set equal to $FS \geq 1.5$;
- $FS = 1$ limit equilibrium condition (resisting f. = driving f.);
- $FS < 1$ unstable condition, limit equilibrium conditions have been exceeded, therefore the final cover has already moved.

The volume on which apply the limit equilibrium method, is represented by the package cover surface, in this regard, from the analysis of figure 8.3 is note that the final cover is formed from a series of layers of different material between them; this implies that, for the purposes of assessing the unit weight of the total mass is considered unit weight mediated between the layers (γ_{med}).

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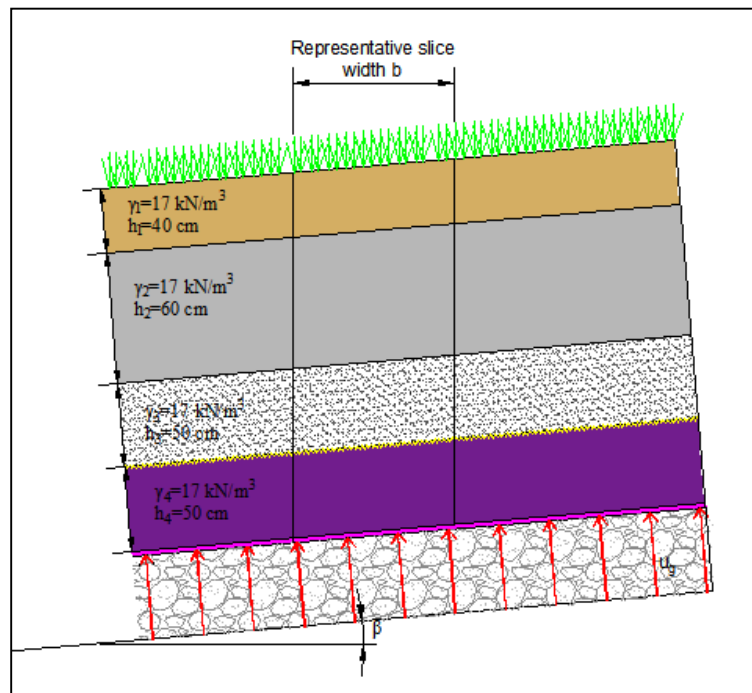


Fig. 8.3 – Infinite slope geometry and material parameters

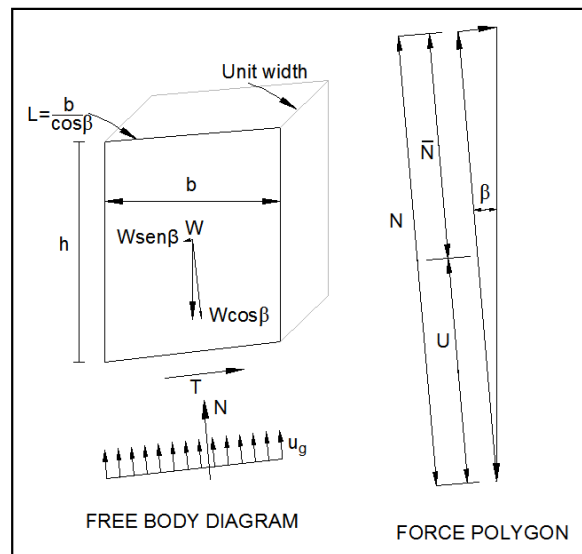


Fig. 8.4 – Free body diagram and force polygon

– Cover layer weight:

$$W = \gamma_{med} \cdot V = \gamma_{med} \cdot A \cdot 1 = \gamma_{med} \cdot \left(h \cdot \frac{b}{\cos\beta} \right) \cdot 1 \quad [N]$$

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That, being a vector force is decomposed into two components: the tangential and normal one

- Normal force (resistant): $N = W \cos \beta$ [N]
- Tangential force (driving): $T = W \sin \beta$ [N]

In accordance with the Mohr – Coulomb criterion the stress is evaluated, which, by definition, is the parameter that indicates the ratio of a force with respect to the surface on which it acts:

- Normal stress:

$$\sigma = \frac{N}{A} = \frac{W \cos \beta}{\frac{b}{\cos \beta} \cdot 1} = \gamma_{med} \cdot h \cdot \cos \beta \quad [Pa]$$

- Shear stress:

$$\tau_M = \frac{T}{A} = \frac{W \sin \beta}{\frac{b}{\cos \beta} \cdot 1} = \gamma_{med} \cdot h \cdot \sin \beta \quad [Pa]$$

By symmetry the stress on the lateral faces of the block are equal and opposite, then the resulting actions have the same line of action parallel to the slope, same direction, same module, and the opposite direction. Therefore cancel each other out and are not involved in the equations of equilibrium.

The infinite slope stability is statically determinate a problem (forces between blocks are cancel and the number of equation is greater than the number of unknowns), for which the solution of the equilibrium limit is exact and the factor of safety can be calculated explicitly :

$$FS = \frac{\tau_R}{\tau_M} = \frac{c' + (\sigma - u_g) \tan \varphi'}{\gamma_{med} \cdot h \cdot \sin \beta} = \frac{c' + (\gamma_{med} \cdot h \cdot \cos \beta - u_g) \tan \varphi'}{\gamma_{med} \cdot h \cdot \sin \beta} \geq 1,5$$

As described in Section 2.5 the surface coverage has long-term slope of 7%; however, as precautionary measures, was assumed equal to 15%.

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Tab. 8.1 – Geometric characteristics of the slope

Geometric characteristics of the slope			
SLOPE			
percentage (i)	0,15	$\text{Cos}\beta$	0,99
angle (β)	8,66	$\text{Sen}\beta$	0,15

By the Mohr - Coulomb criterion parameters c' and ϕ' represent a measure of the shear strength, the greater is the value the greater is the shear strength of the soil. From a precaution point of view, the cohesion of the materials constituting the layers of the cover (c') is assumed to zero, while the angle of friction at the interface between geotextile and biogas drainage, is chosen by adopting the following table (Tenax).

Tab. 8.2 – Internal friction angles at the interface

		BARRIER BENTO	QDRAIN	TEMATEX NW	BARRIER HDPE L	BARRIER HDPE AM	SABBIA	GHIAIA	TERRENO VEGETALE
Geocomposito bentonitico	BARRIER BENTO		18°/23°		9°/12°	28°/32°	28°/32°	30°/33°	24°/26°
Geocomposito drenante	QDRAIN	18°/23°			8°/14°	28°/32°	28°/32°	30°/33°	24°/26°
Geotessile tessuto non tessuto	TEMATEX NW				8°/14°	28°/32°	28°/32°	30°/33°	24°/26°
Geomembrana in HDPE liscia	BARRIER HDPE L	9°/12°		10°/12°			14°/18°		
Geomembrana in HDPE ad adherenza migliorata	BARRIER HDPE AM	28°/32°		28°/32°			25°/29°		
Sabbia	SABBIA	28°/32°		28°/30°	8°/14°	22°/25°			
Ghiaia	GHIAIA	30°/33°		32°/34°					
Terreno vegetale	TERRENO VEGETALE	24°/26°		24°/28°					

Evaluating a friction angle equal to 30°.

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8.2.1. Correlation between factor of safety and biogas pressure

Replaced the parameters useful in the determination of the factor of safety, the following relationship is derived:

$$FS = \frac{\tau_R}{\tau_M} = \frac{18,25 - 0,57u_g}{4,82} \geq 1,5$$

For which, the only unknown is the pressure to be generated from biogas (u_g). In this regard are hypothesized a series of pressure values with the aim to evaluate the performance of the factor of safety and thus the respective stability of the cover.

Tab. 8.3 – Biogas pressure and relative FS

Biogas pressure u_g		FS
[kPa]	[cm_water column]	
22	220	1,15
20	200	1,39
18	180	1,63
16	160	1,87
14	140	2,11
12	120	2,35
10	100	2,59
8	80	2,83
6	60	3,07
4	40	3,31
2	20	3,55
0	0	3,79

The factor of safety factor is evaluated from a value of zero pressure; this assumption implies that hypothetically there's no biogas production: there may be of, inside the MSW matrix, some conditions that inhibit bacterial activity with the result that there is no production of biogas. Obviously, this assumption turns out to be a boundary condition given that it is considering a MSW landfill; but, from a geotechnical point of

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view, assume zero pressure is the condition for which the normal load stabilizing the final coverage is not reduced by the pore pressure.

Being pore pressure equal to zero, the only stress that develop within the porous medium are the effective stress.

This condition allows to obtain the value of the limit factor of safety i.e. $FS = 3.79$ for which there is the greatest chance of stability of the final cover.

A series of hypothetical pressures generated by biogas are taken into account; the purpose is that increasing interstitial stress within the porous medium, value of pressure, eliminating the normal stresses, causes the instability of the surface coverage is estimated.

Having imposed precautionary measure, the minimum value of the factor of safety equal to 1,5, as it arrives from the table 8.3, a higher pressure of 20kPa (equal to 2m of water column), the safety factor is considered to be lower than the limit with the direct consequence of a possible instability of the final cover.

for the landfill object of study, with the parameters that best describe the geometric and structural characteristics of the porous medium, it is estimated that the range of the safety factor is between: $FS = 1.5 \div 3.8$.

The table below shows graphically the behavior of the pressure generated by biogas in kPa and the corresponding value of the safety factor, considering a conservative limit value of $FS = 1.5$.

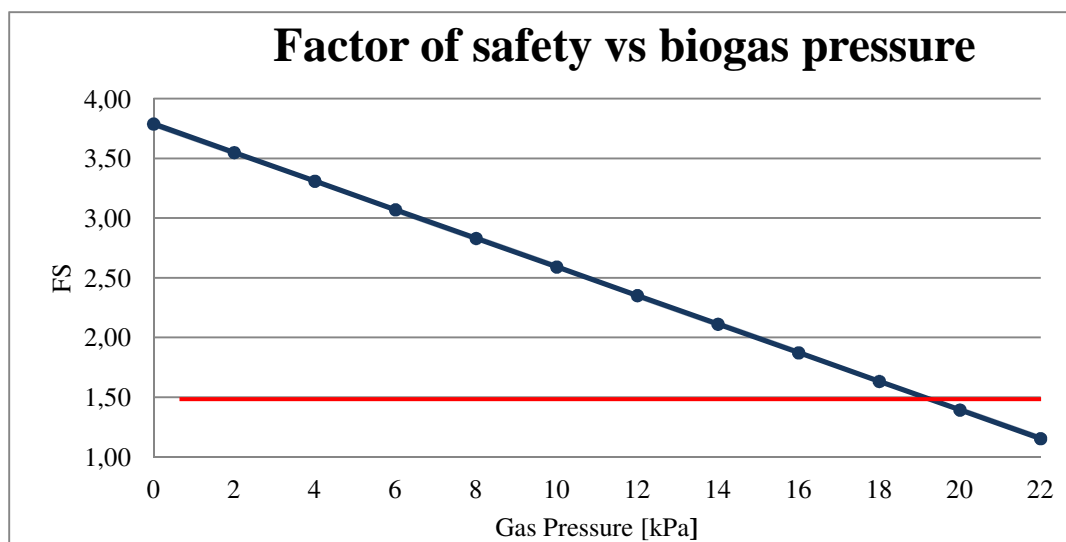


Fig. 8.5 – Values of FS at different biogas pressures

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As seen from the chart above-reported the relationship between the pressure generated by the biogas and the respective value of the safety factor is linear:

$$FS = 3,79 - 0,12u_g$$

Reworking the equation, the opposite relationship is got i.e. the trend of the biogas pressure as a function of the factor of safety factor is derived:

$$u_g(FS) = 31,6 - 8,33FS$$

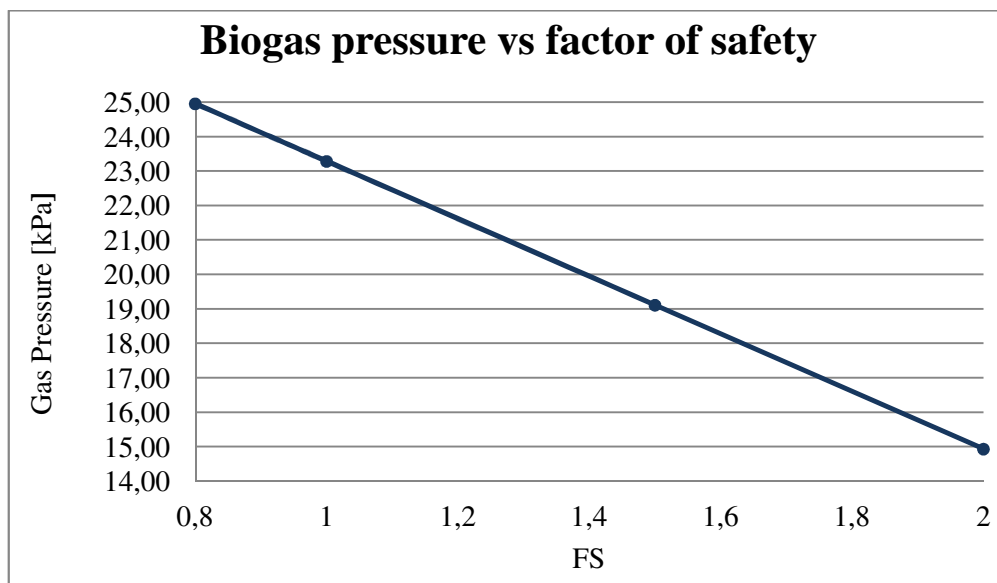


Fig. 8.6 – Values of biogas pressures at different FS

The following assessments are done

Tab. 8.4 – Factor of safety assessments

Factor of safety (FS)	Pressure u_g [kPa]	
0,8	24,96	The limit equilibrium condition has been exceeded. This pressure leads to an instability of the cove layer: the driving forces are greater then resisting
1	23,29	Limit equilibrium condition
$\geq 1,5$	19,11	Stability condition

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Set the value of the factor for which there's the stability of the cover layer and, formed the correlated pressure, it is necessary that, within the biogas drainage layer, this pressure is not exceeded.

This is possible by adopting a material with suitable permeability.

The following is the proposed relationship between the pressure generated by biogas (and thus diffuses within the same layer) and the relative value of biogas transmissivity ψ_g (Thiel R., 1998):

$$u_{g_max} = \frac{\gamma_g \cdot \Phi_g}{\psi_g} \left(\frac{L^2}{2} \right) \quad [Pa]$$

Steps useful to the derivation of this report are presented in the following section.

8.3. Porous media structure: biogas transmissivity

The methodology, proposed by R. Thiel (1998), expected to be included within the biogas drainage layer, at distance D, the parallel trench called "strip drains" which are the extraction wells in the passive conditions.

In Figure 8.7 are summarized relevant information to the derivation of the model adopted.

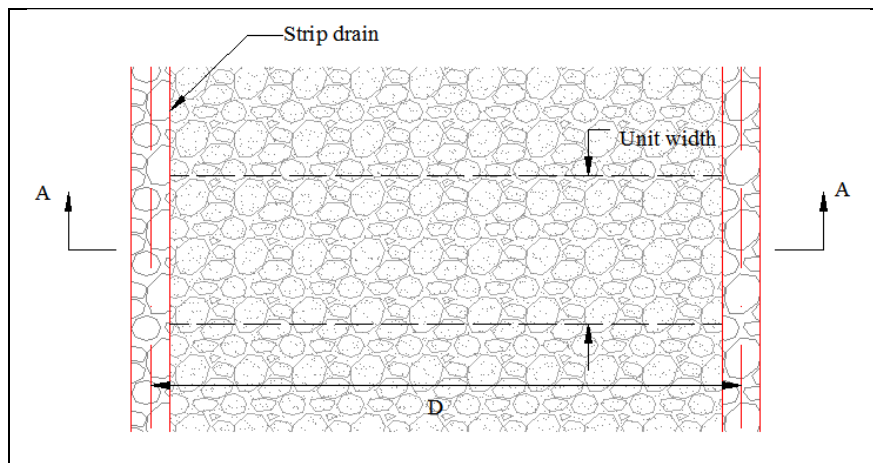


Fig. 8.7a – Model of gas flow to strip drains

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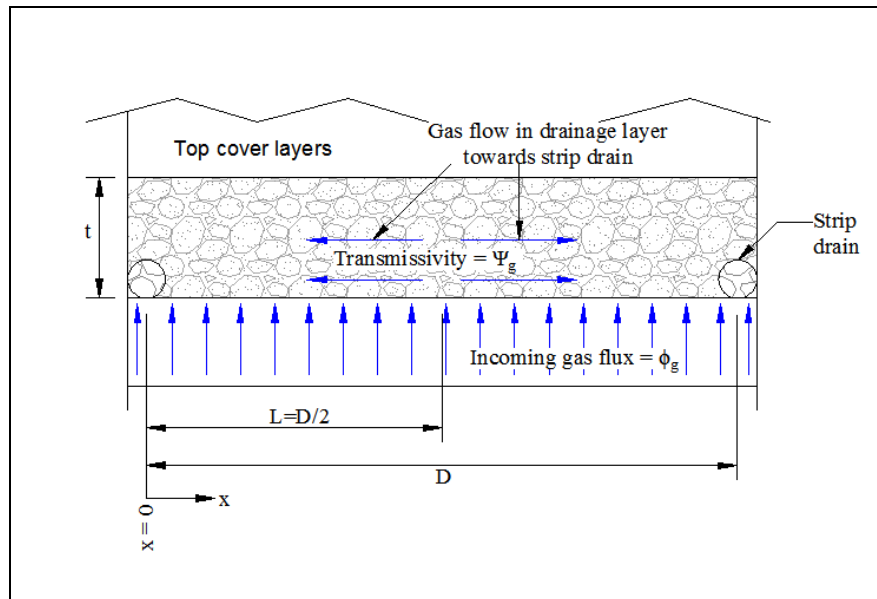


Fig. 8.7b – Model of gas flow to strip drains

The biogas flow (Φ_g) generated by the degradation of the underlying waste is evenly distributed within the drainage layer; ideally, the biogas flow is symmetrical about the center line, then for which the calculation is considered to be half the distance $L = D / 2$, where D is the distance between two consecutive strip drains.

The gas flow rate, within the porous medium, can be compared to the flow of a liquid in laminar condition; this consideration allows the use of Darcy's law which rewritten in terms of the pressure gradient becomes:

$$Q_x = k_w \cdot A \cdot \left(\frac{dh}{dx} \right) \quad \rightarrow \quad Q_x = k_g \cdot A \cdot \frac{1}{\gamma_g} \cdot \left(\frac{du_g}{dx} \right) \quad \left[\frac{m^3}{s} \right]$$

dove

- Q_x = volumetric flow at specific position x [m^3/s];
- k_w = hydraulic conductivity of drainage medium [m/s];
- k_g = gas permeability of porous medium [m/s];
- A = cross section area of drainage layer [m^2];
- γ_g = biogas unit weight [N/m^3];
- u_g = biogas pore pressure [$Pa = N/m^2$].

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Considering t the thickness of the drainage layer, by the transmissivity ψ_g , the ability of the same in the biogas diffusion is evaluated:

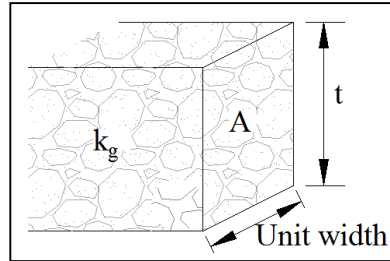


Fig. 8.8 – Schematization of the biogas drainage layer for the transmissivity assessment

$$\psi_g = k_g \cdot t \quad \left[\frac{m^2}{s} \right]$$

Which replaced in the above, bearing in mind that the transverse surface is given by the product of the height of the drainage layer to the thickness, which for convenience has been considered one ($A = t \cdot 1$), is obtained:

$$Q_x = \frac{\psi_g}{t} \cdot A \cdot \frac{1}{\gamma_g} \cdot \left(\frac{du_g}{dx} \right) = \frac{\psi_g}{\gamma_g} \cdot \left(\frac{du_g}{dx} \right) \quad \left[\frac{m^3}{s} \right]$$

As defined previously, the volume of gas per unit width can be written in terms of gas flow diffused in the drainage layer:

$$Q_x = \Phi_g \cdot (L - x) \quad \left[\frac{m^3}{s} \right]$$

With $\Phi_g =$ biogas flux $[m^3/m^2 \cdot s]$.

Equaling the biogas flow (Q_x), the following equation is obtained

$$\frac{\psi_g}{\gamma_g} \cdot \left(\frac{du_g}{dx} \right) = \Phi_g \cdot (L - x)$$

That settled through integral allows to derive the pressure value u_g .

For the purpose to establish a balance, the flow of gas moves, by diffusion, from an area where the pressure is greater ($x = L$) to one where the pressure is lower ($x = 0$), i.e. in correspondence of the extraction shaft suction, which, being in passive condition is located at atmospheric pressure.

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$$\int du_g = \frac{\gamma_g \cdot \Phi_g}{\psi_g} \int_0^x (L - x) dx \rightarrow u_g = \frac{\gamma_g \cdot \Phi_g}{\psi_g} \left(Lx - \frac{x^2}{2} \right)$$

Considering the above-derived equation, the trend of the flow (assessed in Section 7.2) with the pressure values obtained for the raw material analyzed in section 8.5, are compared.

Tab. 8.5 – Values of pressure and biogas flow rate to a given distance x between the collection wells

Half-distance between consecutive wells L = 10m	u_{g_x} [kPa]	Q_{b_x} [m³/y]
0	0,00	781,88
1	0,10	703,69
2	0,20	625,50
3	0,28	547,31
4	0,35	469,13
5	0,41	390,94
6	0,46	312,75
7	0,50	234,56
8	0,53	156,38
9	0,55	78,19
10	0,55	0,00

These values are shown in the following figure:

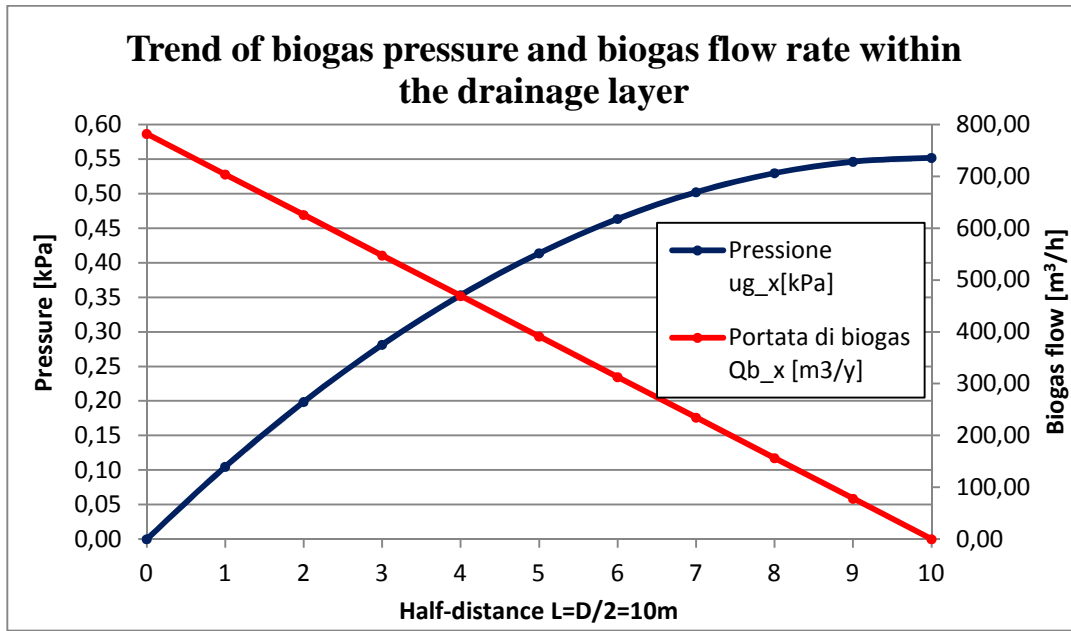


Fig. 8.9 – Trend of biogas pressure and biogas flow rate within the drainage layer

At $x = 0$ there's the extraction well, which, being passive means that in its surroundings, the drainage layer is at atmospheric pressure ($P_{atm} = u = 0$), otherwise, at the farthest point i.e. at $x = L$, the pressure induced by the biogas acquires the maximum value:

- $x = 0 \rightarrow u_g = 0$;
- $x = L \rightarrow u_g = u_{max} = 0,55\text{kPa}$.

Recalling that the pressure gradient (du_g/dx) is the driving force that moves the gas to a point at high pressure to a point at a lower pressure; being at $x = 0$, a low pressure area, there is a substantial diffusion of biogas from $x = L$ moves to $x = 0$, with a consequent increase of flow rate; in contrast, such diffusion towards the collection well, means that at $x = L$, the flow rate of biogas are almost zero.

The graph shows that the maximum pressure of the biogas has to $x = L$:

$$u_{g,max} = \frac{\gamma_g \cdot \Phi_g}{\psi_g} \left(\frac{L^2}{2} \right) = \frac{\gamma_g \cdot \Phi_g}{\psi_g} \left(\frac{D^2}{8} \right) \quad [Pa]$$

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The expression just obtained correlates with the pressure exerted by the biogas to the biogas transmissivity ψ_g .

In design practice is easy to determine the characteristics of a porous medium through the evaluation of the hydraulic permeability coefficient

To this end, it is necessary to determine the correlation between the gas permeability and the hydraulic permeability.

8.4. Correlation between idraulic and biogas permeability of the drainage layer

Are defined:

- **Effective permeability or hydraulic conductivity (k_w)**, due both to the textural characteristics of the physical medium (i.e. the porosity), and to those of the fluid transmitted;
- **Intrinsic permeability (k_i)**, dependent only by internal characteristics of the porous medium; therefore not affected by the fluid flowing through it, either liquid or gas..

The latter assertion implies that in the assessment of the intrinsic permeability of the medium, it would lead to the same result if the porous medium is saturated either with water or with gas.

The outflow of a fluid, generally water, within a permeable medium, is regulated by the Darcy's experimental law:

$$Q_w = k_w \cdot \frac{\Delta H_w}{L} \cdot A = k_w \cdot i_w \cdot A \quad [m^3/s]$$

dove,

- Q_w = hydraulic flow (m^3/s);
- ΔH_w = hydraulic drop pressure (m);

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- L = length of the porous medium (hydraulic path) (m);
- A = sectional area (m^2);
- k_w = hydraulic permeability (m/s);

The intrinsic permeability and the effective are mutually related through the parameters that define the characteristics of the fluid (density and viscosity); supposed that the latter is water, the Darcy's law is then rewritten in terms of intrinsic permeability:

$$Q_w = \frac{K_i \cdot \gamma_w}{\mu_w} \cdot i_w \cdot A = \frac{K_i \cdot g \cdot \rho_w}{\eta_w} \cdot i_w \cdot A \quad [m^3/s]$$

And, by the equality of the two previous relationships the following formulation is derived:

$$k_w \cdot i_w \cdot A = \frac{K_i \cdot g \cdot \rho_w}{\mu_w} \cdot i_w \cdot A \quad \rightarrow \quad k_w = \frac{K_i \cdot g \cdot \rho_w}{\mu_w} = K_i \cdot \frac{\gamma_w}{\mu_w} \quad [m/s]$$

where,

- K_i = intrinsic permeability (independent of the fluid) (m^2);
- γ_w = fluid unit weight (N/m^3);
- μ_w = dynamic viscosity of the fluid ($N \cdot s/m^2$);
- g = gravity acceleration (m/s^2);
- ρ_w = fluid density (N/m^3);

Since K_i appears to be independent of the type of fluid that passes through the porous medium, the coefficient of permeability of the same, evaluated for two different fluids (w = water, g = gas), is defined as:

$$k_w = \frac{K_i \cdot \gamma_w}{\mu_w} \quad ; \quad k_g = \frac{K_i \cdot \gamma_g}{\mu_g}$$

Thus, the relationship between fluid and gas, passes through the intrinsic permeability K_i :

$$\frac{k_w}{k_g} = \frac{\gamma_w}{\gamma_g} \cdot \frac{\mu_g}{\mu_w}$$

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This equation allows to derive the hydraulic permeability of the porous medium by knowing the transmissivity to the gas of the same; both the specific weight and the dynamic viscosity of water are obtained from the literature, while, as regards the biogas, the same parameters were measured experimentally, starting from the individual specific weights:

$$\gamma_{CH_4} = 6,54 \frac{N}{m^3} \quad \gamma_{CO_2} = 17,9 \frac{N}{m^3}$$

considering a percentage of methane and carbon dioxide respectively 45% and 55% is obtained:

$$\gamma_{CH_4}(45\%) = 2,94 \frac{N}{m^3} \quad \gamma_{CO_2}(55\%) = 9,84 \frac{N}{m^3}$$

Tab. 8.6 – Fluid density and viscosity (20°C)

	Density (ρ) [kg/m³]	Unit weight (γ) [N/m³]	Dinamic viscosity (μ) [N•s/m²]	Kinematic viscosity (ϑ) [N•s/m²]
Water	1000	9800	$1,01 \cdot 10^{-3}$	$1,01 \cdot 10^{-6}$
Air	1,28	11,8	$1,79 \cdot 10^{-5}$	$1,75 \cdot 10^{-5}$
Carbon dioxide (CO ₂)	1,83	17,9	$1,50 \cdot 10^{-5}$	$8,21 \cdot 10^{-6}$
Methane (CH ₄)	0,67	6,54	$1,10 \cdot 10^{-5}$	$1,65 \cdot 10^{-5}$
LFG (45% CH ₄ + 55% CO ₂)	1,31	12,8	$1,32 \cdot 10^{-5}$	$1,01 \cdot 10^{-5}$

These values, measured at standard conditions of 20 ° C, if replaced in the previous report prove the fact that the coefficient of hydraulic conductivity is 10 times greater than the coefficient of gas permeability, in any porous medium:

$$k_w = \left(\frac{\gamma_w \cdot \mu_g}{\gamma_g \cdot \mu_w} \right) \cdot k_g = \left(\frac{9,8 \cdot 10^3 \frac{N}{m^3} \cdot 1,32 \cdot 10^{-5} \frac{N \cdot s}{m^2}}{12,8 \frac{N}{m^3} \cdot 1,01 \cdot 10^{-3} \frac{N \cdot s}{m^2}} \right) \cdot k_g = 10 \cdot k_g$$

The validity of this relation has been experimentally demonstrated for sandy medium having hydraulic conductivity between 10^{-5} e 10^{-3} m/s (Muskat, 1937).

In the past, however, the inverse relationship was believed, i.e. the biogas transmissivity was 100 times greater than the hydraulic transmissivity. The result was usually an undersized biogas drainage layers generating potential slope instability of the cover.

8.5. Porous media structure of the drainage layer

Derived the relationship between the water and the biogas permeability, the structure of the granular medium which will constitute the layer of drainage is determined. Note the maximum pressure that the biogas diffuses within the layer itself, it is necessary to calculate the minimum required value in terms of transmissivity that the same layer must be able to guarantee in order to not create excessive pressure which could compromised the stability of the upper layers .

Below a portion of the biogas drainage layer is represented; as anticipated, considering ideally the flow of biogas to spread symmetrically with respect to the centerline $L=D/2=10\text{m}$.

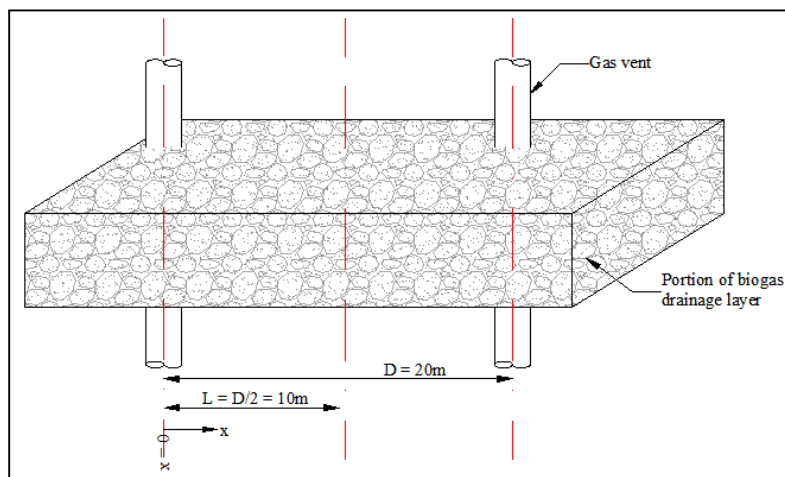


Fig. 8.10 – Consecutive extraction wells within the biogas drainage layer

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Through the linear relationship previously calculated: $u_g(\text{FS}) = 31,6 - 8,33\text{FS}$ for FS values greater than 1.3 (the value imposed by the D.M. 11/03/1988), the maximum pressure that biogas exerts on the final cover is calculated.

For these values is evaluated, through the subsequent relation, the minimum required value in terms of transmissivity that the draining layer must be able to ensure (R. Thiel, 1999)

$$\Psi_{calc_g} = \frac{\gamma_g \cdot \Phi_g \left(\frac{D^2}{8} \right)}{u_{g_max}} \quad [m^2/s]$$

In this report, fixed: the flow of biogas, the density of the same and the distance between two consecutive collection wells, parameters that remain constant; depending on the maximum pressure assessed according to the FS wanted, the respective value of transmissivity minimum necessary to ensure that the porous medium does not allow the establishment of accumulations of biogas is evaluated.

Determined the calculation value of the minimum required transmissivity, a series of correction factors that increase this value, are used. They allow to derive the design value of the minimum transmissivity; the report useful to the purpose is the following:

$$\Psi_{prog_g} = \Psi_{nom_g} \cdot \prod_{I=1}^5 FC_i$$

For which, by the following expression the correction factors are represented:

$$\prod_{I=1}^5 FC_i = FC_{IN} \cdot FC_{CR} \cdot FC_{CC} \cdot FC_{BC} \cdot FC_{OVERALL}$$

For these coefficients values found in literature whose ranges of variation are shown in table 8.9 can be adopted. The overall correction factor varies between $FC_{min} = 2,64$ e $FC_{max} = 9,072$.

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Tab. 8.7 – Correction factors ranges of variation

Description of the corrective factor		Range		Value adopted
FC _{IN}	Correction factor due to a possible intrusion of the upper geotextile within the drainage layer	1	1,2	1,2
FC _{CR}	Correction factor due to the phenomenon of creep	1,1	1,4	1,1
FC _{CC}	Correction factor due to the phenomenon of chemical clogging	1	1,2	1,2
FC _{BC}	Correction factor due to the phenomenon of biological clogging	1,2	1,5	1,5
FC _{OVERAL}	Reductive factor of the uncertainty of the method	2	3	3

From the above ranges of variation the value that best approximates reality is evaluated; the reduction factor is the total proceeds then $FC = 7,128$.

the biogas permeability is evaluated (k_g): the thickness of the drainage layer of 0.5 m is multiplied to the design values of transmissivity to biogas.

See below a summary table of the values obtained.

Tab. 8.8 – Transmissivity and permeability values from FS required

FS	u_g [kPa]	Ψ_g calculating [m²/s]	Ψ_g design [m²/s]	k_g [m/s]	k_w [m/s]
1,5	19,11	8,30E-08	5,92E-07	1,18E-06	1,18E-05
1,6	18,28	8,68E-08	6,19E-07	1,24E-06	1,24E-05
1,8	16,61	9,56E-08	6,81E-07	1,36E-06	1,36E-05
2	14,94	1,06E-07	7,57E-07	1,51E-06	1,51E-05
2,2	13,27	1,20E-07	8,53E-07	1,71E-06	1,71E-05
2,4	11,60	1,37E-07	9,75E-07	1,95E-06	1,95E-05
2,6	9,93	1,60E-07	1,14E-06	2,28E-06	2,28E-05
2,8	8,26	1,92E-07	1,37E-06	2,74E-06	2,74E-05
3	6,59	2,41E-07	1,72E-06	3,44E-06	3,44E-05
3,2	4,92	3,23E-07	2,30E-06	4,60E-06	4,60E-05
3,4	3,25	4,89E-07	3,49E-06	6,97E-06	6,97E-05

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3,55	1,99	7,96E-07	5,68E-06	1,14E-05	1,14E-04
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In accordance with the table 8.10, the minimum value of the precautionary factor of safety of 1.5 corresponds to a biogas conductivity (k_g) of about $1,2 \cdot 10^{-6}$ m/s, remembering that the hydraulic conductivity is 10 times greater than the biogas permeability, it is necessary to search for a material with hydraulic conductivity (k_w) of at least $1,2 \cdot 10^{-5}$ m/s.

In this regard, in Table 8.9 are identified values of hydraulic permeability of the main classes of material obtained through laboratory tests.

Tab. 8.9 - Permeability coefficient for different materials

k_w [m/s]	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}
Drainage	Good						Low		Practically zero				
Materials	Clear gravel	Clean sands, mix between gravel and clean sands			Very fine sand, organic and inorganic silt, mixed sands, silt and clays etc		Impermeable soil, clays with structural modifications generated by vegetation and in situ alteration		Impermeable soil homogeneous clays below the blanket of atmospheric alteration				

The model used has allowed us to investigate the range of permeability helpful sizing the drainage layer, and, as can be seen from Table 8.6, the range is between $k_w = 10^{-5} \div 10^{-4}$ m/s.

An analysis of the typical values of the permeability of the soils presented in Table 8.9 shows that, in the above-mentioned range, refers to the following types of porous medium: clean sands, a mixture of gravel and clean sand or just clean gravel. These classes of soils allow a different distribution of biogas in them; in this regard it is convenient to represent the trend of the pressure generated by the biogas as a function of the permeability of the material forming the drainage layer.

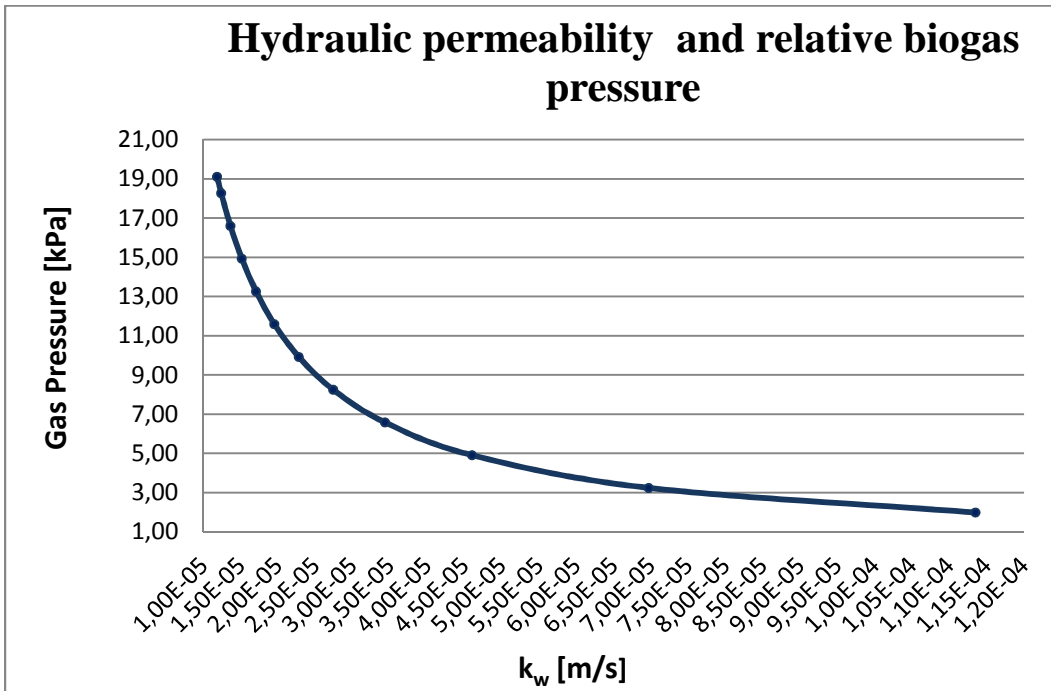


Fig. 8.11 – Hydraulic permeability and relative biogas pressure

Analyzing the graph of figure 8.11, it is clear how, with increasing permeability of the porous medium, the pressures that are established in its interior are gradually decreasing; with the obvious positive effect on the stability of the final cover. In this regard is shown below the graph which allows to evaluate, depending on the permeability of the drainage layer, the relative safety factor.

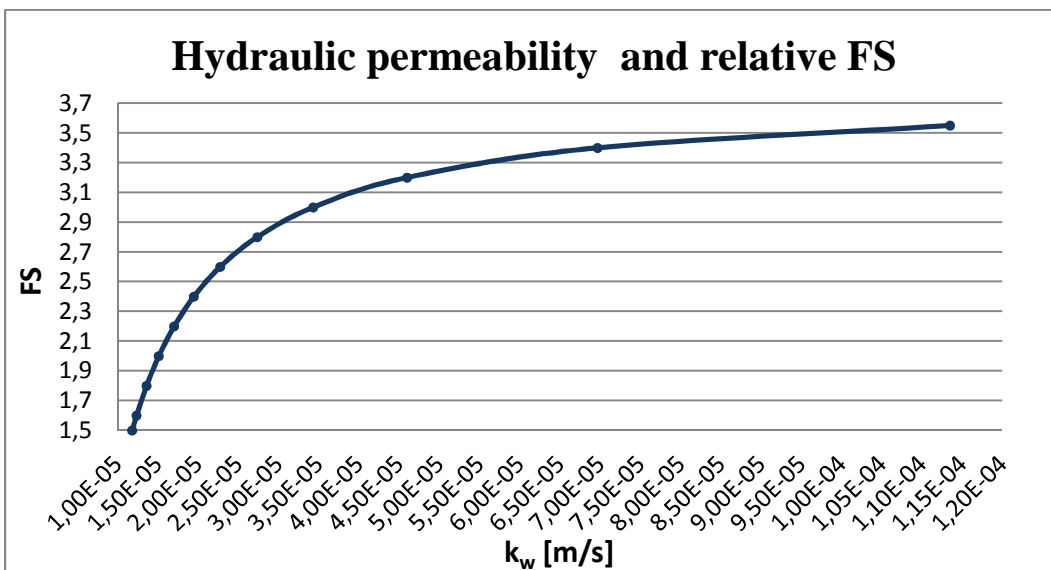


Fig. 8.12 – Hydraulic permeability and relative FS

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The materials used for the construction of these layers of drainage are commonly coming from the quarry (sand and gravel); however, it is possible to use raw waste (but compatible with the landfilling) by getting a double benefit:

- Lower cost compared to materials from the quarry (€/m³);
- Reduced environmental impact through the reduction in the volume of materials from the quarry


In this regard, the minimum value of permeability which needs to have the material in order to ensure the stability of the final cover is estimated; a laboratory test on the following inert waste was carried out:

Tab. 8.10 - CER code and analyzed material description

CER code		Material description
19 12 09	19 12	Wastes from the mechanical treatment of waste (for example sorting, crushing, compacting)
	09	minerals (for example sand, stones)

The analysis evaluated the parameters shown in Figure 8.11.

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CARATTERISTICHE DI PROVA		
Peso di volume iniziale	12,14	kN/m ³
Umidità iniziale	6,9	%
A provino	18220	mm ²
L provino	116,6	mm
Grad. Idraulico iniziale	3,4	

PARAMETRI DI CALCOLO		k=QL/Ath
TEMPO s	Lettura cm ³	Kcost m/s
60	1540,0	4,11E-04
120	3090,0	4,07E-04
180	4650,0	4,13E-04
VALORE MEDIO		4,10E-04

Fig. 8.13 – Response of the analyzed material

The analysis carried out on the raw material for the construction of the biogas drainage layer, estimated a permeability equal to $k_w=4,1 \cdot 10^{-4}$ fully confirming the predictions provided by the model adopted.

Note the permeability of the analyzed material, the value of pressure that is generated within the same and the degree of security provided are derived.

The model has determined the following values:

Tab. 8.11 - Characteristic parameters of inert waste recovery

k_w [m/s]	k_g [m/s]	Ψ_g design [m ² /s]	u_g [kPa]	FS
4,10E-04	4,10E-05	2,05E-05	0,55	3,72

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Derived the value of the gas permeability, which, as above mentioned results to be 10 times lower than the water permeability, the drainage design transmissivity and therefore the pressure that is generated in its interior are evaluated.

From the value of the parameters summarized in Table 8.13 it can be concluded that the porous medium in question, having good permeability, guarantees the stability of the top cover.

8.6. Feasibility study of the evaluated model

The relationships necessary to implement the model have been obtained by exploiting the Darcy's law, the validity of which exists only in the case of a flow in the laminar regime.

This limit can be evaluated through the use of the dimensionless Reynolds number:

$$Re = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho \cdot v \cdot d}{\mu_f} \quad [/]$$

Dove,

- ρ = fluid density [kg/m³];
- v = flux velocity [m/s];
- d = extraction well diameter [m];
- μ_f = fluid dynamic viscosity [N•s/m²].

For which, by the ratio between the inertia forces and viscous forces goes on to a dimensionless value that, compared with a reference value, allows to evaluate the type of motion of the fluid.

In fluid mechanics, whereas the outflow of a fluid inside a tube, having a characteristic dimension of the diameter d , this reference value is 2000; means, for values below the motion can be considered laminar.

Experimental tests, are evaluating the behavior of the flow of various fluids, both liquid and gaseous these, within a porous matrix, it was proved that the reference value below

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which the motion can be considered laminar is given by the range 1 to 10 and, in a conservative way, the limit to the application of Darcy's law is 1.

With regard to the characteristic size, generally, in a porous medium, is associated with the size of the grains constituting the solid matrix, though, would be more appropriate to consider the average value of d as pore size, but, this being an operation is rather complicated d prefer to adopt as the value of the diameter of the solid constituents of the porous medium.

The speed assumed by Darcy, is a fictitious speed, macroscopic, obtained from the ratio between the flow rate of biogas diffused inside of the drainage layer and the cross section of the same. Referring to Figure 8.14, is known as, through the macroscopic approach, the flow occurs through the entire section of the porous medium. In reality it is not so, because the biogas can only diffuse through the pores communicating, it is considered the actual speed, microscopic, whose value must be greater than the speed accordingly fictitious.

Is defined as the ratio between the actual speed the speed fictitious and porosity n :

$$v_e = \frac{v}{n} \quad [m/s]$$

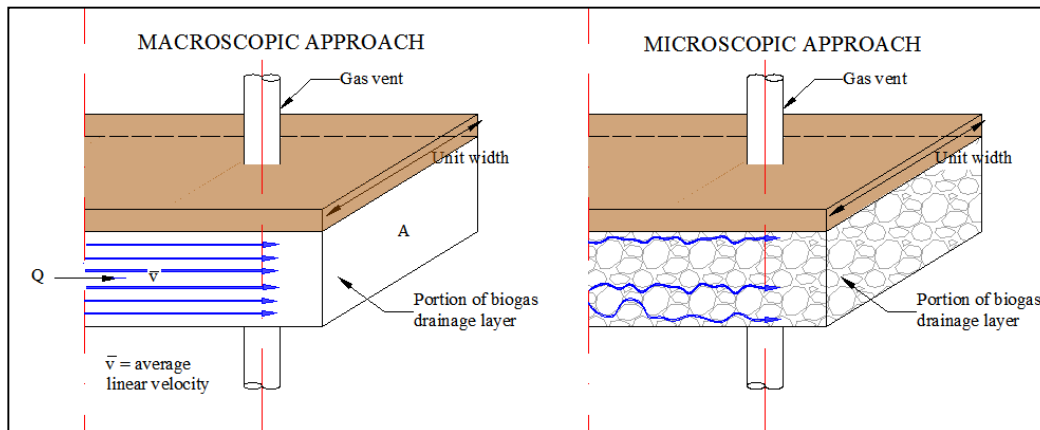


Fig. 8.14 – Velocity through the macroscopic and microscopic approach

In reference to Figure 8.15, by way of simplification, a well catchment with its area of influence is shown:

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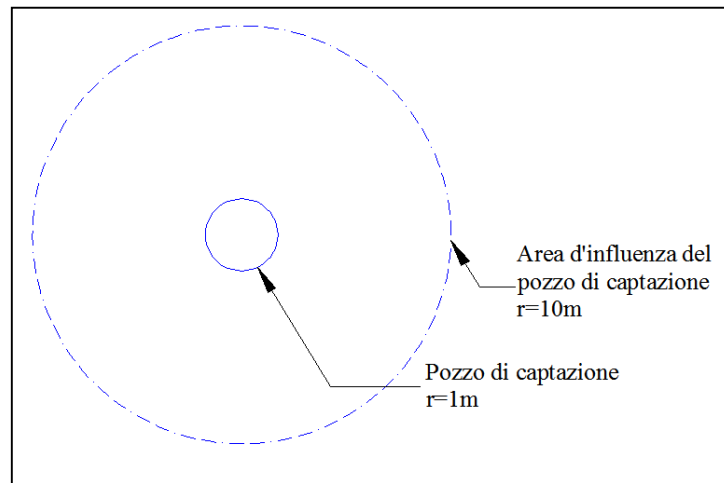


Fig.8.15 – Extraction well and radius of influence

Below useful calculations in order to derive the value of the dimensionless Reynolds number, are developed.

Tab. 8.12 – Parameters for the Reynolds number calculation

Biogas flux (Φ_b)	$2,48 \cdot 10^{-6} \text{ m}^3/\text{m}^2 \cdot \text{s}$
Porous medium porosity (n)	0,46
Grain size (d)	0,008 m
Biogas density (ρ)	$1,31 \text{ kg/m}^3$
Biogas dynamic viscosity (μ)	$1,32 \cdot 10^{-5} \text{ kg/s} \cdot \text{m}$

Considering the area of influence of the well catchment, the overall flow conveyed within this area is calculated:

$$Q = \Phi_b \cdot A = 2,48 \cdot 10^{-6} \cdot \pi \cdot 10^2 = 7,8 \cdot 10^{-4} \text{ m}^3/\text{s}$$

The significant speed for the calculation of the number of Re is the maximum, i.e the velocity entrance in the extraction well with radius of influence equal about 1m.

$$v = \frac{Q}{A_{pc}} = \frac{7,8 \cdot 10^{-4}}{\pi \cdot 1} = 2,48 \cdot 10^{-4} \text{ m/s}$$

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Whose effective velocity is estimated to be:

$$v_e = \frac{v}{n} = \frac{2,48 \cdot 10^{-4}}{0,46} = 5,4 \cdot 10^{-4} [m/s]$$

Derived this value, the Reynolds number is evaluated

$$Re = \frac{1,31 \frac{kg}{m^3} \cdot 5,4 \cdot 10^{-4} \frac{m}{s} \cdot 0,006m}{1,32 \cdot 10^{-5} \frac{kg}{s \cdot m}} \approx 0,43$$

Being $Re \ll 1$, the motion of the fluid can be considered, in all areas of drainage, certainly laminar making the calculation model based on the relationship of Darcy valid.

Content analysis and conclusions

This thesis main aim is to evaluate, in extreme conditions of extraction system's temporary interruption, the necessary minimum permeability of the porous media, which the biogas drainage is made of, to maintain the final cover's stability.

This permeability level guarantees an adequate biogas flux towards the exit holes from the mineral layer so that the biogas pressures haven't negative effects on the final cover stability.

To accomplish this, the first step, described in **Chapter 4**, has been the evaluation of the biogas amount released by the MSW degradation within relative predictive biogas models.

Starting from the biogas emissions data collected directly in the Comune di Grumolo delle Abbadesse(VI) 's landfill, it has examined the progression in time of biogas. These data have been estimated within the predictive models to see the reliability of the experimental data themselves.

These simulations have confirmed the biogas peak production measured in the experimental phase unless a time shift.

The case study landfill, according to the D.Lgs 36/2003 law, is endowed with both the plant for biogas extraction and recovery and the biogas drainage layer. **Chapter 5** and **6** provide a technical description of the artifacts composing the extraction system, the evaluation of the radius of influence and analysis of the biogas diffusion in passive conditions into the drainage layer.

Chapter 7 describes, instead, the project of the biogas drainage layer in case of extraction system's temporary interruption. The design of the layer has been elaborated following the above mentioned predictive models.

It has been noticed that the biogas volumetric flow is linear inside the drainage, having a peak value around the extraction well and an almost zero value in the middle of the wells.

The **Chapter 8** shows the stability analysis of the final cover using the limit equilibrium method. The conditions of the stability have been analyzed using the infinite slope schema. This approach, which defines some simplifying assumptions described in the same chapter, allows to handle the problem in simpler way but, nevertheless, conservative using a geometry which omits the stability actions at the slope's boundaries.

The cover materials's cohesion has been assumed to zero and the cover's slope has been increased with respect to the real value in "long term" to guarantee more safe results.

The factor of safety of the slope has been calculated as the ratio of resisting forces to driving forces acting on the interface between the biogas drainage layer and mineral cover. The relation between the factor of safety and the biogas pressure is linear within the pressure values considered. This relation has pointed out that the final cover stability is guaranteed with pressure values lower than 20kPa.

Biogas transmissivity has been calculated in order to obtain such pressure values. So it has been evaluated the relative permeability of the biogas drainage layer.

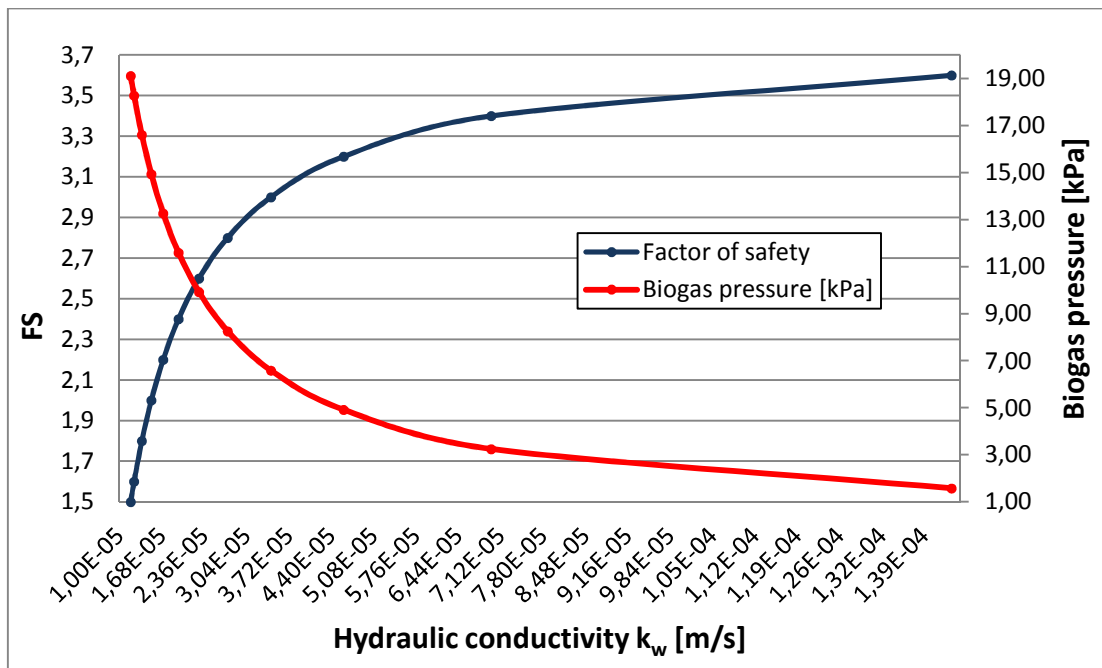
In order to achieve the porous media structure, usable as drainage layer, has been studied the correlation between hydraulic permeability and biogas one showing that the first one is ten times greater the latter.

The hydraulic permeability's minimum value, which guarantees the above mentioned value of safe factor, can be obtained with a drainage layer composed by clean sands, mixture of gravel and clean sand or simply clean gravel.

In order to check out the best economical solution with the lower environmental impact, it has been decided to adopt raw material rather than using of the above described material.

The permeability coefficient and the mechanical characteristics of the raw material follows the model confirming the chance to opt for this economical solution.

The last chapter provides a graph obtained by the model implementation, which allows to get two of three variables (factor of safety, hydraulic permeability of the porous media, biogas pressure on the cover) when it's known one of them.



The final consideration is that when the hydraulic permeability of the porous media increases there's a reduction of the pressure on the landfill's final cover.

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