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**Measurement of soil stresses in small scale  
laboratory model tests on granular soils**

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## **Summary**

The aims of this thesis are to understand the problems evolved with measuring soil stress with small scale laboratory test in granular soil by studying the possibilities and limitations and by testing the transducers.

The first part of the analysis will examine the available devices and techniques to measure stress in the soil, focusing in particular on small transducers used for small scale laboratory tests. The second part of this analysis will consider literature research about soil stresses' measurement in geotechnical laboratory, with an emphasis on granular soil. After that it will deal with a test on the stress transducers currently used at Soil Mechanical Laboratory of the University of Duisburg-Essen. The final part of the analysis consists of a discussion about the possibilities and limitations of measuring stresses in granular soils under small scale condition.



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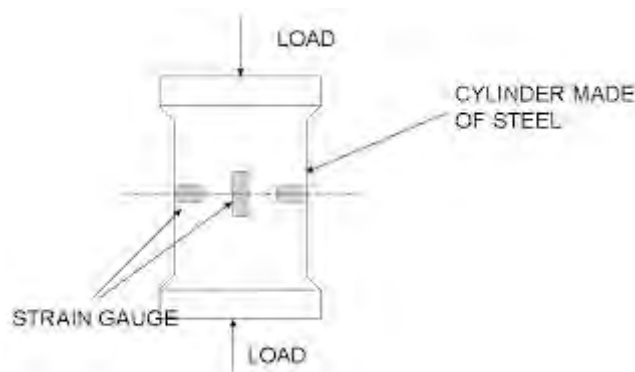
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## 1. Introduction

A transducer is a device that converts a signal in one form of energy to another form of energy. Energy can be of different kinds, such as electrical, mechanical, electromagnetic, chemical, acoustic and thermal. In small scale laboratory tests a pressure sensor is used, that detects pressure (a mechanical form of energy) and converts it to an electrical signal, that will be displayed on a remote gauge (Agarwal, 2005).

A load cell is a transducer that is used to create an electrical signal whose magnitude is directly proportional to the force being measured. There are various types of load cells such as strain gauge load cells, piezoelectric load cells, hydraulic load cells, pneumatic load cells and vibrating wire load cells.

In the strain gauge load cell [Figure 1-1], the load action deforms a strain gauge through a mechanical arrangement. The strain gauge measures the deformation as a change in electrical resistance, which is a measure of the strain and hence the applied force. The electrical signal output is approximately few millivolts and so requires amplification by an instrumentation amplifier. These load cells are particularly stiff and tend to have long life cycles in application. The principle of work of strain gauge load cells is that the strain gauge contracts when the material of the load cells deforms appropriately. Then they convert the load acting on them into electrical signals. When weight is applied, the strain changes the electrical resistance of the gauges in proportion to the load (Techniques).



*Figure 1-1 Strain Gauge Load Cell (Engineering S. o., 2013).*

In piezoelectric load cells the principle of deformation is the same of the strain gauge load cell; the difference is that the output voltage is generated by the basic piezoelectrical material, which is proportional to the deformation of the load cell. They are used for dynamic and frequent measurements of force.



Hydraulic load cells work with a piston and cylinder arrangement. The piston is placed in a thin elastic diaphragm and it doesn't actually come into contact with the load cell. Mechanical stops are placed to prevent excessive deformations of the diaphragm when the loads exceed a certain limit. The load cell is completely filled with oil or others liquid, and when the load is applied on the piston, the movement of the piston and the diaphragm result in an increase of oil pressure which in turn produces a change in the pressure on a Bourdon tube connected with the load cells. Because this sensor has no electrical components, it is used often in outdoor environments. An hydraulic load cell is shown in the Figure 1-2.

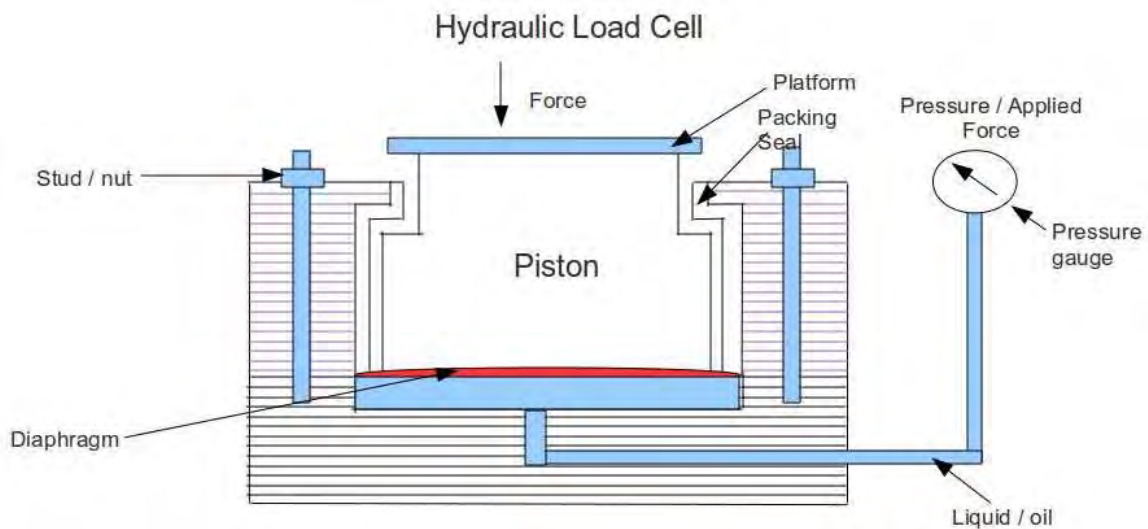


Figure 1-2 Hydraulic Load Cell (Engineering I. a., 2011)

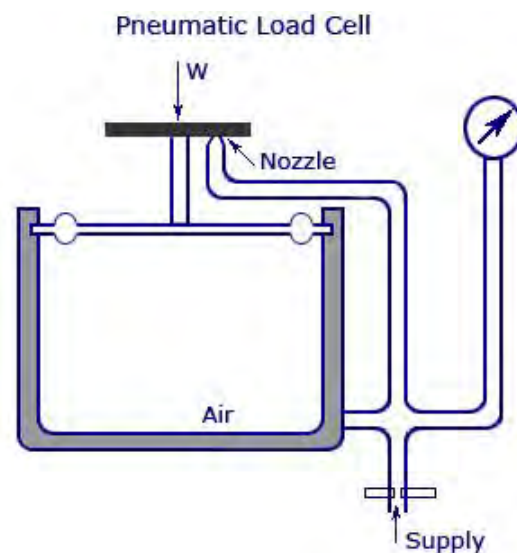


Figure 1-3 Pneumatic Load Cell (Today, 2011).

Pneumatic load cells [Figure 1-3] are designed to automatically regulate the balancing pressure. Air pressure is applied to one end of the diaphragm and it escapes through the nozzle placed at the bottom of the load cell. To measure the pressure inside the cell a pressure gauge is attached with the load cell. The deflection of the diaphragm affects the airflow through the nozzle as well as the pressure inside the chamber.

Another kind of cells is the vibrating wire load cells [Figure 1-4]. They work with a vibrating wire sensor which measures force using a wire that vibrates at a high frequency. The applied external force changes the tension on the wire, this changes the frequency. The frequency is measured and indicates the amount of force on the sensor (contributors, 2014).

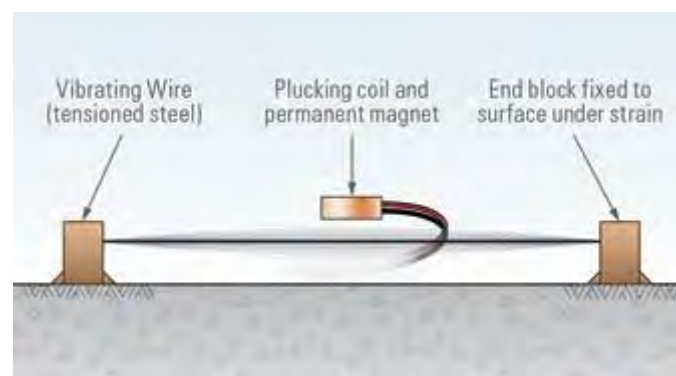


Figure 1-4 Vibrating Wire Tecnology (Geokon, 2013).

These listed above are the main kinds of transducers. This thesis deals with the devices for the measurement of soil stresses, in particular in small scale models where for some reasons (cell properties and geometry, environmental condition, calibration procedures, installation) they underestimate the soil stress giving wrong or unreliable results.

The aim of this thesis is to give an overview of the transducers available on the market, identifying the more suitable for measuring soil stresses in small scale laboratory tests. Furthermore it deals with a literature search about the use and problems of transducers for measuring soil stresses, in order to understand the key concepts and the right way of proceed for having reliable results. In the last part it meets with practical laboratory tests to test the stress transducers currently used at the Soil Mechanical Laboratory of the University of Duisburg-Essen. And as a conclusion it treats with the summary of the main results.



## 2. Available transducers in the market

In this chapter results of a web search are presented about various kinds of available transducers on the market, their use and the techniques to measure stresses in the soil. In particular the search is developed about some features; that are listed and described below.

Capacity: maximum load that a transducer can measure and still maintains specifications.

Accuracy: the ability of an instrument to measure load or distance to the absolute true and correct value.

Resolution: the smallest unit of measure or the smallest change that can be displayed or recorded by an instrument.

Over range capacity: load that can be applied continuously without causing permanent destructive change exceeding specification (%).

Temperature range: range of temperatures that can be applied continuously without causing permanent destructive change to the transducers (°C).

Weight: approximate weight of the main unit.

Non linearity [Figure 2-1]: maximum distance from the calibration curve and the rated point with increasing loads (TML).

$$\text{Non linearity} = \frac{\Delta \varepsilon_L}{\varepsilon_{RO}} \times 100 (\%) \quad (\text{Eq. 2.1})$$

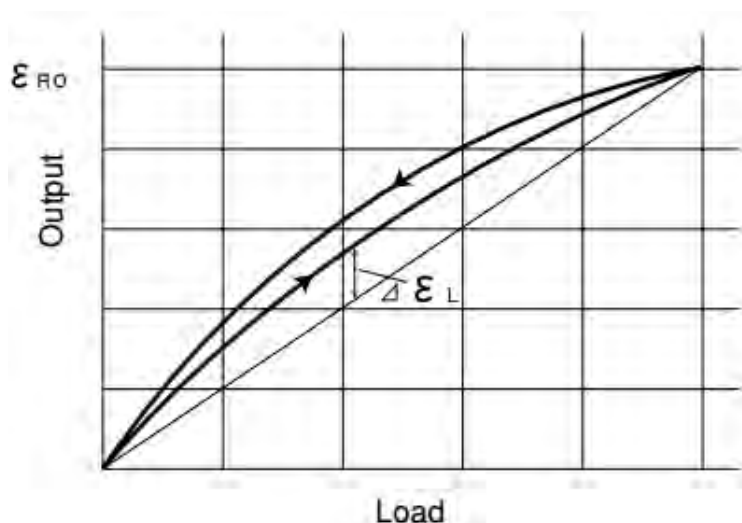


Figure 2-1 Non-linearity (TML).

This market search has carried to the following companies.

## 2.1. Geokon

Geokon produces a large range of transducers, but the most interesting ones for measuring stress pressure are the hydraulic transducers. These earth pressure cells, named “Model 4800 Earth Pressure Cells“ are designed to measure stresses in soil or pressure of soil on structures.

### 2.1.1. Theory of operation

The earth pressure cells will respond to soil pressure but also to ground water or water pressure, hence they measure total pressure. As defined by Terzaghi’s principle of effective stress, to separate the effective stress ( $\sigma'$ ) from the total stress ( $\sigma$ ) it is necessary to simultaneously measure the pore water pressure ( $u$ ), using a piezometer;

$$\sigma' = \sigma - u \quad (\text{Eq. 2.2})$$

These parameters coupled with the soil strength characteristics will determine soil behavior under loads.

The earth pressure cells are composed by two flat plates welded together at their periphery, separated by a small gap filled with hydraulic fluid. The earth pressure acts to squeeze the two plates together thus building up a pressure inside the fluid. If the plates are flexible enough (i.e. thin enough relative to their lateral extent), then at the center of the plate the effect of the edge perimetry is negligible and it can be stated that the external soil pressure and the internal fluid pressure are perfectly balanced.

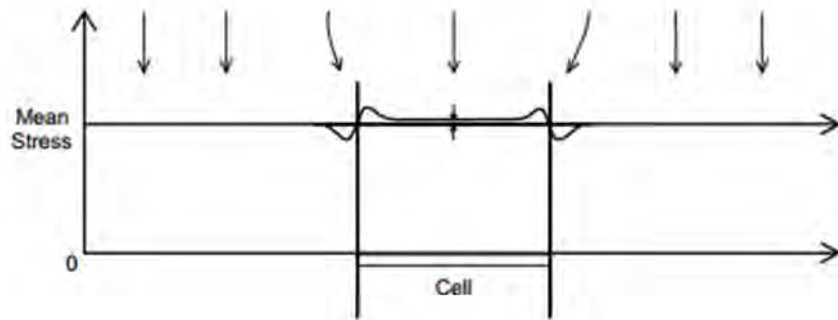
This is true only if the deflection of the plates is kept to a minimum and thus it is important that the cell is stiff. This means that the fluid inside the cell should be as incompressible as possible, having very little volume change under increasing pressure.

Various tests have shown that the introduction of a flat stress cell into a soil mass will alter the stress field in a way dependent on the relative stiffness of the cell with respect to the soil and also with respect to the aspect ratio of the cell. A thick cell will alter the stress more than a thin cell, for this reason a thin, stiff cell is best (aspect ratio of at least 20 to 1 to be desirable).

On regard to this it is necessary to emphasize that in geotechnical small scale laboratory model tests, the size of the device in relation to the container of the experiment or the soil volume is very important. In addition if a device is very thin but large like a sheet, it may result as a reinforcement of the soil. This subject will be discussed later.

Ideally, the cell ought to be as stiff as the soil. But in practice this is difficult to achieve. If the cell is stiffer than the soil then it will over-register the soil pressure because of a zone of soil

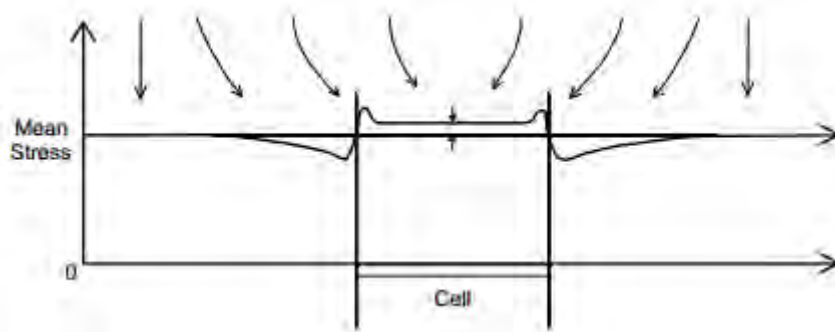
immediately around the cell which is sheltered by the cell so that it does not experience the full soil pressure. This is represented in the Figure 2-2.



*Figure 2-2 Stress Distribution, Weak Soil with Stiff Cell (Geokon, 2013)*

As can be seen there is a stress concentration at the rigid rim. In the center of the cell the soil stress is only slightly higher than the mean soil stress, which is only slightly higher than the stress which would be obtained if the cell is not present.

In a stronger soil the destressed zone around the edge of the cell is more extensive and as a result at the center of the cell the degree of over-registration of the mean stress is greater. This is shown in the Figure 2-3.



*Figure 2-3 Stress Distribution, Strong Soil with Stiff Cell (Geokon, 2013)*

And finally in a stiff soil the cell may be less stiff than the soil, in which case the cell will under-register the main soil stress because the stresses in the soil tend to bridge around the cell. This is represented in the Figure 2-4.

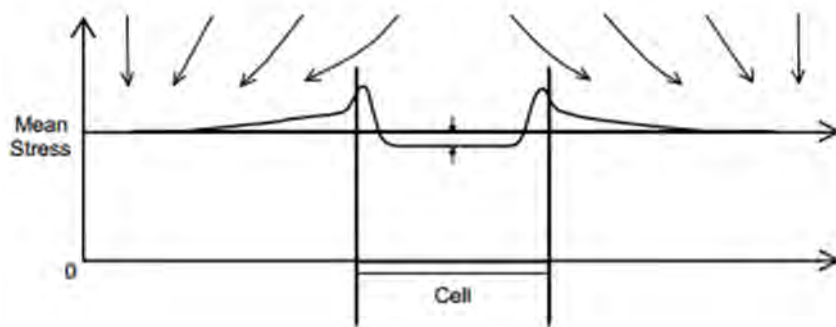


Figure 2-4 Stress Distribution, Stiff Soil with Weak Cell (Geokon, 2013)

It is noticeable that other factors are important, such as the inherent variability of soil properties which give rise to varying soil stresses at different locations and a corresponding difficulty in getting a good sample of the mean stress from a limited number of cell locations. In addition the response of the cell to its immediate surroundings depends very largely on the question if the soil mass immediately around the cell has the same stiffness, compressibility, degree of compaction as the undisturbed soil mass. It is very important in the installation methods to pay particular attention to this detail (Geokon, 2013).

### 2.1.2. Model 4800 Earth Pressure Cells

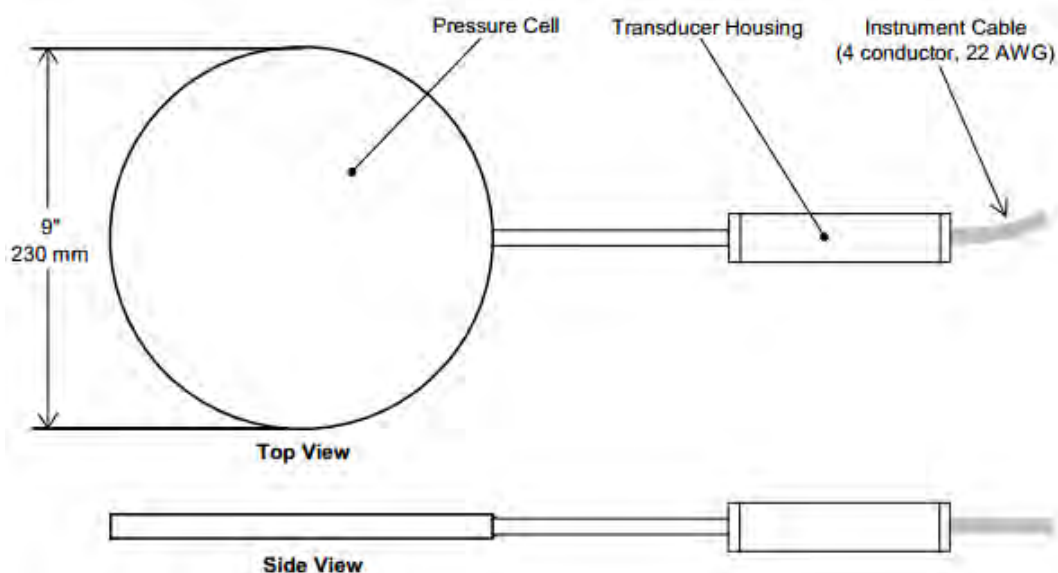


Figure 2-5 Model 4800 Circular Earth Pressure Cell (Geokon, 2013)

These cells [Figure 2-5] are constructed from two stainless steel plates welded together around the periphery to leave a narrow space between them. This space is completely filled

with de-aired hydraulic oil which is connected hydraulically to a pressure transducer where the oil pressure is converted to an electrical signal which is transmitted through a signal cable to the readout location. The de-aired oil materially improves the fluid stiffness and the performance of the cell. The cable is attached to the transducers in a sealed, waterproof manner.

The cells may be rectangular or circular in shape. The standard size for the rectangular model is 150 mm x 250 mm, for the circular it is 230 mm in diameter. Standard thickness for both styles is 6 mm (aspect ratio  $\approx 40$ ). The specifications are reported in Table 2-1.

<b>Specifications</b>	
Capacity	70KPa - 20MPa
Resolution	$\pm 0.025\%$ full scale
Accuracy	$\pm 0.5\%$ full scale
Non - Linearity	$\pm 0.5\%$ full scale
Over Range Capacity	150% full scale
Temperature Range	-20 to +80° C
Cell Dimensions (active area)	230 mm
Cell Material	304 Stainless Steel
Transducer Material	303 & 304 Stainless Steel
Weight	2.3 Kg

*Table 2-1 Specifications Model 4800 Circular (Geokon, 2013)*

### **2.1.3. Installation**

It is wise to check the cells for proper functioning before every installation.

Earth pressure cells are normally installed in fills and embankments. They can be placed with surfaces horizontal to measure vertical stresses; but also with other orientations, to measure stresses in other directions, for example a cell placed with the flat surfaces vertical will measure horizontal stresses in a direction perpendicular to plates of the cell. They are sometimes placed at angles of 45 degrees.

Attempts to measure earth pressure in fills frequently meets with failure. There are two problems. The first is that the stress distribution in the fill can be inherently variable due to varying properties of the ground and varying degrees of compaction of the ground. Therefore the soil stress at one location may not be typical of the surrounding locations. The second prob-



lem is that a cell installed directly in the fill could result in the creation of an irregular zone immediately around the cell where there may be a different, more fine-grained material, under a lesser degree of compaction. The material around the cell may be poorly compacted because of the need to avoid damage to the cell.

Cables placement vary with individual installation. But all installations have in common the requirements that: the cable must be protected from damage by angular particles of the material in which the cable is embedded; the cable must be protected from damage by compaction equipment; in earth and rock embankments and backfills, the cable must be protected from stretching as a result of differential compaction of the embankment; in concrete structures, the cable must be protected from damage during placement and vibration of the concrete.

## 2.2. Itmsoil

### 2.2.1. Vibrating wire pressure cell



*Figure 2-6 Vibrating Wire Pressure Cell (Itmsoil, 1983)*

#### General information

The cell [Figure 2-6] consists of a circular or rectangular flat jack formed from two sheets of steel welded together around their periphery. The narrow gap between plates is filled with hydraulic oil. The cell is connected to a vibrating wire transducer by a short length of stainless steel tubing, forming a closed hydraulic system. The transducer body is constructed throughout from stainless steel. The sensing wire diaphragm and anchoring tube form a totally sealed independent unit. The coil assembly is coaxially mounted and sealed by epoxy potting. Separation of the above components and transducers outer case are by flexible “O” ring thus preventing case stresses from affecting transducer readings. An armored cable connects the transducer to a terminal unit or direct to the readout unit. Pressure stress cells for installation

in concrete or shotcrete are fitted with a compensating tube, which allows adjustment of initial cell volume to offset concrete shrinkage.

Pressure applied to the diaphragm causes it to deflect thus changing the wire's tension and resonant frequency. The readout box supplies an electrical pulse to the coil/magnet assembly, which in effect plucks the wire and causes it to vibrate at its resonant frequency. The period of oscillation may accurately be measured. The relationship between a change in the period of oscillation and the strain of the wire is non-linear.

The cells have very good long-term stability but they are sensitive to temperature, and allowance for temperature variations may be necessary when incorporating the results. The cells can accommodate a thermistor to monitor temperature if such variations are anticipated (Itmsoil, 1983). The specifications are reported in Table 2-2.

<b>Specifications</b>				
Capacity [KPa]	300   500   700   1000   1500   2000   3000   4000   6000   10000   15000			
Resolution	0.025% full scale			
Accuracy	±0.1% full scale			
Non - Linearity	±0.1% full scale			
Over Range Capacity	150% full scale			
Temperature Range	-20 to +80° C			
<b>Weights, Dimensions and Materials</b>				
Type	Two active faces – 200mm	Single active faces – 240mm	Two active faces – 300mm	Single active faces – 345mm
Active face diameter	176mm	176mm	276mm	276mm
Weight	2.7kg	5.4kg	4.5kg	9.1kg
Material	Stainless Steel	Powder coated	Stainless Steel	Powder coated

Table 2-2 Specifications Vibrating Wire Pressure Cell (Itmsoil, 1983).

### Installation

To obtain correct readings a proper installation of a pressure cell in fill is important. Ideally the material immediately adjacent to the cell should be identical to and at the same density as the machine compacted fill in the general area under investigation. The degree of success experienced in achieving this ideal will depend on the type of soil and on the care taken in preparing the site, placing the cell and backfilling. Placement in sand is easily carried out but calibrations are relatively unreliable and non-reproducible. Placement in clay is easier and if properly carried out calibrations are fairly reliable.

#### **2.2.2. Vibrating wire push-in cell**



*Figure 2-7 Vibrating Wire Push-In Cell (Itmsoil, 1983)*

### General information

This device [Figure 2-7] measures total earth pressures in all soil types, and due to the presence of a piezometer, it measures pore water pressure and therefore the derivation of effective pressure. The cell is formed from two sheets of steel welded around the periphery, with the narrow gap between the plates being filled with oil. A vibrating wire pressure transducer is connected by a short steel tube, forming a sealed hydraulic system. A porous filter disc is incorporated in the cell and is connected to a second vibrating wire transducer, together forming an integral piezometer. The two vibrating wire transducers are mounted in tandem behind the spade-shaped cell and protected within the installing pipe.

The main features of this device are: uses proven vibrating wire technology; designed to be pushed into all soil types; sensor that allows derivation of effective pressure; measures total earth pressures in all soil types; fast response to low volume pressure changes; fitted with thermistor for temperature monitoring (Itmsoil, 1983). The specifications are reported in Table 2-3.

<b>Specifications</b>	
Capacity [KPa]	300   500   700   1000   1500   2000   4000
Resolution	0.025% full scale
Accuracy	0.1% full scale
Non - Linearity	0.5% full scale
Over Range	150% full scale
Temperature Range	-20 to +80° C
Material	Powder Coated Steel Cell
<b>Weights &amp; Dimensions</b>	
Length Including Protective Pipe	1000mm
Width	100mm
Diameter of Protective Pipe	50mm
Weight	7.5kg

*Table 2-3 Specifications Vibrating push-in Cell (Itmsoil, 1983).*

### Installation

A borehole is formed to a depth just short of the installation level. The Push-In Pressure Cell is lowered to the base of the borehole via the push-in casing. Once at the base, the orientation of the cell is checked before pushing it to its final elevation below the base of the borehole. The temporary push-in casings are then removed leaving the cell in-situ. After the removal of the push-in casings, the borehole is grouted. The sensor cables connect the transducers to either a terminal unit or data logger.

The main applications of this device are: measuring the total horizontal stresses in vertical boreholes; measuring horizontal and vertical stresses in horizontally drilled boreholes, such as around tunnels and cliff faces; as a site investigation tool to measure the in situ stresses in the ground prior to any disturbance or construction; measuring total pressure within tailings dams; measuring foundation bearing pressures (Itmsoil, 1983).

### 2.3. TML

TML produces strain gauge-type civil engineering transducers that use strain gauges as detecting sensors. These transducers measure concrete strain, soil pressure, water pressure, stress, displacement, inclination, and other various physical quantities and convert them electrically. The most interesting devices for our purpose are classified below (TML).

#### Soil Pressure Gauge, diameter 200mm

This gauge is designed with a dual-diaphragm structure that can minimize the deformation of the sensing area of the device. It is used to measure the pressure in soil and to monitor the behavior of embankments. The specifications are reported in Table 2-4.

Specifications	
Capacity [KPa]	200   500   1000   2000
Non - Linearity	1.5% full scale
Temperature Range	-20 to +60° C
Weight	6kg

*Table 2-4 Specification Soil Pressure Gauge, diameter 200mm (TML)*

#### Soil Pressure Gauge, diameter 50mm

These gauges [Figure 2-8] are small in size and have a dual diaphragm structure, so they are widely used to conduct model experiments. They are all made of stainless steel with excellent corrosion resistance. They can measure minute displacement of pressure-sensitive area due to double diaphragm structure, and also can measure dynamic earth pressure. The specifications are reported in Table 2-5.

Specifications	
Capacity [kPa]	200   500   1000   2000
Non - Linearity	2% full scale
Temperature Range	-20 to +60° C
Weight	160g

*Table 2-5 Specification Soil Pressure Gauge, diameter 50mm (TML)*

In particular in the Soil Mechanical Laboratory of the University of Duisburg-Essen these specific devices are used.

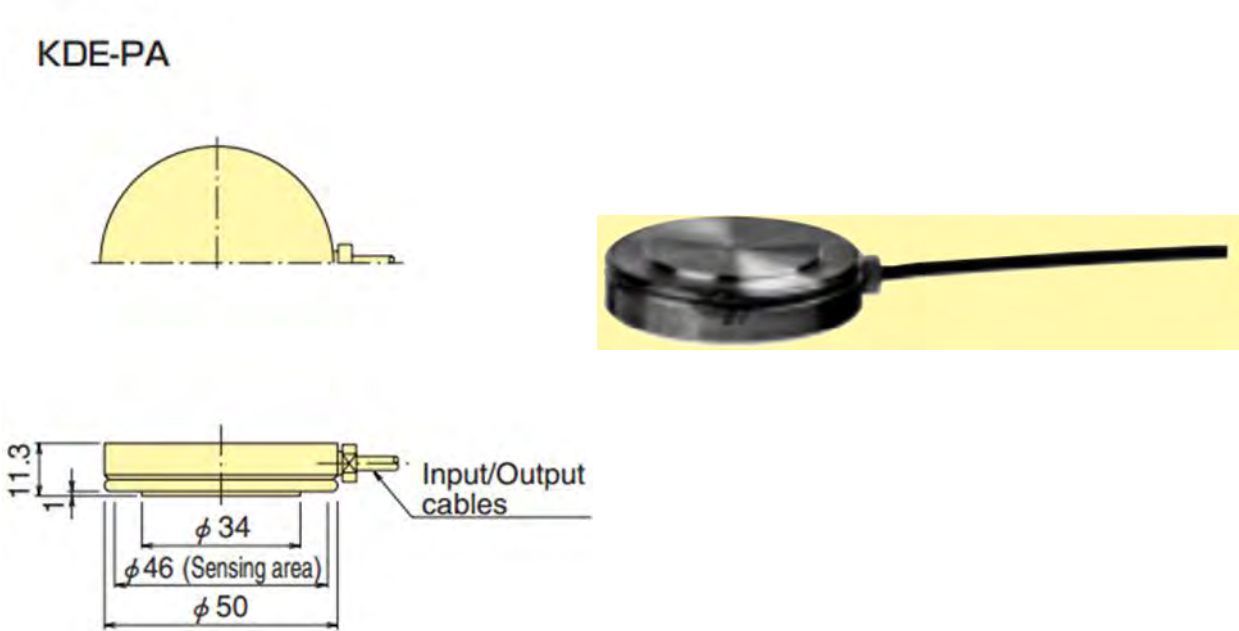


Figure 2-8 Soil Pressure gauge, diameter 50mm (TML)

Load Cell type Soil Pressure Gauge, diameter 100mm

They are load-cell-type soil pressure gauges and designed with a high level of resistance to lateral pressure. The main features are: stainless steel with excellent corrosion resistance, ro-buster than the diaphragm type. The specifications are reported in Table 2-6.

Specifications	
Capacity [KPa]	200   500   1000   2000
Non - Linearity	1% full scale
Temperature Range	-20 to +60° C
Weight	1.2Kg

Table 2-6 Specification Load Cell, diameter 100mm (TML)

Load Cell type Soil Pressure Gauge, diameter 200mm

They are load-cell-type soil pressure gauges and designed with a high level of resistance to lateral pressure. As the previous model they are made of stainless steel with excellent corro-

sion resistance and robust than the diaphragm type. The specifications are reported in Table 2-7.

<b>Specifications</b>	
Capacity [KPa]	200   500   1000   2000
Non - Linearity	1% full scale
Temperature Range	-20 to +60° C
Weight	5.2Kg

*Table 2-7 Specification Load Cell, diameter 200mm (TML)*

*Flat type Soil Pressure Gauge, diameter 180mm*

The main features of these kind of devices are: pressure-sensitive areas with small aspect ratio (1/18); minute deformation of pressure-sensitive area due to double diaphragm structure; sensor section not affected by soil pressure; all stainless steel with excellent corrosion resistance. The specifications are reported in Table 2-8.

<b>Specifications</b>	
Capacity [KPa]	200
Non - Linearity	1% full scale
Temperature Range	-20 to +60° C
Weight	2.5Kg

*Table 2-8 Specification Soil Pressure Gauge (TML)*

## **2.4. GLÖTZL**

Glötzl is a German company that produces cells for earth pressure and in particular it produces the model EESK [Figure 2-9] that is a small cell suitable for model experiments.

These electric earth pressure transducers and pore water pressure transducers for model tests have been specially developed for the measurement of earth, hydrodynamic and aerodynamic pressures over a wide frequency band up to 5000 KPa. The dimensions of the model EESK

are 75x13mm. As standard model, an electric pressure sensor with connection cable is water tight (Gloetzl, 1958). The specifications are reported in Table 2-9.



Figure 2-9 Model EESK (Gloetzl, 1958)

Specifications	
Capacity [KPa]	100   200   500   1000   2000   5000
Non - Linearity	0.5 % full scale
Over Range Capacity	50 % full scale
Temperature Range	-40 up to +100 °C
Dimension	75x13 mm
Weight	350g

Table 2-9 Specifications Model EESK (Gloetzl, 1958).

**2.5. Tekscan**

Tekscan has presented a revolutionary technology enabling the measurement and presentation of normal stress distribution over an area in real time. The system was originally developed for dental purposes and has been used in other medical and mechanical application as well (Tekscan).

In particular there are specific models for measuring soil stresses. They are made of an ultra-thin, tactile pressure sensor which measure stresses at a large number of points in proximity to one another, hence providing a realistic normal stress distribution. Their flexibility seems to overcome the intruding effect introduced by rigid load cells and this allows a better representation of the actual existing conditions.



This is made possible through a system of combined hardware and software components [Figure 2-10]. The hardware system is comprised of three physical units: a sensor, a data acquisition board, and a connection unit made of an attachment handle with a cable. Sensor presentation software allows analysis, recording, and replaying of the collected data (Hajduk, 1997).

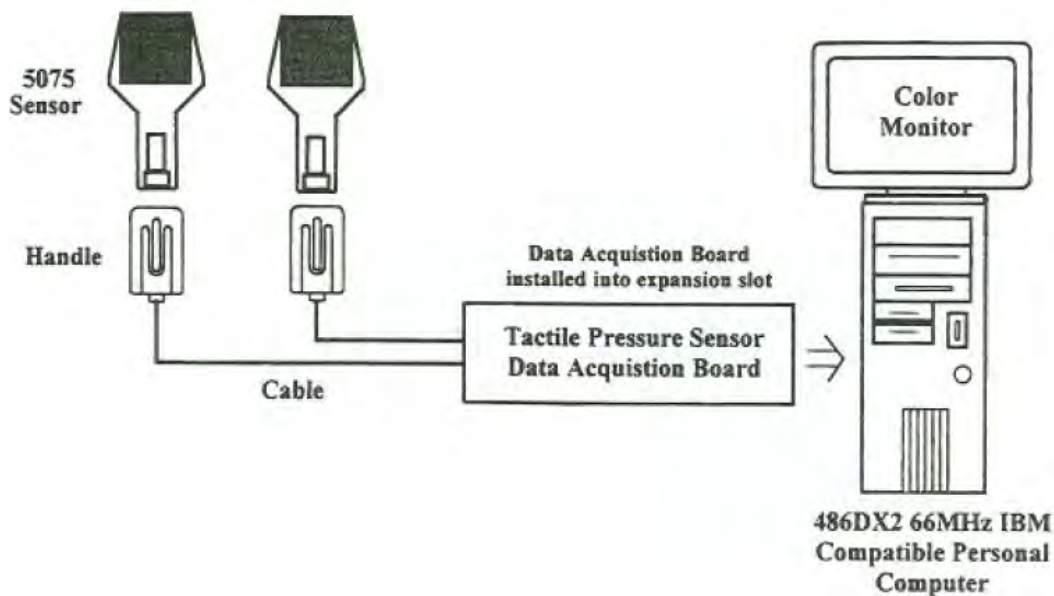


Figure 2-10 Tekscan Pressure Sensor Schematic Diagram (Hajduk, 1997)

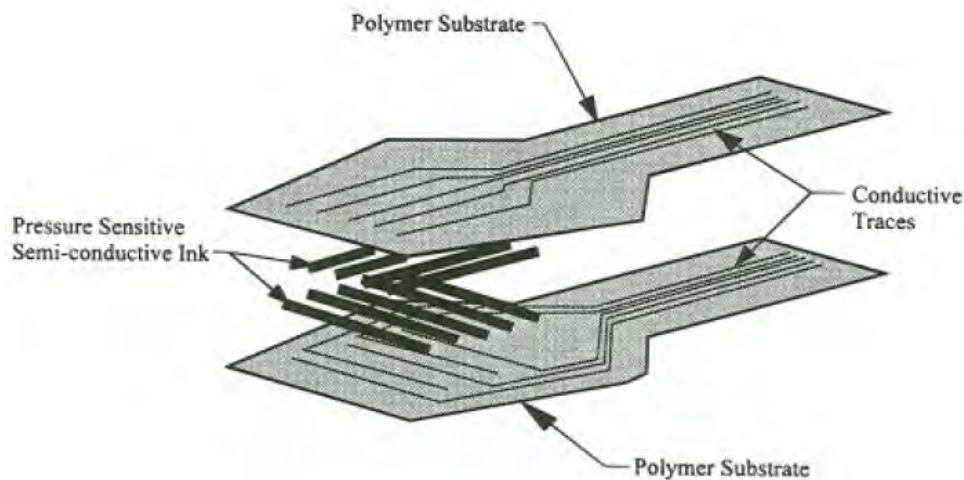


Figure 2-11 Tekscan, Exploded view of sensor construction (Hajduk, 1997)

An individual pressure sensor, as shown in Figure 2-11, is comprised of rows and columns of conductive material separated by semi-conductive ink. The intersections of these rows and columns form sensing areas. When force is applied, the electrical resistance of the semi-conductive ink is changed; this is then recorded through the data acquisition board. The rows,

columns, and semi-conductive ink layer are encased between and protected by two layers of polyester, which are bonded together with adhesive material. The sensor is extremely thin relative to the sensing area size. The thickness of the sensor is a fraction of a millimeter, but the exact dimension varies with size of the sensor allowable pressure range.

When selecting a sensor for a test, a number of factors should be considered.

#### *Sensor Size and Shape*

In most cases, it is desirable to select a sensor that covers the pressure measurement area as completely as possible. Multiple sensors can be used to cover a large area, when a single large sensor may have insufficient spatial resolution for the test. In addition, multiple smaller sensors can be placed in widely spaced, yet important, areas to reveal regional pressure distributions with high local spatial resolution while areas without interest have no measurement sensor. Sensors are often cut, punched, shimmed, or trimmed to fit an application when access is an issue.

#### *Sensel Density*

Sensel density is the number of active sensels per unit of area. More sensels in a given area yield better accuracy for locating individual contact locations; higher pressure distribution resolution; and better ability to visualize small structures. An alternative way to think of resolution is the pitch, or distance between the center of one sensel (sensing element) and its neighbor. Sensors with a greater number of rows and columns per unit of distance (higher density or finer pitch) have better spatial resolution. The smallest X-Y dimension that the system can indicate is the pitch.

The system reports pressure and area related to the entire sensel area. If a pointed needle applies load to one sensel, it may actually contact only a tiny area with very high pressure. However, the reported contact area will be the entire sensel area, and the reported pressure will be derived from the entire sensel area. Thus, in the case of a point load on a large sensel, the system will report a contact area larger than the actual area of contact. The sensel area, including both the active and inactive area, is the minimum area resolution. The sensel reports as either loaded or not – regardless of what percentage of its active surface area has physical contact.

#### *Sensor Pressure Range*

To have a first estimate of contact pressure one has to divide total force by the total area. However, interface pressures are frequently uneven, especially with hard or non-compliant contacting materials. Using the average pressure often significantly underestimates the peak pressure range of individual locations. When hard surfaces touch, it is typical to have large regions with no contact pressure and small regions with very high contact pressure.

Usually, it is desirable to have some “overhead,” to be able to register peak pressure points of the interface. If the sensor becomes overloaded or saturated in some regions, it will identify locations with high pressures, but not how high those pressures are. When the sensor saturates, the saturation pressure is the highest pressure that will be indicated, even if the actual pressure is two, three or ten times the saturation value.

#### *Temperature range*

Standard Tekscan sensors are specified to operate over a temperature range from -40° to 60°C.

#### *Sensor Durability*

Another consideration is durability and thickness. The ultra-thin materials are typically not as durable as thicker materials. Typically, the thicker the sensor, the more durable it will be. To minimize sensor thickness, Tekscan uses the thinnest polyester that can be successfully produced. The resulting thickness of approximately 0.1 mm is the thinnest possible.

#### *Sensor Performance*

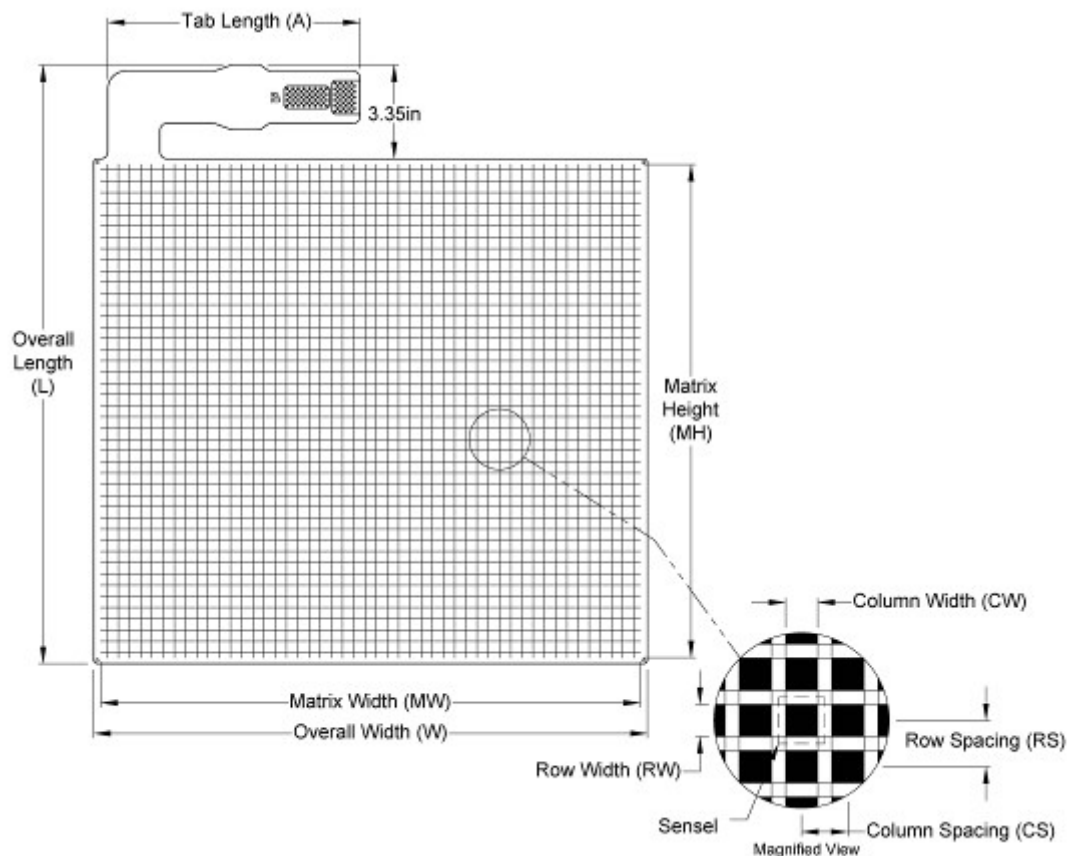
Because the sensing array is a combination of “sensing areas” (the intersection between the conductive rows and columns) and “inactive areas,” (non-responsive areas between the intersections) best results follow from calibration with materials whose compliance is similar to or identical to the material of the test. In the case of a small point load on a large sensel, the system will report a contact area that is larger than the actual area of contact. The sensel area, including both the active and inactive area, is the minimum spatial resolution. The sensel is either loaded or not - regardless of what percentage of its surface area is loaded. The system will report pressure and area data, based on the sensel area.

#### *Sensor Life*

Sensor usage affects how long a sensor will provide good data. Typically, when a sensor is loaded many times, its pressure range increases. It is said to become “colder.” Poor test results can often be traced to using a sensor beyond its useful life or not recalibrating or equilibrating the sensor often enough. The useful life of a sensor is highly application-dependent. The gentle or aggressive nature of an application will determine how long a sensor will last. If the sensor is placed between two soft surfaces that do not distort the surface shape, with low to moderate pressures, the sensor will last longer. Applications involving two hard surfaces at higher pressures tend to have shorter sensor life. Sensors that are exposed to sliding or shear forces or abrasion across their surface will also degrade more rapidly. Still, it is possible that sensors visibly wrinkled or distressed may continue to provide good results because the active aspects of the sensor are internal. However, sensors with punctures or broken traces usually

become non-responsive in those areas. An effective way to evaluate sensor performance is to periodically load it with a known test condition (Tekscan).

The sensor that seems to be suitable for measuring soil pressure is the model 3140, which is shown in *Figure 2-12*. It has a sensing area of 501.6 x 477.0; columns and rows have a pitch of 10.2 mm for a total of 2112 sensing locations. The resolution is of 1 sensel per cm<sup>2</sup>. The specifications are reported in Table 2-10.



*Figure 2-12 Tekscan Pressure Sensor Model 3140 (Tekscan).*

In conclusion, it was demonstrated that tactile pressure sensor can be calibrated to be used with granular material; they provide normal stress measurements of granular material during loading with a good degree of accuracy.

These sensors can also be used in small scale laboratory tests, but it is necessary to pay particular attention in their size compared to the model container and the size of granular material. Otherwise it could give wrong results because it can act as reinforcement for the soil.

Range	690 Kpa
Overall Width	501.6 mm
Matrix Height	477.0 mm
Columns Pitch	10.2 mm
Rows Pitch	10.2 mm
Total No. Of senses	2112
Resolution (senses density)	1 sense per cm <sup>2</sup>

*Table 2-10 Specifications Model 3140 (Tekscan).*

## 2.6. Exemple and Comparison

In small scale laboratory tests the suitability of the transducers depends especially on its size, the measurement range that must correspond to the expected magnitude of the measured quantity and on the measurement error.

For example, to study the problem about a jack-up barge in the sea that impacts brusquely in the ground under rough sea conditions; has been set-up a small scale model, at the Soil Mechanical Laboratory of the University of Duisburg-Essen. This prototype, that is basically a tank, simulates the impact between the column and the soil, as shown in Figure 2 13.

The tank [Figure 2 15] is 180cm tall and has a diameter of 160cm; it is filled for 100cm with sand and over that there are 67cm of water. Load cells are embedded in the sand in three different levels, respectively under 10cm of sand, under 20cm and under 30cm [Figure 2 13]. There are four load cells for each level [Figure 2 14]. The test consist in dropping the load [Figure 2 16] in the container and reading the output of the cells. These cells (KDE-PA of 50mm with) have a capacity of 500KPa and they seem to have some problem in measuring soil stress; they underrated the soil pressure of about a half.

If we consider the maximum load of 30 Kg, and we divide it by the approximate area of the wedge that impact in the soil, that is about 0.002m<sup>2</sup> (5cm diameter); the pressure of the impact is  $\approx 15000 \text{ Kg/m}^2$  that correspond to  $\approx 150 \text{ kPa}$ . This is the maximum pressure that we produce in the test, but the capacity of the cell is more than three times that value and exactly 500 kPa. This high range of measure of the cell is one of the problems about the test.

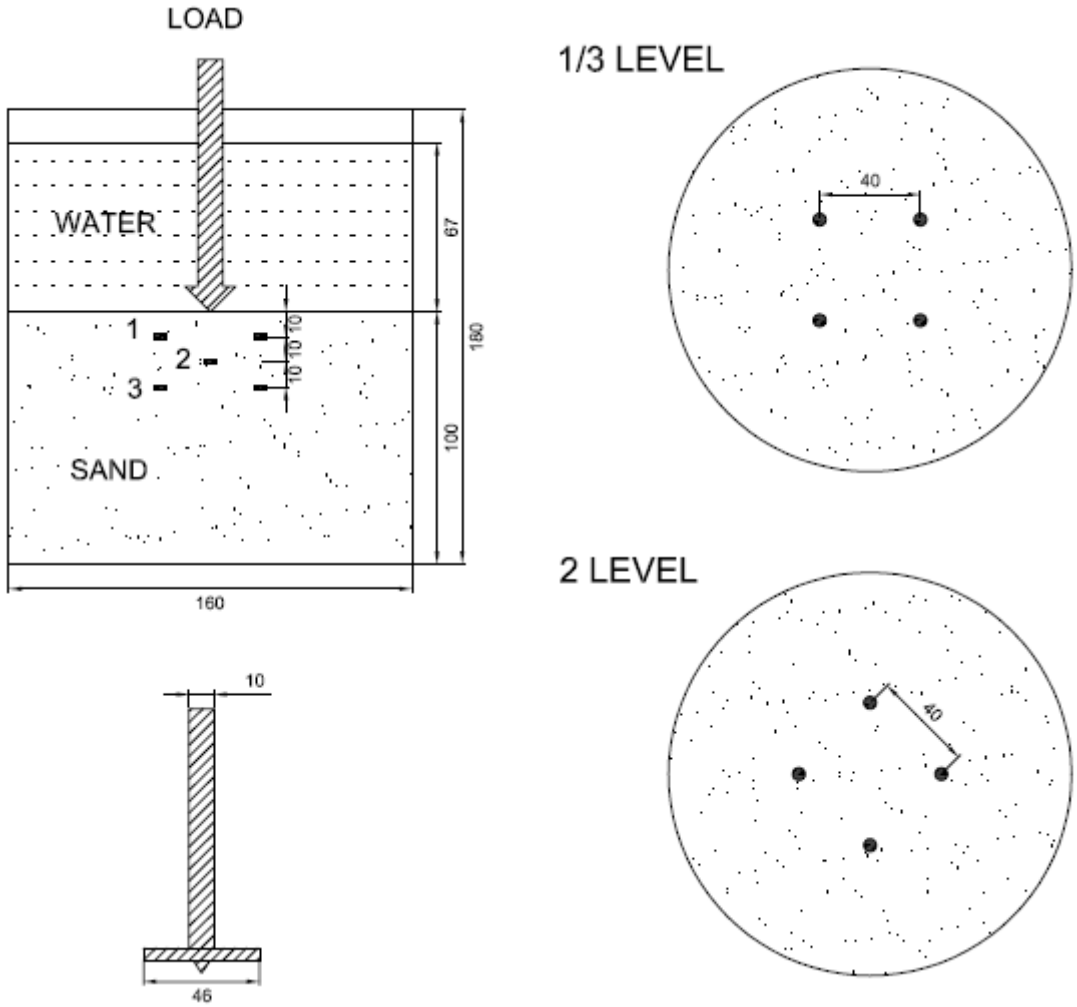


Figure 2-13 Container for the measurement of impact load



Figure 2-14 Disposition of the load cells in the left; Container in the right.



*Figure 2-15 Load used for the test*

As it is possible to see from the example of the test in Soil Mechanical Laboratory of University of Duisburg-Essen, for small scale laboratory test the range and the dimensions of the devices are important. For this reason is noticeable that Geokon devices are not suitable, they are big and suitable for experiments in real constructions. Itmsoil vibrating wire pressure cells have the same problem of size, and also vibrating wire push-in cell are not suitable for our purpose, due to their shape. A valid solution could be Tekscan devices, they are really interesting because they can measure normal stress distribution over an area in real time; they can be used in small scale laboratory tests, but it is necessary to pay particular attention in their size compared to the model container and the size of granular material, in order to avoid boundary effects and non-uniform stress distribution from point loading due to large pieces of aggregate.

Results gained so far have shown that Glötzl cells with a diameter of 75mm and TML devices, the models KDE-PA of 50mm with, are the best available candidates for model tests.

### **3. Literature review on use of transducers for measuring soil stresses**

This chapter deals with a search of test set ups with small transducers in the literature, in order to identify the difficulties and the problems and to get some advices for the right use of this kind of devices.

For example Muhammad Arshad (2014) reported on the measurement of the boundary normal pressures on reduced-scale model piles and the stress changes within the surrounding sand under repeating lateral load. Allard (1990) used the transducers for the determination of total normal stresses in the soil around driven piles. In another article Van Dausen (1992) they were used for the measurement of stresses, strains, and deflections in pavements structures. Also Labuz (2011) studies transducers for soil measurement and the importance of their calibration. H.D. Harris and D.M. Bakker (1993) in an article they talked about a special soil stress transducer, which they have developed in order to measure the normal stress in six different directions. In addition Askegaard (1988) reported problems about small transducers in measuring soil displacement. Talesnick (2005) developed a soil contact pressure transducer based on the null method; in which air pressure balances the output of a strain gage bridge bonded to the sensing element. This action maintains the sensing element in an undeflected state. The result is that the membrane does not interact with the surrounding soil, and errors due to arching are eliminated. Finally Trudeep (2012) talked about the different kinds of in-house calibration for soil pressure transducers.

The evaluation of soil stress implies the use of a stress cell to measure stresses at discrete points in a given soil. The use of a measuring device for soil stresses involves many considerations that are often not fully appreciated. The insertion of an instrument into the soil to measure the actual stress field alters the stress state that would otherwise exist (the free-field soil stress state). Ideally a stress cell, to be transparent, should have exactly the same constitutive properties as the soil it replaces; but this is virtually impossible to achieve (Allard, 1990).

From these articles it is clear that in order to understand the nature of the interaction between a stress cell and the surrounding soil a complete knowledge of the physical characteristics of the transducers and the soil must be obtained. Because of the soil-cell interaction, the stress registered by the cell does not correspond to the free-field soil stress. Below are presented the various factors that influence total stresses in a soil.

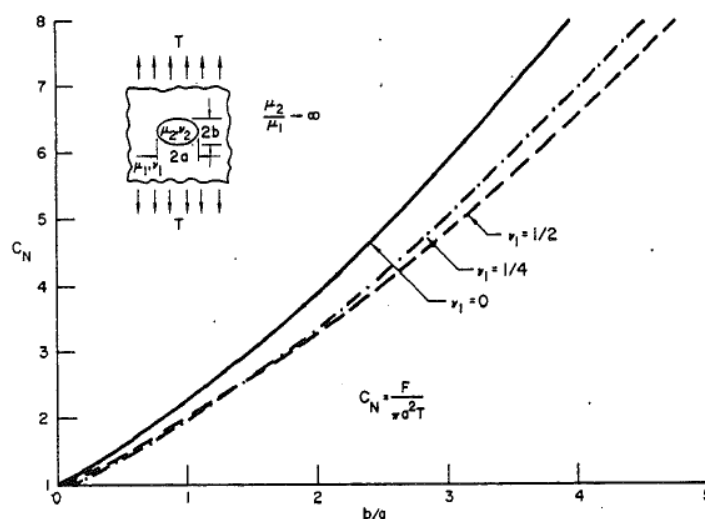
#### **3.1. Cell Properties and Geometry**

Often the research needs to assess the stresses to be expected or its range in advance which may be difficult. When purchasing commercially available cells it is up to the user to select



the proper cell for the application and then apply the necessary corrections and adjustments to any subsequent data. However, the possibilities of available transducers on the market are limited, especially in the small scale.

An important geometrical property of a stress cell is the aspect ratio. The aspect ratio is defined as the ratio of cell thickness to diameter,  $b/a$ . It highly influences the registration ratio ( $C_N$ ), as shown in *Figure 3-1*. Registration ratio is the ratio of normal stress measured by the cell to the free field normal stress that would exist if the cell was not present. Minimizing the aspect ratio decreases the change in registration that may be caused by change in Poisson's ratio of the soil. The aspect ratio also affects the relative percentage of horizontal stresses sensed normal to the cell. This effect is known as 'lateral stress rotation' (Van Deusen, April, 1992).



*Figure 3-1 Influence of cell geometry on registration* (Van Deusen, April, 1992)

Also the presence of wires and protuberances existing at the back of some kind of transducer contribute to the disturbance of the stress field. It is important to select a thin cell with wires coming out in the plane parallel to the sensing area.

Another factor is the soil-cell stiffness ratio, or modular ratio (Allard, 1990).

The soil-cell stiffness ratio is  $S$  defined as:

$$S = \frac{E_{soil} d^3}{E_{cell} t^3} \quad (\text{Eq. 3.1})$$

Where

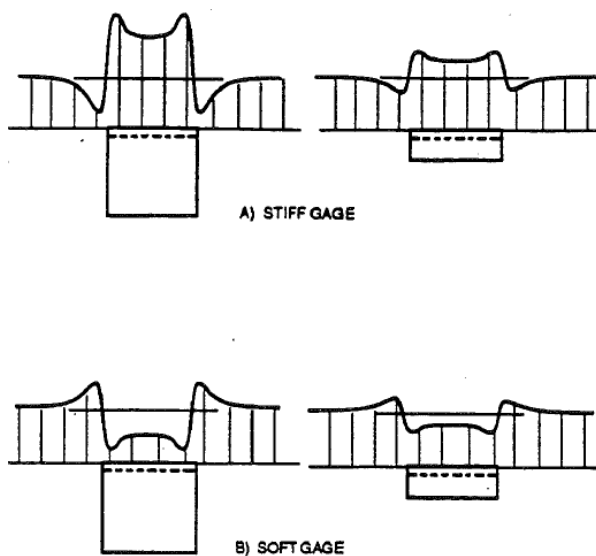
$E_{soil}$  = Young's modulus of the soil

$E_{cell}$  = Young's modulus of the cell material

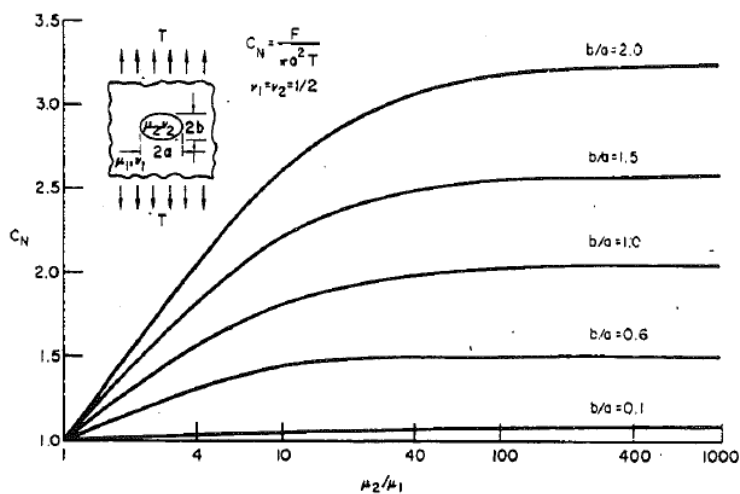
$d$  = cell diaphragm diameter

$t$  = cell diaphragm thickness

Because the stress field is distorted by the presence of the gage the stress measured by the cell will in general not be equal to the free-field stress. If the cell is soft compared to the surrounding soil it will tend to under-register, whereas, if the cell is rigid the opposite will occur (*Figure 3-2*). Theoretical analyses have shown that the change in registration ratio is negligible as long as the cell is sufficiently rigid with respect to the soil as is well demonstrated by the plot shown in *Figure 3-3*.



*Figure 3-2 Illustration of the effects of stress cell geometry and stiffness on the in situ vertical stress distribution (Van Deusen, April, 1992)*



*Figure 3-3 The relationship between registration ratio and stiffness ratio for a spheroidal inclusion under uniaxial load (Van Deusen, April, 1992)*

Furthermore the active face of a stress cell will deflect under the applied stresses. This deflection will cause some degree of arching in the soil surrounding the cell. Based on experiments conducted at the U.S. Army Engineer Waterways Experiment Station it is suggested that the central deflection of the cell shall not be greater than  $1/2000$  of the diameter (Van Deusen, April, 1992). This condition is difficult to check by the users, when the loaded cell is embedded in the soil, and for this reason it must be guaranteed by the manufacturers of the cell.

The stress distribution on the cell face is another important factor influencing stress determinations. Non-uniform stress distribution also arises from point loading due to large pieces of aggregate adjacent to the active cell face. It is suggested that the diameter of the active face be 10 to 50 times larger than the mean soil particle size.

The presence of the cell disrupts the stress field and causes a percentage of the lateral free field stress to act normal to the cell (effect known as lateral stress rotation). This effect cannot be eliminated from the measurement and it is suggested that knowledge of the soil Poisson's ratio and the cell aspect ratio can be used to derive theoretical correction factors. Another technique involved the placing of two cells at each measurement location. By installing two cells, one horizontally and the second in a vertical orientation, measurement from each cell could be used to estimate the necessary correction factor.

Another influence of lateral stresses is the relative sensitivity of the sensing device to lateral compression. With stress cells employing strain gage circuits as the sensing device there may be some degree of lateral stress cross-sensitivity.

### **3.2. Environmental Condition**

Among the factors affecting stress determination there are stress cell durability and the effects of temperature. Sensing devices that utilize strain gauge circuits are susceptible to degradation due to moisture infiltration. For this reason, the cell should be completely sealed, especially where lead wires exit from the cell housing. Also, due to the presence of moisture in the layers, the cell housing should be constructed of materials that are not susceptible to corrosion, e.g. stainless steel or titanium.

Strain gages are sensitive to changes in temperature; if the cell utilizes strain gage circuitry as its sensing element, then the gages should be arranged in such a manner that compensates for temperature effects. Furthermore the metals used in stress cell construction possess thermal properties far different from that of soil. Temperature changes will induce relative displacement of the cell surfaces with respect to the surrounding material. These displacements may be considered as an extraneous deformation and incorporated into any subsequent theoretical correction factors. In cells utilizing diaphragms filled with liquids such as oil or mercury, the effect of temperature dependent volume changes of the liquid must be taken into considera-

tion. These effects cannot be eliminated even with cells possessing temperature compensated strain gage arrangements and correction factors should be derived during cell calibration (Van Deusen, April, 1992).

### **3.3. Calibration Procedures**

The output from an earth pressure cell is usually related to the normal stress in soil through fluid calibration, where a known pressure is applied to the cell and the output is recorded. However, distribution of normal stress within a soil is not uniform, and the cell is not an ideal membrane and bending stiffness affects the response. These factors complicate the performance of the cell. A calibration procedure in a soil at a given density should be done in order to have an accurate measure of average normal stress (Labuz, 2011).

Cell calibration is a function of the geometry of the cell and the stiffness of the soil in which it is embedded; the testing container has a substantial effect on the cell performance because if it is small compared to the cell, the effect of the sidewall friction becomes important (Allard, 1990).

Thus, in order to derive a correlation between the voltage outputs of a stress cell to an in situ applied stress, it is necessary to calibrate the cell. There are many different procedures and recommendations for the calibration of stress cells. For example a laboratory calibration could be done by design a chamber such that the distribution of stresses within the chamber can be assumed to be uniform. The knowledge of the exact stress distribution within the testing chamber is very important. It is important to know what the stress should be at the location of the cell so that output from the cell may be evaluated properly. However, this refined procedure is used for expensive constructions. For small scale laboratory tests it may be so much expensive and time consuming.

An alternative method is to calibrate the cell in a fluid such as air or water. Correction factors based upon laboratory calibrations in soil are preferred but in many cases this may be impractical.

In large-scale laboratory tests with cells embedded in soil, experiments discovered that constructing a jacket around the soil specimen with a large rubber membrane, and applying a layer of grease between the outside of the jacket and the inner wall of the chamber, was an effective means of obtaining tractable stress distributions.

The ultimate goal of a laboratory calibration studies is to gain a detailed understanding of the performance of a particular stress cell relative to a specific type of soil. The soil should preferably be the same type of soil with which the cell will be used in the field and boundary con-

ditions imposed by the container should duplicate stress conditions that may be expected in the field (Van Deusen, April, 1992).

### **3.4. Installation**

The general procedure to prepare a laboratory container with sand and cells for the measurement of the soil stress is to fill sand by air pluviation. If the container is small compared to the cells, in order to reduce the friction between the sand particles and the container's inner wall, it is wise to line it internally using a double latex membrane with a talcum powder coating between the membranes. However, the friction effect is present just in a zone close to the border and in the middle of the container the soil acts as undisturbed. If the cell and the bulb of pressure don't have interaction with the friction zone the procedure describe above is not necessary because the container is considered big enough to ensure that side effects are not present. When the desired height of sand is reached the first cell is placed horizontally on the levelled surface, with its sensing surface facing upwards. After pluviating the sand again it is possible to place other cells in the same way. The wires from the embedded cells run horizontally to the inner wall of the container, and then vertically to the top of the sand specimen. The best containers have the possibility to run the wires outside completely horizontally thanks to holes in the sidewall. The cell's sensing surface should not be compressed before any external load is applied. It is possible to tap the outer wall of the container to achieve a specific densification (Muhammad Arshad, 2014).

## 4. Tests about transducers currently used at the Soil Mechanical Laboratory of the University of Duisburg-Essen

This chapter deals with a series of simple tests on TML model KDE-PA transducers (50mm diameter) to check the proper operation and to find some relations about the interference which the transducers could have when they are embedded so close in the soil.

First of all are discussed the aspect described in chapter 3. As regard the geometry an important parameter is the aspect ratio, defined as the ratio of cell thickness to diameter:

$$11,5 / 50 = 0.23$$

It highly influences the registration ratio, which is the ratio of normal stress measured by the cell to the free field normal stress that would exist if the cell was not present. This aspect ratio could be smaller, a good aspect ratio is less than 0,1. *Figure 3-3* shows that the increasing of the aspect ratio results in an overregistration of the soil pressure.

Because the stress field is distorted by the presence of the gage the stress measured by the cell will in general not be equal to the free-field stress. The cells used for the test are stiffer than the sand and this causes an overregistration of the pressure.

TML model KDE-PA is a strain gauge-type transducers that use strain gauges as detecting sensors. As described in the previous chapter sensing devices that utilize strain gauge circuits are susceptible to degradation due to moisture infiltration. The transducers used for the tests are not new; they were used before in wet sand condition. Thus, it is not to exclude some problem about degradation.

### 4.1. Explanation

First of all with regard to the calibration, a transducer was tested on the table by placing a known weight on it and checking the output pressure measured by it. The transducer is connected to a laptop that through the software LabVIEW is able to show the results. The pressures measured are compared with the ideal pressure that is calculated by dividing the load [kg] applied on the cell by its area.

Sensing area of the cell =  $1662 \text{ mm}^2$  (46mm sensing diameter)

$1 \text{ Pa} \approx 1 \text{ N/m}^2$ .

After that were performed many test in the tank shown in *Figure 4-1* that is available in the Soil Mechanical Laboratory of the University of Duisburg-Essen. It has a diameter of 160cm and is filled with sand for 100cm; its dimensions are big enough to ensure that side effects are not present.

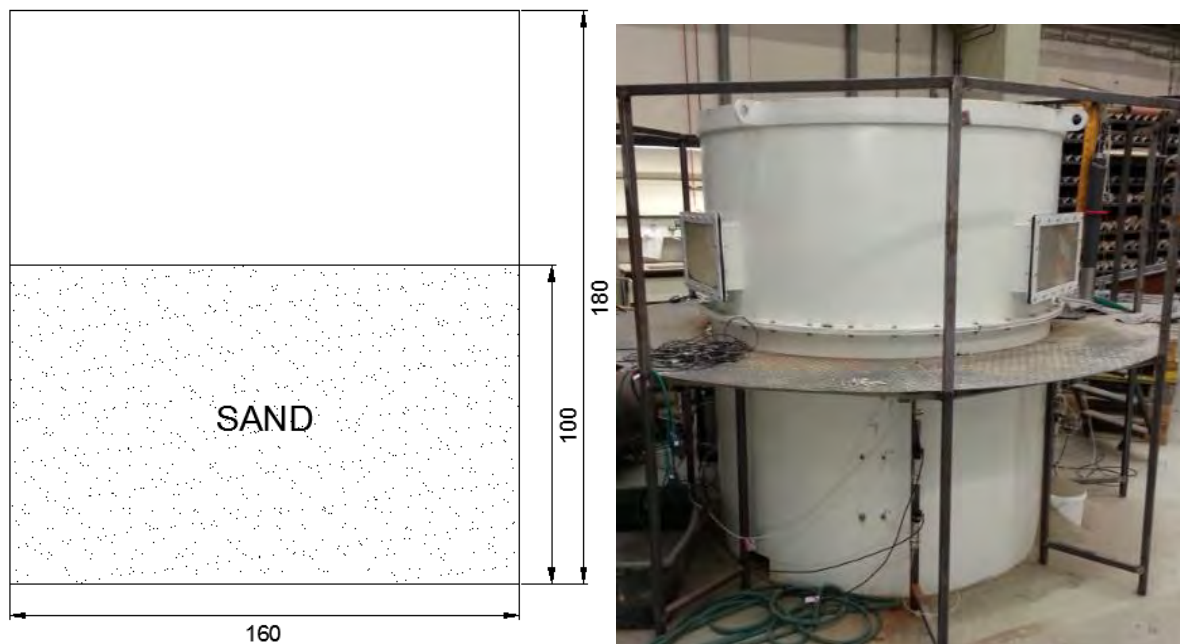


Figure 4-1 Tank Specification in the left, Tank Picture in the right.

The moist sand used has a density of  $25,8 \text{ KN/m}^3$ , and its grain-size distribution is shown in Figure 4-2, where it is possible to see that it is quite uniform. However, the sand on the surface is pretty dry and a reasonable value as specific gravity could be  $16 \text{ KN/m}^3$ .

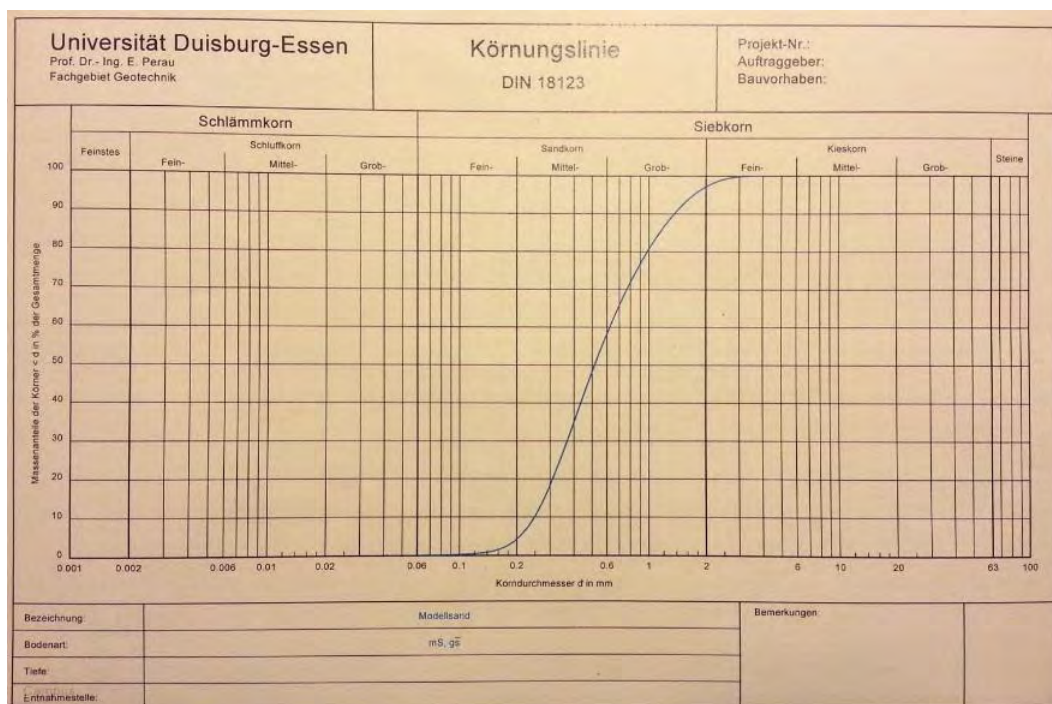


Figure 4-2 Grain-size distribution (Duisburg-Essen, 2014)

The cells are embedded in the sand at different locations for each test. Tests consist of recording the soil stress measured by the cells, first just under soil weight and then they are further stressed by a weight positioned at the sand surface.

We are interested in comparing the ideal values with the pressures recorded. The ideal values however are not the reality, because they are based on the theory of linear elasticity, which means small deformations and linear relationships between the components of stress and strain.

They are calculated with the formula:

$$\sigma_{tot} = \gamma z + \sigma_q \quad (\text{Eq. 4.1})$$

Where:

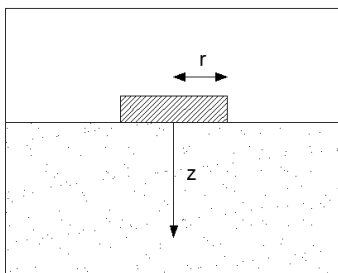
$\gamma_d$  : is the dry unit weight of the sand (16 KN/m<sup>3</sup>);

$z$  : is the depth;

$$\sigma_q = q \left\{ 1 - \frac{1}{[1 + (r/z)^2]^{3/2}} \right\} \quad (\text{Eq. 4.2})$$

Is the stress increment under the central vertical due to the load by a circular area (Inc., 2012) (in these tests are used weights with a circular shape). *Figure 4-3* shows the convention of the signs.

$r$  : is the radius of the circular weight.



*Figure 4-3 Convention signs.*

The formula above is able to provide the stress increment just under the central vertical of the weight. In order to calculate the pressure in other points the diagram shown in *Figure 4-4* is used (Grasshof, 1982). It gives a reduction coefficient in function of the distance from the central vertical and the depth, and it must be multiplied to the value of the load.



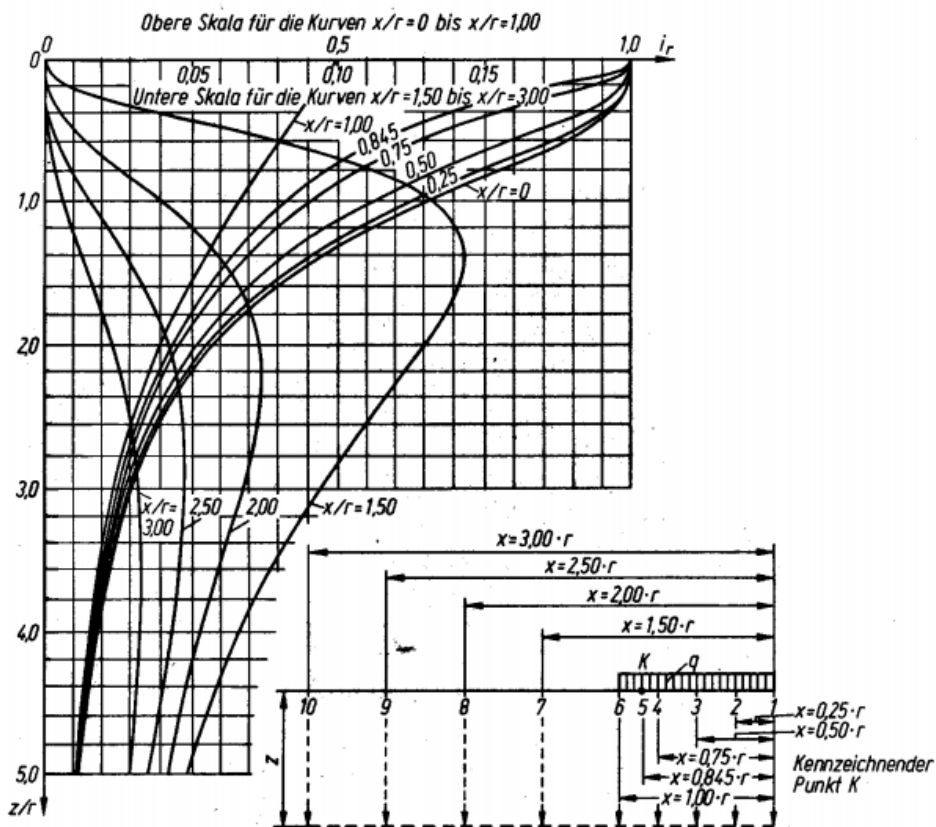


Figure 4-4 Diagram of the reduction coefficients to get the pressure value under a circular shape load (Grasshof, 1982).

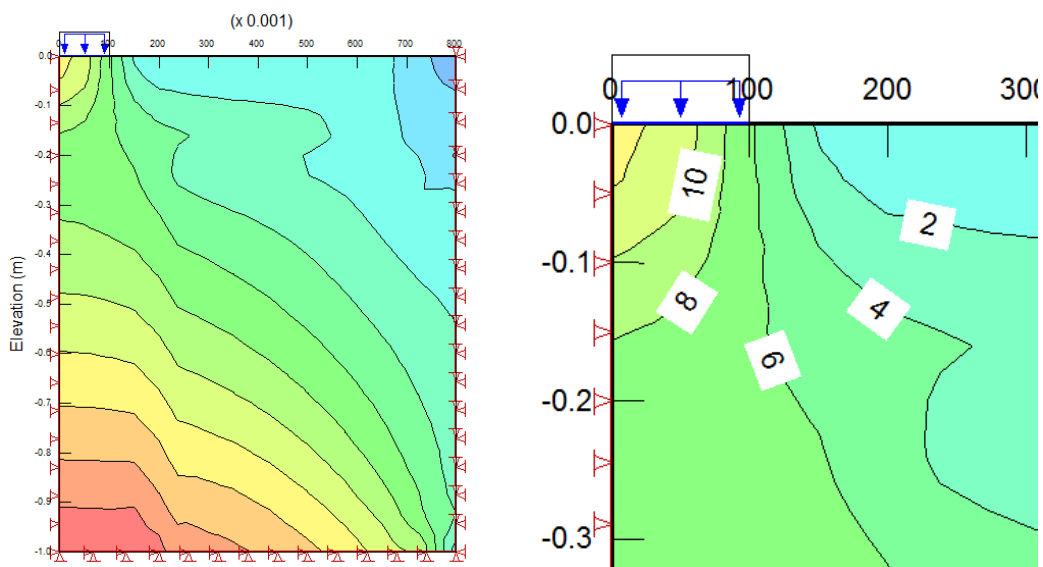
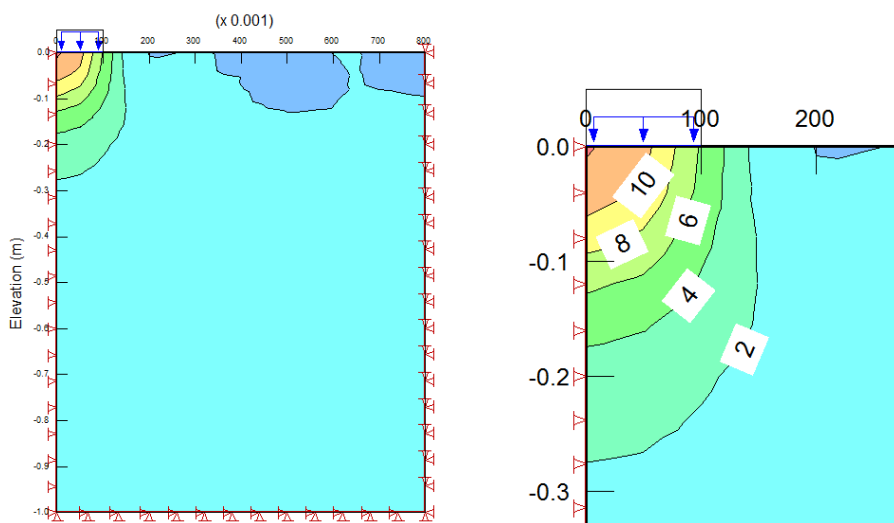


Figure 4-5 Example of a numerical solution of the soil pressure (sand weight plus load of 40 kg) on the left, particular on the right.

The ideal results can be calculated also by a numerical program, in this case the software Geo-Slope is used. *Figure 4-5* shows the pressure distribution in the tank by the weight of the sand and a surface load of 40kg. The labels on the picture are in kPa.

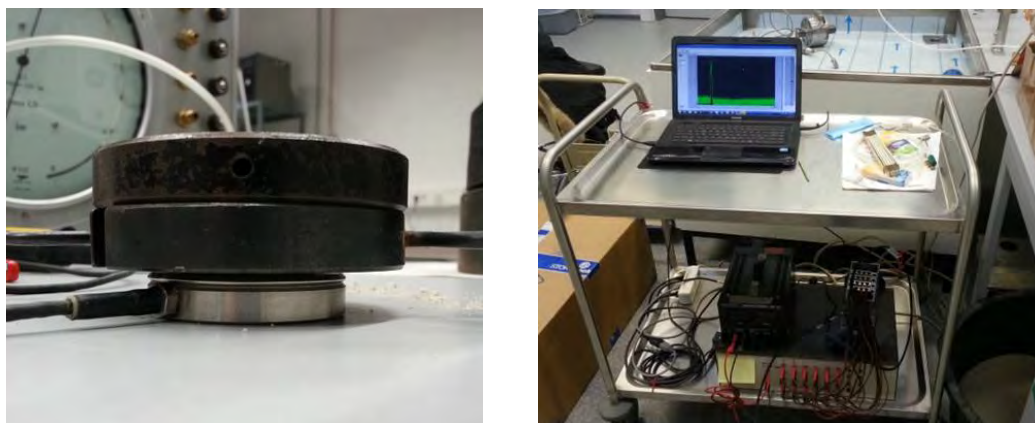
*Figure 4-6* shows the distribution of the pressure only due to the surface load of 40kg. It is possible to see the bulb of pressure that decreases with depth and distance from the center.



*Figure 4-6 Example of a numerical solution for a surface load (40 kg) only.*

## 4.2. Calibration on the Table

As described above the first operation consists in testing a transducer on the table by placing a known weight on it and checking out if the output displays the same value. The cell is connected by cable to a laptop, which by means of the program LabVIEW is able to show the data recorded. This is shown in *Figure 4-7*.



*Figure 4-7 Cell tested on the table on the left; Instrumentation on the right.*

The results are shown in Table 4-1. In the first column the load over the cell is reported, in the second the pressure measured by the cell, in the third the calculated ideal pressure and in the last the percentage error in relation to the ideal value.

Load [Kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	2,38	0,00	$\rightarrow \infty$
0,5	5,28	2,94	+79,7
1	7,95	5,88	+35,2
2	14,31	11,76	+21,6
5	31,05	29,41	+5,6
10	58,68	58,82	-0,2
20	123,15	117,65	+4,7
40	245,04	235,29	+4,1
50	270,80	294,12	-7,9
60	288,17	352,94	-18,4
40	245,34	235,29	+4,3
30	186,94	176,47	+5,9
20	123,69	117,65	+5,1
10	61,15	58,82	+3,9
5	32,93	29,41	+12,0
2	15,29	11,76	+29,9
1	8,41	5,88	+42,9
0,5	6,06	2,94	+106,1
0	2,80	0,00	$\rightarrow \infty$

*Table 4-1 Calibration of the cell on the table.*

It is possible to see that the cell gives small percentage error of the pressure just in a range of 5 – 40 Kg (30-240 kPa). For loads outside this range the error overcome the 20% and consequently the measurements are not so reliable. The charts show in *Figure 4-8* *Figure 4-9* display the relationships between the real and ideal curves, and the error. The phenomenon of hysteresis seems to not be present.

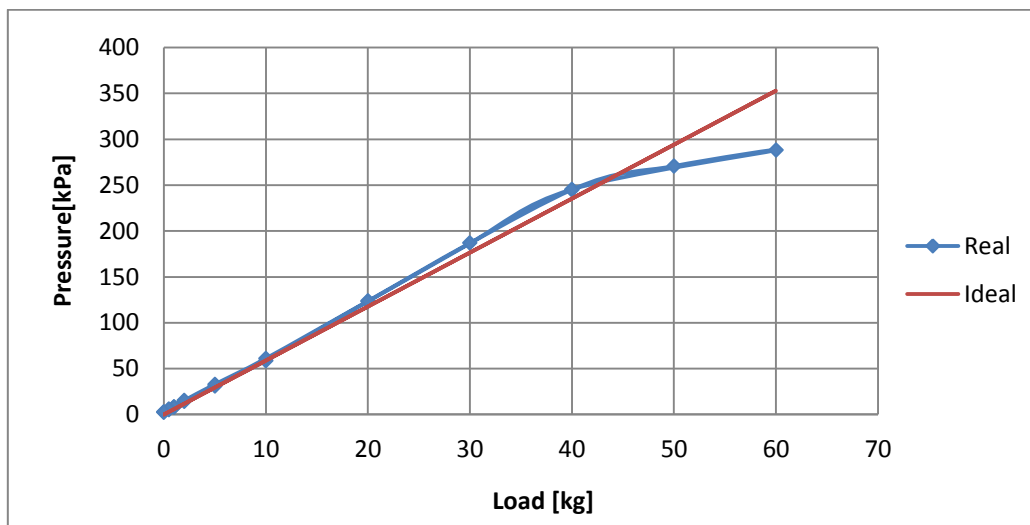


Figure 4-8 Chart of the calibration of the cell on the table

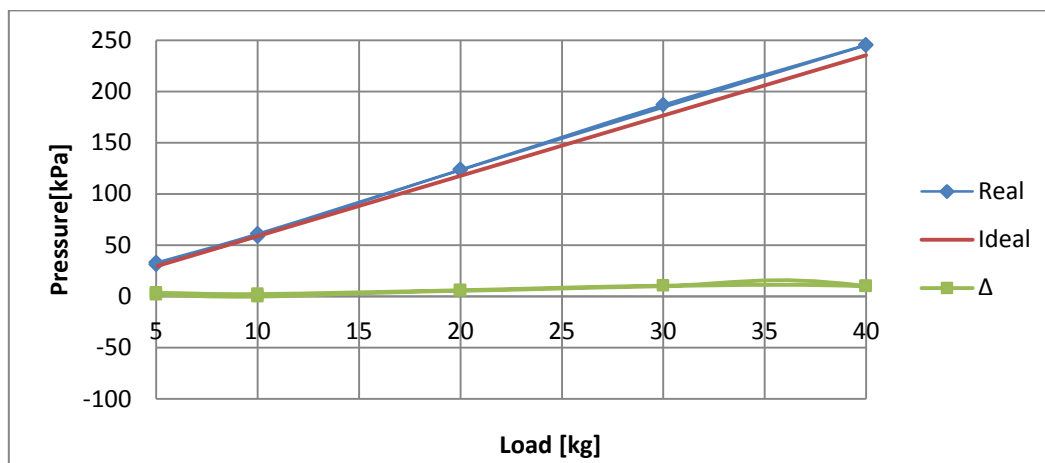


Figure 4-9 Chart about the calibration of the cell on the table and the error, in a load range of 5 – 40 kg.

### 4.3. Measurements in the sand, one cell 5cm depth

After the calibration on the table the cell is placed on the sand in the test tank. For this purpose a hole is made in the sand, the cell is placed and then it was carefully covered by 5cm of sand and the surface is made flat. This is shown in *Figure 4-10*.

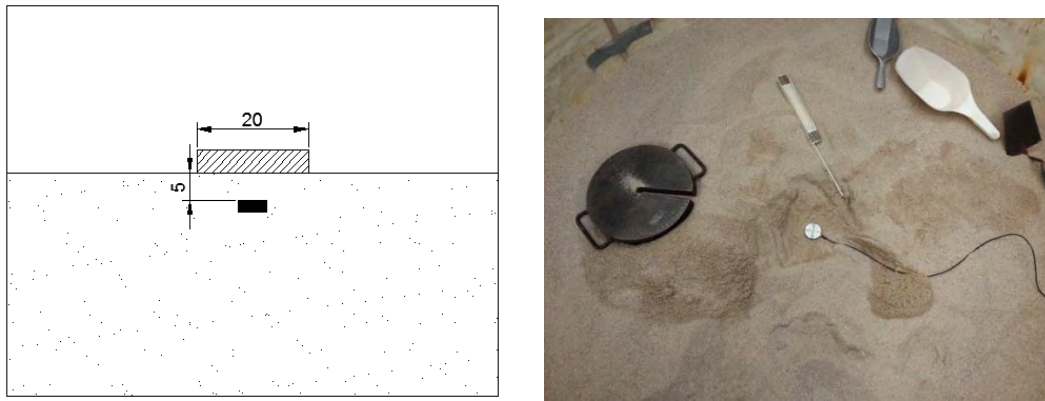


Figure 4-10 Cell placed in the sand on the left; Instrumentation on the right.

The first measure is done without weight over the ground surface, after that a series of known weights (5 – 10 – 20 – 40 – 60 kg) are positioned on the flat surface and the measurements of the cell were recorded at each step. Table 4-2 shows the results and Figure 4-11 displays the relationship between real, ideal and error curves.

Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	0,28	0,80	-65,4
5	2,01	2,22	-9,5
10	5,26	3,64	+44,6
20	9,22	6,47	+42,5
40	17,72	12,14	+45,9
60	21,91	17,81	+23,0
20	11,92	6,47	+84,1
0	0,35	0,80	-56,6

Table 4-2 Measurement, 1 cell 5cm depth.

In this case the cell underregisters the soil pressure for light weight and overregisters for heavy weight, and is also present hysteresis. Between the positioning of the load and the recording of the measure in average pass one minute, so the cell has the time to stabilize. Hysteresis could be justified because of in the first phase of loading the sand is loose, while in the unloading phase the sand is more compacted because of the weight applied on it. Indeed the in the unloading the pressure measured is higher than in the loading.

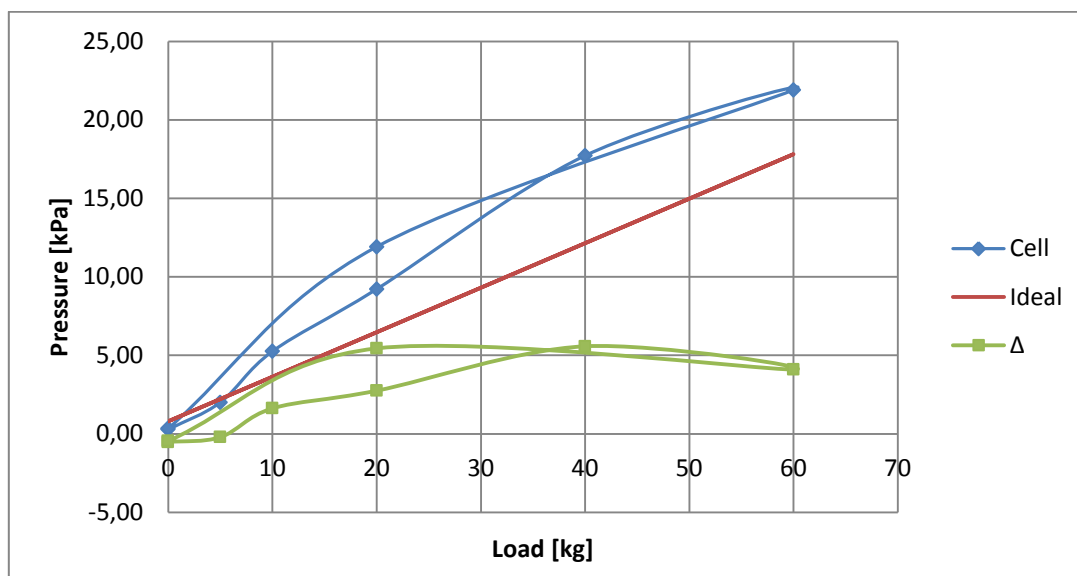


Figure 4-11 Chart results one cell 5cm depth.

#### 4.4. Measurements in the sand, one cell 15cm depth

In this test there is one cell embedded in the sand 15cm depth, and as in the previous test the stress that is registered when there is no weight over it and when a known weight is placed over the ground surface are registered. This is shown in Figure 4-12.

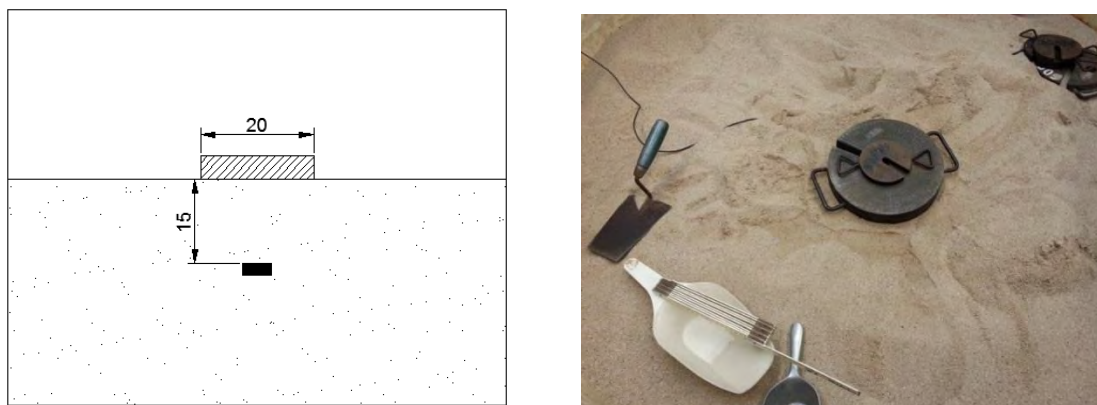


Figure 4-12 Cell placed in 15 cm depth on the left; Instrumentation on the left

The Table 4-2 shows the results and the Figure 4-11 displays the relationship between real and ideal curves, the error curve is even plotted.

Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,06	2,40	-56
5	1,67	3,06	-45
10	3,54	3,72	-5
20	6,19	5,04	+23
40	11,82	7,68	+54
60	18,02	10,32	+75
20	7,47	5,04	+48
0	1,66	2,40	-31

Table 4-3 Results of 1 cell 15cm depth.

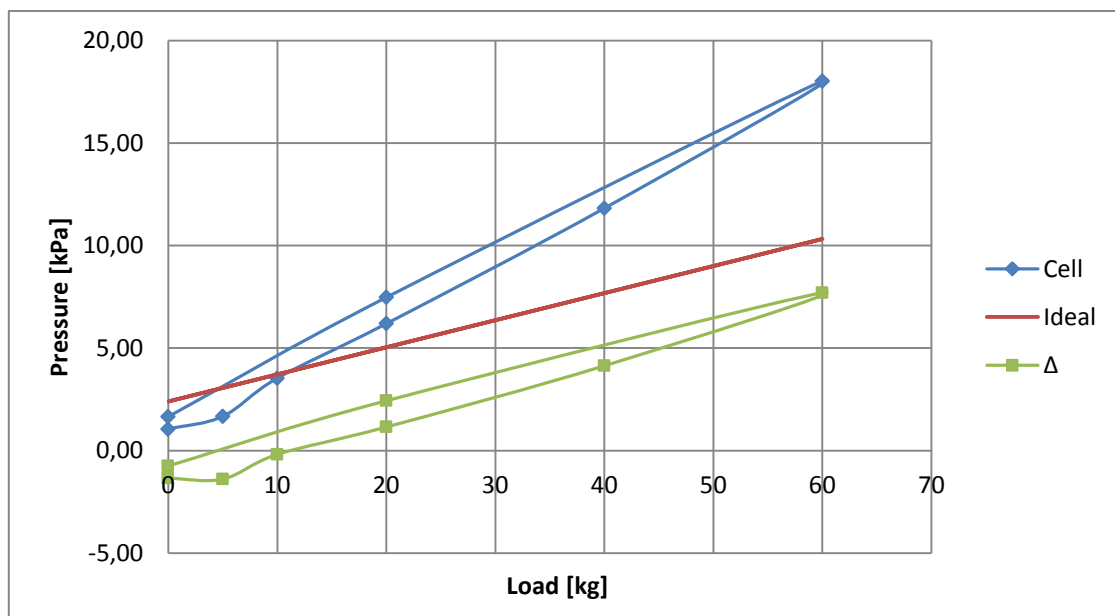


Figure 4-13 Pressure measured by the cell, ideal pressure and error.

In this case the cell follows a linear distribution, but the error increases with the increasing of the load. The lines seem following a different inclination, the pressure measured is higher than the ideal pressure calculated. With regard to hysteresis, in this instance is less evident than the previous test but it is possible to notice that the unloading curve is over the loading one, because of the more compression of the soil.

#### 4.5. Measurements in the sand, two 2 cells in a vertical line

In this test there are two cells embedded in a vertical line, one of them is 10cm depth (cell 1) and the other one 20cm (cell 2). This is shown in *Figure 4-14*. As in the previous tests the first measure is without weight and the following with an increasing load.

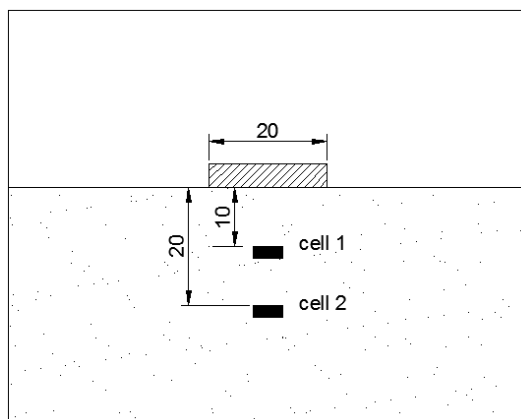


Figure 4-14 Cell placed in the sand.

Table 4-4 shows the results, Figure 4-15 displays the relationship between real and ideal curves, and Figure 4-16 plots the distribution of the errors.

Load [kg]	CELL 1			CELL 2		
	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,23	1,60	-23,1	2,96	3,20	-7,6
5	3,44	2,61	+32,0	3,40	3,64	-6,6
10	4,77	3,61	+32,0	3,96	4,09	-3,2
20	8,36	5,63	+48,5	5,68	4,97	+14,2
40	16,27	9,65	+68,5	9,01	6,74	+33,6
60	23,67	13,68	+73,0	12,33	8,52	+44,8
20	9,51	5,63	+69,0	6,06	4,97	+21,9
0	1,83	1,60	+14,4	2,59	3,20	-19,0

Table 4-4 Results about two cells in a vertical line.

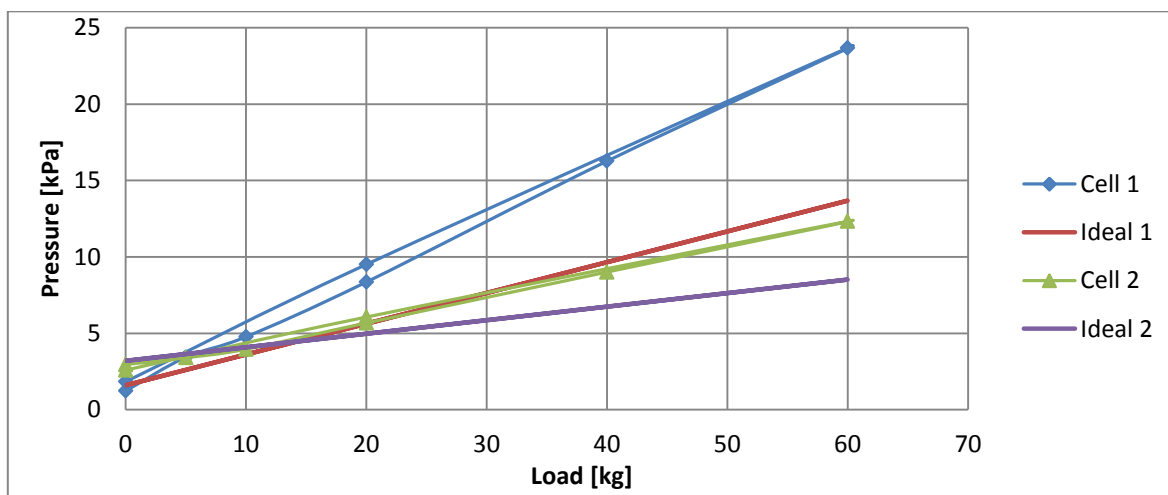


Figure 4-15 Chart results of two cells in a vertical line.



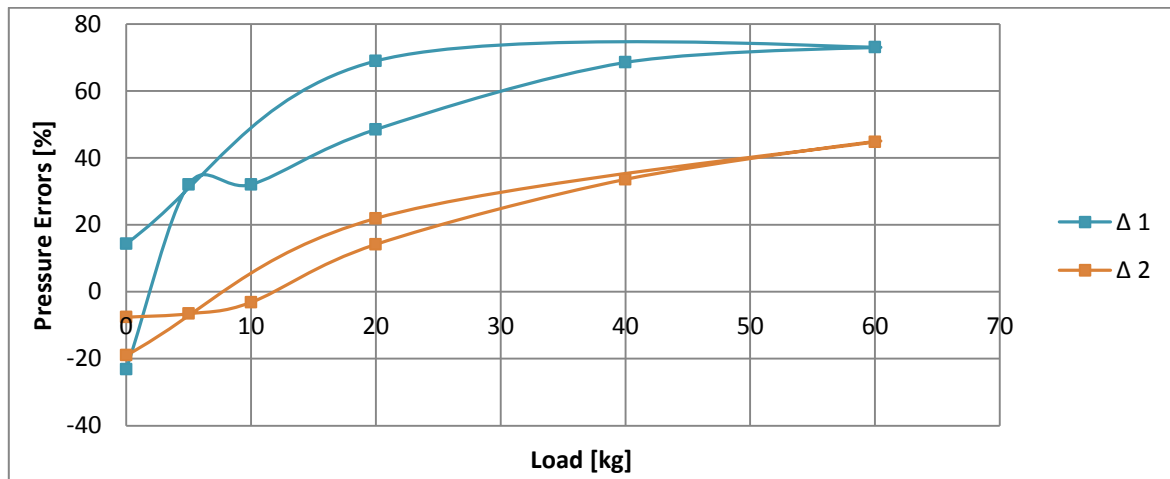


Figure 4-16 Errors distribution.

In this test the behavior saw in the previous test is confirmed, both the cell overregisters for heavy weight. In order to understand better the behavior of the cells, the contribute of the sand pressure and of the load pressure (under a load of 40 kg) are divided, and the plots are shown in Figure 4-17 and Figure 4-18.

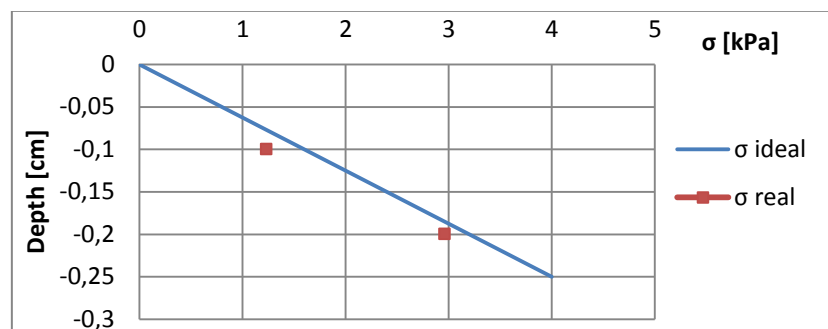


Figure 4-17 Contribute of the sand to the pressure.

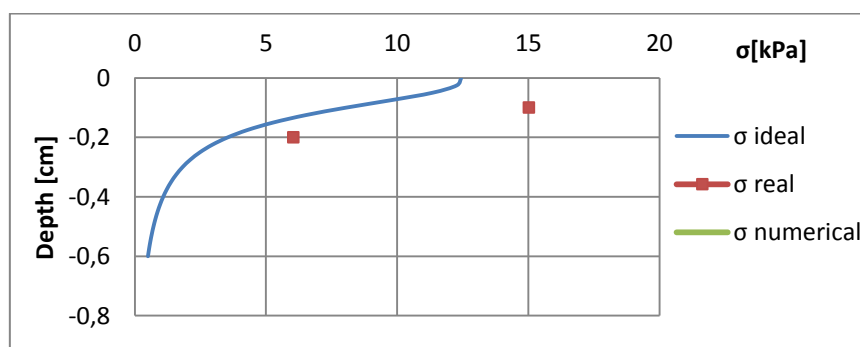
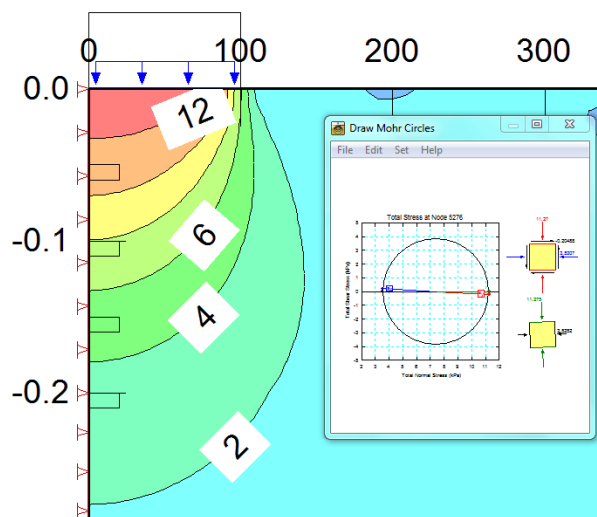


Figure 4-18 Contribute of the load (40 kg) to the pressure.

The ideal load stress distribution is calculated also with the numerical program, as shown in *Figure 4-19*. It gives exactly the same the same ideal values as calculated with the formula, probably the program implement the same formula.

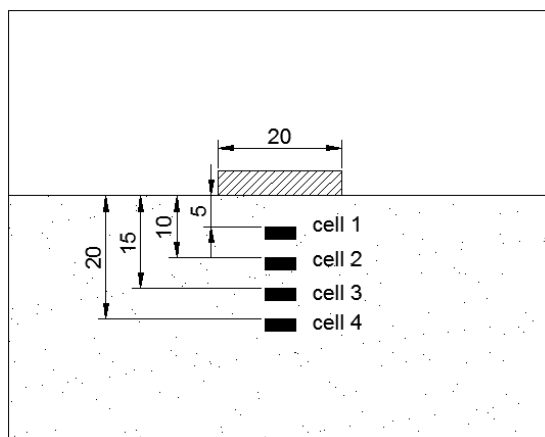


*Figure 4-19 Loadl pressure with a load of 40kg*

It is possible to see that under a load of 40 kg, the majority of the error is given by the load, and it increase with the increasing of the load. Anyway the cells seem to follow the bulb of pressure.

**4.6. Measurements in the sand, 4 cells in a vertical line**

In this test there are four cells embedded in a vertical line, 5cm depth (cell 1), 10cm depth (cell 2), 15cm depth (cell 3) and 20cm depth (cell 4), as shown in *Figure 4-20*.

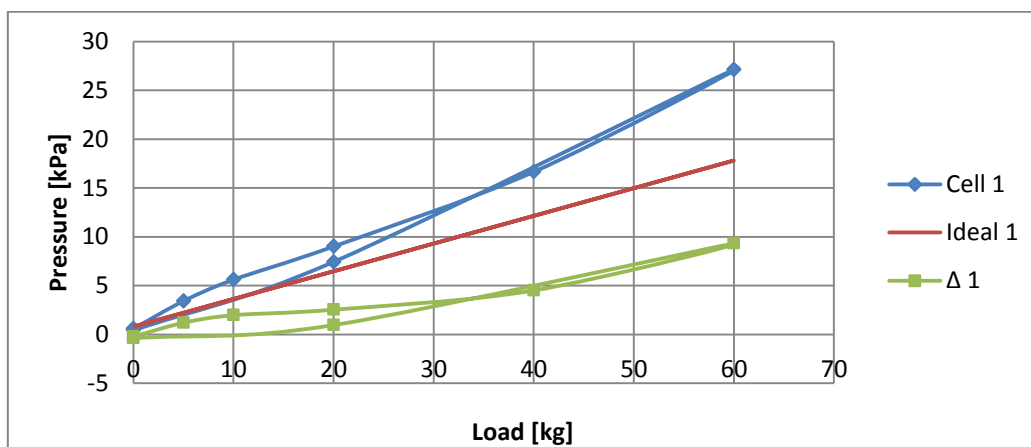


*Figure 4-20 Cells placed in the sand*

Table 4-5 shows the results, *Figure 4-21* displays the outputs of the four cells, the ideal curves and the errors.

	CELL 1			CELL 2		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	0,59	0,80	-26,6	1,49	1,60	-6,8
5	3,41	2,22	+53,8	3,52	2,61	+34,8
10	5,61	3,64	+54,2	5,48	3,61	+51,7
20	9,01	6,47	+39,2	8,81	5,63	+56,5
40	16,65	12,14	+37,1	15,66	9,65	+62,3
60	27,13	17,81	+52,3	24,57	13,68	+79,6
20	7,43	6,47	+14,8	7,65	5,63	+36,0
0	0,42	0,80	-47,4	1,30	1,60	-18,6
	CELL 3			CELL 4		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	4,76	2,40	+98,3	4,03	3,20	+26,0
5	4,62	3,06	+51,0	4,95	3,64	+35,8
10	6,53	3,72	+75,5	5,63	4,09	+37,9
20	8,85	5,04	+75,6	6,63	4,97	+33,4
40	13,98	7,68	+82,0	10,90	6,74	+61,6
60	19,78	10,32	+91,7	14,58	8,52	+71,2
20	7,71	5,04	+52,9	6,49	4,97	+30,5
0	3,11	2,40	+29,4	3,47	3,20	+8,3

Table 4-5 Results of the 4 cells under a vertical line.



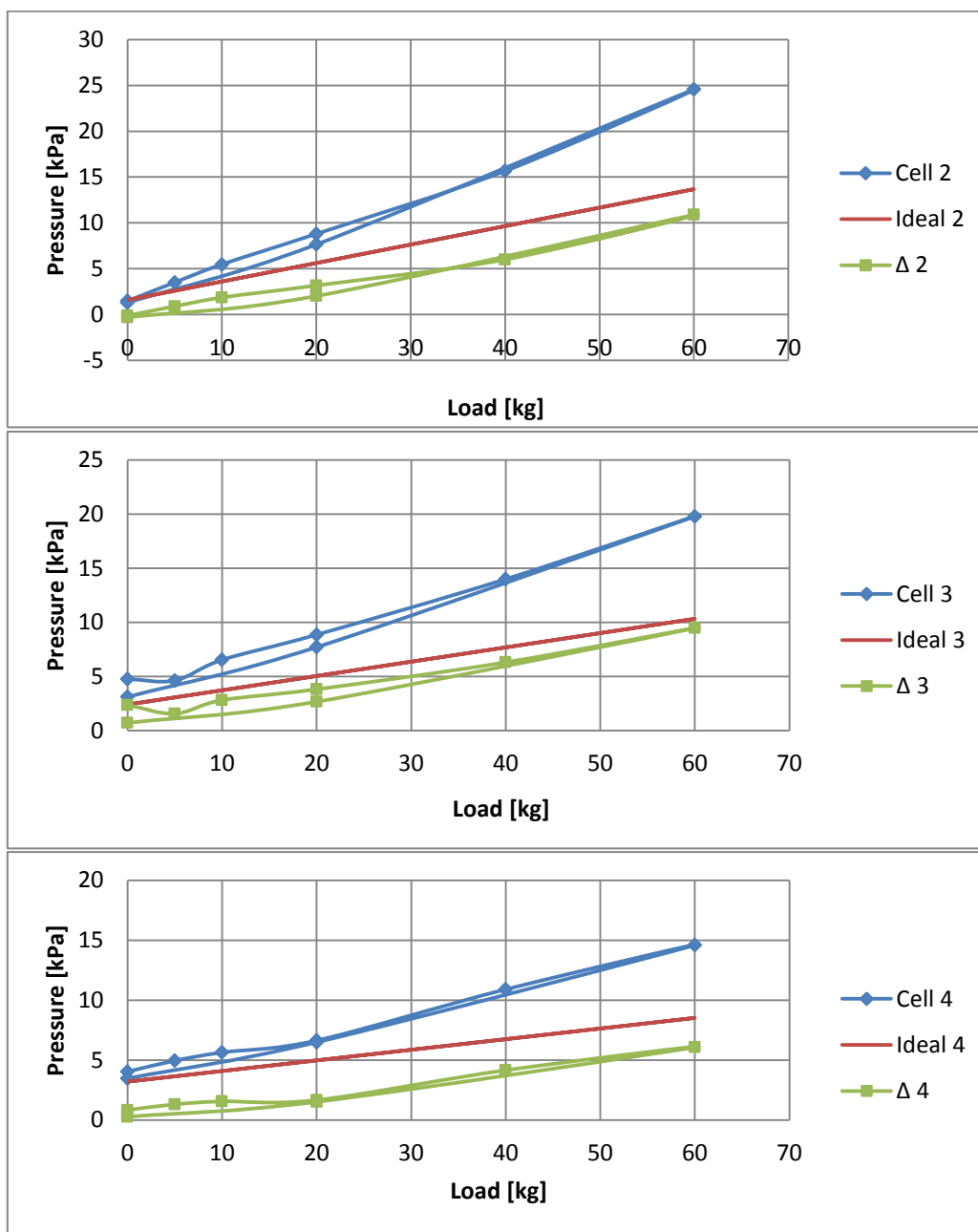


Figure 4-21 Charts of the pressure measured by the 4 cells, the ideal curves and the errors.

Also in this test is possible to see that all the four cells overregister for high weight and the error grows with the load.

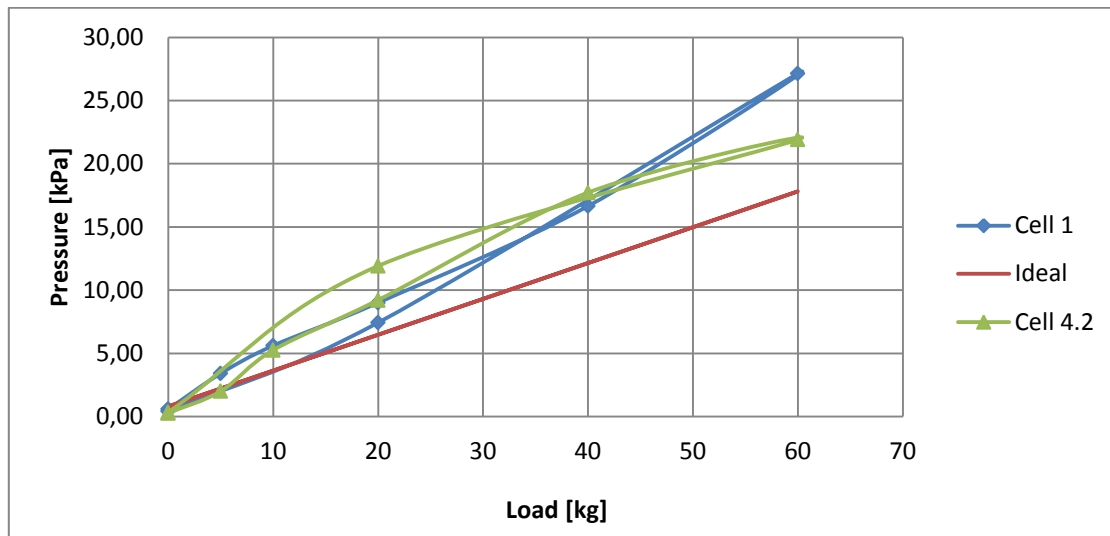


Figure 4-22 Comparison between cell 1 and the cell in the chapter 4.2

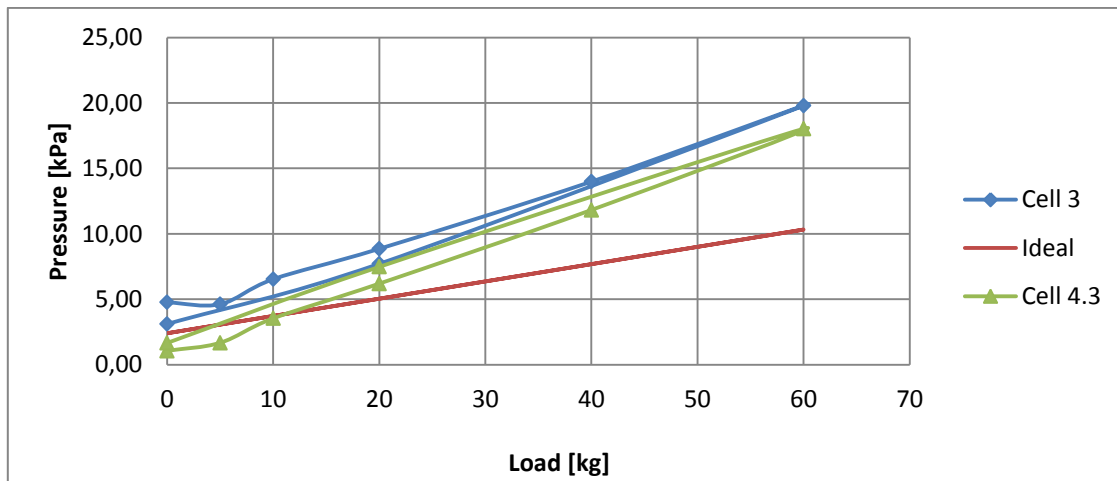


Figure 4-23 Comparison between cell 3 and the cell in the chapter 4.3

In Figure 4-22 is plotted the graphs of the cell 1 compared with the cell in the chapter 4.2 (both embedded under 5 cm of sand) and in Figure 4-23 is compared the results of the cell 3 versus the cell in the chapter 4.3 (both embedded under 15cm of sand). The results are pretty similar, thus is wildcat to draw some conclusion from them.

Going back to the four cells in a vertical line, two graphs are done in order to divide the soil weight pressure to the load pressure given by a load of 40 kg. They are shown respectively in Figure 4-24 and in Figure 4-25. It seems that the cell 1 and 2 measure the right pressure under the sand weight, while the lower cells (3 and 4) overregister. Furthermore the contribute of the load (40 kg) to the pressure always overregister, but for all the cells the level of over-registration is comprised in a range of 3 – 6 kPa.

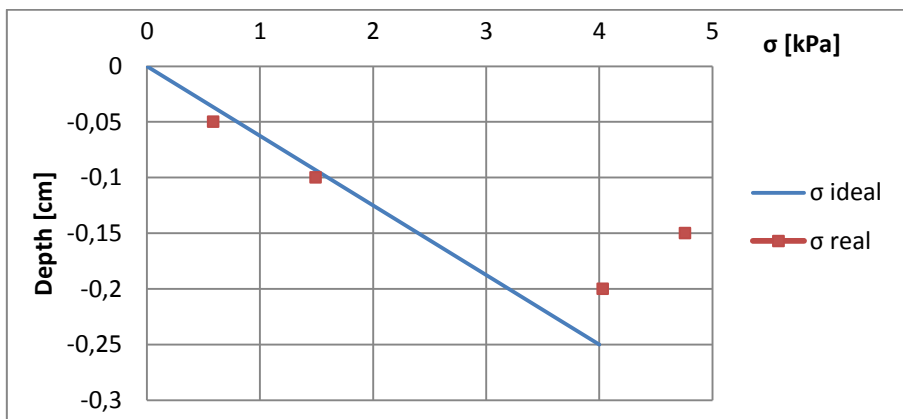


Figure 4-24 Contribute of the sand to the pressure

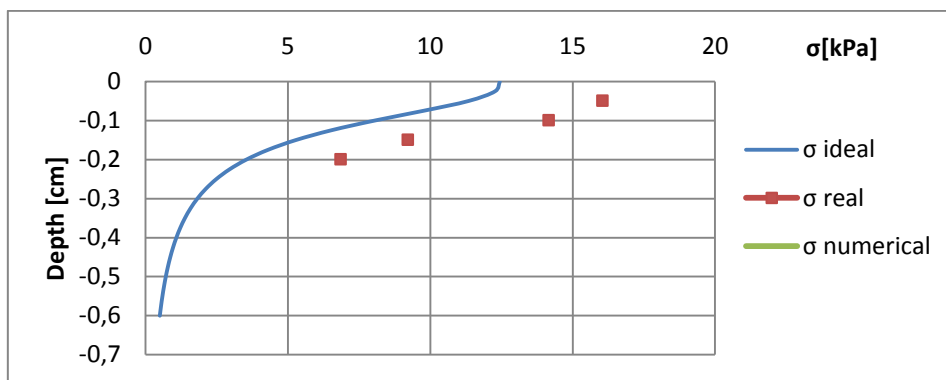


Figure 4-25 Contribute of the load (40kg) to the pressure

The same comparison is made with a load of 10 kg, as shown in Figure 4-26. Also this time all the cell overregistered, and the results seem following the pressure bulb.

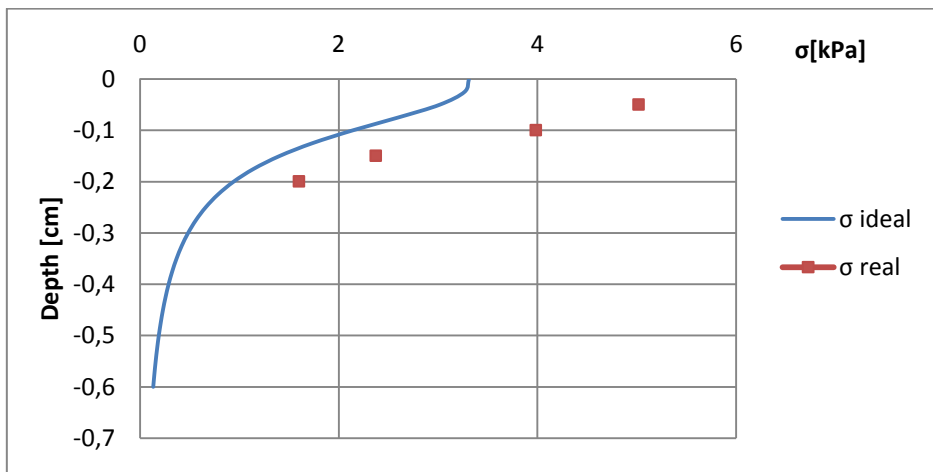
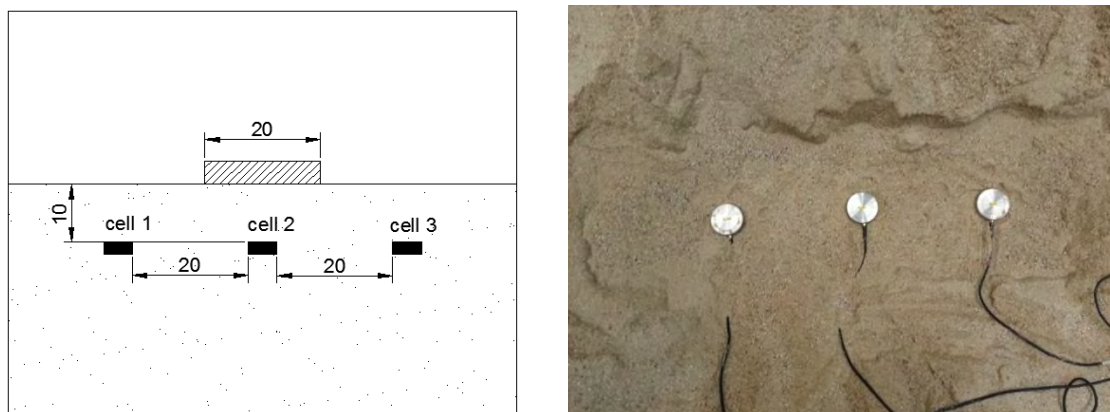


Figure 4-26 Contribute of the load (10kg) to the pressure

#### 4.7. Measurements in the sand, 3 cells in a horizontal line

In this test there are three cells embedded in a horizontal line, 10cm depth and 20 cm away from each other. This is shown in *Figure 4-27*. The procedure is the same as in the previous tests.



*Figure 4-27 Cells placed in the sand on the left; Cells Picture on the right.*

Table 4-6 shows the results, *Figure 4-28* displays the pressure measured by the three cells and the distribution of the ideal pressure; while *Figure 4-29* plots the errors.

	CELL 1			CELL 2			CELL 3		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,55	1,60	-2,9	1,07	1,60	-33,2	1,04	1,60	-34,8
5	0,74	1,63	-54,9	2,86	2,61	+9,7	0,92	1,63	-43,4
10	1,11	1,66	-33,4	4,57	3,61	+26,5	1,69	1,66	+1,8
20	0,81	1,72	-52,9	8,65	5,63	+53,7	1,14	1,72	-34,0
40	1,29	1,84	-29,9	16,49	9,65	+70,9	1,15	1,84	-37,7
60	1,27	1,96	-35,5	23,00	13,68	+68,2	1,03	1,96	-47,7
20	1,27	1,72	-26,4	9,89	5,63	+75,8	0,96	1,72	-44,2
0	0,90	1,60	-43,9	1,68	1,60	+5,2	1,26	1,60	-21,4

*Table 4-6 Results of the 3 cells embedded in a horizontal line*

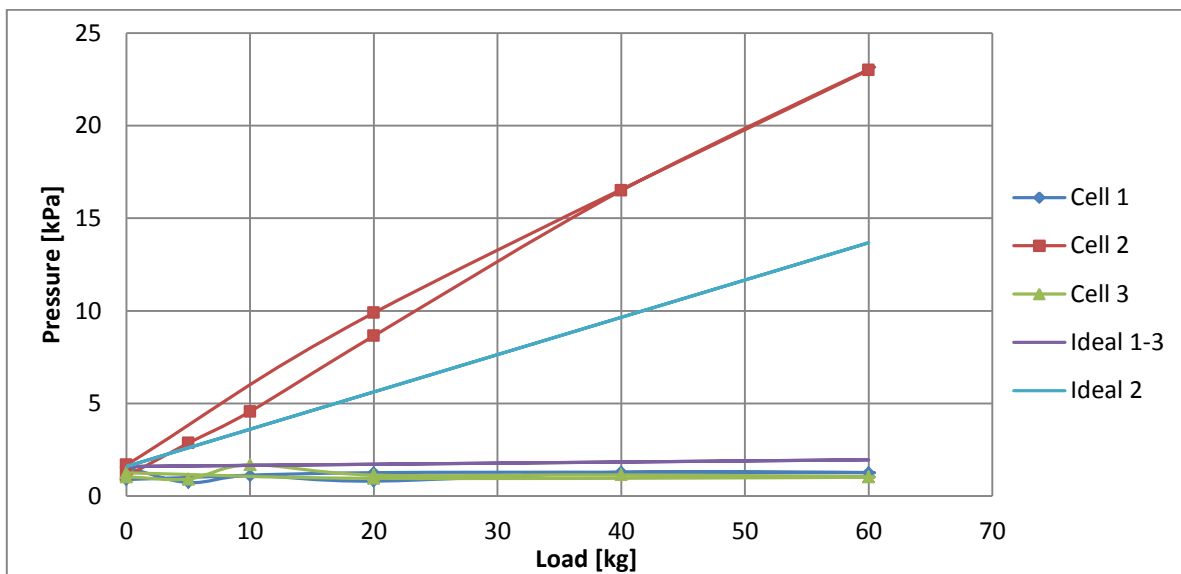


Figure 4-28 Chart of the pressure measured by the 3 cells and distribution of the ideal pressure

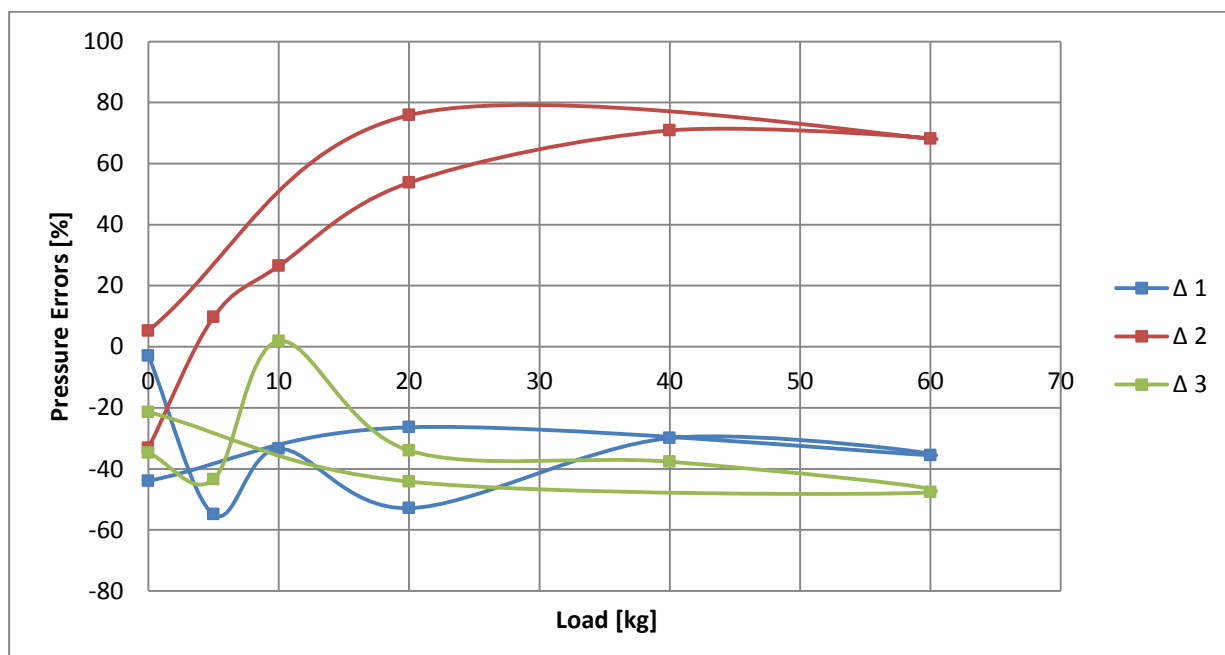


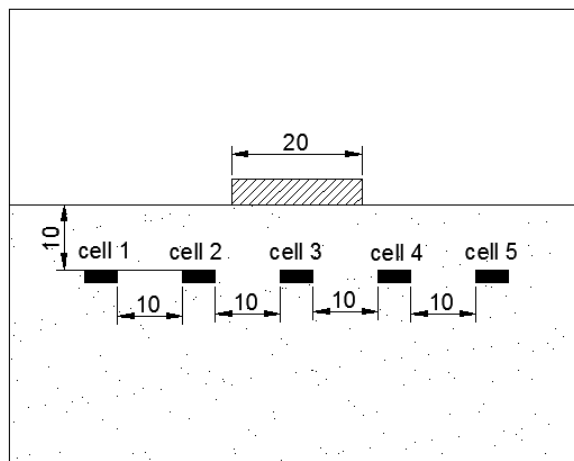
Figure 4-29 Distribution of the errors

This test shows that the soil pressure is underestimate. Only the Cell 2 is sensibly affected by the load in agreement with the ideal curves. But it overregisters and the error grows with the increasing of the load.



#### 4.8. Measurements in the sand, 5 cells in a horizontal line

In this test there are five cells embedded in a horizontal line, 10 cm depth and 10 cm away from each other. This is shown in *Figure 4-30*.



*Figure 4-30 Cells placed in the sand*

The Table 4-7 shows the output of the cells, *Figure 4-31* displays the pressures measured and the ideal distribution while *Figure 4-32* shows the errors.

	CELL 1			CELL 2			CELL 3		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	0,95	1,60	-40,8	1,29	1,60	-19,3	1,06	1,60	-34,0
5	1,23	1,63	-24,7	1,80	2,27	-20,8	2,69	2,61	+3,1
10	1,12	1,66	-32,5	1,88	2,95	-36,2	4,35	3,61	+20,4
20	0,79	1,72	-54,1	1,52	4,30	-64,6	8,43	5,63	+49,8
40	1,02	1,84	-44,5	2,21	7,00	-68,5	17,18	9,65	+77,9
60	0,34	1,96	-82,5	1,53	9,69	-84,2	27,73	13,68	+102,7
20	0,30	1,72	-82,6	1,68	4,30	-60,9	12,20	5,63	+116,9
0	0,77	1,60	-51,6	1,42	1,60	-11,1	0,99	1,60	-38,3
	CELL 4			CELL 5					
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,35	1,60	-15,6	0,96	1,60	-39,8			
5	1,25	2,27	-45,2	1,33	1,63	-18,2			
10	1,72	2,95	-41,7	1,13	1,66	-32,2			
20	1,20	4,30	-72,1	0,92	1,72	-46,6			
40	2,28	7,00	-67,4	1,36	1,84	-26,1			
60	2,46	9,69	-74,7	0,93	1,96	-52,8			
20	1,73	4,30	-59,8	0,84	1,72	-51,2			
0	1,29	1,60	-19,3	1,75	1,60	+9,2			

*Table 4-7 Results of the 5 cells embedded in a horizontal line*

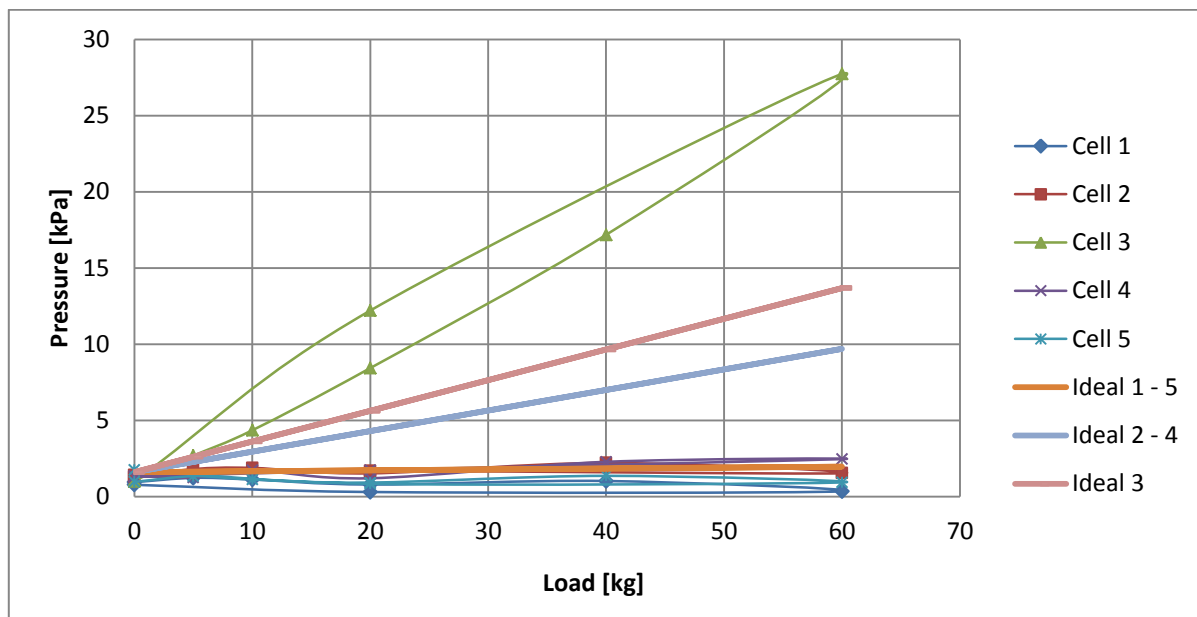


Figure 4-31 Pressure measured by the 5 cells, and ideal distribution.

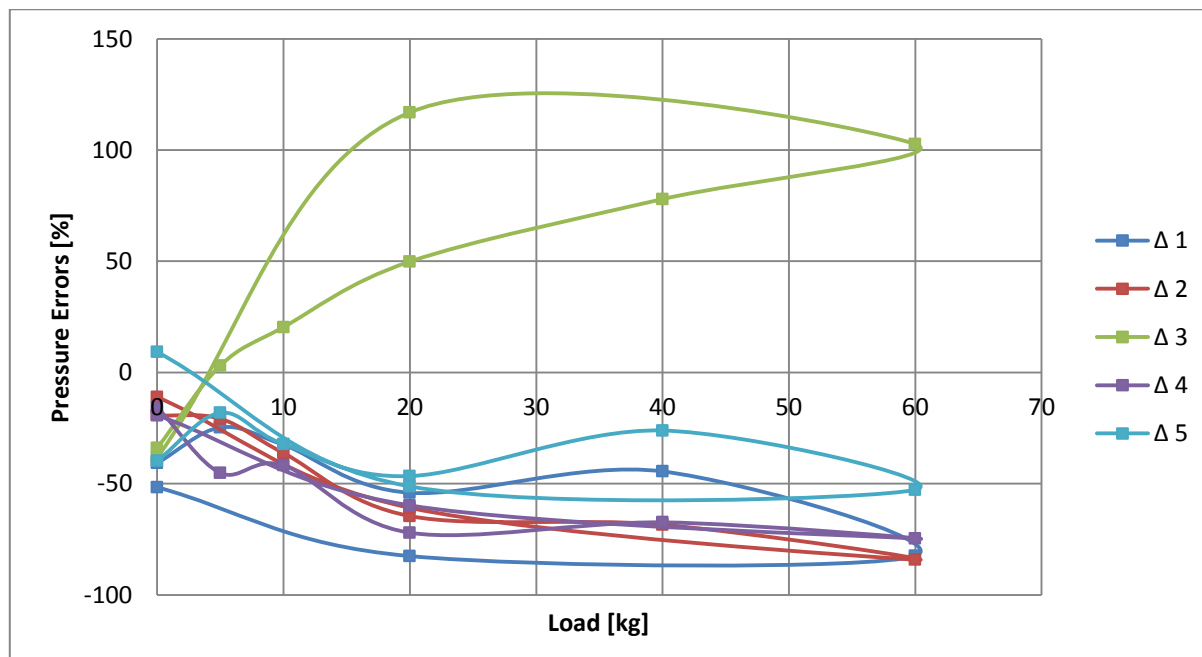
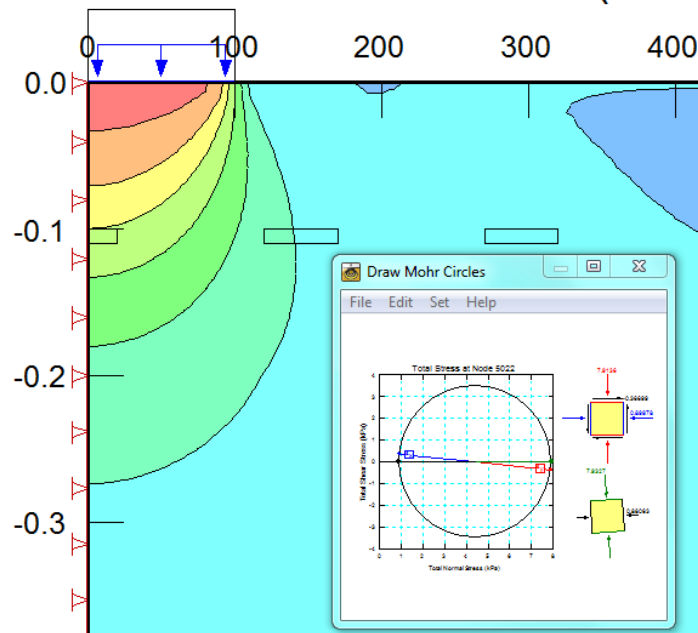


Figure 4-32 Errors of the 5 cells.

Cell 3 shows the same behavior already seen in the previous tests, that is overregistration of the load, while the four external cells even do not react to the load on top. This is correct for the Cell 1 and 5 but wrong for Cell 2 and 4. This can be justified by the not perfect placement of the load on the top of the sand; probably it was positioned a bit decentralized from the line of the cells.

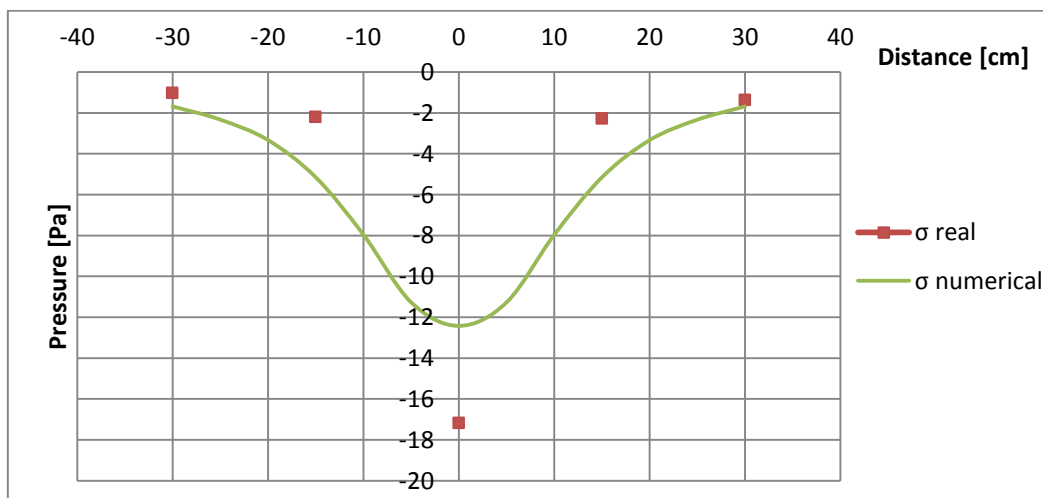
This test was made in order to compare the results of Cell 1 and 5 with the 2 external cells of the chapter 4.7, because of they are embedded in the same position. This now has no sense inasmuch as the cells don't react to the load.

The contribute of the pressure given by a load of 40 kg is calculated also with the numerical program, as shown in *Figure 4-33*.



*Figure 4-33 Load pressure with a load of 40kg*

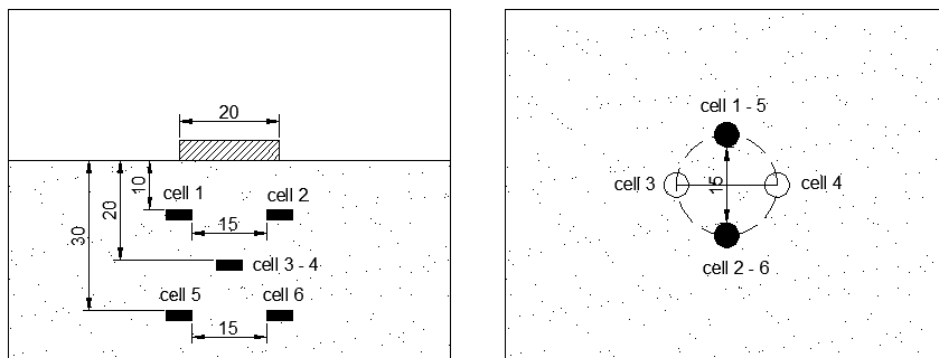
The chart in *Figure 4-34* represented the ideal pressure, only given by the load of 40 kg calculated with the numerical program, versus measured pressure. There is possible to see that the Cell 3 overregister the pressure while the other four don't react to the load.



*Figure 4-34 Trend of the ideal pressure versus measured pressure, under a load of 40kg*

### 4.9. Measurements in the sand, 6 cells with 3 different depths

In this test there are six cells embedded in three different horizontal planes. In the first, 10cm depth, there are two cells; in the second (20cm depth) other two and in the third (30cm depth) too. The cells disposition is shown in *Figure 4-35*.



*Figure 4-35 Cells placed in the sand, cross section in the left and top view in the right*

Table 4-8 shows the output of the cells, while *Figure 4-36* represents the errors.

	CELL 1			CELL 2		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,30	2,58	-49,5	0,40	2,58	-84,5
5	0,77	3,23	-76,3	1,71	3,23	-47,1
10	1,29	3,89	-66,9	2,27	3,89	-41,7
20	1,47	5,20	-71,7	2,77	5,20	-46,6
40	1,77	7,81	-77,3	2,44	7,81	-68,7
60	1,29	10,43	-87,6	1,54	10,43	-85,2
	CELL 3			CELL 4		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,69	5,16	-67,3	1,94	5,16	-62,5
5	2,15	5,45	-60,5	2,10	5,45	-61,5
10	1,78	5,74	-69,1	2,41	5,74	-58,0
20	2,71	6,31	-57,0	3,96	6,31	-37,3
40	4,68	7,46	-37,2	6,36	7,46	-14,8
60	6,28	8,61	-27,1	6,98	8,61	-19,0
	CELL 5			CELL 6		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	3,12	7,74	-59,7	2,55	7,74	-67,1
5	3,37	7,85	-57,1	2,67	7,85	-66,0
10	3,78	7,95	-52,5	3,16	7,95	-60,3
20	3,99	8,17	-51,1	3,67	8,17	-55,1
40	6,77	8,60	-21,3	5,22	8,60	-39,2
60	8,46	9,02	-6,3	9,72	9,02	+7,7

*Table 4-8 Results of the 6 cells embedded in 3 different depths*

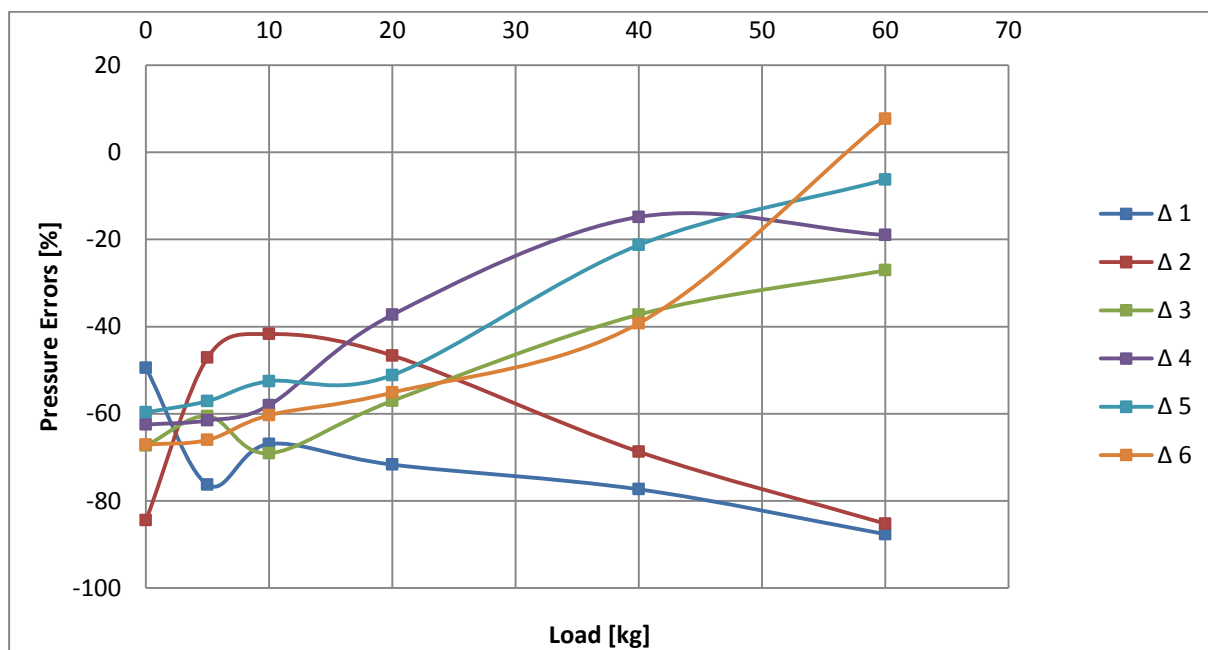


Figure 4-36 Errors of the 6 cells

From the previous graphs it is possible to see that the errors are quite big. While Cell 3, 4, 5 and 6 (belonging to the planes 20 cm and 30 cm depth) reduce the errors increasing the load; Cell 1 and 2 (10 cm depth) seem not react to the load. This may be caused from an imperfect placement of the load over them.

Two graphs are done in order to divide the soil weight pressure to the load pressure given by a load of 40 kg. They are shown respectively in *Figure 4-38* and in *Figure 4-39*. The contribute of the pressure given by a load of 40 kg is calculated with the numerical program, as shown in *Figure 4-33*. It is confirmed the behavior of Cell 1 and 2 that they are not working properly. Cell 3, 4, 5 and 6 underregister the soil weight and overregister the load.

Table 4-9 has done an estimation of the error reached by placing the cell 1 cm far away from the right position. It is possible to see that the error decreases with the depth and has a significant contribution.

depth [cm]	$\Delta$ [%]
10	15,22
20	7,05
30	4,93

Table 4-9 Errors given by placing the cells 1 cm far away from the right position.

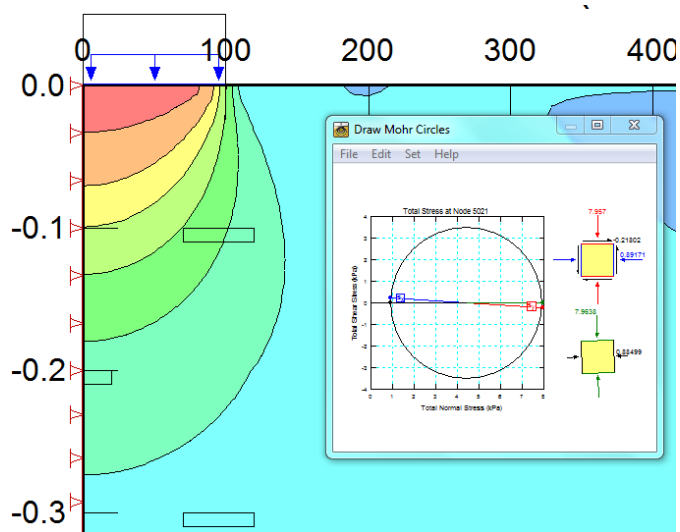


Figure 4-37 Load pressure with a load of 40kg

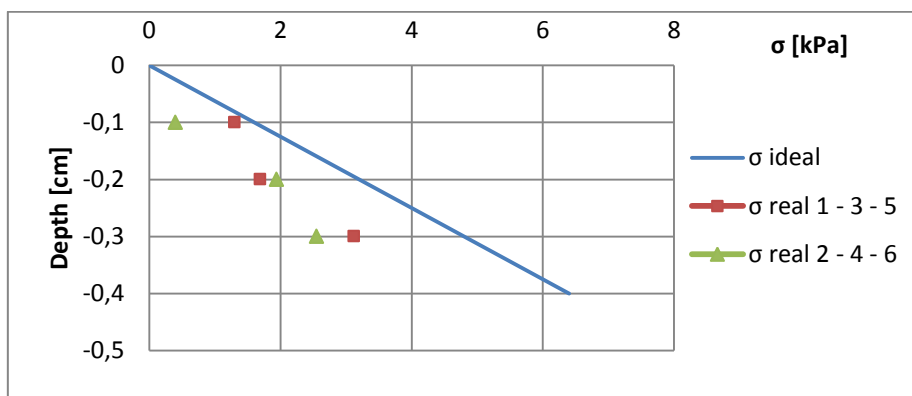


Figure 4-38 Contribute of the sand to the pressure

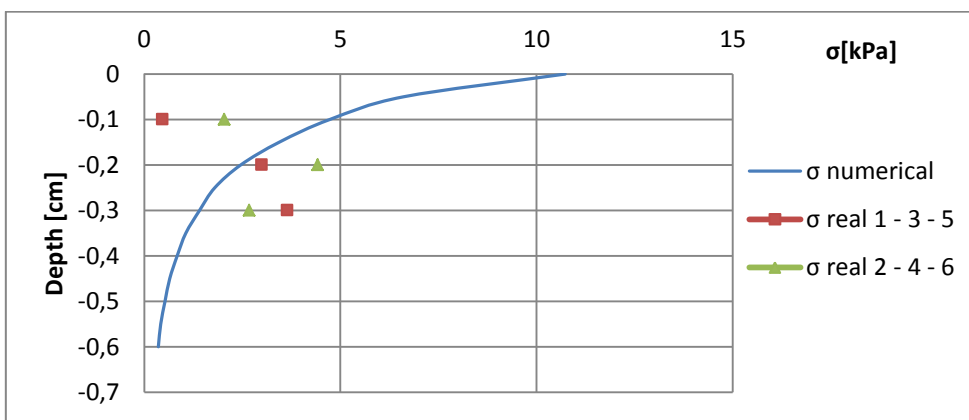
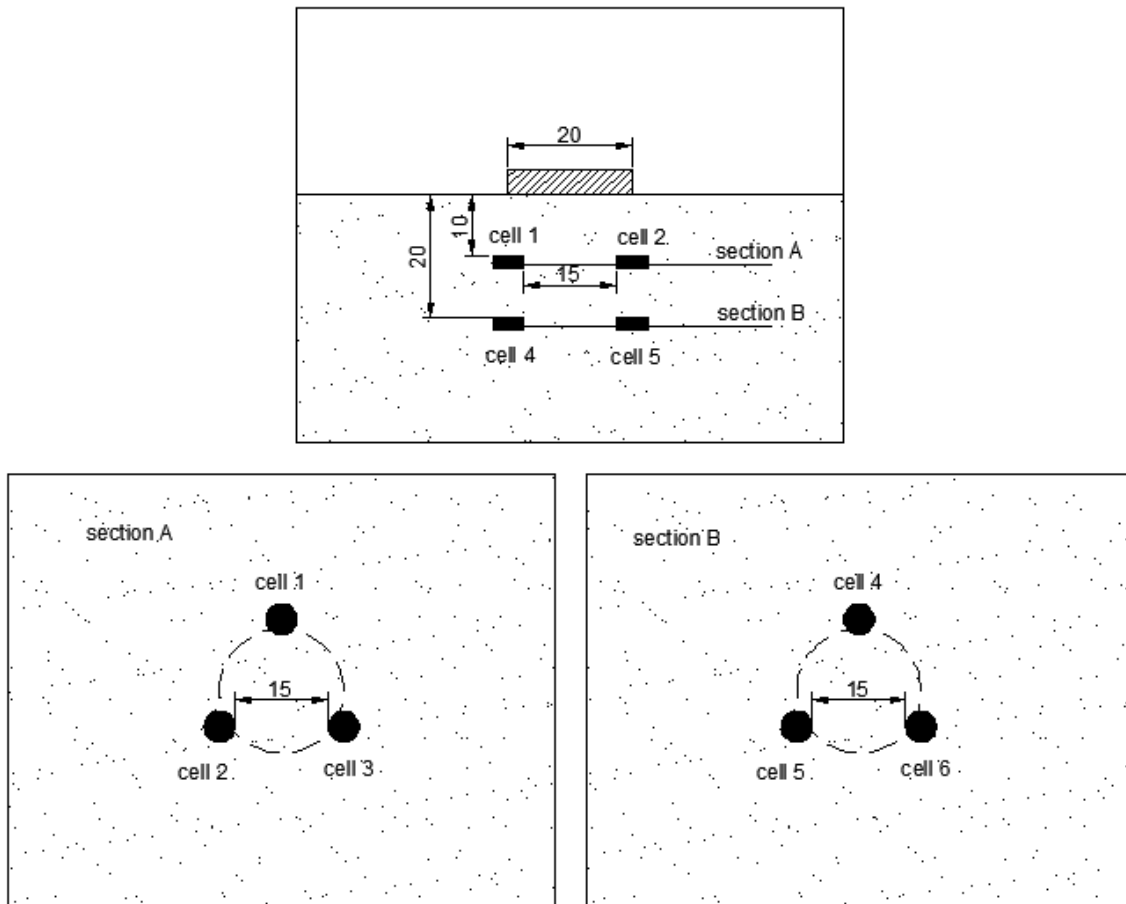


Figure 4-39 Contribute of the load (40kg) to the pressure

#### 4.10. Measurements in the sand, 6 cells 2 different depths vertical aligned

In this test there are six cells embedded in two planes, one 10cm depth and the other 20cm depth. These planes are overlapped, the disposition is shown in *Figure 4-40*



*Figure 4-40 Cells placed in the sand, cross section above and top views in the beneath*

Table 4-10 shows the output of the cells, while the *Figure 4-41* shows errors.

	CELL 1			CELL 2		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,82	1,60	+13,5	1,00	1,60	-37,6
5	2,51	2,25	+11,5	0,60	2,25	-73,5
10	4,18	2,91	+43,6	0,78	2,91	-73,1
20	7,71	4,22	+82,8	1,16	4,22	-72,5
40	15,39	6,83	+125,2	2,59	6,83	-62,1
60	26,59	9,45	+181,3	2,22	9,45	-76,5
20	9,45	4,22	+124,1	1,34	4,22	-68,3
0	0,96	1,60	-40,1	1,20	1,60	-25,1
	CELL 3			CELL 4		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	0,77	1,60	-52,0	2,50	3,20	-22,0
5	1,26	2,25	-44,2	2,56	3,49	-26,7
10	2,23	2,91	-23,3	3,21	3,78	-14,9
20	4,70	4,22	+11,4	5,09	4,35	16,9
40	7,31	6,83	+6,9	7,68	5,50	39,5
60	7,24	9,45	-23,4	11,58	6,65	74,1
20	3,55	4,22	-15,8	5,44	4,35	25,1
0	0,81	1,60	-49,3	2,36	3,20	-26,4
	CELL 5			CELL 6		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	2,94	3,20	-8,3	2,15	3,20	-33,0
5	2,78	3,49	-20,2	2,52	3,49	-27,7
10	2,75	3,78	-27,1	2,49	3,78	-34,2
20	3,63	4,35	-16,6	3,92	4,35	-10,0
40	3,88	5,50	-29,5	5,97	5,50	+8,4
60	4,29	6,65	-35,6	8,17	6,65	+22,8
20	3,09	4,35	-29,0	4,48	4,35	+2,8
0	2,78	3,20	-13,0	1,97	3,20	-38,3

*Table 4-10 Results of the 6 cell embedded in 2 planes*



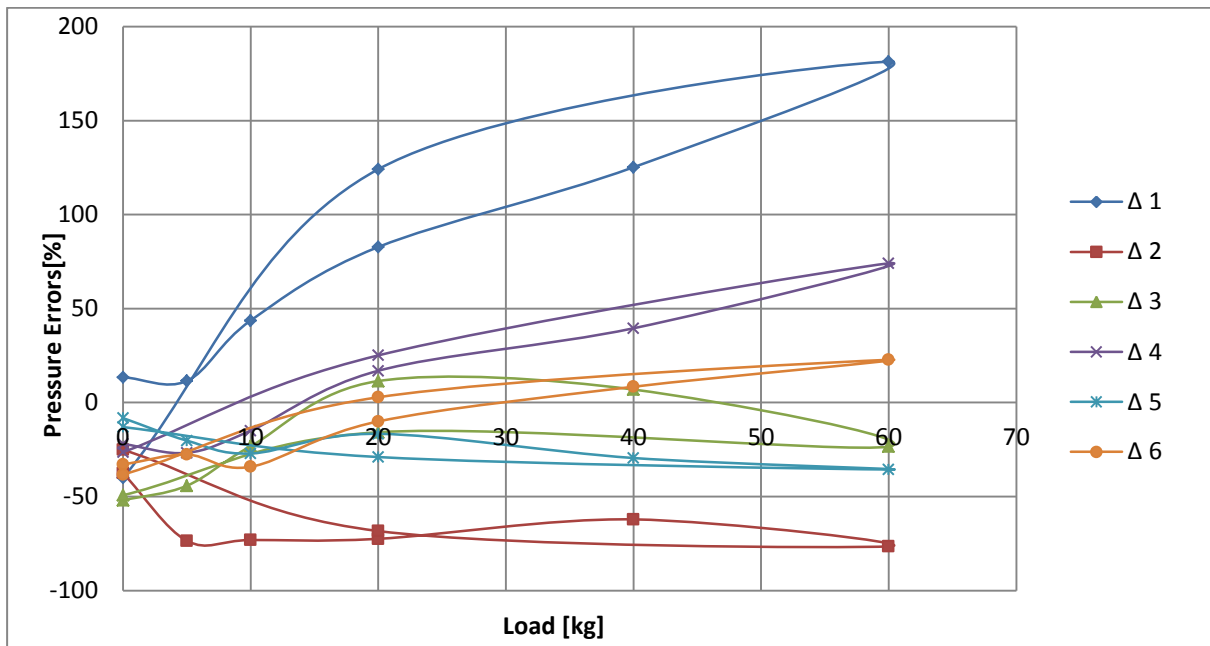


Figure 4-41 Errors of the 6 cells

It is possible to say that the load is not perfectly positioned in the center, and for this reason Cell 1 overregisters and Cell 2 underregisters the soil pressure. In the second plane (20cm depth) pressures are more uniform. But in order to understand the situation better is made one more plot (Figure 4-42) that show the trend of the ideal pressure versus the average of the pressure for each plane. Both planes underregister for low weight and overregister for heavy weight.

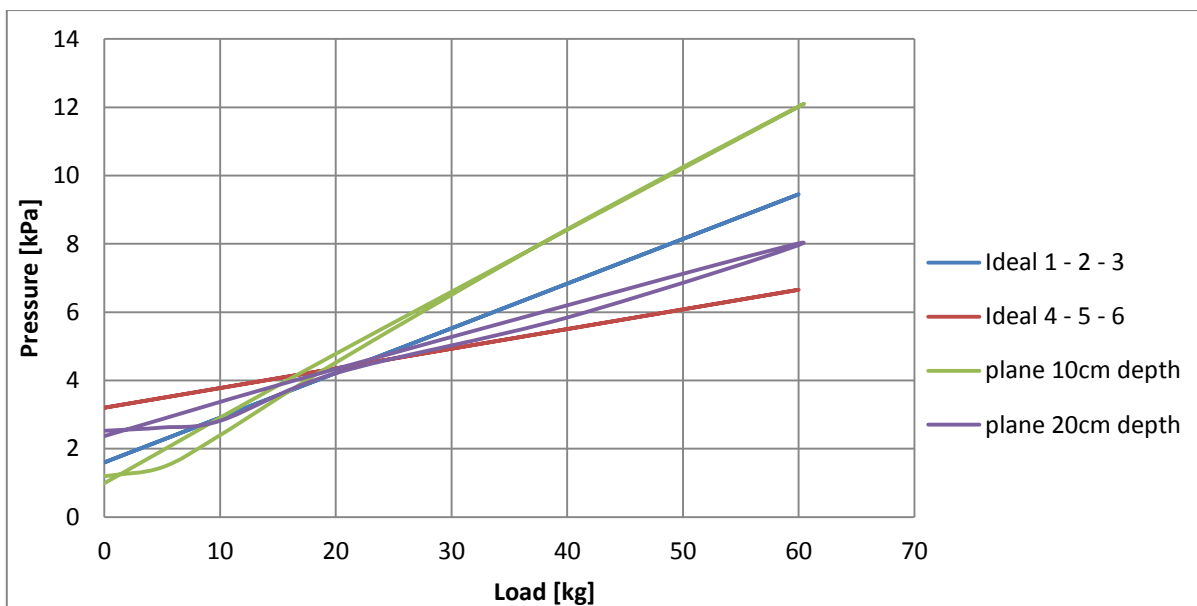


Figure 4-42 Distribution of the ideal pressure and the average of the pressure of each plane

In order to understand in a better way the situation, the contribute of soil weight pressure is separated from the load pressure given by a load of 40 kg. They are shown respectively in *Figure 4-43* and in *Figure 4-44*. The contribute of the pressure given by a load of 40 kg is calculated with the numerical program. Apart from not perfect centration of the load that caused the overregistration of the Cells 1 and the underregistration of the Cell 2, is confirmed the behavior that both planes underregister for low weight and overregister for heavy weight.

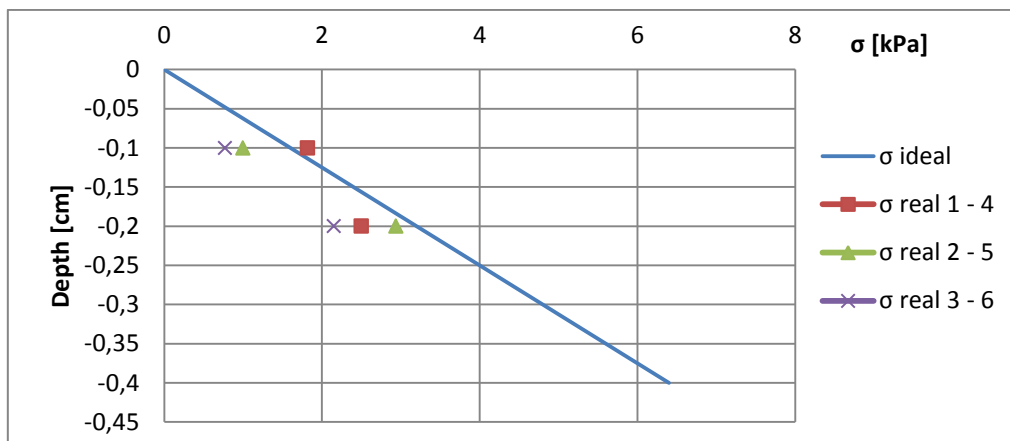


Figure 4-43 Contribute of the sand to the pressure

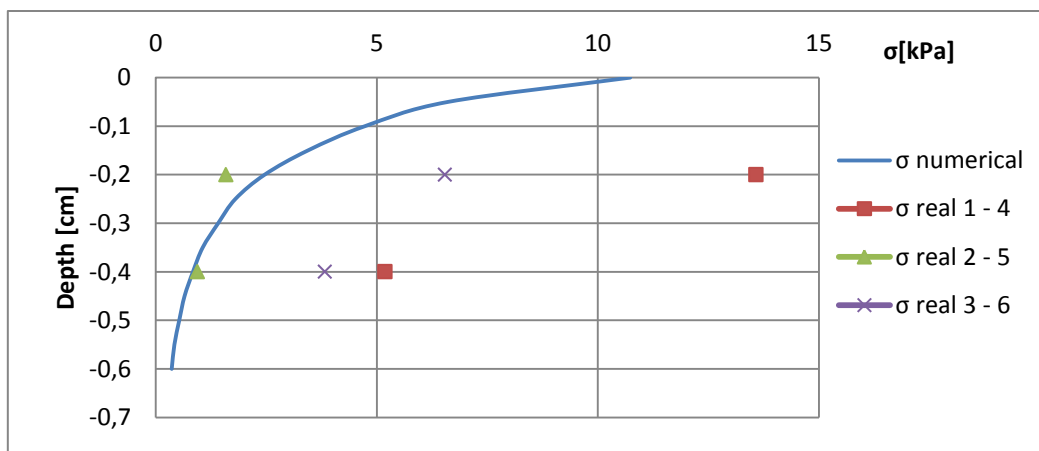


Figure 4-44 Contribute of the load (40kg) to the pressure

#### 4.11. Measurements in the sand, 6 cells 2 different depths not vertical aligned

In this test there are six cells embedded in two planes, one 10cm depth and the other 20cm depth. These planes are not overlapped, the disposition is shown in *Figure 4-45*.

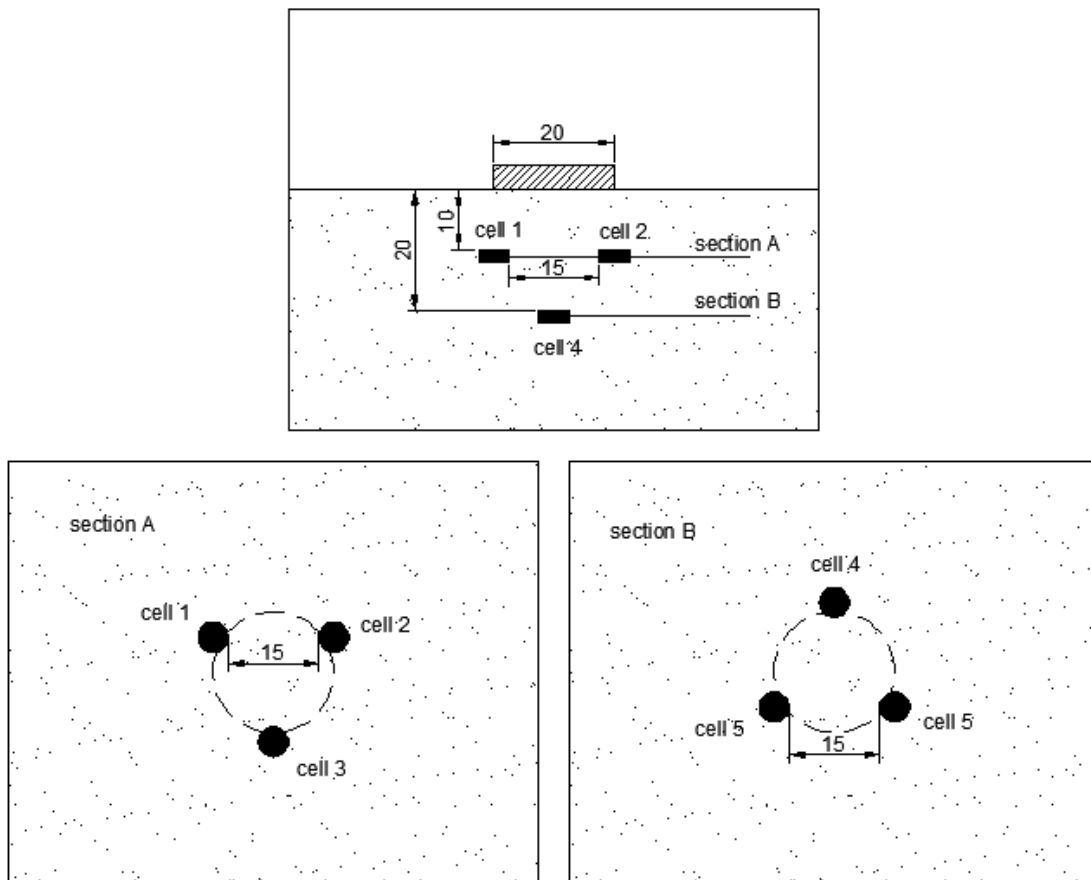


Figure 4-45 Cells placed in the sand, cross section above and top views in the beneath.

Table 4-11 shows the output of the cells, Figure 4-46 displays the errors of the six cells.

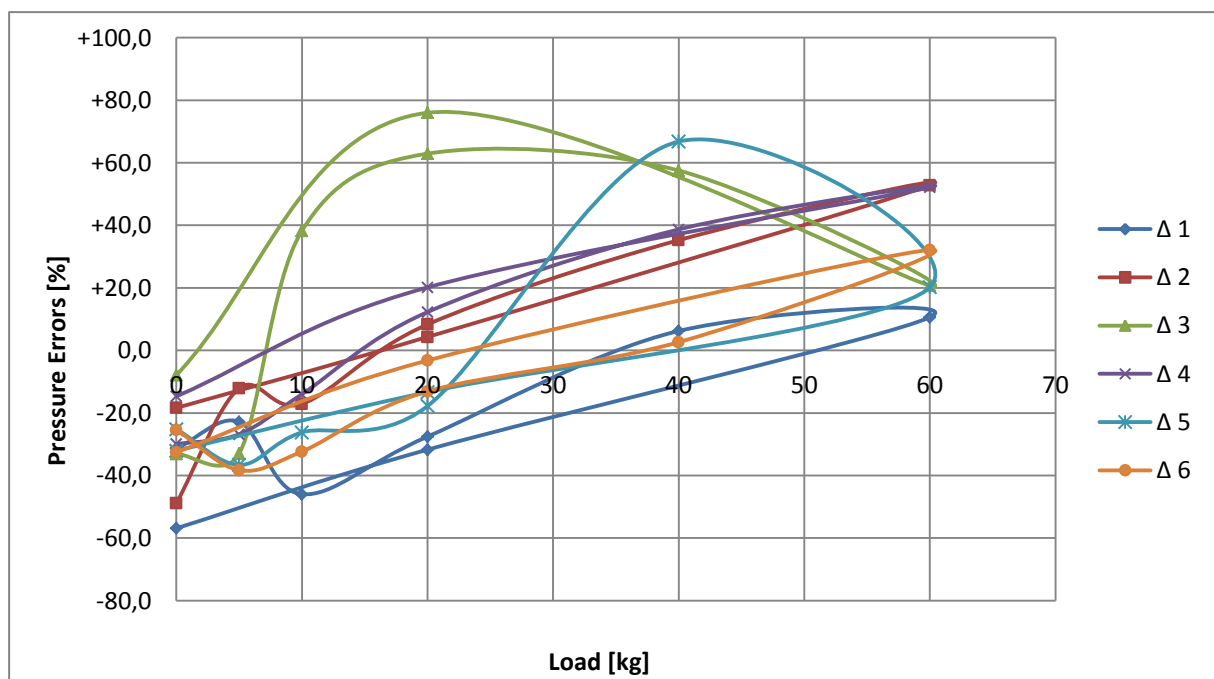


Figure 4-46 Errors of the 6 cells

	CELL 1			CELL 2		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,10	1,10	-31,4	0,82	1,60	-48,9
5	1,74	1,74	-22,8	1,98	2,25	-12,1
10	1,57	1,57	-46,0	2,41	2,91	-17,1
20	3,06	3,06	-27,6	4,57	4,22	+8,3
40	7,26	7,26	+6,2	9,24	6,83	+35,3
60	10,45	10,45	+10,6	14,44	9,45	+52,8
20	2,88	2,88	-31,7	4,40	4,22	+4,3
0	0,69	0,69	-56,9	1,31	1,60	-18,4
	CELL 3			CELL 4		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	1,07	1,60	-33,1	2,24	3,20	-30,0
5	1,51	2,25	-33,0	2,55	3,49	-26,8
10	4,02	2,91	+38,3	3,25	3,78	-14,0
20	6,87	4,22	+62,9	4,89	4,35	+12,3
40	10,77	6,83	+57,5	7,63	5,50	+38,7
60	11,42	9,45	+20,8	10,12	6,65	+52,1
20	7,42	4,22	+76,0	5,23	4,35	+20,2
0	1,47	1,60	-7,9	2,73	3,20	-14,7
	CELL 5			CELL 6		
Load [kg]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]	Pressure [kPa]	Ideal [kPa]	$\Delta$ [%]
0	2,39	3,20	-25,2	2,39	3,20	-25,4
5	2,21	3,49	-36,6	2,15	3,49	-38,3
10	2,79	3,78	-26,2	2,56	3,78	-32,3
20	3,58	4,35	-17,8	3,78	4,35	-13,1
40	9,18	5,50	+66,8	5,65	5,50	+2,6
60	8,00	6,65	+20,2	8,79	6,65	+32,1
20	3,77	4,35	-13,3	4,21	4,35	-3,2
0	2,17	3,20	-32,1	2,16	3,20	-32,5

Table 4-11 Results of the 6 cell embedded in 2 different planes not aligned.

Pressure measured by the cells seems to be really confused and thus it is not possible to describe the distribution.

As done in the previous tests, in order to understand in a better way the situation, the contribute of soil weight pressure is separated from the load pressure given by a load of 40 kg. They are shown respectively in *Figure 4-47* *Figure 4-38* and in *Figure 4-48*. The contribute of the pressure given by a load of 40 kg is calculated with the numerical program. The cells present the same behavior seen in the previous tests, they underregister for low weight and overregis-

ter for heavy weight. Only Cell 2 seems to underregister the contribute of the load, but it may be a mistake because the errors of the cell is so big and thus not reliable.

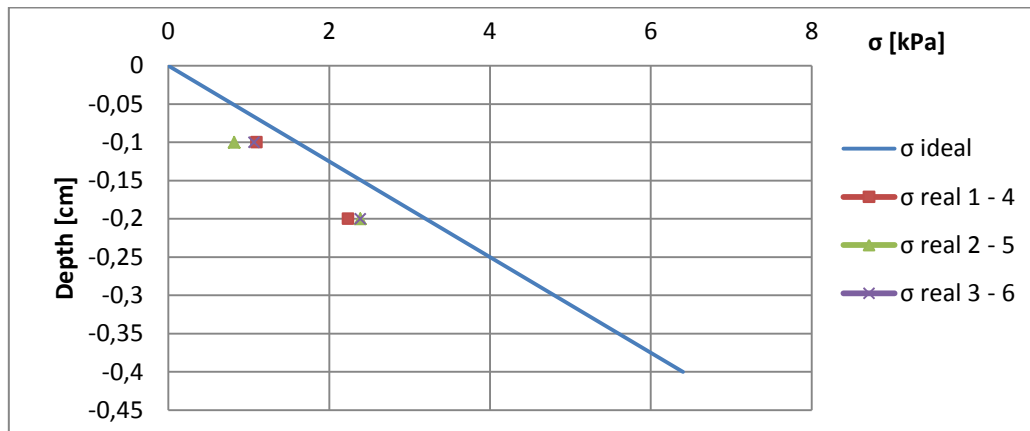


Figure 4-47 Contribute of the sand to the pressure

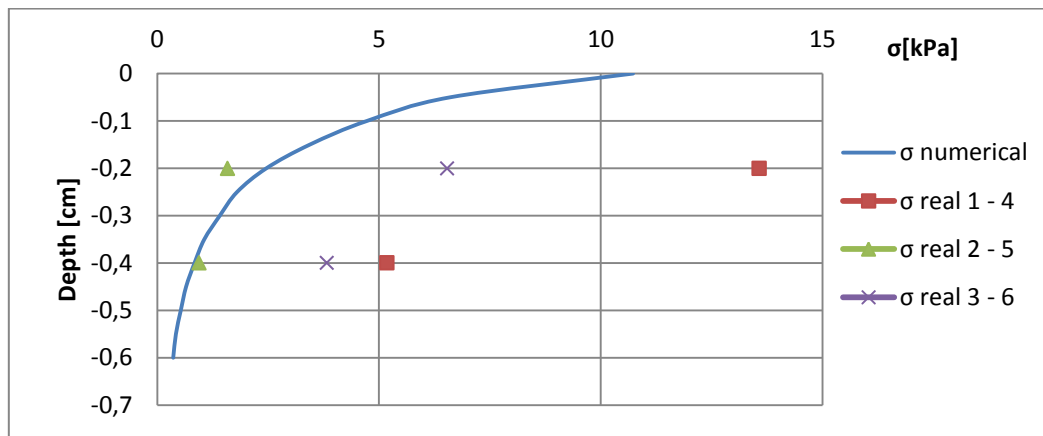
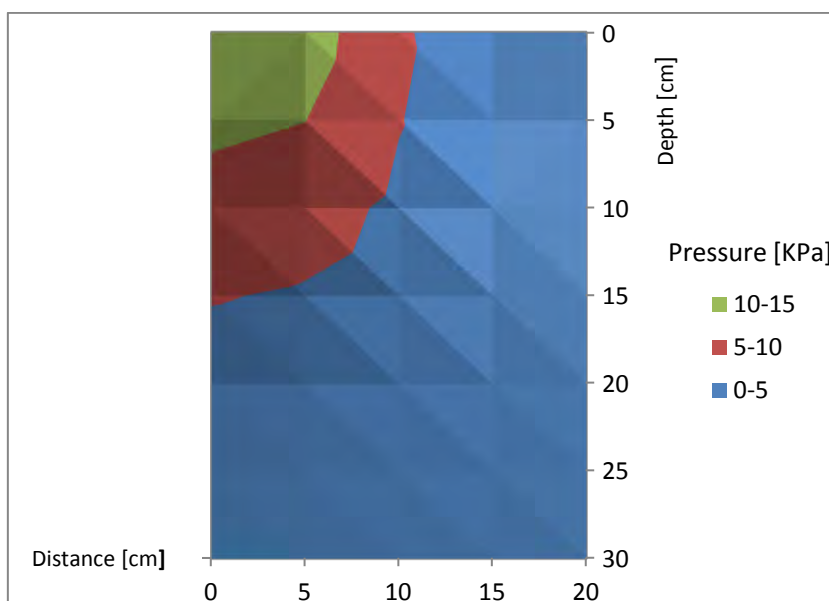


Figure 4-48 Contribute of the load (40kg) to the pressure

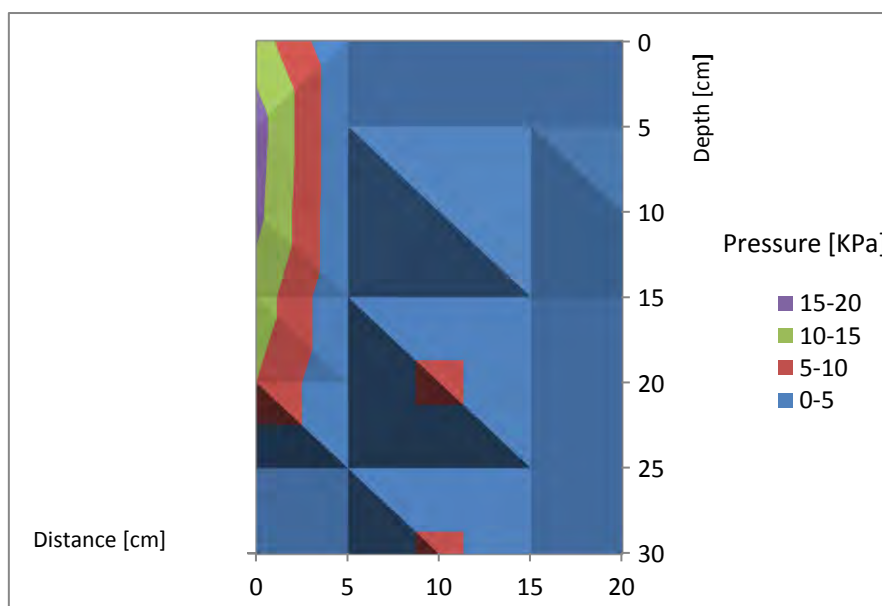
## 5. Summary of test results

The previous tests have shown that the cells give an idea of the trend of the pressure in the sand but the results are not always reliable.

With the ideal data and the average data of all the tests done (Table 5-1 and Table 5-2) it was possible to build two contour plots, one for the ideal values and one for the real one as shown in *Figure 5-1* and *Figure 5-2*.



*Figure 5-1 Contour Plot of the ideal values under a load of 40Kg*



*Figure 5-2 Contour plot of the real values under a load of 40Kg*

[cm]	0	5	10	15	20
0	12,42	12,29	5,95	0,05	0
5	11,19	10,08	5,23	0,97	0,16
10	7,96	6,86	4,15	1,68	0,56
15	5,21	4,61	3,19	1,76	0,84
20	3,37	3,08	2,37	1,56	0,93
25	2,51	2,34	1,90	1,37	0,9
30	1,84	1,74	1,49	1,16	0,84

*Table 5-1 Ideal values under a load of 40Kg.*

[cm]	0	5	10	15	20
0	12,42	-	-	-	0
5	17,18	-	-	-	-
10	16,40	-	4,74	-	1,29
15	12,90	-	-	-	-
20	9,95	-	6,77	-	-
25	-	-	-	-	-
30	-	-	6,77	-	-

*Table 5-2 Real values under a load of 40Kg.*

It is again possible to see that when a load is placed on the surface of the sand, the cells embedded directly under the shape of it always overregistered, while the cells placed farther from the vertical line of the load underregister or they even do not react to the load on top.

In this chapter some hypothesis are explained about this problem.

First of all is considered the aspect ratio, as seen in chapter 4, is pretty big and this may cause an overregistration of the soil pressure. Furthermore the stress field is distorted by the presence of the gage the stress measured by the cell will in general not be equal to the free-field stress. The cells used for the test are stiffer than the sand and it causes an overregistration of the pressure. This may be the major problem about the overregistraion seen in every tests done in the chapter 4.

The cells used, despite they are one of the smallest kinds available on the market, are too big for this purpose. As seen from the calibration on the table, they start to become reliable from a pressure of 30kPa (error less than 10%) but in the tests done in the previous chapter is never reached such a value. The capacity of the cell is 500kPa and for lower pressures it has big errors.

In addition the ideal values that we assumed as truth come from the assumption of linear elasticity, and so they are not the real values.

Besides, the sand used is not uniform with the depth; in the surface it is loose and dry while increasing with the depth it becomes more compacted and wet. And also the installation caused a disturbance of the sand that becomes looser. In particular with increasing of the load the sand becomes more compacted and usually the weight sinks a couple of centimeters in the sand, that could be one of the major reason about the underregistration before placing the load and overregistration with the increasing of the load.

From the previous tests (chapter 4.6 compared to 4.2 and 4.3) it seems that the cells, sometimes very close each other (less than 5 cm) don't interact. Or the interaction error is smaller than other errors and so not visible, thus is wildcat to draw some conclusion from them.





## 6. Conclusions

In conclusion that there are many kind of transducers for measuring soil stress': strain gauge load cells, piezoelectric load cells, hydraulic load cells, pneumatic load cells and vibrating load cells. The market search has shown up that these devices could have different shape, size and range of measurement. Furthermore there is a new kind of pressure sensor (made by Tekscan) minimally invasive, that was invented for medical purposes and now is starting to be used also for small soil pressure.

In small scale laboratory model test is very important considering the size and range of the device that we want to use, because if they are so invasive or they have a high range of measurement, they may give unreliable results. However the possibilities of the available transducers on the market are limited. Besides is important an accurate calibration procedure and a careful installation in order to leave as much as possible the undisturbed condition of the soil.

Small scale laboratory tests about transducers (TML model KDE-PA, 50 mm diameter) placed on the sand in the tank at the Soil Mechanical Laboratory of the University of Duisburg–Essen, have proved that they are not the suitable devices for measuring small pressure. When a load is placed on the surface of the sand, the cells embedded directly under the shape of it always overregistered, while the cells placed farther from the vertical line of the load underregister or they even do not react to the load on top.

Finally, the cells used despite they are one of the smallest kinds available on the market, are too big for this purpose; for small scale laboratory model tests should be better to use other kind of pressure device, less invasive, such as Tekscan. Or if the purpose is to test that kind of cells (TML model KDE-PA, 50 mm diameter), is necessary to work with higher loads and bigger models in order to experience a pressure suitable for that device (capacity 500kPa) and not just a small part of it.



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