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Effectiveness of suction to de-aerate granular materials: an application in material handling industry

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Abstract

Effectiveness of suction to de-aerate granular materials:
an application in material handling industry

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Removing air from bagged bulk material is a major concern for the material handling industry. A common technique is the application of suction by means of a probe, right before sealing the bag. Recent industrial experience shows that, for some granular materials, the effectiveness of this de-aeration technique is limited, probably due to the reduction in permeability associated to the decrease in porosity. The goal of this project is to understand and to remedy this limited effectiveness.

The hypothesis that has been handled in this work, is the creation of an over compressed bulb of granular material that prevents the complete suction of the excess air and limits the compaction of the material. The creation of the bulb is defined by the permeability of the material, since it has been decompressed, is very susceptible to the pressure. Therefore, the dependency of the permeability with the pressure is the main reason why the bulb is created.

In order to solve the issues behind the de-aeration process, the bulb creation process is modelled using mathematical models, which describe the suction in a porous media under certain conditions. The first one is a steady model, which describes the final state of the suction. The other one is a transient model, consequently, it describes the entire suction process. Those models are solved using numerical methods, obtaining information about the suction behaviour in granular materials and the bulb generation.

Finally, with the knowledge acquired, the same models are used to optimize the suction processes and propose a new method. The method, consist in a mobile probe that moves during the suction, reducing the over-compressed bulb behaviour.

Acknowledgements

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Finally, thanks to a friend of mine, Ilias for non stopping when it comes to cheer me up during all the project. Possibly, if I did not have the mutual support this project would not have been what it is now.

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Chapter 1

Introduction

1.1 Importance of de-aeration in granular industry

Within the industry of bulk material handling, fine grained bulk materials such as cement, plastic powder, milk powder etc. are often charged with large quantities of air during the material handling. This phenomenon becomes more relevant when the handling system is pneumatic, since an aeration process is induced to the material , see Fig.(1.1). While filling and bagging, these air quantities cause low bulk densities, consequently, the volume of packaging and storage increase significantly.

(a) Truck and silos (b) Truck pneumatic filling system

Figure 1.1: Truck filling silos with cement

This result would be less important in industries where the cost of the product compared to its volume is high. However, one of the properties that have most of the bulk materials is the low cost of material per volumetric unit. Therefore, most of the cost when buying granular materials is associated to the transportation of those, so the capability to increase the mass transported per transport unit is a key for most bulk material industries. In simple terms, after the material quality and the price, the bulk density is one of the most important things that customers take in account when choosing a bulk material supplier.

Besides the transport, the material storage is another key factor in bulk material industry. That is because it is often used in huge quantities such as cement in civil engineering projects or they are used as raw material for other industries. In consequence, those materials would be stacked in large quantities since they are always the first need in production chains, so again, the capability to make the material occupy less space is a great benefit for the industries.

(a) Bag storage (b) Maritime transportation

Figure 1.2: Storage and transportation of bulk material

In consequence, nowadays bulk material industries relay on air extraction/de-aeration processes in order to get rid of the extra air in the material after the handling, filling and bagging process. Doing that the transportation and storage cost is reduced, so the selling product is more attractive for customers. As an example, the transport cost of cement from Asia to America is around 50% of the total cost of cement, so increasing the bulk density by 10% the total cost is reduced by 4%. That is being calculated assuming the bulk density of cement without de-aeration is around 1.1g /cm3 and the cost of cement is per ton of material.

Finally yet importantly, there are materials that can be degraded when being in contact with the air for a prolonged time, due to the humidity or yet one of the air constituent itself. Therefore, the extraction of the air from packages is also important for keeping the physical and chemical properties of the inside materials.

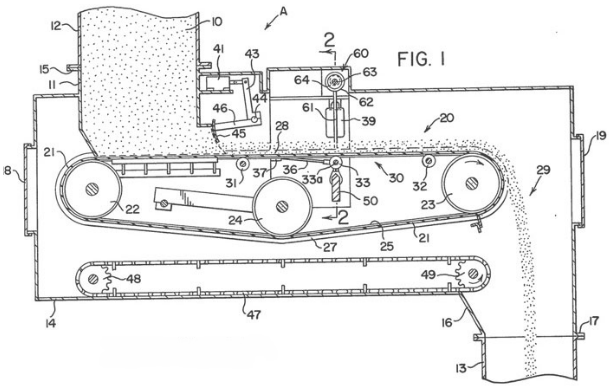
1.2 Bagging process

For bagging, an automatized machine that have three main components; the feeder system, the dispenser and a weighing machine, do the standard filling process. The feeder system, see "The STOCK Gravimetric Feeder - Chagrin Falls, Ohio, (1995)", has a funnel where the bulk material is introduced inside the machine, see Fig.(1.3a), afterwards various sensors determine how much material is introduced inside the sack, see Fig.(1.3c). The feeding can be done with a belt conveyor system or with pneumatic pipes, in both cases the material is being aerated during its transportation. The other component is the dispenser, see Fig.(1.3b), which introduces the bulk material into the bag, this process of filling the bag do not introduce air into the material. Finally, a weighing machine is needed to ensure that the amount of material inside the bag is correct.

Therefore, the process os packing is very simple, a conveyor belt or a pneumatic pipe is used to transport the bulk material to the bagging machine, which fills the bags. Afterwards an automatized machine palletize the bags for its posterior transportation, see Fig.(1.4).

(a) Feeder funnel

(b) Dispenser



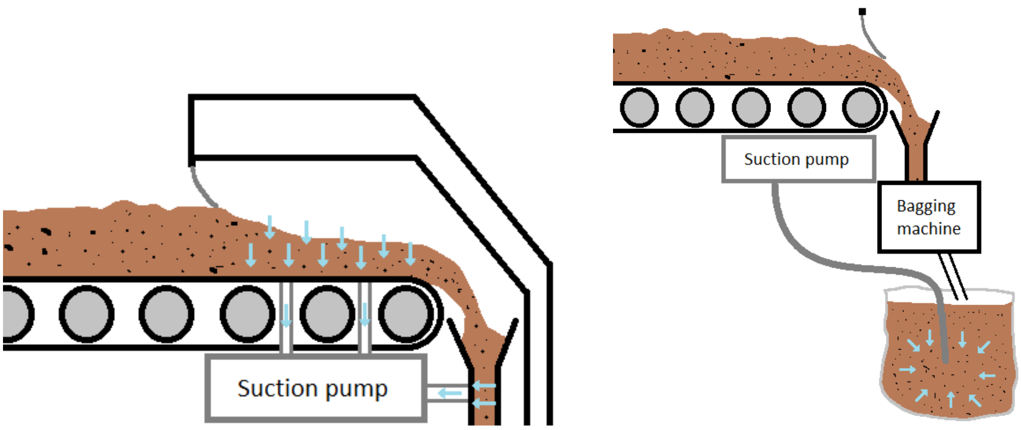
(c) Feeder system

Figure 1.3: Bagging machine components

1.3 De-aeration methods

The de-aeration processes are needed in order to get rid of the extra air, and provide an extra compaction to increase the bulk density. Since the filling process itself do not introduce air in to the granular material, the de-aeration can be done after or during the filling process. Doing the de-aeration process during the filling means introducing suction to the granular material when it is inside the feeder, see Fig.(1.5a). The main issue is the low compaction it provides, since even if the grains were compacted when suction is applied, after the fall they would loose any sort of compaction. The other way is applying suction to the material after it is bagged, see Fig.(1.5b). This one does remove the exceeding air and compacts the bulk material inside the bag.

Figure 1.4: Bagging and palletizing system



(a) Before filling de-aeration (b) After filling de-aeration

Figure 1.5: De-aeration methods

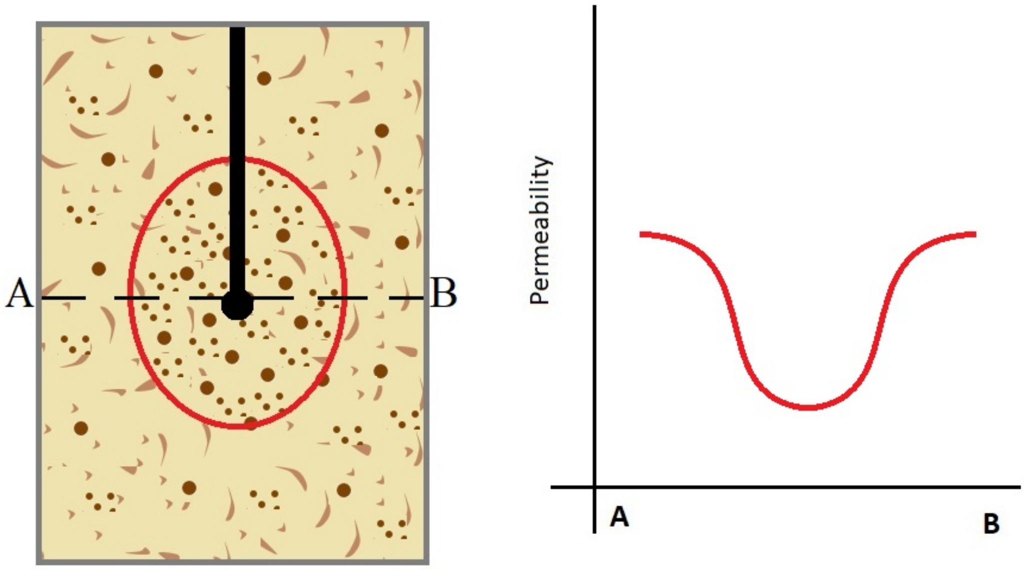
Due to its benefits, the second procedure is the one chosen in this project to analyse and optimize. The method is very simple, after the bag is filled, a probe is introduced into the bag and suction is applied. The process extracts the excess of air and compact the granular material.

Chapter 2

Issues with suction in granular material

During the suction phase, sometimes the amount of air extracted and the level of compaction are not the ones expected. Indeed, the amount of air extracted is too low and the process itself is not efficient. The hypothesis proposed in this project that could explain the behaviour, is the generation of a bulb made of over-compressed material, see Fig.(2.1a), that does not allow the air flow through it. Even if the main purpose of suction is compressing the soil, the purpose of de-aeration is not fulfilled, since the bulb is only a little portion of the whole package.

The bulb generation is due to a combination of the granular material properties, see Fig.(2.1b) and the extraction method, which can be modelled and analysed using a mathematical model. Consequently, the process can be reproduced using such model and solved with numerical models taking in account the material properties. Afterwards the model can be analysed to solve the problem, since is done using a computer, it is simple to change variables and conditions. Unlike approaching it with a full experimental method that would make the cost too expensive, due to the amount of experiments that the investigation will need. At the end, this project is aiming to simulate, identify and



(a) Over-compressed material bulb (b) Permeability across the bag

Figure 2.1: Bag after suction

solve the issues behind the inefficiency with suction process in granular materials, using computational methods.

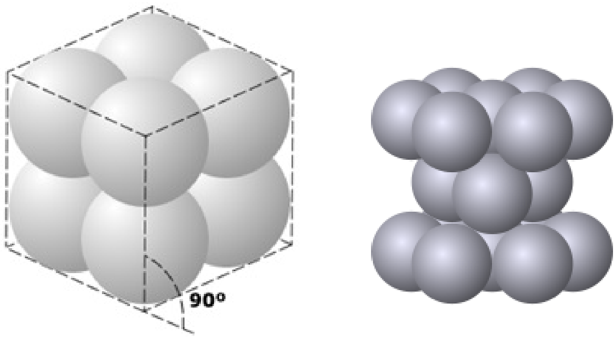
To do so, the material properties related with the suction process is explained alongside with the phenomena that are involved in the bulb generation. Afterwards, the mathematical model that describes the suction in granular materials will be exposed.

2.1 Material properties

The definition of the material in any model is very important, since are the properties of the material that will describe the behaviour of it. Therefore, the follow material properties are the ones that have a significant impact in the fluid flow through a porous media.

- The porosity ϕ measures the void spaces in materials, see "Definicin de la Porosidad

- La Comunidad Petrolera, (2012)". It is the ratio of the void to total volume (2.1). In granular materials, assuming the particles are spherical, the porosity has a theoretical maximum and minimum values. The value depends on the organization of the particles. If it has a cubic distribution the porosity is the maximum possible, see Fig.(2.2a), whereas it is hexagonal the porosity is the minimum, see Fig.(2.2b).



(a) Cubic $\phi = 0.48$ (b) Hexagonal $\phi = 0.26$

Figure 2.2: Theoretically maximum and minimum porosity

$$\phi = \frac{V_V}{V_T} \tag{2.1}$$

where:

V_V, is the void volume,

V_T, is the total volume.

- The permeability κ is the property that describes the ability of a porous material to allow fluids pass through it; it depends on the porosity, see Brown et al. (1993), and the shapes of those pores. Consequently, it is directly related with the porosity and will be used to determine the degree of soil compaction and the bulb dimension. It can be calculated using the following equation (2.3):

$$\kappa = v\frac{\mu \Delta x}{\Delta u} \tag{2.2}$$

where:

$\kappa =$ is the medium permeability,

v = is the superficial fluid flow velocity,

μ = is the dynamic viscosity,

Δx = is the thickness of the porous medium analysed,

Δu= is the fluid pressure gradient.

The permeability and porosity are related with the following equation, see "Relacin entre porosidad y permeabilidad - La Comunidad Petrolera, (2012)".

$$r = \sqrt{\frac{8\kappa}{\phi}} \tag{2.3}$$

where:

κ = is the medium permeability,

ϕ = is the porosity,

r = the average grain radius.

- The air density ρ is important since most of the equations that are used in this project require the fluid to be incompressible, so the air density must be constant doing the suction. To know if the air behaviour like that, the Mach number (2.4) will be used, since if it is lower than 0.3 the air can be used as incompressible.

$$M = \frac{v}{c} \tag{2.4}$$

where:

v = is the local flow velocity with respect to the boundaries,

c = is the speed of the sound in the medium.

- Dynamic viscosity; since the permeability does not take in account the fluid that is flowing, another property is needed in order to determine how easier is for the fluid to flow through the granular material. This property is the dynamic viscosity μ, which opposes the relative motion between two surfaces of the same fluid if they have different velocities, see IUPAC (2014). Consequently, along with the permeability it determines how much pressure is needed to make the fluid flow at a determined rate.

- The pressure u is the force applied perpendicular to the surface of an object per unit area over which that force is distributed. It can be described as the gauge pressure, zero-referenced against ambient air pressure, or as the absolute pressure.

  In this project the gauge approach is used, however the signs are changed. A positive pressure in this document stands for a negative gauge pressure or vacuum.

2.2 Vacuum pumps

A vacuum pump is a device that removes gas molecules from a sealed volume in order to leave behind a partial vacuum. Consequently, the minimum absolute pressure that can be achieved in a suction process is zero.Therefore, the maximum vacuum that can be applied to the granular material would be almost the void.

This fact is very important, since the maximum pressure (minimum gauge pressure) that a pump induces to the sack will be the same independent of its power. Nevertheless, this is only true if the pump can keep up with the air flow rate. Therefore, if all the pumps can keep up with the flow rate,it dose not mater how much power they have, all off them will make the pressure at the probe almost one.

On the other hand, the throughput of the pump is defined as the flow rate multiplied by the gas pressure at the probe. Since it can be maximum one, the difference between two pumps with different power is the maximum air flow they can provide, having the same pressure.

Finally the last important aspect of a pump is the absolute pressure it can reach. However, nowadays almost all industrial pumps can archive easily absolute pressure of 0.1 kPa. Consequently, the difference in suction if the pressure at probe was 0 kPa or it was 0.1 kPa would be negligible.

2.3 Phenomena behind the bulb creation

Previous the modelling of the suction process, a explanation of the most important phenomena behind the bulb creation are exposed below.

2.3.1 The air pressure gradient inside the package

To create suction a pressure gradient is applied to the air in order to make it flow. When this gradient is applied a pressure field is created, which affects both the air and the grains. On the grains perimeters the pressure is not equal in all directions, see Fig.(2.3), therefore the result of all the pressure is a force towards the probe. This can be understood as a force field pointing out the suction probe. This force field is similar to the gravity, in such manner the forces are greater when closer to the pipe and all the forces point towards one point. Another important property that differs from the gravity is that it depends on the volume of the particle, not on the mass, such like an hydrostatic force.

Finally, since the grains above the one analysed are pulled also, the total increased force that act on the grain analysed due to suction, is the pressure at the grain u_{grain} minus the pressure outside $u_{atm} = 0$. This is because, the gradient affect the grains above the one analysed, therefore it has to resist also the forces that act on the grains above, it also will transmit the forces to the next grain below. To compensate that force field, the interaction within grains change and the grain structure is reorganized in order to resist the load. Overall, a soil compaction process is created when suction is applied.

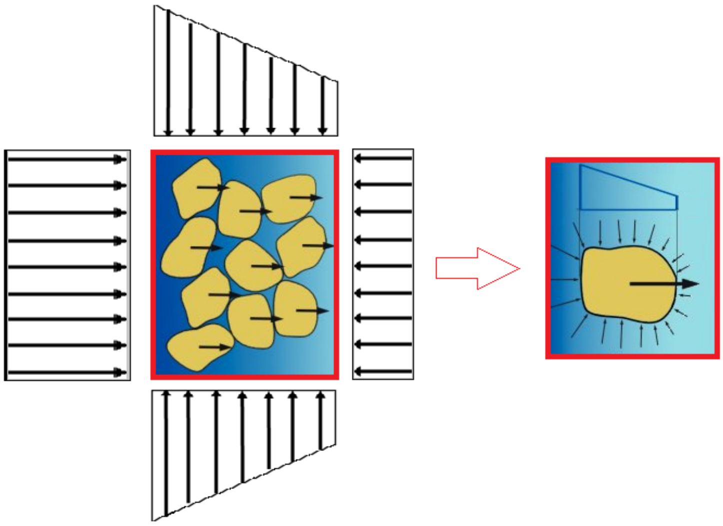


Figure 2.3: Suction effect on grain

2.3.2 The package walls pressure

When air is extracted, the pressure inside the package is reduced. If the sacks are permeable it dose not matter since the reduction in pressure is linear, consequently, the difference in pressure between outside and inside at the sack walls is null. Therefore, the sack wall does not compress the soil. However, if the sack is impermeable the difference in pressure between outside and inside is no linear, as a consequence, the sack wall press the material inside, see Fig.(2.4).

2.3.3 Inter-granular pressure due to the material own weight

Another important phenomenon related to the permeability, is the pressure due to the material own weight. It does not affect the fluid inside the pours, however, the increase of the inter-granular pressure compacts the material. Usually in soil mechanics, the pressure is calculated as a hydrostatic pressure. However, if the the granular material is storage inside a silo, the friction within the walls and the grains will reduce the vertical pressure at the bottom. Janssen analysed this behaviour and proposed a formula (2.5) to take in

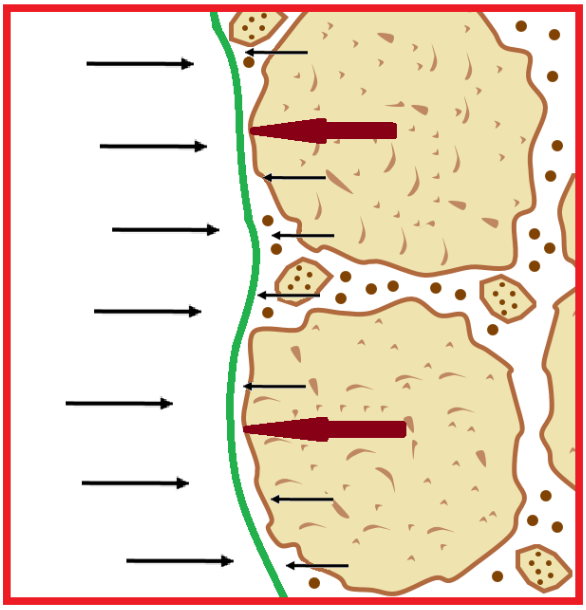


Figure 2.4: Impermeable sack wall pressure

account this phenomenon.

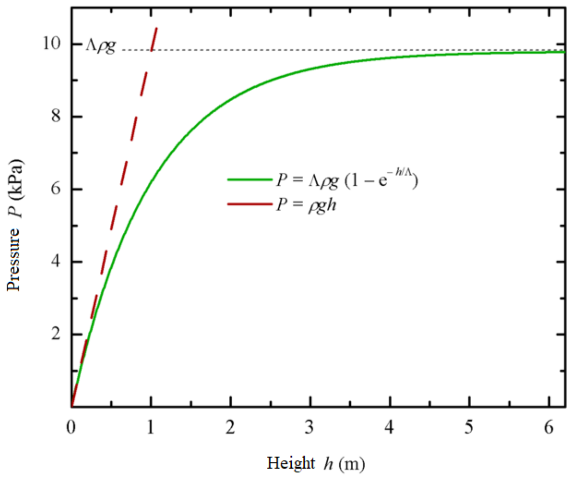


Figure 2.5: Inter-granular pressure comparison

$$P = \Lambda \rho g \left(1 - e^{-h/\Lambda}\right) \tag{2.5}$$

where:

P = is the pressure between grain due to the material above, does not take in account the fluid pressure inside

Λ = is a parameter that depends on the static friction

g = is the gravitational acceleration,

ρ = is the bulk material density,

h = is the elevation at the chosen point

2.3.4 Well graded granular material

If the material is well graded the grain size is disparate, see Fig(2.6) and it produces a local reduction near the pipe. That is because, the mobility of the small grains is greater than bigger grains, consequently, those smaller grains are the ones moving first towards the suction pipes. That will make the permeability in that zone be the one determined by the smaller grains, thus lower, reducing the overall suction. If the material is poorly graded this has not effect since all the material have the same permeability. Since in bulk material industry the material is usually poorly graded, the bulk material is homogeneous, this is not a common suction issue.

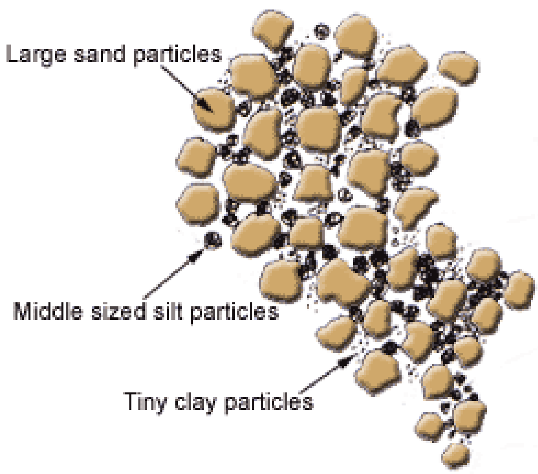


Figure 2.6: Well graded material

Chapter 3

Mathematical modelling of non-linear flow in porous media

A mathematical model is the representation of the physics of a real world phenomenon as group of equations (Governing, Defining and Constitutive equations) and constrains. Mathematical models can be analytically solved for some simple cases, whereas more complex flow regimes require a discrete, numerical representation of the process which is then solved using a computer.

In this work, two mathematical models are used, one is static and the other transient. The need of using two models is the difference in complexity of those, the simple one is used to explain the basic aspects of the suction process. Whereas the complex, it gives a more detailed output, therefore, it will be used to optimize the suction process.

However before explaining the two main mathematical models, two important matters will be addressed. The first one is the introduction of the pressure dependent permeability, that defines the bulb creation. The following one is the Darcy's law, which describe the fluid flow though a porous medium.

3.1 Suction-dependent permeability

In order to explain the bulb generation a pressure depended permeability has been proposed. The main idea behind this approach is the fact there are numerous phenomena that compress the grains during a suction process.Therefore if the granular material is compressed its porosity is also reduced, consequently the permeability will be lowered too.

This fact determines the bulb generation, since in the areas where the permeability is low, the material is more compacted and the airflow is reduced. This reduction in the airflow on the surrounding probe area prevents the suction process in the others parts of the bag. Therefore, this suction-dependent behaviour is the one analysed with numericals methods in order to determine how the bulb is generated and its size.

On the another hand, the pressure depends also on the permeability, making the mathematical problem be non-linear, since both depends of each other. That makes the model more difficult to solve and understand. Consequently, in this work the permeability is modelled in different ways before approaching the suction-dependent one. Those permeabilities are described below attached to a graph that describe them.

- A constant permeability, see Fig.(3.1), due to its simplicity, that will allow a fast understanding of how the pressure is distributed in porous media when suction is applied. The down side is the lack of an impermeable bulb, since the porosity will be equal in the entire medium. However, in the other hand, since the problem is linear this method is the simplest to solve.

- A permeability that depends on the distance, see Fig.(3.2), allows the introduction of increase in pressure due the material own weight. In addition, it is possible to analyse the behaviour of the pressure surface when the permeability is not constant. This way of describing the permeability still makes the problem linear.

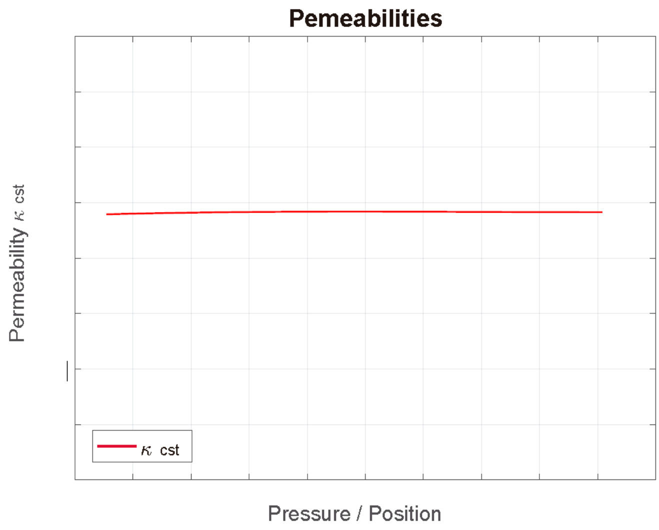


Figure 3.1: κcst

- Finally, the pressure dependent permeability, see Fig.(3.3), is analysed, this is the more realistic approach and the hardest to solve due to its non-linearity. This approach is the one used to optimize the suction processes, since is the approach that describes better how the granular material compacts under the suction. Consequently, is has the capability to describe the position and size of the impermeable bulb.

3.2 Darcy's law

Darcy's law is a relationship between the pressure, viscosity, permeability and instantaneous flow rate in a porous media given a distance and a flow area. It describes the flow of an incompressible fluid through a porous medium (3.1), see Wang and Anderson (1982).

$$Q = -\frac{\kappa A \Delta u}{\mu L} \tag{3.1}$$

where:

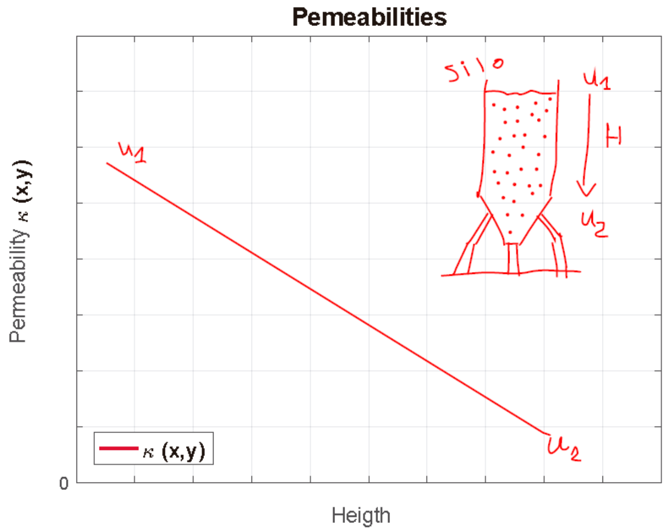


Figure 3.2: $\kappa(x, y)$

Q = total discharge,

κ = is the medium permeability,

Δu = is the pressure gradient,

A = is the section area of the medium analysed,

L = is the length of the medium analysed.

This expression can be simplified as the following one (3.2); which is the one used in this project to relate the air flux with the pressure field.

$$q = -\frac{\kappa}{\mu}\nabla \boldsymbol{u} \tag{3.2}$$

where:

q = is the flux,

μ = is the dynamic viscosity,

u = is the fluid pressure.

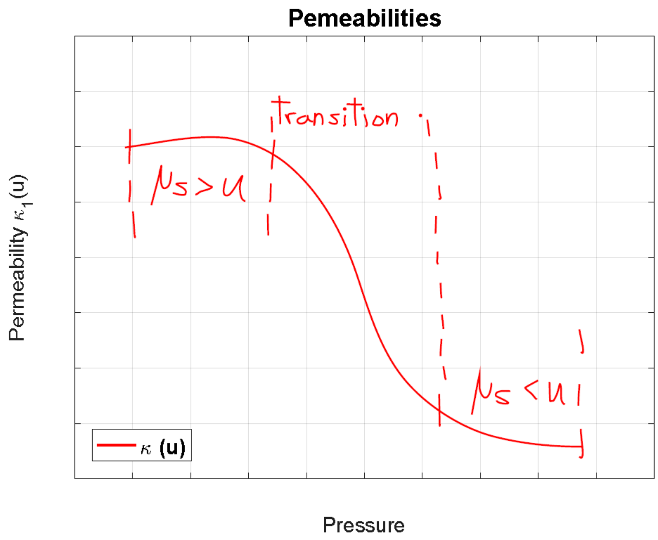


Figure 3.3: $\kappa(u)$

3.3 Steady problem

The first mathematical model used is a steady-state flow problem, see Wang and Anderson (1982), in which the flow rate, permeability, density and suction will be constant. This model determines the final state when suction is applied. It has some limitations since there is no time component, so it is hard to determine how the bulb has been created. In addition, the modelling of an impermeable bag using this model is not useful since the final state will always be the bag empty of air with a homogeneous porosity. However, it is simple and fast to solve and can determine the volume of the bulb created in permeable bags.

To obtain the govern equation that describes this model, a mass conservation approach is used, see Blazek (2005). It implies that, the rate of change of mass inside the control volume will be equal to the difference between the influx and out-flux of mass from the control volume, see Fig.(3.4).

Density $= \rho\,(x, y, z, t)$

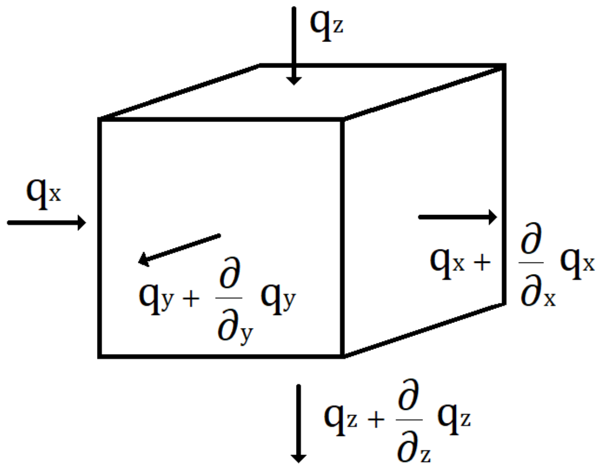


Figure 3.4: Control volume

Flux $= \bar{q}\,(t) = \left(q_x\,(x,y,z,t)\,,q_y\,(x,y,z,t)\,,q_z\,(x,y,z,t)\right)$

Mass inside control volume $= \rho dxdydz$

Mass flux into the control volume $= \rho q_x dydz + \rho q_y dxdz + \rho q_z dxdy$

Mass flux out of the control volume $= \left(\rho q_x + \frac{\partial}{\partial x}\rho q_x\right) dydz + \left(\rho q_y + \frac{\partial}{\partial y}\rho q_y\right) dxdz + \left(\rho q_z + \frac{\partial}{\partial z}\rho q_z\right) dxdy$

$$Mass_{IN} - Mass_{OUT} = \frac{\Delta Mass}{\Delta Time} \quad \rightarrow \quad \frac{\partial}{\partial x}\rho q_x + \frac{\partial}{\partial y}\rho q_y + \frac{\partial}{\partial z}\rho q_z = \frac{\partial \rho}{\partial t} \tag{3.3}$$

Since the air is considered as incompressible, the ρ can be erased from the equation. In consequence, the divergence of the flux must be zero. (3.4).

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0 \quad \rightarrow \quad \nabla \bar{q} = 0, \quad \text{mass conservation} \tag{3.4}$$

Once the mass conservation has been described, Darcy's law is used in order to express the flux in terms of pressure, permeability, and viscosity. After this substitution,the viscosity can be pulled out of the partial derivative. Finally, equation (3.5), which is similar to the Laplace equation, will be solved using numerical methods.

$$\frac{\partial\left(\kappa/\mu\right)\partial \boldsymbol{u}_x}{\partial x^2}+\frac{\partial\left(\kappa/\mu\right)\partial \boldsymbol{u}_y}{\partial y^2}+\frac{\partial\left(\kappa/\mu\right)\partial \boldsymbol{u}_z}{\partial z^2}=0 \quad \rightarrow \quad \frac{1}{\mu}\nabla\cdot(\kappa\nabla\boldsymbol{u})=0, \quad \text{steady equation} \tag{3.5}$$

where:

$\mu =$ is the dynamic viscosity,

$\kappa =$ is the permeability,

$\boldsymbol{u} =$ is the pressure.

The initial conditions are:

- Two Dirichlet boundary conditions:
  - the pressure at the probe will be one
  - the pressure at the contour will be zero.
- A constant viscosity
- An initial permeability that can be homogeneous or not depending on the κ used. If its used κ = cst or κ(u), it will be homogeneous, if i used κ(x,y,z) it will depend on the position, therefore, it will be heterogeneous.

The last thing to mention about the steady problem is the relation with the different permeabilities and the govern equation.

- κ = cst: the κ can be pulled out of the equation and it is only needed to solve the Laplace equation, which is linear.

- κ(x,y,z): since the κ depends on the position (x,y,z), it cannot be extracted from the equation. However, the value of κ is know previous the solution of the equation, thus the problem is still linear.

- κ(u(x,y,z)): this time the pressure depend on the position,consequently, κ also depends on it. In consequence, the kappa cannot be pulled out fo the equation. Moreover, since its needed to solve the equation to know κ, the problem is non-linear.

3.4 Transient problem

To improve the suction modelling and erase the limitation of the previous model, a transient flow model is used. This model allows the study of the bulb generation since it no longer describes only the final state, moreover it allows the description of the system along all the different phases of the bulb generation. In addition, the study of impermeable bags is useful, even if the final state is the same as in th previous model, since the evolution of the process can help to understand the suction issues.

Since the suction action is an air diffusion process, a groundwater diffusion equation (3.6) is used, due to the similarity of the problem, see Wang and Anderson (1982). However, the groundwater equation uses different parameters such as the hydraulic conductivity, hydraulic head, and storage coefficient and other ones like the source term that are not used. Those parameters are changed using those new parameters: pressure, permeability, viscosity and a hydraulic diffusion coefficient. The final equation is similar to the heat equation, but it does not measure the temperature flux due to a differential temperature field, instead it measures a fluid flux due to a pressure field.

$$S_S \frac{\partial h}{\partial t} = -\nabla \cdot (K \nabla h) - G \quad \rightarrow \quad \frac{S_S}{\rho g} \frac{\partial \boldsymbol{u}}{\partial t} = -\nabla \cdot \left(\frac{K}{\rho g} \nabla \boldsymbol{u} \right) \tag{3.6}$$

where:

S_S = is the specific storage,

h = is the hydraulic head,

t = its the time variable,

K = is the hydraulic conductivity,

G = is the source term.

Finally, after the $\frac{K}{\rho g} = \frac{\kappa}{\mu}$ and $\frac{\rho g}{S_S} = \alpha$ substitution;

$$\frac{\partial \boldsymbol{u}}{\partial t} = \frac{\alpha}{\mu} \nabla \cdot (\kappa \nabla \boldsymbol{u}) \tag{3.7}$$

where:

$\boldsymbol{u}$ = is the fluid pressure,

κ = is the medium permeability,

μ = is the dynamic viscosity,

α = is a diffusion coefficient.

The initial conditions are:

- A Dirichlet boundary condition; the pressure at the probe will be one

- A Neumann boundary condition; the flux at the contour is zero
- The viscosity will be constant
- An initial permeability that can be homogeneous or not depending on the κ used. As in the previous model.

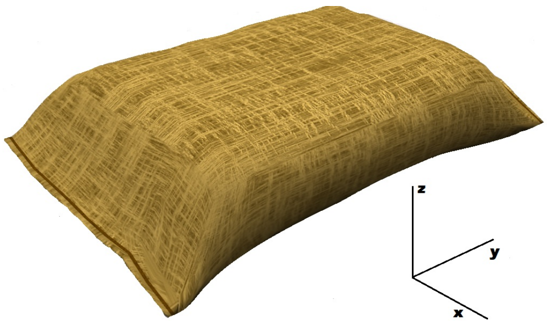
Once again the last thing to mention are the interactions between the different permeabilities and the model, which are the same as the steady one.

Chapter 4

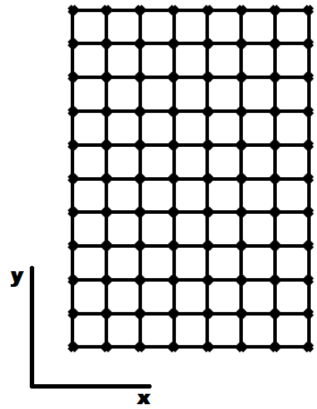
Numerical models

In this project there are two governing equations, the steady equation, which is an elliptic PDE (partial differential equation), and the transient equation, which is a parabolic PDE. The analytical solutions of the previous equations are hard to find, moreover if the problem si non-linear, but as an engineering point of view, a numerical approximation of those could be enough to solve the suction issue. Therefore, the use of numerical methods to solve those equations will be the way to go in this project.

In this project the medium analysed will be a rectangular sack Fig.(4.1a), since the z component of the sack will be shorter then the other two, x and y, the problem is treated as bi-dimensional. The discretization, see Moukalled et al. (2015), of the sack is done by creating a rectangular mesh the same size as the sack, see Fig.(4.1b). Therefore, the solution of the governing equation is the pressure on the mesh nodes. Once the pressure is known, the flow, permeability and porosity are calculated. In consequence it possible to calculate the amount of air inside the sack after the suction and the reduction in volume that has occurred during the process. Said that, the next approach is how to solve the two governing equation and analyse them.



(a) 3D sack



(b) Discretyzed sack mesh

Figure 4.1: Analysis medium (A sack)

4.1 Stationary problem

In order to analyse the steady flow equation, it has to be solved first. For that, the strong form of the equation (4.1) has to be transformed into its weak form, using weighted residuals, see Finlayson (1972).

$$\frac{1}{\mu}\nabla \cdot (\kappa \nabla \boldsymbol{u}) = f \quad \text{in}\, \Omega \tag{4.1}$$

$$\boldsymbol{u} = 0 \quad \text{in}\, \Gamma_d, \text{ bag walls} \tag{4.2}$$

$$\boldsymbol{u} = 1 \quad \text{in}\, \Gamma_d, \text{ probe} \tag{4.3}$$

$$f = 0 \quad \text{in}\, \Omega \tag{4.4}$$

$$\tag{4.5}$$

with $\partial\Omega = \Gamma_d$

To do so, a test function v such that v=0 on Γ_d, will multiply the equation. In addition, the whole equation will be integrated using integration by parts.

$$\int_{\Omega} v\frac{1}{\mu}\nabla\cdot(\kappa\nabla\boldsymbol{u})\,d\Omega=\int_{\Omega} vf\,d\Omega \tag{4.6}$$

Once the equation has been integrated, the boundary conditions are applied obtaining the weak form (4.7).

$$a\left(v,\boldsymbol{u}\right) = \frac{1}{\mu}\int_{\Omega}\nabla v\cdot(\kappa\nabla\boldsymbol{u})\,d\Omega \tag{4.7}$$

$$l\left(v\right) = \int_{\Omega} vf\,d\Omega \tag{4.8}$$

So now the main idea is to find $\boldsymbol{u}\epsilon H^1$ such that $\boldsymbol{u}=\boldsymbol{u}_d$ on Γ_d that verify $a(v,u)=l(v)$ for any test function $v\epsilon H^1$ such that $v=0$ on Γ_d. As mentioned above, the medium analysed, the bag, is discretized using a mesh. Therefore, the pressure is no longer a continuous equation, instead it is an interpolation (4.9).Each $\boldsymbol{u}_j$ is the pressure at a j-node.

$$\boldsymbol{u}\left(\bar{x}\right)\backsimeq\boldsymbol{u}^h\left(\bar{x}\right)=\sum_j\boldsymbol{u}_jN_j\left(\bar{x}\right) \tag{4.9}$$

Since $\boldsymbol{u}_j$ no longer depends on the position, substituting the interpolation in the weak form , the integral can be solved since the functions inside are known.

$$a\left(v,\sum_j\boldsymbol{u}_jN_j\right) = \frac{1}{\mu}\int_{\Omega}\nabla v\cdot\left(\kappa\nabla\sum_j\boldsymbol{u}_jN_j\right)d\Omega \tag{4.10}$$

$$\sum_j a\left(v,N_j\right)\boldsymbol{u}_j = \sum_j\left(\frac{1}{\mu}\int_{\Omega}\nabla v\cdot(\kappa\nabla N_j)\,d\Omega\right)\boldsymbol{u}_j \tag{4.11}$$

However, the $\boldsymbol{u}_1 \dots \boldsymbol{u}_j$ are still unknown and there is only one equation $a(v, \boldsymbol{u}) = l(v)$. To solve that issue, the imposition of various test function $v = N_i$ will provide more equations to find $\boldsymbol{u}_1 \dots \boldsymbol{u}_j$. As consequence, a system of equations is obtained.

$$a(N_i, N_j) = \frac{1}{\mu} \int_{\Omega} \nabla N_i \cdot (\kappa \nabla N_j) \, d\Omega l(v) \tag{4.12}$$

$$l(N_i) = \int_{\Omega} N_i f \, d\Omega \tag{4.13}$$

$$\boldsymbol{u}_1 a(N_1, N_1) + \boldsymbol{u}_2 a(N_1, N_2) + \ldots + \boldsymbol{u}_j a(N_1, N_j) = l(N_1) = 0 \tag{4.14}$$

$$\boldsymbol{u}_1 a(N_1, N_1) + \boldsymbol{u}_2 a(N_1, N_2) + \ldots + \boldsymbol{u}_j a(N_1, N_j) = l(N_2) = 0 \tag{4.15}$$

$$\vdots \tag{4.16}$$

$$\boldsymbol{u}_1 a(N_i, N_1) + \boldsymbol{u}_2 a(N_i, N_2) + \ldots + \boldsymbol{u}_j a(N_i, N_j) = l(N_i) = 0 \tag{4.17}$$

This system can be written as a matrix equation. Considering the matrix components as $k_{i,j} = a(N_i, N_j)$ and the $\boldsymbol{u}_1 \dots \boldsymbol{u}_j = \bar{\boldsymbol{u}}$ as a vector. The solution of the govern equation will be a linear system of equations $K\bar{\boldsymbol{u}} = \bar{f}$ (4.18).

$$\begin{vmatrix} k_{1,1} & k_{1,2} & \cdots & k_{1,j} \\ k_{2,1} & k_{2,2} & \cdots & k_{2,j} \\ \vdots & \vdots & \ddots & \vdots \\ k_{i,1} & k_{i,2} & \cdots & k_{i,j} \end{vmatrix} \begin{vmatrix} \boldsymbol{u}_1 \\ \boldsymbol{u}_2 \\ \vdots \\ \boldsymbol{u}_j \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{vmatrix} \tag{4.18}$$

The K matrix is singular so the system cannot be solved a priori, however using the Dirichlet conditions $\boldsymbol{u} = \boldsymbol{u}_d$ on Γ_d the matrix system will be reduced. To do it, rows and columns attached to a known pressure are deleted, as a consequence, the matrix is reduced into K_{RED} and the vectors $\bar{\boldsymbol{u}}$ and $\bar{f}$ are also reduced. Consequently, the information contained in the deleted columns is transferred to the $\bar{f}$ vector, changing its components. To define the new components, first a vector $\bar{\boldsymbol{u}}_d$ is defined as $\bar{\boldsymbol{u}}_J = 0$ if $\boldsymbol{u}_j$ is unknown and $\bar{\boldsymbol{u}}_j = \boldsymbol{u}_j$ if $\boldsymbol{u}_j$ is known. Once $\bar{\boldsymbol{u}}_d$ is defined, the new $\bar{f}_{RED}$ components are $f_{RED,\,i} = f_i + \sum_j k_{i,j} \cdot \boldsymbol{u}_{d,\,j}$.

$$\begin{vmatrix} k_{1,1} & k_{1,2} & \cdots & k_{1,j} \\ k_{2,1} & k_{2,2} & \cdots & k_{2,j} \\ \vdots & \vdots & \ddots & \vdots \\ k_{i,1} & k_{i,2} & \cdots & k_{i,j} \end{vmatrix} \begin{vmatrix} \boldsymbol{u}_1 \\ \boldsymbol{u}_2 \\ \vdots \\ \boldsymbol{u}_j \end{vmatrix} = \begin{vmatrix} \sum_j k_{1,j} \cdot \boldsymbol{u}_{d,\,j} \\ \sum_j k_{2,j} \cdot \boldsymbol{u}_{d,\,j} \\ \vdots \\ \sum_j k_{i,j} \cdot \boldsymbol{u}_{d,\,j} \end{vmatrix} \tag{4.19}$$

After reducing the matrix, the new equation system is equivalent to the the first one, however it is not singular and can be solved by calculating the K_{RED}^{-1} matrix, obtaining the unknown pressures $\bar{\boldsymbol{u}}_{RED} = K_{RED}^{-1} \cdot \bar{f}_{RED}$. The final solution is $\bar{\boldsymbol{u}}_f = \bar{\boldsymbol{u}}_d \cup \bar{\boldsymbol{u}}_{RED}$.

To solve the previous system the $k_{i,j}$ components are calculated. Since the $N(\bar{x})$ equations are known, the integrals are solvable. However depending on the κ the system obtained might be not linear. In consequence, the next approach is the explanation of the interaction with the κ and the system equation obtained by using numerical methods.

- $\kappa = cst$ and $\kappa(\bar{x})$

  If κ is constant, it can be pulled out of the integration, and the system obtained is linear since the K obtained do not depend on the pressure.

$$a\left(N_i, N_j\right) = \frac{\kappa}{\mu} \int_{\Omega} \nabla N_i \cdot \nabla N_j \, d\Omega \tag{4.20}$$

  If $\kappa(\bar{x})$ depends on the position, it cannot be pulled out of the integration, but since the $\kappa(\bar{x})$ is known the integrations can still be calculated. Also the system obtained is still linear.

$$a\left(N_i, N_j\right) = \frac{1}{\mu} \int_{\Omega} \nabla N_i \cdot \left(\kappa\left(x\right) \nabla N_j\right) \, d\Omega \tag{4.21}$$

- $\kappa(\boldsymbol{u})$

  However, if $\kappa(\boldsymbol{u})$ depends on the pressure, the $K(\boldsymbol{u})$ will also depend on it. As a consequence, the $K(\boldsymbol{u}) \cdot \boldsymbol{u} = \bar{f}$ system will be not lineal. In order to solve the system a fixed-point iteration, Picard method, see Berinde (2007),is used.

$$\boldsymbol{u}_{RED,\,i+1} = K_{RED}^{-1}\left(\boldsymbol{u}_i\right) \cdot \bar{f}_{RED,\,i} \tag{4.22}$$

  The method consist in use a initial pressure $\boldsymbol{u}_i$ to obtain a new one $\boldsymbol{u}_{i+1}$, then the $\boldsymbol{u}_{i+1}$ is used to obtain the $\boldsymbol{u}_{i+2}$. This process is being iterated until $\boldsymbol{u}_{n+1} = \boldsymbol{u}_n \pm tolerance$ is being satisfied. Once, the condition is satisfied the final pressure is $\bar{\boldsymbol{u}}_f = \bar{\boldsymbol{u}}_d \cup \bar{\boldsymbol{u}}_{RED,\,n+1}$.

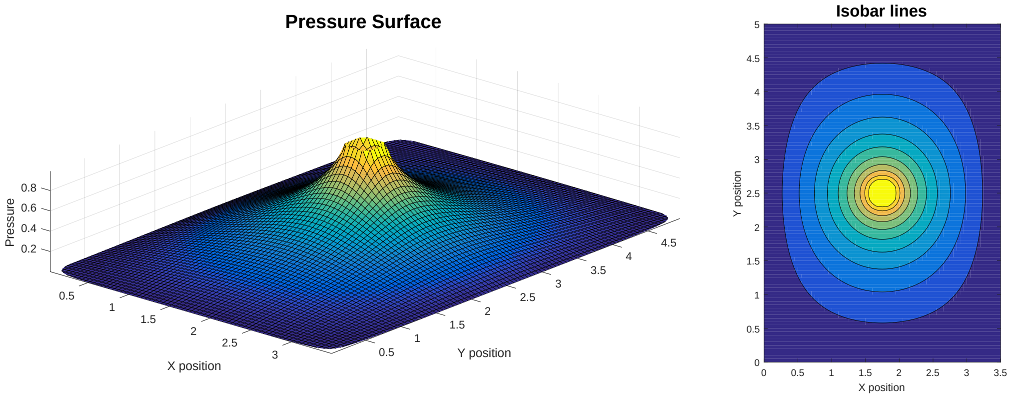
$$a\left(N_i, N_j\right) = \frac{1}{\mu}\int_{\Omega} \nabla N_i \cdot \left(\kappa\left(\boldsymbol{u}\right) \nabla N_j\right)\, d\Omega \tag{4.23}$$

Once the govern equation is solved, the model is analysed with different permeabilities. For more information about the steady-state flow system solution see Wang and Anderson (1982) and Moukalled et al. (2015).

4.1.1 Analysis of the steady governing equation with constant permeability

The first system analysis is done using a constant permeability, this is due to its simplicity, which allows an easy explanation of the pressure field behaviour under suction conditions. During the air extraction, the pressure gradient tends to increase towards the suction probe, see Fig.(4.2a), therefore, the isobar lines tend to group as they get closer to the pipe, see Fig.(4.2b). That behaviour can be explained using the isobar planes,taking in account the z component, the mass conservation and Darcys law. In a control volume the mass does not change, therefore the income flow and the out flow are equal, in specific using a volume control defined by two isobar planes. Therefore, the flow through the area in he area of those is reduced

to ry and increase (3.1).



(a) 3D Pressure surface κ cst (b) Isobar lines κ cst

Figure 4.2: Pressure distribution inside the sack κ cst

This pressure distribution is the one of the cause of the low bulk density after suction, since the entire pressure gradient is mostly concentrated near the probe. Consequently, the rest of the sack does not have a compression force, inducing low bulk density in the major part of the medium. Also, see Fig.(4.3), this behaviour does not depend on the permeability either the granular material, since changing it only affects the flow rate, not the pressure field. However, as it will be explained in the next section, if the permeability is not constant this behaviour get worst towards the de-aeration process.

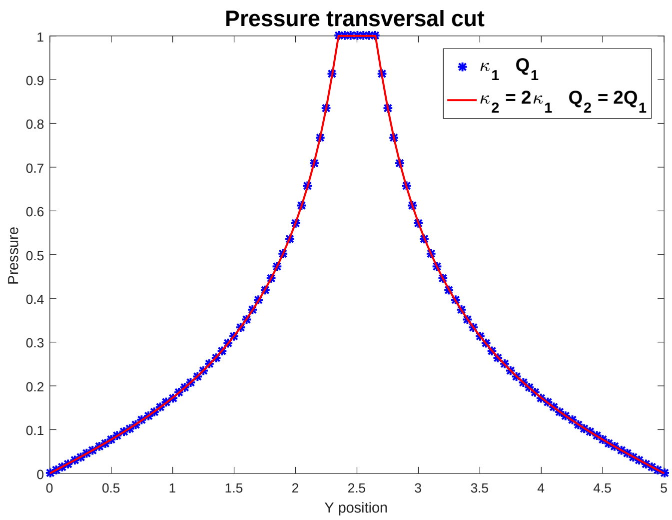
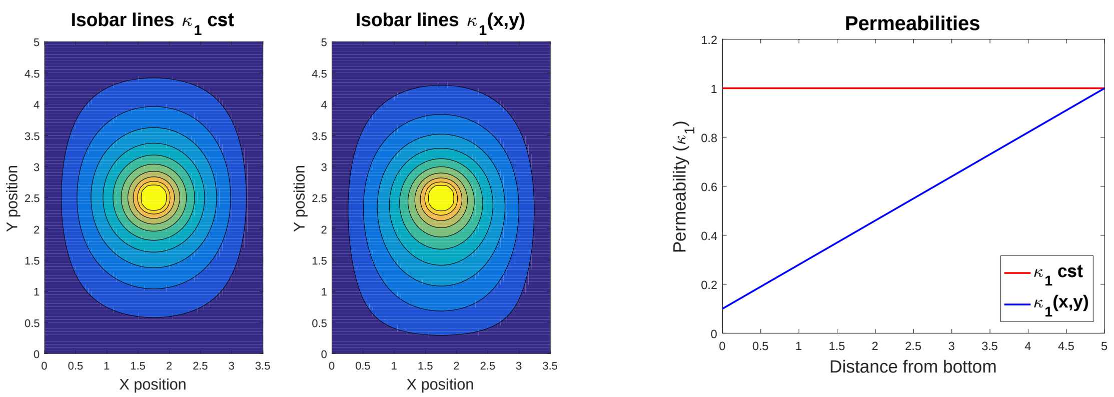


Figure 4.3: Pressure transversal middle cut with κ cst

4.1.2 Analysis of the steady governing equation with position dependent permeability

The second analysis its done using a dependent permeability, see Fig.(4.4b), in specific, a one decreasing toward the sack/silo bottom due to self weight pressure. This kind of permeability makes the isobar lines tend to move towards the direction where it decreases, see Fig.(4.4a). The phenomenon is defined by the same properties that explained the previous behaviour and has two effects depending on the side analysed, above or below the probe, see Fig.(4.5). If it is above, both the area and the κ is reduced towards the pipe, so the pressure gradient increases even more than before, consequently the isobar lines will move towards bottom. However if it is below, the area will decrease towards the probe unlike the κ that will not, therefore κ compensates the area reduction and makes the isobars move also towards bottom.



(a) Isobar lines comparison

(b) κ cst and κ(x,y). permeabilities

Figure 4.4: Isobar lines and permeabilities comparison

In short, the isobar lines tend to group towards the areas where the permeability is lower. This phenomenon has low impact on bagging de-aeration processes, but in case of de-aerating a silo to improve its storage capacity, positioning the pump below the middle point will increase the suction performance. That is because the isobar lines will have the same spacing towards all directions, making the process equal in the entire silo.

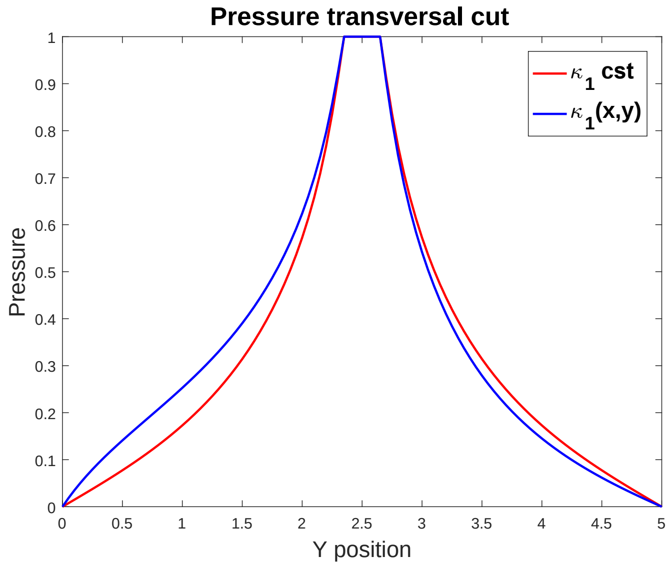
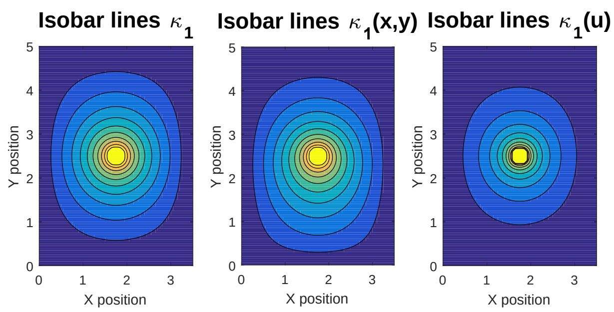


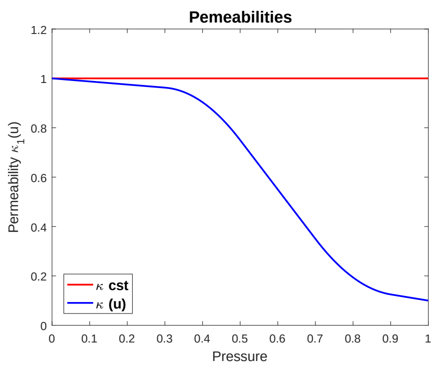
Figure 4.5: Pressure transversal middle cut with κ cst and κ(x)

4.1.3 Analysis of the steady governing equation with pressure dependent permeability

Last, the permeability tested is the pressure dependent one. In this test, the isobar lines where even close then the one obtained with a constant permeability, see Fig(4.6a). That is due a snowball effect. That means, once the suction is applied and due to κ(u), the isobar lines grouping behaviour is starting to get worse on its own, like a snowball throw downhill that get bigger alone.



(a) Isobar lines comparison



(b) κ cst and κ(u). permeabilities

Figure 4.6: fig:Isobar lines and permeabilities comparison

To explain this effect, see Fig.(4.7), the iteration process to obtain the final pressure field are used. At the first iteration, the pressure field is close to the one created by a constant permeability, therefore the pressure gradient at the centre is bigger and the soil is compressed there. Consequently, the κ(u) that takes in account that compression is reduced in that area, so the isobar lines will get closer in the next iteration. This is due to the phenomenon explained in the distance dependent pressure, which states that the isobar lines tend to group toward the areas where the permeability is lower. Therefore, in each iteration the isobar lines get closer to the probe until it reaches an equilibrium and it is only needed tree iterations to reach almost its equilibrium state, which means that this process occurs fast.

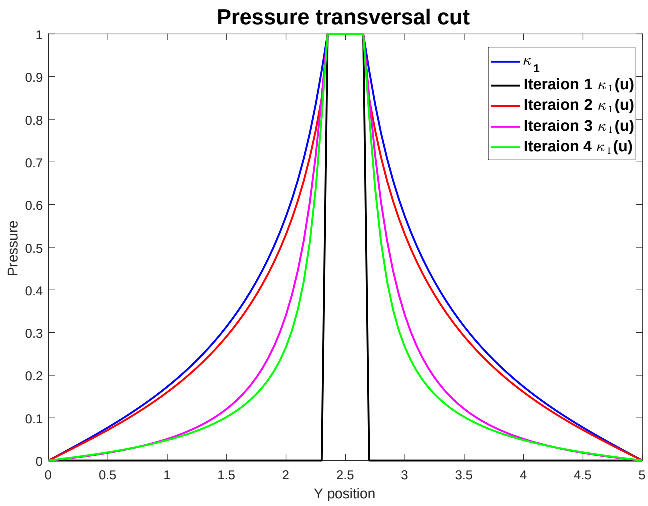


Figure 4.7: Pressure transversal middle cut with κ (u) iteration evolution

The "snowball effect" is the main cause behind the inefficiency during the suction, since as it can be shown on the , see Fig.(4.6), in the final iterations the pressure gradient only starts to be relevant at one meter deep inside the sack. Consequently, the pressure field that compact the soil and extract the air do not reach all the medium and the process is inefficient. Finally, to reproduce this effect in a proper way, since the iteration only give us an idea how the process works, the transient model will be the next focus to enhance the understanding of the bulb creation phenomenon.

4.2 Dynamic problem

Once again, to solve the transient equation, the strong form (4.24) has to be transformed into its weak form (4.28).This process is done the same way as the steady equation, having the strong form;

$$\boldsymbol{u}_t = \frac{\alpha}{\mu}\nabla\cdot(\kappa\nabla\boldsymbol{u}) \qquad \text{in}\,\Omega \tag{4.24}$$

$$\boldsymbol{u} = 1 \qquad \text{in}\,\Gamma_d\text{, pressure at probe} \tag{4.25}$$

$$(\kappa\nabla\boldsymbol{u})\cdot\mathbf{n} = 0 \qquad \text{in}\,\Gamma_n\text{, sack walls are impermeable} \tag{4.26}$$

$$\tag{4.27}$$

with $\partial\Omega = \Gamma_d \cup \Gamma_n$

it is transformed to its weak form,

$$\int_\Omega v\boldsymbol{u}_t\,d\Omega = \frac{1}{\mu}\int_\Omega \nabla v\cdot(\kappa\nabla\boldsymbol{u})\;d\Omega + \int_{\Gamma_n} v\cdot 0\,d\Gamma \tag{4.28}$$

Once the weak form is obtained,it can be write as a system of vectors and matrix. However, since there is a new matrix M multiplying an unknown vector $\bar{\boldsymbol{u}}_t$, is not possible to solve it as a system of equations.

$$M\bar{\boldsymbol{u}}_t = K\bar{\boldsymbol{u}} + \bar{f} \tag{4.29}$$

In order to solve the new system, the time is discretized, as a consequence, $\bar{\boldsymbol{u}}_t$ can be described as $\frac{\boldsymbol{u}_{t+\Delta t}-\boldsymbol{u}_t}{\Delta t}$. Doing it this way, the Euler method, see Masip & Marc (2011), is used to solve the system, that no longer depends on the time.

$$\frac{dy}{dt} = f(t,y) \qquad \frac{dy}{dt} \approx \frac{y(t+\Delta t) - y_(t)}{\Delta t} \tag{4.30}$$

$$y_{n+1} = y_n + \Delta t f(t_n, y_n) \tag{4.31}$$

Applying the Euler algorithm (4.30) on the obtained transient matrix system (4.29), $\bar{\boldsymbol{u}}(t)$ is calculated as a discrete function (4.33).

$$\bar{\boldsymbol{u}}_t = M^{-1}(K\bar{\boldsymbol{u}} + f) \qquad \bar{\boldsymbol{u}}_t \approx \frac{\bar{\boldsymbol{u}}(t+\Delta t) - \bar{\boldsymbol{u}}(t)}{\Delta t} \tag{4.32}$$

$$\bar{\boldsymbol{u}}_{n+1} = \bar{\boldsymbol{u}}_n + \Delta t M^{-1}(K\bar{\boldsymbol{u}}_n + f) \tag{4.33}$$

where $\bar{\boldsymbol{u}}_{n+1} \approx \bar{\boldsymbol{u}}(t_{n+1})$

After applying the Euler algorithm, the system can be solved by operating the matrices and vectors (4.34). An initial pressure $\bar{\boldsymbol{u}}_i$is required, this pressure is the one at the sack just after the suction starts.

$$\begin{vmatrix} \boldsymbol{u}_1(t_{n+1}) \\ \boldsymbol{u}_2(t_{n+1}) \\ \vdots \\ \boldsymbol{u}_j(t_{n+1}) \end{vmatrix} = \begin{vmatrix} \boldsymbol{u}_{1,n} \\ \boldsymbol{u}_{2,n} \\ \vdots \\ \boldsymbol{u}_{j,n} \end{vmatrix} + \Delta t \cdot \begin{vmatrix} m_{1,1}^{-1} & m_{1,2}^{-1} & \cdots & m_{1,j}^{-1} \\ m_{2,1}^{-1} & m_{2,2}^{-1} & \cdots & m_{2,j}^{-1} \\ \vdots & \vdots & \ddots & \vdots \\ m_{i,1}^{-1} & m_{i,2}^{-1} & \cdots & m_{i,j}^{-1} \end{vmatrix} \cdot \left(\begin{vmatrix} k_{1,1} & k_{1,2} & \cdots & k_{1,j} \\ k_{2,1} & k_{2,2} & \cdots & k_{2,j} \\ \vdots & \vdots & \ddots & \vdots \\ k_{i,1} & k_{i,2} & \cdots & k_{i,j} \end{vmatrix} \cdot \begin{vmatrix} \boldsymbol{u}_{1,n} \\ \boldsymbol{u}_{2,n} \\ \vdots \\ \boldsymbol{u}_{j,n} \end{vmatrix} + \begin{vmatrix} f_{1,n} \\ f_{2,n} \\ \vdots \\ f_{i,n} \end{vmatrix} \right) \tag{4.34}$$

where

$m_{i,j} = \int_\Omega N_i N_j$; the $m_{i,j}^{-1}$ will be obtained doing M^{-1}

$k_{i,j} = \frac{\kappa}{\mu} \int_\Omega \nabla N_i \cdot \nabla N_j \, d\Omega$

$f_i = 0 \cdot \int_{\Gamma_n} N_i \, d\Gamma = 0$

$t_{n+1} = tn + \Delta t$

Analysis of the transient model using an impermeable sack

The advantage of the transient numerical model over the steady one, is the allowance of time tracking on the system and the capability to reproduce the behaviour of an impermeable sack. Consequently, if the walls are impermeable the pressure field behaviour is almost the same as the steady model, see Fig.(4.8, 4.9), consequently the phenomena explained above are valid also if the sack is impermeable. However, there is a difference in the behaviour if the sack is impermeable, in the transitory model during the suction process the permeability has a transition from κ(u) to κ cst.

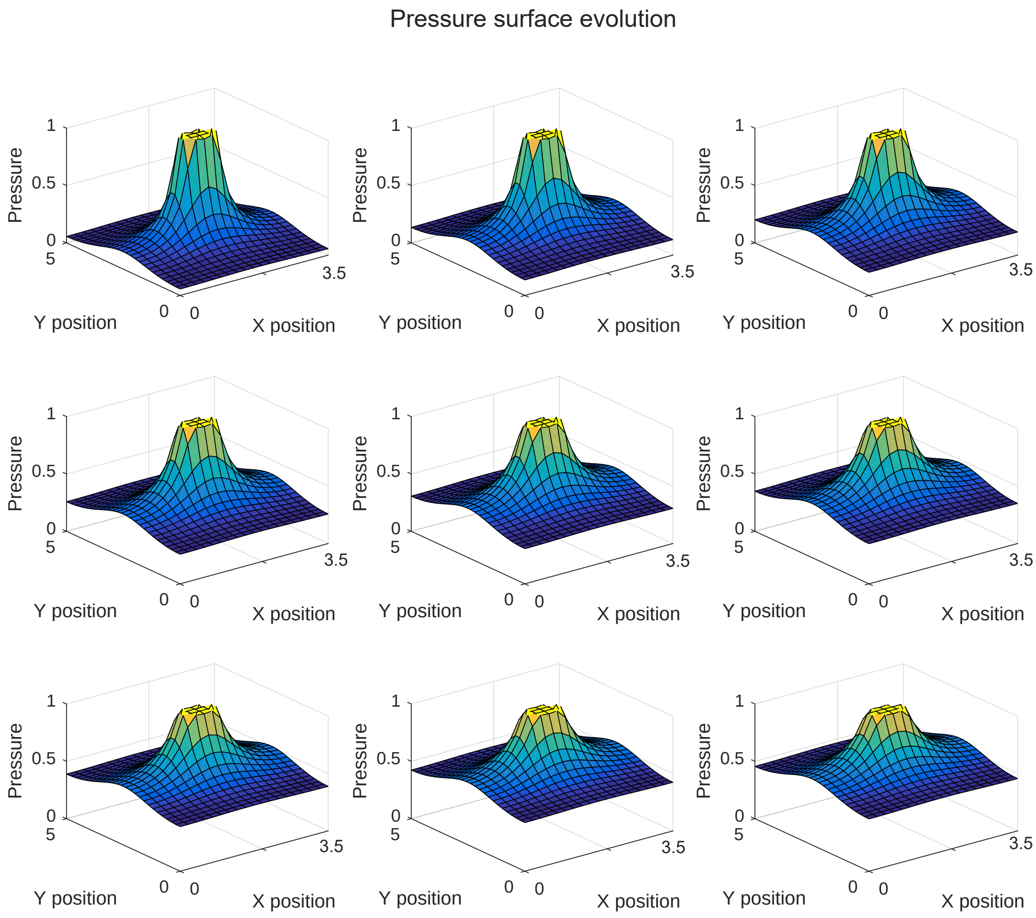


Figure 4.8: Pressure time evolution of a sack during a suction process κ(u)

This transition is made principally by the rise of the pressure at the walls, unlike the stationary model the pressure at the sack walls is not zero during the suction process, see Fig.(4.9). This increase in pressure in the entire sack is followed by a reduction in permeability. Since permeability has a minimum value, there is a point where the permeability reduction that affect the whole sack reach the permeability of the compacted bulb. At that point the whole sack has the same permeability and it will be constant, therefore it had a transition from dependent to constant.

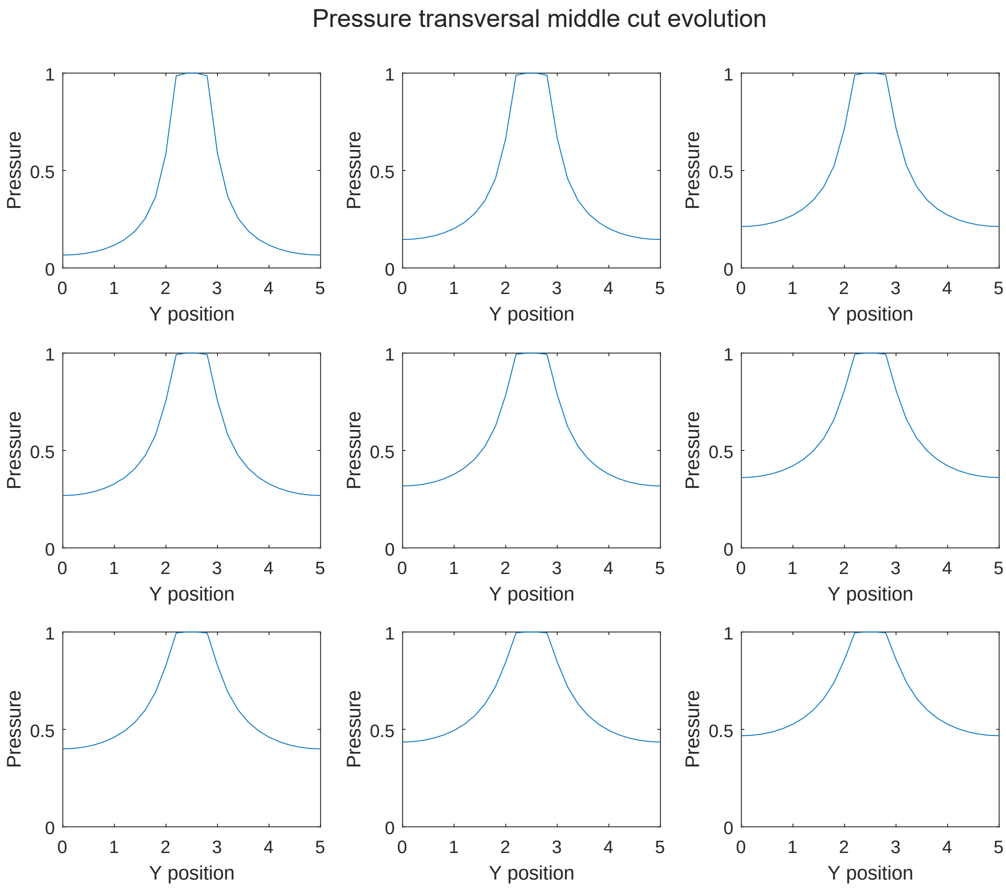


Figure 4.9: Pressure time evolution of a sack during a suction process κ(u)

The use of impermeable sacks makes it possible to reach a full suctioned material, but in reality this process would take a lot of time, see Fig.(4.10), since the homogeneous suction will be done through a very poor permeable material. Indeed, using an impermeable sack helps to the process since the walls compress the material, however the process need to be even more efficient.

4.2.1 Full air extraction analysis; κ cst and κ(u) comparison

This analysis is intended to show the difference between the constant and dependent permeability during the suction process of an impermeable sack. Also this analysis will be done use one and two suction probes. The analysis will be using different graphs, the first one, see Fig.(4.10), shows in the y axis the fraction in % of air extracted and in the x axis the time, also using the same time scale there is another graph, see Fig.(4.11), which represents the flow rate.

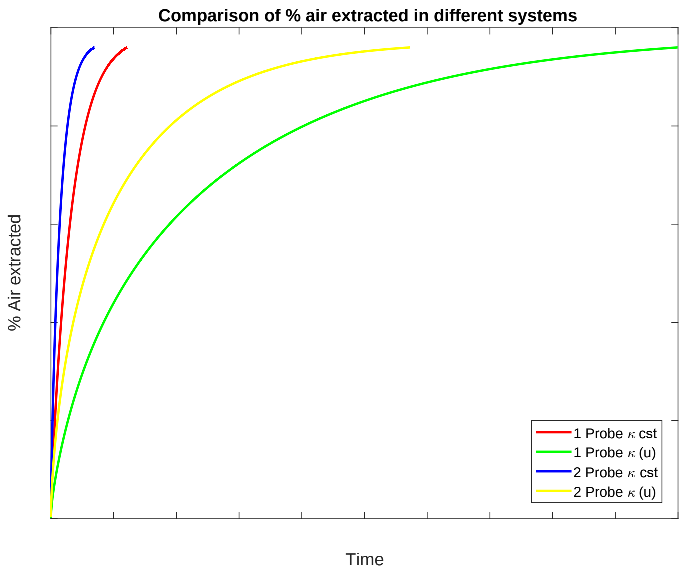


Figure 4.10: Time evolution of the air extracted

The first expected behaviour is the flow rate at the beginning as it is equal in both systems, one probe and two, with the same permeability. That is because, at the start of the suction, the permeability is the same in both cases, κ cst and κ(u), since the suction has not already compact the soil and reduce its permeability.

The next important aspect is the reduction in flow as the suction progress, that is mainly caused by two processes. The first cause, is the difference between steady and transient systems, whereas in the first one it possible to reach an equilibrium in the second one it is not possible. That is because in transient systems the sack walls are impermeable and do not allow an incoming air flux into the system, consequently, it is not possible to reach an equilibrium state. Therefore, the air inside starts to reduce, as a consequence, the maximum gradient available inside the sack is also reduced, see Fig.(4.8). This phenomenon has a huge impact on κ(u), since the increase in pressure reduce the permeability and also the maximum gradient available, both effects stacks and the flow gets reduced drastically, see Fig.(4.11).

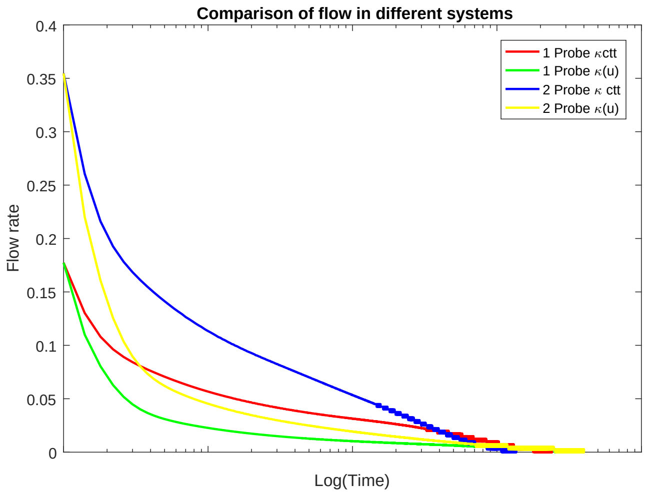


Figure 4.11: Time evolution of the air flow rate during the entire suction process

The other cause is the diffusion process; at the beginning the suction rate is high since there is air available near the probe. However, after this air is extracted, to keep the suction going its need to pull air from the sack near the probe. This is the diffusion process, and it takes more energy and time as the suction goes on, since the distance the air has to travel is getting bigger as the process continues.

Finally, another important matter, is the linearity dependence with the number of probes of the systems that have the same κ cst or κ(u) respectively. This can be illustrated in one graph, see Fig.(4.10), choosing a determined % of air extracted and looking how much time is needed to reach that state. As its shown for the most of the time, when two probes are suctioning, the air extracted is approximately the double compared to one probe in both permeabilities.

However, this linearity behaviour is only possible if the medium is big enough,that means, if the number of probes introduced in a medium is large, introducing a new probe wont decrease the flow rate of the other. Therefore, the total flow rate will be $Q_{TOTAL} = nprobes \cdot Q_{1\,PROBE}$. Otherwise, if the area is not big enough, introducing a new probe will disturb the others and decrease the flow rate of them, reducing the total flow $Q_{TOTAL} = nprobes \cdot \psi Q_{1\,PROBE}$ with $\psi < 1$. In other words, each probe has an influence area, if two influence areas superpose the probes attached to them will loss flow rate. Consequently, if the medium has a limited area,it also has a limited number of probes that allow the linear behaviour occur. Overall, the flow rate depends on the suction area of the probes and its distribution along the medium.

Chapter 5

Exploit of numerical models to optimize suction in granular media

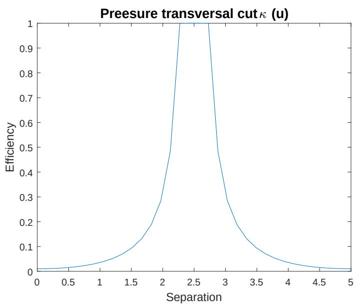
The optimization of the system is a crucial part of the project, however, before optimizing the system is needed to define the scope, how much air is needed to have a good de-aeration. To define it, the maximal and minimal theoretical compaction will be analysed

The maximum compaction is archived having the grains in a hexagonal organization which has a porosity of $\phi = 0.26$, see Fig.(2.2), whereas the minimum, cubic organization, is $\phi = 0.48$. Therefore, the reduction of air needed to pass from maximum to minimum is around 60%, however, the material does not arrive with a perfect cubic distribution and the aim is not to fully compact the material. Therefore, a extracting 30% of the air, should be a good scope during a de-aeration process.

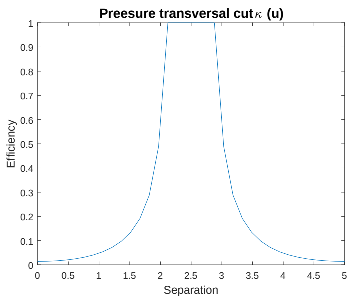
5.1 Two pipes position optimization

The air flow depends on the suction area of the probes and its distribution, consequently, the position of the probes matter. To solve this optimization problem, it has been tested different distributions of two probes, see Fig.(5.1), in order to understand how them affects the pressure field and the total flow rate.

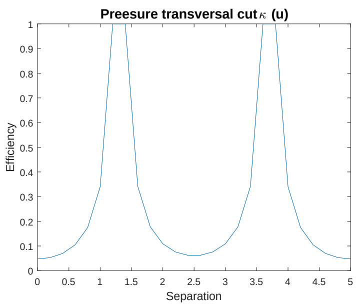
The first probe distribution, is having the two probes together, see Fig.(5.1b), which increased a bit the flow rate. However, one pump disturb each other and the flow rate is far away from doubling the flow rate of a single probe, see Fig.(5.1a, 5.2). In the second one, the two probes are distributed in such way both off them affects the same area, see Fig.(5.1c), that distribution doubled the flow rate, the maximum possible, since the probes do not disturb each other. Finally it has been set the probes at the sack edges, see Fig.(5.1d), therefore, the effective area of the each probe has been reduced in half. Consequently, it works nearly as a one probe, but in fact, the suction area is the same as the first combination such is the flow rate.



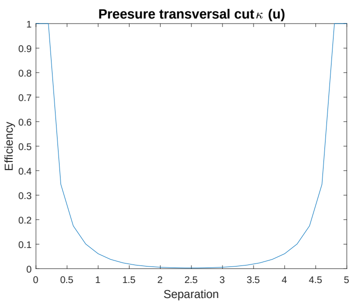
(a) One probe



(b) Two probes together



(c) Two probes distributed



(d) Two probes at the edges

Figure 5.1: Pressure comparison for different probe positions

Once the particular cases has been analysed, a full cover of position has been done comparing the flow rate to one probe, see Fig.(5.2). The result obtained as the same as before, if the probes are close together they disturb each other, once them start to separate the flow increases. However, when they get closer to the sack walls, the flow is reduced again since there is less area to extract air.

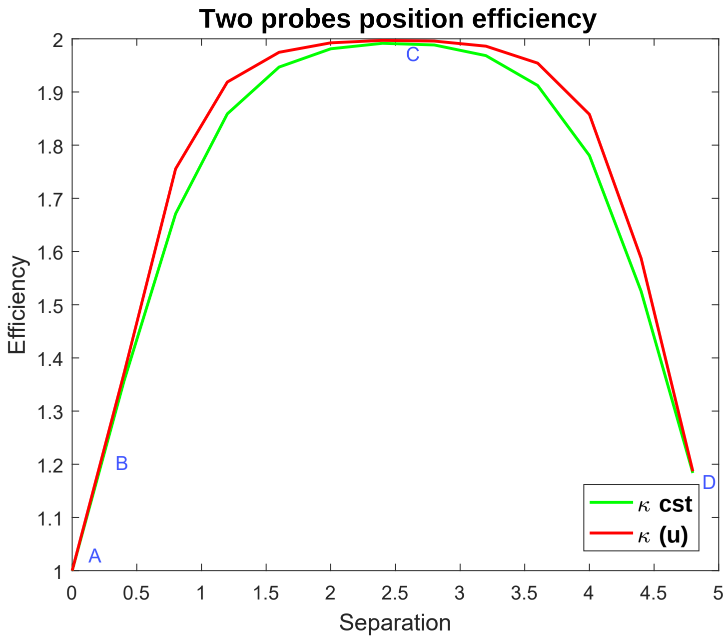


Figure 5.2: Suction efficiency of two probes depending on the position

5.2 Mobile pipe suction system

In order to improve the suction process a new system with a mobile probe is proposed. The system is basically the same as a one static probe but it moves along the sack during the suction action. The modelling of this system has been done changing the probe place in a couple of steps during the process. Even so in the reality it can be done in a linear way, doing it this way has revealed an important information, see Fig.(5.6), that will be explained later.

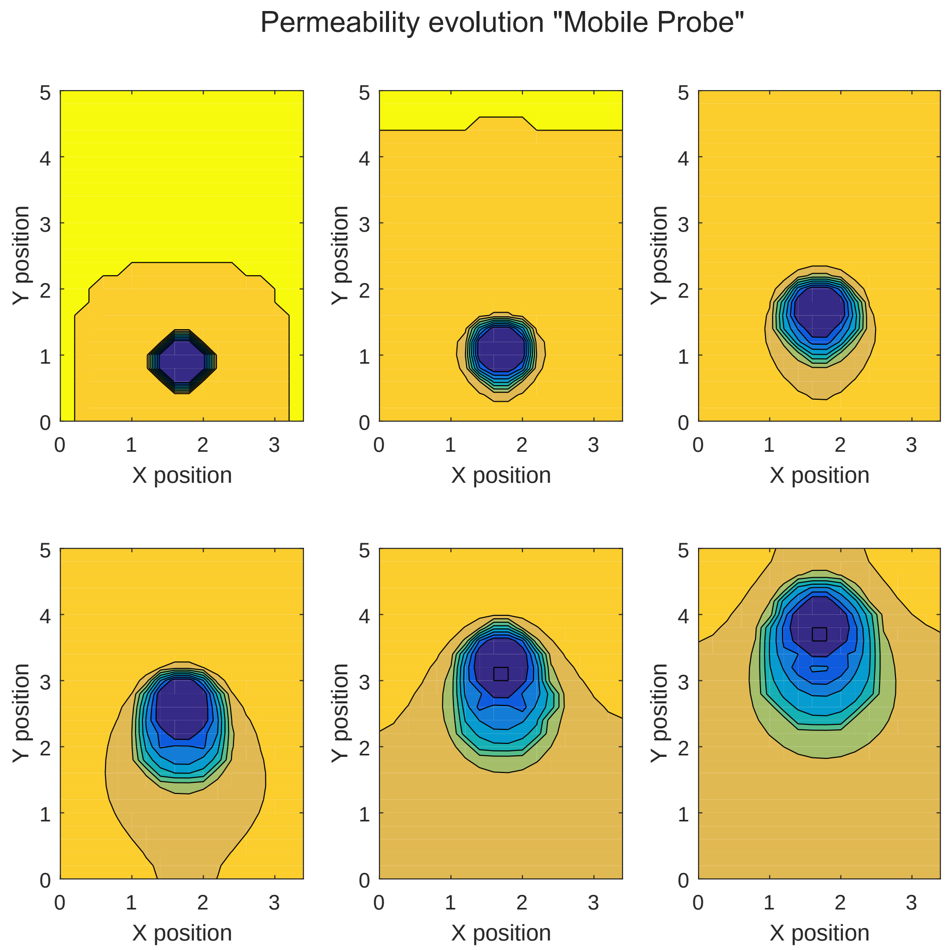
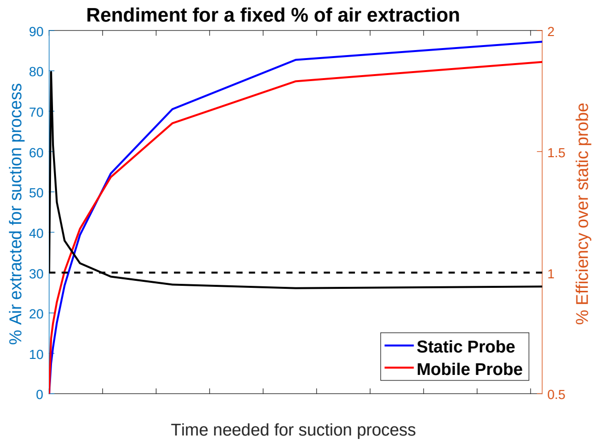


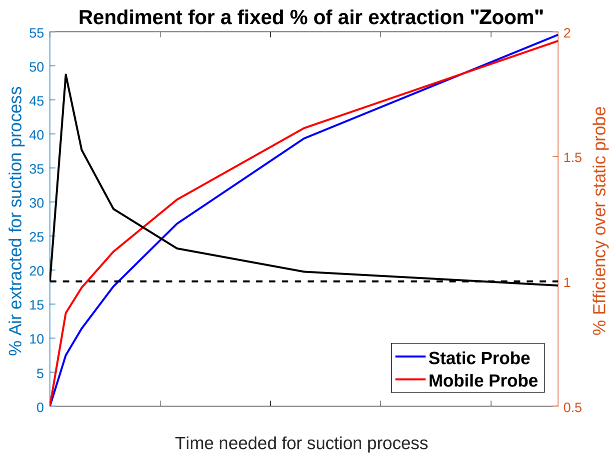
Figure 5.3: Evolution of κ(u) during a mobile suction process

The main idea behind the system is the fact that each time the probe moves the new material near it is no longer compressed, therefore, the suction is not being reduced in the new area. In addition, each time the probe moves it create another bulb increasing the amount of material compacted, see Fig.(5.3). Overall it solves the two main issue of de-aeration, the lack of flow rate and the compressed area.

If the mobile system is compared with the single static probe performance, an important behaviour appears, the new system is only efficient if the suction times are small and the final amount of air extracted is little, see Fig.(5.4a). But in the end, since the aim is not a full air extraction, the new system is clearly better than using a one single static probe, see Fig.(5.4b).



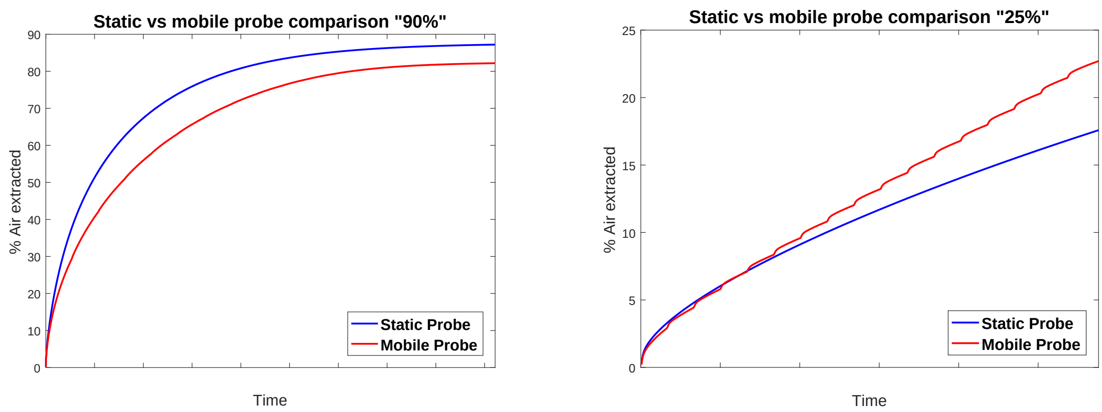
(a) Final air extracted and efficiency for fixed suction time



(b) Final air extracted and efficiency for fixed suction time "Zoom"

Figure 5.4: Efficiency comparison between static and mobile systems

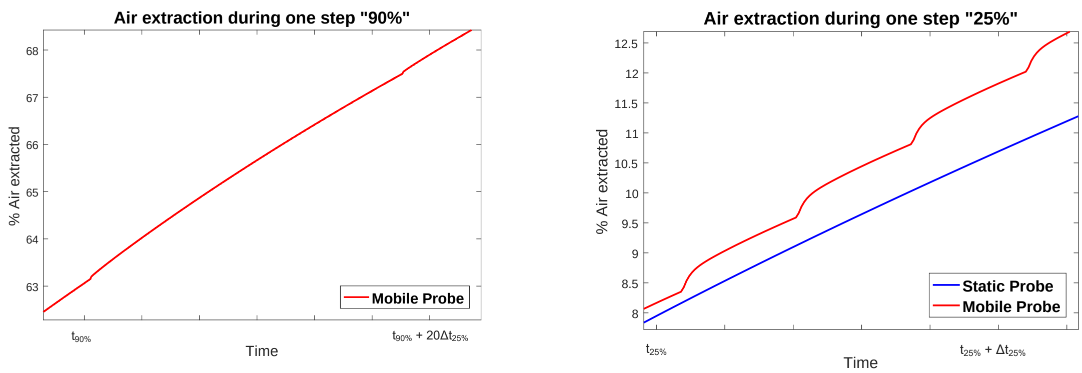
To explain that behaviour, an analysis of two suction process, one extracting around the 90% the air and the other one 25%, is done, see Fig.(5.5). There are two main reason that explain the behaviour, the difference between the flow rate and the little increase of it during each suction step, see Fig.(5.5b). The steps are the reason why the mobile method is more efficient in short suction process, since each time the probe change the position, the flow rate increase significantly making it faster than the static one, see Fig.(5.6a). However, after that increase in flow rate, the air flow starts to fall down and can become lower than the static probe. As is shown in the 90% extraction, see Fig.(5.5a), where the time for each step is long enough, the increase in flow rate for each step is not big enough



(a) Air extracted (t) of a full extraction (b) Air extracted (t) of a partial extraction

Figure 5.5: Air extraction comparison between static and mobile probe systems

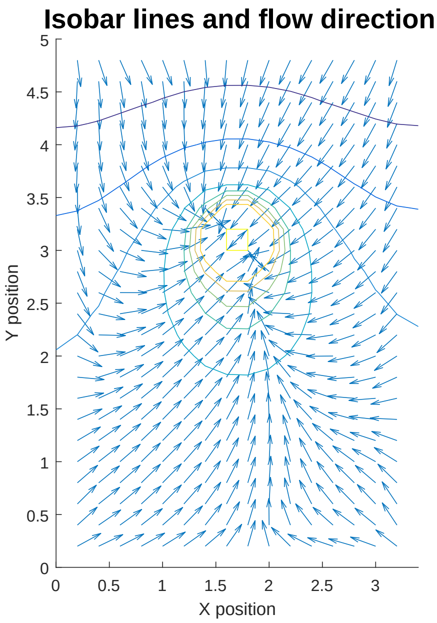
to compensate the low flow rate of the mobile probe, see Fig.(5.6b). Therefore, the mobile probe is less efficient compared to the static one if the suction times are large enough.



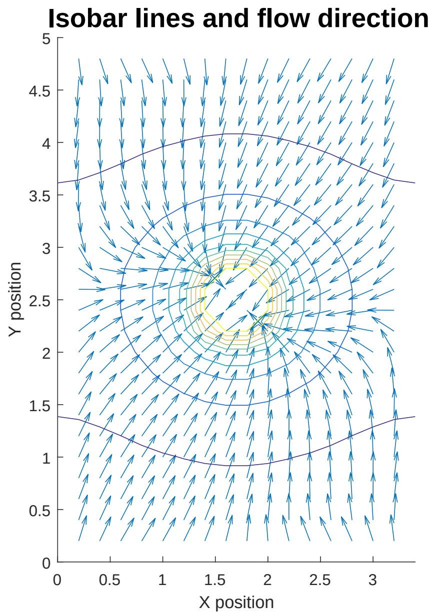
(a) Extraction of 25% of the air (b) Extraction of 90% of the air

Figure 5.6: Air extraction during on step in a mobile probe system

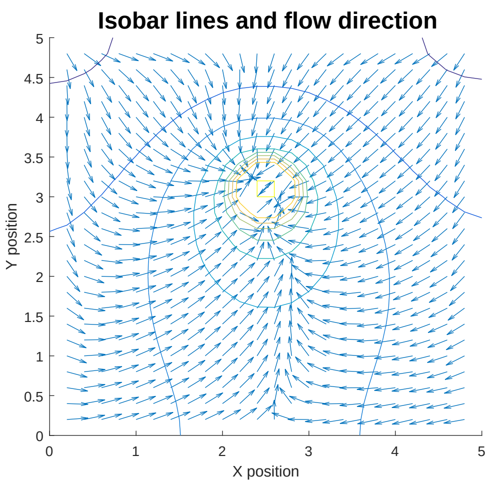
The final approach of this system is analyse why the air flow get reduced in time after each step. The reason, is the fact that when the probe moves, it leaves a trail of compressed soil, which prevents the probe to extract air efficiently in that area. The reduction of suction comes from the fact that the isobar lines tend to group in the areas with lower permeabilities. Consequently, the flow will go throw that direction, which has a lower permeability, reducing the efficiency of the process. In addition, the distance that a particle of air has to do to reach the probe is larger. In the, Fig (5.7a, 5.7c), bot behaviours are shown, in the top side the air goes forwards to the probe, while in the bottom part the air goes first to the compressed are and then moves to the probe. As it can be shown this effect does not occur when the suction probe is immobile, see Fig.(5.7b, 5.7d).



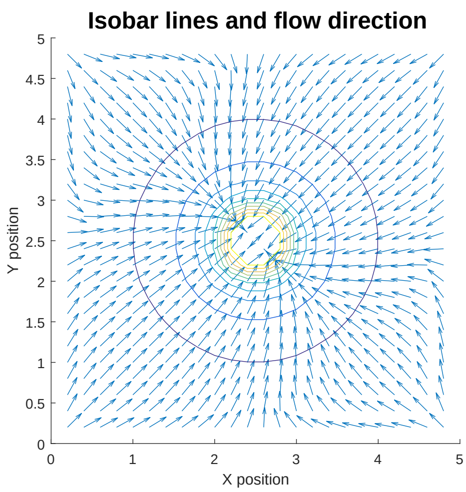
(a) Mobile probe 3.5 x 5 sack



(b) Static probe 3.5 x 5 sack



(c) Mobile probe 5 x 5 sack



(d) Static probe 5 x 5 sack

Figure 5.7: Comparison of flow direction and isobar lines between static and mobile probes

Chapter 6

Final remarks

6.1 Conclusions

Nowadays the packaging, transport and storage of bulk material is an important economic activity. Thus the efficiency of each process is very important towards the final profit more several industries. One technique used to improve all three processes is the suction of the air inside the sack, reducing the package volume. However, this process has some issue with some granular material, obtaining low efficiencies.

To solve the problem, in the past, an experimental approach would be done, making a lot of experiments to determine how the suction works in a porous material. Therefore, the amount of money and time spend would be huge, and the optimization could be not worth. However, in the actually, the analyse of those phenomenon can be done using mathematical models, that can be solved with numerical methods. The reason why is more cheap in the present, is the increase of computational potency and cost reduction of it during the last years.

Consequently, the numerical models are powerful tool for engineers towards the solution of problems that need to be represented in some way. That is because, when using numerical models once them are solved changing the parameters is usually simple. Consequently, it allows engineer to analyse a lot of cases and different virtual tests, in a very short period of time. Unlike the experimental approach, that would need different experiments to analyses different aspects increasing the investigation time. However, the experiments are still need since all those models need to be calibrated in order to reproduce the reality, also not all the phenomenon can be described as a numerical model. Thus the importance of keeping the research of new phenomenon to model or new methods to do it.

On the other hand, the calibration is not all that matters, since the behaviour of the phenomenon can be represented even if its value does not fit the reality. In this project, the models are not calibrated, however, the behaviour of the suction problems has been represented and the optimization of it has been done. Finally, the study of the suction problem has left some final conclusions.

Regarding to the work itself:

- The first objective of the work was the reproduction of the suction using numerical methods in a granular medium, which has been fulfilled successfully. The model has been able to describe the bulb creation and the suction process, allowing the knowledge of the bulb extension. In addition, the models have been useful to understand better the processes of diffusion in the porous medium.

- The next aim was the optimisation of the suction systems, regarding that, different methods were optimized to increase the efficiency of extraction processes. The first one was the use of two probes and his correct position to maximize both, the extraction of air and the compacted area. A second method with a variable probe, that has been optimised by defining in which speed the probe has to be extracted. Finally, it has been developed the form of the probe to maximize the process of de-aeration.

Regarding to the suction process:

- The surface of pressures does not depend on the permeability if is constant, therefore, the process of bulb generation can occur with any granular material. This is due to the pressure surface which tends to compress more the material around the probe.

- The lines of pressure tend to group where the permeability is lower, because of the need of a greater pressure gradient to maintain the flow rate.

- If the permeability depends on the pressure, the phenomenon described in the first conclusion is aggravated and the over compressed material is generated. This is due to the combination of the two behaviour explained above. If the suction itself tend to compress more the area near the probe, the permeability will also be lower in that area. Consequently, the isobar line will move towards the probe and compressing even more the material there. This chain reaction will continue until an equilibrium is reach.

- The use of impermeable sack helps in the process of de-aeration, but only during the first moments. Therefore, if the objective is only to archive porosities close the minimum, 30% of air extraction, the utilisation of waterproof sacks is a great investment. They will provide better compaction and better protection against the environment.

- The air flow is proportional to the suction area, if it is properly distributed. Consequently, the use of probes with a great suction area or using multiple probes, are the easiest ways to improve the suction processes.

- It is not needed to have such a powerful pumps in order to improve the suction. Moreover, if the process is not optimum, using more powerful pumps will not change the final result. Therefore, the focus has to be the correct utilization of the power

6.2 Recommendations

Here are some recommendations to optimise a suction system.

- Using the maximum admissible suction area for the bomb utilized, depending on the material design the probe and process in such way the bomb can be used to its full potential. Therefore, the airflow in the probe has to be the maximum allowed by the bomb so that it keep the vacuum at the probe, the absolute pressure there has to be zero. On the other hand, it can be done the other way, first calculate the area necessary to archive a flow rate and later choose a bomb that fulfils the requirements.
- Induce vibrations to the sack to increase the energy input into the system, this way the reorganization of the grains will be faster.
- Last, the utilization of waterproof sacks, unlike the permeable, these offer a better compaction due to the pressure that the walls exert on the inside material.

6.3 Proposals to improve the model

Finally, some guidelines to improve the models and enhance this work are given.

- In this project a permeability has been assumed that decreases continuously with the increase of pressure. This assumption has been drawn from the interaction between static friction and the force exerted by the suction on the grains. However, possibly this behaviour is not quite accurate, therefore, a deeper study of permeability is necessary.
- Another possible improvement is the calibration of the model with real experiments,

thus obtaining the actual data of both, the time required to extract the excess air and the actual size of the bulb. 100mm

- When vibrating, the particles are rubbing against each other as a result static friction is not taken in account, therefore, the suction needed to compact the material is smaller. This process can be analysed by introducing the effect of vibration on the model.

Chapter 7

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