Mechanical Engineering Bachelor’s Final Project

Design of a CPT calibration chamber

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Date: 27-7-2010

Place: Universität Bremen - MARUM.

Universität Bremen
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1. REPORT

1.1. Aim and calibration chamber development

The aim of this project is to design a calibration chamber, which will be used to do the corresponding CPT (Cone Penetrating Test) in the laboratory. During the CPT, the cone penetrates into the chamber, which is full of sample, and depending on the sample’s resistance against the cone is possible to know the sample’s properties and features, in order to study the kind of structure which will be placed in the North Sea’s seabed, where the windmills will be placed on.

The first design of the calibration chamber was 300 mm tall and 120 mm wide (inner chamber diameter); this inner chamber is holed almost everywhere, and has the objective to give a shape to the sample, since the rubber membrane is too much flexible, and it is placed in the lower base, and into it is the rubber membrane, which contains the sample. In the lower part of the sample there is the piston (fitted in the lower base) who lets a bit of movement during the CPT, since when the rod penetrates in the sample compress it and produces a volume change in the calibration chamber. Around the inner chamber is the outer house, and among this one and the inner chamber is full of water, in order to simulate the conditions of the seabed, such as the pressure at a given depth. For the realization of this project is considered a maximum pressure of 20 bar. This first design also had the frame screws out the outer chamber, as well as, the piston did not have any hole to let the water go through it.

The changes made in the second design of the calibration chamber have been necessary in order to get a successful calibration chamber design. These changes include the inner chamber, which disappears, and a double closing is placed instead of it to give shape to the rubber membrane with the sample into it; the frame screws (there are 3 instead of 4), which in this case are placed into the outer house, simulating a triaxial cell design; the piston has 4 holes that cross it completely to make easier the water removal due to the piston movement during the CPT; in the lower base a grooving has been made to help the water remove through a hole which cross the lower base until the outer, and in the initial position it coincides with the piston’s hole. Of course, the most important change it has been made is the diameter’s size, which now is the double than before, 240 mm.

In the next section will be explained the calculations required for the realization of this project, such as the volume change caused by the penetration of the cone into the sample, the diameter required for filling and draining of water from the calibration chamber, the number of holes in the inner chamber, the quantity of sample excelled through inner chamber holes, and the required thickness of the outer house to withstand the pressure during the CPT.

1.2. Background

1.2.1. CPT definition

Cone Penetration Testing (CPT) is a versatile, time efficient method to geotechnical characterise sediment strength and pore pressure in offshore settings and on land. The majority of the penetrometers rely on heavy trucks (figure 1) or rigs to provide the necessary force to push the CPT probe into the ground. But in this project is developed a CPT for work with the Sea bottom. In that chase the CPT is dropped by a ship form the surface of Sea, then it is going down by its weight (figure 2). It is linked to the ship by wire. When CPT impacts again to bottom its Test-stick is bent. After that CPT is recuperated pulling the wire.
1.2.2. History

Cone penetrometers were first of all used for *in situ* determination of the stiffness of the penetrated material (soil or sediment). In the Roman era, the number of slaves, which were required to push a certain rod into the ground, was used as a measure for the strength of the ground. This crude method to quantify the strength can be considered as a forerunner of cone penetrometer devices, standing out today for an effective ground probing instrument. The first cone penetrometer tests, as we know them today, were carried out with a mechanical cone penetrometer by the Dutch engineer Barentsen. The principle of this so-called Dutch cone based on a gas pipe with an inner diameter of 19 mm and a steel rod, which could move vertically (up and down) freely inside the pipe (Figure 3). A 10 cm² cone with a 60° apex angle was attached to the steel rod and both, the pipe and the rod, were manually pushed stepwise into the ground, therefore reaching a
remarkable penetration depth of up to 12 metres. The penetration resistance was measured by a manometer. This instrument represents the first version that evaluates pile bearing capacity.

A decade later, the Dutch device was parlayed with an “adhesion jacket” behind the cone by Begemann, which additionally measured the local skin friction. Begemann was the first to postulate, that the friction ratio (ratio between the sleeve friction and the cone resistance) can be used for a classification of the profiled soil layers in terms of soil type (e.g. clay, silt, sand). Although further principles of mode of operation, mainly hydraulic penetrometers, have been developed, mechanical cone penetrometers are still widely used (Figure 4). The first electrical cone penetrometer, where the signals were transmitted to the penetrating probe in the ground via a cable inside the hollow penetrometer rods, was developed in Berlin at the Deutsche Forschungsgesellschaft für Bodenmechanik (Degebo) during the 2nd World War. Providing continuous testing with a constant penetration rate, elimination of uncertainty given by friction of the inner rod and the outer rods of the mechanical penetrometer and the higher accuracy of the much more sensitive load cells describe the main improvement of electrical cones in contrast to mechanical ones. In 1965, the company Fugro developed an electrical cone, whose geometry formed the basis for the International Reference Test Procedure (ISSMEFE 1989; Lunne et al. 1997). Among other things, it was established, that “standard” CPT deployments were to be carried out at a constant rate of 2 cm/s. In addition to the determination of penetration resistance, pore pressure measurements were performed with piezocones, which were deployed adjacent to CPT profiles. In 1974, the first piezocone developed by the Norwegian Geotechnical Institute was presented. The first published combined measurements of cone resistance and pore pressure were carried out in sensitive Canadian clays by Roy at 1980. In the progressing development of cone penetrometers they were fitted with different sensors, measuring physical and geotechnical parameters such as density, salinity, and conductivity. A detailed overview is given in Burns and Mayne (1998).

An appropriate improvement took place in the 1970ies, when on-shore devices have been modified for seagoing use (e.g. Dayal 1978; Schultheiss 1990). Depending on the penetration depth, two different principles of instruments were developed. To reach deep penetration (tens of meters), rigs are required, which have to be lowered to the seafloor and then push the cone by hydraulic force with constant velocity into the sediment. To the contrary, lance-shaped free-fall cone penetrometers were lowered on a cable or freely dropped, running through the water column and penetrating the sediment with their own momentum gained through their acceleration and weight. The non-constant penetration velocity and depth is determined by the cone’s momentum and the stiffness and cohesion of the sediments. Penetrating only surficial sediment down to 10 meters maximum, the free-fall devices do not disturb the uppermost soft layers as heavily as the rigs. Hence, artefacts in CPT results from consolidation by the rig are avoided.

The actual standard geometry of a cone available for on- as well as off-shore CPT application consists of a 60° cone with a 10 cm² base area and a 150 cm² friction sleeve located above the cone. In addition, 15 cm² cone penetrometers (diameter = 43.7 mm, sleeve area = 225 cm²) are used, especially in case of incorporation of additional sensors (e.g. pore pressure sensor) into the probe. For offshore seabed tests, 15 cm² cones are preferred. The influence of the different geometry of the 10 cm² (standard) and the 15 cm² cone can be neglected, as in practice cone penetrometers range in cross section from 5 cm² to 15 cm² give very similar corrected cone resistance data.
Figure 3: Dutch cone

Figure 4: Cone development

- a) Mechanical cone with conical mantle (1948)
- b) Mechanical cone with friction sleeve (1953)
- c) 2 cm$^2$ electrical friction cone (1996)
- d) 5 cm$^2$ electrical friction cone (1997)
- e) 10 cm$^2$ electrical piezocone for wireless testing (1997)
- f) 10 cm$^2$ electrical piezocone (1994)
- g) 10 cm$^2$ electrical seismic piezocone (1998)
- h) 10 cm$^2$ disposable piezocone (1988)
- i) 15 cm$^2$ electrical friction cone (1989)
- j) 25 cm$^2$ electrical friction cone (1986)
1.2.3. Cone Penetration Parameters

Generally, tip and sleeve readings and pore pressure measurements during insertion of a cone penetrometer into the sediment produce a profile measuring geotechnical properties. The tip as well as the sleeve of a penetrometer are equipped with strain gauges to measure stresses exerted by the sediment during penetration. Cone resistance $q_c$ is defined as the force acting on the cone tip divided by the area of the cone, and sleeve friction $f_s$ results in the force acting on the friction sleeve divided by the area of the sleeve. Pressure transducers detect the ambient pore pressure $u$ during measurement on a port on the cone tip ($u_1$ position), on the cone shoulder ($u_2$ position) and/or behind the friction sleeve ($u_3$ position).

The measured cone parameters underly a certain variability, which is generally caused by the heterogeneity and diversity of the sediment and a certain degree of error in testing procedures. Inherent sediment variability is given by natural, often superimposed geological processes, whereas measurement error is based on inaccuracies of the measurement system and variations in equipment geometries. During penetration, the cone causes a material to deform elastically, plastically or fail within a spatial volume in the vicinity of the penetrometer during insertion of the instrument. This means the measurements are not absolute point measurements, but represent the extent and the characteristics of the failure zone, which again depend on physical properties of the material (e.g. stiffness, plasticity, consolidation, density, water content). In general, firm materials are compressed upon penetration of the instrument, while pore fluids either cause high excess values (low permeability sediments) or get displaced (high permeability in loose sands), the latter resulting occasionally in subhydrostatic values. In soft, fine-grained sediments, clay fraction particles migrate radially from the axis of the penetration path and may get suspended by the fluids when stress is induced by insertion of the cone. The effects described here are more pronounced in dynamic (free-fall) CPT deployments than in constant rate tests (2 cm/s).

**Cone resistance**

One of the major challenges in cone penetration testing is the establishment of a systematic relationship between $q_c$ (and $f_s$ for that matter) and sediment physical properties such as bearing capacity or undrained shear strength. In general, penetrometrists either correlate cone resistance $q_c$ with a given set of sedimentary physical properties, which can be used to calculate cone resistance for geotechnical and geological application (e.g. liquefaction, slope stability), and/or carry out back-calculation of sediment physical properties from measured cone resistance (e.g. undrained shear strength). To reduce the variations of the input strength, which can produce large deviations in the calculation of cone resistance, theoretical solutions are used. A large number of theoretical analyses have been carried out, but none of them is rigorous. All those models are generally confronted with large deformations and a non-linear behaviour of the sediment. The failure zone due to penetration of a cone can commonly divided into a plastically deforming region and, at some distance, an elastically deforming region, whereas along the lance-sediment interface intense shearing remoulds the material. The extent of this failure zone depends mainly on shear strength and the shear modulus of the sediment. A variety of theoretical solutions for cone penetration have been proposed in the past approaching the penetration problem with different theories. These include: i) the bearing capacity theory (Terzaghi 1946), ii) the cavity expansion theory (Bishop 1945), and iii) the strain path method (Baligh 1985).

For the bearing capacity theory (i), the cone resistance is assumed to be equal to the collapse load of a deep foundation in the soil. The extension of this theory to penetrometer analysis assumes a failure mechanism. Chari and Abdel-Gawad (1981) summarise theoretical failure analysis by Meyerhof (1961), Terzaghi (1946) and Durgunoglu and Mitchell (1973) (Figure 5).
The limitations of this theory are in the neglect of the material stiffness and the compressibility as well as the ignorance of the influence of the penetration process on the initial stress regime around the cone shaft. Consequently, this theory is usually adapted to shallow penetration, which involves a mechanism where the displaced material can escape as an entity to the surface. In deep penetration, however, the displacement is controlled by elastic deformation of the material. Satisfying the latter, the cavity expansion method (ii) is used regarding the force required to produce a (deep) hole in an elastic-plastic medium, which is equal to expanding a cavity of the same volume under the same conditions (e.g. Salgado et al. 1997; Yu and Mitchell 1998). Thus, elastic and plastic sediment deformation during cone penetration are taken into account as well as the influence of the penetration process on the initial stress regime and the effect of stress around the tip, in turn influencing \( q_c \). Prior to this, Yu and Mitchell (1998) demonstrated that preponderant cavity expansion solutions give the closest agreement between predicted and measured resistance values. The strain path method (iii) is an improvement of the cavity expansion theory, as the latter does not model the strain paths correctly (Baligh 1986a). Baligh (1986a) suggested the application of the strain path method to account for the complex deformation history of the sediment during cone penetration.

These theoretical approaches were used to interpret the strength of fine-grained, cohesive sediments based on CPT/CPTU data. The in situ undrained shear strength depends on sediment failure, anisotropy, stress history and strain rate. Regarding the non-linear stress-strain behaviour due to cone penetration, no single value for undrained shear strength exists. Nevertheless, theoretical analysis describes the relationship between cone resistance and \( s_u \) as follows:

\[
q_c = N_c \times s_u + \sigma_0
\]

with the theoretical cone factor \( N_c \) and the total pressure \( \sigma_0 \) (see Lunne et al 1997). Depending on the theory used, \( \sigma_0 \) may be \( \sigma_{vo} \), \( \sigma_{ho} \) or \( \sigma_{mean} \) (Lunne et al. 1997). A lot of solutions for the cone factor are given in a summary by Lunne et al. (1997; see their Table 5.5). As theoretical solutions simplify the complex phenomenon of cone penetration, they have to be verified from actual field and laboratory-based data, which estimate \( s_u \) from CPT data using the following equation:
\[ s_u = \frac{q_t - \sigma_{vo}}{N_k} \]

with the empirical cone factor \( N_k \) and the total stress \( \sigma_{vo} \). Depending on the sediment, \( N_k \) ranges between 11 and 19 for normally consolidated marine clay (Kleven 1986), and averages 17 for non-fissured, overconsolidated clays (Kjekstad 1978). The relationship between \( s_u \) and \( q_c \) is modified with CPTU employing the cone resistance corrected for pore pressure effects:

\[ s_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \]

The corrected cone resistance is represented by \( q_t = q_c + \left(1 - a\right) \times u_2 \), with \( u_2 \) = the measured pore pressure and \( a = \text{area ratio of the cone} \), which is defined as the ratio between the cross-sectional area of the strain gauge and the cross-sectional area of the cone. In CPT nomenclature \( (q_t - \sigma_{vo}) \) is named as the net cone resistance \( q_{net} \). Depending on the plasticity \( N_{kt} \) ranges between 10 or less and 20 for normally consolidated clays (see Table 3 in Karakouzian et al. 2003). Often used values are \( N_{kt} = 10, 12, 15 \) (e.g. Baltzer et. al. 1994; Sultan et al. 2007a).

Numerous geotechnical sediment parameters of (e.g. deformability [expressed by constrained modulus, elastic modulus, shear modulus], stress history) may be derived from cone resistance, but they are not further considered in this thesis.

**Sleeve Friction**

The frictional force exerted by the sediment onto the friction sleeve of a CPT cone during penetration defined as sleeve friction \( f_s \). Similar to cone resistance, it is measured using electrical strain gauges mounted onto the stainless steel core of the CPT probe. The friction sleeve is similar to cone geometry subject to CPT standards and has a defined area depending on the diameter of the cone (for 10 cm\(^2\) cone = 150 cm\(^2\) and for 15 cm\(^2\) cone = 225 cm\(^2\)). Different arrangements of the CPT strain gauges are used:

1. Cone resistance and sleeve friction are detected by individual, independent strain gauges during compression while the instrument penetrates.
2. The sleeve strain gauge measures in tension while cone is recorded by a compressional strain gauge.
3. The cone strain gauge and the sleeve strain gauge are connected to the same stainless steel core to record \( q_c \) and \( f_s \). The sleeve friction is finally obtained by the difference in load of the friction sleeve and the cone resistance strain gauge.

Configuration (3) is referred to as the “subtraction cone”, which has been demonstrated to be more robust. Sleeve friction \( f_s \) is used for soil classification, one of the most important issues in CPT profiling. The friction ratio, \( F \), calculated by dividing sleeve friction by the net cone resistance \( (q_{net}) \), is believed to provide a first-order description of the soil type as a repeatable index for the mechanical behaviour of its in situ properties adjacent to the CPT probe. A tentative application of that first-order soil classification was undertaken with data obtained with the SW-FF-CPT in fine-grained harbour deposits and brackish sediments. Recent studies have shown that the measurement of sleeve friction \( f_s \) is less accurate and less reliable than that of cone resistance in spite of corrections for pore pressure effect. Consequently, \( f_s \) is of subordinate importance in comparison to cone resistance \( q_c \) and pore pressure \( u \), which both are viewed as the key parameters in CPT studies. In this thesis, sleeve friction was measured in each profile, but its interpretation was omitted for the above reasons on most occasions.
**Pore Pressure**

Pore pressure is simply the pressure of the fluids in the voids between the solid grains of the sediment matrix. It should be noted that only saturated matrices will be here considered as they are most relevant for marine sediments. In any marine geological environment realm the surrounding pressure is measured and defined as the pore pressure consisting of a hydrostatic component $u_0$, resulting from the thickness of the water column, and an excess pore pressure component $\Delta u$ in the sediment due to loading:

$$u = u_0 + \Delta u$$

Excess pore pressure $u$ can be consequentially estimated to be zero, if hydrostatic conditions occur in the sediment (Figure 6). Nonhydrostatic pore pressure provides direct evidence for advection of pore fluids in the sediment, glacial, tectonic, sedimentary or anthropogenic loading, or dynamic processes such as earthquake tremor.

An insertion of any kind of probe into a sediment causes changes in the stress and pore pressure regimes surrounding the penetrometer. The total magnitude of measured pore pressure during penetration tests consists of the hydrostatic component $u_0$, the excess pore pressure due to changes of the normal stress $\Delta \sigma_n$ resulting from the displacement of material by the insertion of the probe, and on excess pore pressure due to changes in the shear stress, caused by the shear deformation of the soil adjacent to the cone body:

$$U = u_0 + \Delta \sigma_n + \Delta \sigma_{\text{shear}}$$

(Figure 7). Both $\Delta \sigma_n$ and $\Delta \sigma_{\text{shear}}$ comprise a stress component induced by the profiling CPT lance and another component of pre-existing (excess) pore pressure in the geosystem. The zone of the influence of the normal stress is considered as a function of the stiffness, as expressed by the rigidity index $I_r$. In field measurements, pore pressure is defined as a total magnitude response of $\Delta \sigma_n$ and $\Delta \sigma_{\text{shear}}$ and can be only distinguished in an analytical way.

![Figure 6: Hydrostatic and excess pore pressure in marine sediments](Image)

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Considering a measured pore pressure signal, it can be divided into two different parts that contain different geotechnical as well as geological informations. The first part of the signal is characterised by a pressure pulse associated with probe insertion and the sediment properties followed by an evolution of the insertion pore pressure over the time, which formed by the insertion response depends on \textit{in situ} permeability. When the instrument is halted over a long period of time, the induced pore pressure will approach its ambient conditions, which is the final component of pore pressure evolution. The duration, which is needed for the complete decay of the insertion pore pressure as a function of the permeability of the sediment varies between days and months. The dissipation decay may record two different signals. Burns and Mayne assume that the dissipation of the shear-induced pressure occurs more rapidly than that of the cone-induced pore pressure, as the volume of sediment affected by the frontal impact is much larger than that affected by the sliding probe. Dissipation tests performed in soft, fine-grained silts and clays show a monotonous decrease of pore pressure (similar to observations in the laboratory one-dimensional consolidation tests). In contrast, dissipation tests in heavily overconsolidated fine-grained sediments often reflect dilatory pore pressure response with an increase in pore water pressure followed by a decrease and a return to hydrostatic values. Similar to the cone resistance, many analytical approaches have been developed to describe the changes in pore pressure during and after an insertion of a probe into sediment. This also includes the same theoretical solutions as mentioned in the context of cone resistance. An overview of the historical development of piezocone dissipation modelling until the 1990ies is given in Burns and Mayne. The theoretical analysis of dissipation of pore pressure based on the consolidation theory was used to predict the coefficient of horizontal consolidation \( C_h \), from time taken for 50\% of the maximum insertion pore pressure \( U_{\text{max}} \) to dissipate \( (t_{50}) \) (Bennett et al. 1985):

\[
C_h = \frac{r^2 \times T_{50}}{t_{50}}
\]

where \( r \) is the radius of the probe and \( T_{50} \) is a dimensionless time factor. Calculating \( C_h \), the permeability \( k \) can be determined as follows:

\[
k = \frac{C_h \times y_w}{D}
\]
with \( D = \) constrained modulus and \( y_w = \) unit weight of water.

As the failure zone during penetration is a function of the stiffness expressed by the rigidity index \( I_r = G/s_u \), Bennett et al. 1985 suggest an empirical relationship for soft marine sediments between \( U_{\text{max}} \) and undrained shear strength as

\[
S_u = \frac{U_{\text{max}}}{6}
\]

Based on the theoretical solution, when the soil is modelled as an elastic, perfectly plastic material, it follows:

\[
U_{\text{max}} = S_u \times \ln \left( \frac{G}{s_u} \right)
\]

with \( G \) being the elastic shear modulus (Randolph et al. 1979).

An essential aspect of pore pressure measurement with cone penetrometers is the position of the pressure port. Due to changes in normal stress during penetration, the largest effect on the magnitude of pore pressure is under beneath the cone, whereas the relative changes in shear stresses are small (<20%; see Baligh 1986b). It has been long known that the pore pressure measured at the cone (\( u_1 \)) is higher than measured behind the cone (\( u_2 \)) or along the. Song and Voyiadjis (2005) described in detail the pore pressure behaviour taken at the different locations during penetration tests in a calibration chamber (33% kaolin - 67% fine-grained sand) with a constant penetration rate of 2 cm/s. The pore pressure responses for the \( u_1 \) and \( u_2 \) position show a similar trend with an initial increase followed by the decay to steady-state (constant equilibrium conditions such as stabilized pore water flow and stress-strain conditions). In contrast, the \( u_3 \) pressure signal is characterised by an initial fluctuation with an increase followed by a decrease before it increases again to reach the steady-state. The absolute values of the steady state condition at the end of the penetration process are higher the closer the pore pressure is measured near the tip. The decrease of the signal is assumed to be linked with a dilative behaviour of the specimen caused by lightly overconsolidated conditions (OCR = 1.5). In addition to the pore pressure signal and its absolute magnitude, the position of the pore pressure port influences also the dissipation behaviour. In lightly over-consolidated as well as normally consolidated specimens, the induced pore pressure measured at \( u_1 \) dissipates more rapidly than that in \( u_2 \) position.

1.2.4. CPT’s Geological Application

Cone Penetration Testing provides measurements to determine the strength (\( q_c \)), cohesion (\( f_s \)) and the pore pressure (\( u \)) of profiled sediments. Considering the geotechnical aspect of them, both they seem to be controlling factors for (saturated) sediment behaviour and stability. Saturated sediments can be considered as a two-phase-system, where the voids between the solid particles are filled with fluid (Figure 8). Depending on the cohesion forces acting between the grains, the skeleton of the solids is characterised by a certain strength, which is largely a function of mineralogical composition. On the other hand, the forces of the pore water (i.e. pore pressure) are counteracting the binding forces between the particles, and hence lower the strength. This relationship is expressed in the principle of effective stress (\( \sigma' \)) presented by Terzaghi (1946):

\[
\sigma' = \sigma - u
\]
where $\sigma = \text{total stress}$ and $u = \text{pore pressure}$. Relating to the stability of (saturated) sediments and modifying the Mohr-Coulomb relationship with respect to effective stress, it can be expressed as follows (Terzaghi 1946; Hubbert and Rubey 1959):

$$\tau = c' + \sigma' \tan \Phi$$

The equation implies that overpressuring weakens the sediment as the fluid is sustaining an extra part of the stresses acting against the granular skeleton. As a consequence, both the overall, and the interparticle friction ($\sigma' \tan \Phi$) are reduced. This means that it is the effective stress rather than the total stress, which controls deformation and stability of sediments. The occurrence of overpressuring is often combined with fine-grained, cohesive sediments characterised by low permeability and linked with geological processes such as tectonic deformation, mineral dehydration, decomposition of gas hydrates, hydrocarbon formation and high sedimentation rate. In these scenarios, the expulsion of the pore fluid is not in equilibrium with the reduction of the pore space by consolidation (Figure 9) (e.g. Schultheiss 1990; Maltman 1994). Generally, the reduction in effective stress (and strength) by overpressure is a crucial factor in all scenarios of sediment deformation and mass wasting (Hampton et al. 1996; Mienert 2004). This fact underlines the necessity of pore pressure measurement, which is only \textit{in situ} possible. Going back to cone penetration testing, these devices establish synchronous and continuous \textit{in situ} measurements of both (strength and pore pressure), which are vital to study different kind of potential failure mechanisms of sediments.

![Figure 8: Micro-scale view on forces acting in water-saturated sediments](image-url)
Cone penetration is also a very suitable method for landslide studies as it is possible to identify failed and non-failed sediment bodies by their in situ physical properties. Remoulded sediment for example is characterised by a lower cone resistance and sleeve friction. In intact sediments adjacent to failed sediments, the shear surface can be detected by a decrease of the measured strength, because failure almost always occurs in the weakest material. Determining different pore pressure regimes is also critical to figure out the role of pore pressure in failure and may further serve to reconstruct historical events. A further application may be the study of the dynamics of surficial sediments in terms of liquefaction. Such a kind of fluidisation is associated with a build up in the pore pressure due to loading rather than pore water advection. If the pore pressure exceeds the confining (i.e. effective) stress, the particle skeleton is supported by the fluid and the sediment. Another aspect is long-term pore pressure measurement. As the pore pressure regime is influenced by various processes), which are characterised by different geo-dynamic processes, pore pressure observations on different time-scales are a crucial contribute to geo-mechanical studies. Therefore the piezocone has to be arrested for a defined duration in the sediment to collected ambient data.

1.3. Design requirements

In order to do this project have been taken into account a number of considerations, such as working requirements, assembly or manufacturing of parts. These are shown below.

1.3.1. Working requirements

- The calibration chamber has been designed with several holes, some of them to let the water go in and out, to measure the pore pressure and also to let the air pressure exit.
- Some groovings have been also mechanized to fit the rubber membrane, to seal the different parts and to place other auxiliary components, such as bearings.
1.3.2. Assembling requirements

- The calibration chamber must be mounted in a certain order, because otherwise, it will not be useful to carry out the CPT in the laboratory.
- It has been designed thinking in an easy assembly and disassembly once the CPT has finished; therefore, to get out the sample, removing the cover (joined to the upper base just with 4 screws) is enough.

1.3.3. Manufacturing requirements

- All auxiliary parts, such as screws, o-rings or threads are standard parts, but the frame screws, which have a no standard measure.
2. ARTICLES AND CONDITIONS

2.1. Rules used

2.1.1. Boiler formula

In order to know the minimum thickness of the outer house (which depends on the inner pressure), it has been necessary to follow the “boiler formula”, called as DIN 2413-1, and described in paragraph 3.1.5 and 3.2.3.

The steel used for the outer house is V2A 304, which has an elastic limit of 210 N/mm²; the corresponding calculations are also in paragraph 3.1.5 and 3.2.3.

2.1.2. O-rings

The O-rings have been selected following the DIN 3771, and is possible to appreciate it in catalogue 10.

2.1.3. Bearings

The bearing placed in the cover has been selected to seal the cover against the water to avoid it comes in and out, and to let the cone movement softly; the rubber selected for the bearing is NBR DIN 3760 AS Lx, a double lip with resort bearing, and it is shown in the catalogue 11 and 12.

2.2. Catalogs of materials used
Figure 10: O-Ring catalog
**Figure 11**: Bearings catalog
Figure 12: Bearings catalog
2.3. **Calibration chamber assembly**

Have a look at plan assembly at paragraph 4.2

2.3.1. **Required items for assembly**

2.3.1.1. *Centering*

This item has the aim to support the cone vertical position when the cone is going down while the Cone Penetrating Test.

2.3.1.2. *Cover*

The developed function by it is to cover the top part of the calibration chamber, and it’s useful specially to fill the rubber membrane with the sample without the needing of withdraw any more item.

It has four threads around its center in order to be joined to the centering, and a bearing to let a soft cone vertical displacement.

A hole has also been made in the cover to let the exit of the pressured air.

2.3.1.3. *Upper base*

This item plays a role as a link between the upper parts (cover, centering and upper cover) and the lower parts, such as the closing and the outer house, due to the fact that almost all parts are linked by it.

In the lower part of the upper base is placed an o-ring which is fitted in the grooving, in order to fix the rubber membrane.

It has four threads to join with the cover, three more threads to join with the upper cover, and another three threads where are placed the main screws.

A hole has also been made in the upper base to let the measurement of the pressure pore.

2.3.1.4. *Upper cover*

The upper base is the joining item between the upper base and the outer house through three threads made along its periphery.

An o-ring is also placed just between the upper cover’s inner wall and the upper base to assure a complete staunchness, avoiding the pressure and water loss.
2.3.1.5.  *Outer house*

This item has been designed to last up to 20 bars of pressure, and the calculations are explained in paragraphs 3.1.5 and 3.2.3.

2.3.1.6.  *Closing team*

This closing items have been designed to, once the rubber membrane is fitted in the upper base’s lower part and the lower base’s upper part, let an uniform filling.

2.3.1.7.  *Lower Base*

The lower base has two side conduits, one to allow the water in and out, that is communicated with the piston, and the other one to measure the side pressure membrane. In the bottom of the lower base fits the interchangeable lower cover, and in the upper part of the lower base fits the three frame screws and the outer house.

2.3.1.8.  *Piston*

The piston is placed in the inner gap of the lower base, with a tolerance, of course, to allow the piston go up and down while the CPT.

The piston has four stoppers in each one of its sides; they are made of a porous material to let the water go through them and out of the calibration chamber. Moreover the piston has a grooving all around its periphery to let the water go through the lower bases’s conduit, and finally out, although the water always runs a closed circuit.

2.3.1.9.  *Interchangeable lower cover*

This piece is joined to the lower base by four screws, and in the middle it has a hole to measure the vertical water pressure.

2.3.2.  *Assembling steps*

The first step to assembly this group is to place the o-rings in the corresponding piece.

In the interchangeable lower cover is necessary to put in the o-ring in the upper side, but just after placing the rubber bag (which will be the manager that the piston has smooth displacements with the water pressure that comes from the bottom by the hole), since the rubber bag will be fixed by the o-ring. Look at figure (35) in 4.1.

Afterwards, the interchangeable lower cover will be fixed by the four screws. Look at figure (32) and (36) in 4.1.
The following step will be the placement of the piston, with their stoppers piston, into the lower base. Look at figure (31), (33) and (34) in 4.1.

Once is placed the piston, the three frame screws will be screwed in the lower base and fixed with coils in the top part of the upper base. Look at figure (31) and (22) in 4.1.

Now that have been mounted the upper base and the lower base will have to be placed the two o-ring in the mentioned pieces to achieve that the rubber membrane remains fixed by them. Look at figure (23) and (31) in 4.1.

Subsequently the closing team will be mounted around the rubber membrane in order to get an uniform filling of the sample. This closing team is formed for two frameworks (figure 27 and 28), a closing female (figure 29), a closing male (figure 30) and the respective hinges (frameworks and closings). Look at 4.1.

Later the o-ring will be placed in the lower base grooving, to be able to mount, immediately afterwards, the outer house in the lower base. Look at figure (31) in 4.1.

Later one will come to the placement of another o-ring in the small angle formed by the outer house wall and the upper base. Look at figure (22) in 4.1.

Thus the o-ring will remain fixed by the upper cover with 3 screws; in this way will be avoided the entry and/or exit of the water towards the outer of the calibration chamber.

Now is almost finished the calibration chamber assembly; one will proceed to the placement of the last one o-ring in the grooving of the cover lower face and the bearing in the middle of the piece. Look at figure (20) and (21) in 4.1.

The above mentioned bearing is the manager to allowing a smooth scrolling of the cone during the CPT.

Later the cover will be fixed to the upper base by 4 screws and the cone will be placed.

Finally one will proceed to the centering placement, fixed to the cover by 4 screws, which function will be to avoid any eccentric displacement of the cone movement, which will be vertical.
3. CALCULATIONS

3.1. First calibration chamber design

Below, in the pictures, is shown the calibration chamber with the cone and rod, simulating a CPT. In this first design the frame screws have been designed out of the outer house.

The brown piece is the rubber membrane, adjusted to the inner house inwardly, in order to allow a bit of flexibility to the sample through the holes, after filling. Also visible are the screw holes, the holes piston, the bearing housing, the vertical in & out water pressure (in the lower base), the conic air pressure exit and the conic hole for the measurement of the pressure pore.

Figure 13: First calibration chamber design
3.1.1. Determination of the volume change

The next tables summarize the volume change suffered by the calibration chamber due to cone and rod penetration during the CPT.

ROD

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGHT [mm]</th>
<th>VOLUM [mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>160</td>
<td>8042.48</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>15707.97</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
<td>27143.36</td>
</tr>
</tbody>
</table>

Table 1: Volume change due to the rod
To get the cone’s height, it is necessary to use some trigonometric rules, exactly, the Pythagora’s theorem:

![Figure 15: Cone height calculation](image)

\[ h = x \cdot \sin 60^\circ \]
\[ r = x \cdot \sin 60^\circ \rightarrow x = \frac{4 \cdot \cos 60^\circ}{5 \cdot \cos 60^\circ} = 8 \rightarrow h = 6.92 \]
\[ x = \frac{5 \cdot \cos 60^\circ}{6 \cdot \cos 60^\circ} = 10 \rightarrow h = 8.66 \]
\[ x = \frac{6 \cdot \cos 60^\circ}{8 \cdot \cos 60^\circ} = 12 \rightarrow h = 10.39 \]

This table summarizes the cone & rod volume change:

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGHT [mm]</th>
<th>VOLUM [mm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>6.9282</td>
<td>116.08</td>
</tr>
<tr>
<td>5</td>
<td>8.66</td>
<td>226.72</td>
</tr>
<tr>
<td>6</td>
<td>10.3923</td>
<td>391.78</td>
</tr>
</tbody>
</table>

**Table 2**: Volume change due to the cone
CONE & ROD

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGHT [mm]</th>
<th>TOTAL VOLUM [mm³]</th>
<th>TOTAL VOLUME [litters]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>160</td>
<td>8158,56</td>
<td>0,008</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>15934,68</td>
<td>0,016</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
<td>27535,14</td>
<td>0,027</td>
</tr>
</tbody>
</table>

Table 3: Volume change due to the cone & rod

CALIBRATION CHAMBER

The following calculation shows the calibration chamber volume, in order to know the new volume change managed in the calibration chamber.

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGHT [mm]</th>
<th>VOLUM [mm³]</th>
<th>TOTAL VOLUME [litters]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>250</td>
<td>2827433,38</td>
<td>2,83</td>
</tr>
<tr>
<td>60</td>
<td>300</td>
<td>3392920,06</td>
<td>3,39</td>
</tr>
</tbody>
</table>

Table 4: Calibration chamber volume

NEW VOLUME [litters]

<table>
<thead>
<tr>
<th>HEIGHTH [mm]</th>
<th>RATIO [mm]</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>2,836</td>
<td>2,843</td>
<td>2,855</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>3,401</td>
<td>3,409</td>
<td>3,420</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: New volume change managed in the calibration chamber
PISTON SURFACE

Knowing the piston’s surface, is possible to know the height achieved by the piston due to the new volume, and so, the maximum piston movement.

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>SURFACE [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>11309.73</td>
</tr>
</tbody>
</table>

Table 6: Piston surface

ACHIEVED HEIGHT BY THE NEW VOLUME [mm]

<table>
<thead>
<tr>
<th>NEW VOLUME [liters]</th>
<th>VOLUME [mm]</th>
<th>ACHIEVED HEIGHT [mm]</th>
<th>INCREASED HEIGHT [mm]</th>
<th>MAXIMUM HEIGHT [mm]</th>
<th>INCREASED HEIGHT [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,836</td>
<td>250,72</td>
<td>0,72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,843</td>
<td>251,41</td>
<td>1,41</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,855</td>
<td>252,43</td>
<td>2,43</td>
<td></td>
<td>2,43</td>
<td></td>
</tr>
<tr>
<td>3,401</td>
<td>300,72</td>
<td>0,72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,409</td>
<td>301,41</td>
<td>1,41</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,420</td>
<td>302,43</td>
<td>2,43</td>
<td></td>
<td>2,43</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Achieved height by the piston due to the new volume

MAXIMUM MOVEMENT BY THE PISTON

55 mm + 2,43 = 57,43 = 58 mm

3.1.2. Determination of the in & out pore water hole

As is known, is possible to link the pipe flow with its surface and the speed in it, through the next formula:

\[ Q = v \cdot s \]
Q: flow $[m^3/s]$

v: speed $[m/s]$

s: surface $[m^2]$

First at all, the flow must be calculated with this other formula:

$$Q = \frac{V}{t}$$ \hspace{1cm} [2]

V: volume $[m^3]$

t: time $[seconds]$

Taking into account that is wished to empty the calibration chamber in a maximum time of 10 minutes, saying, 600 seconds, and having 2 different alternatives for calibration chamber flow calculation depending its height:

Height = 250 mm → $V = 2827433,388 \text{ mm}^3 = 2,83 \cdot 10^{-3} \text{ m}^3$

$$Q = \frac{V}{t} = \frac{2,83 \cdot 10^{-3} \text{ m}^3}{600 \text{ s}} = 4,71 \cdot 10^{-6} \text{ m}^3/\text{s}$$

Height = 300 mm → $V = 3392920,066 \text{ mm}^3 = 3,39 \cdot 10^{-3} \text{ m}^3$

$$Q = \frac{V}{t} = \frac{3,39 \cdot 10^{-3} \text{ m}^3}{600 \text{ s}} = 5,65 \cdot 10^{-6} \text{ m}^3/\text{s}$$

Also is know that the cone penetrating rate is constant, with a speed of $2 \text{ cm/s}$, saying, $0,02 \text{ m/s}$.

Now with the cone penetrating speed and the flow, is possible to find out the hole diameter that is necessary to empty the water calibration chamber in 10 minutes.

Knowing that the hole surface is:

$$S (A_s) = \frac{\pi}{4} \cdot d^4$$ \hspace{1cm} [3]

Case a)

$$Q = v \cdot S \rightarrow S = \frac{Q}{v}$$
\[
\frac{\pi}{4} \cdot d^4 = \frac{4.71 \cdot 10^{-6} \frac{m^3}{s}}{0.02 \frac{m}{s}}
\]

\[d = 0.01732 \text{ m} = 17.32 \text{ mm} \approx 18 \text{ mm}.
\]

Case b)

\[Q = v \cdot S \rightarrow S = \frac{Q}{v}
\]

\[
\frac{\pi}{4} \cdot d^4 = \frac{5.65 \cdot 10^{-6} \frac{m^3}{s}}{0.02 \frac{m}{s}}
\]

\[d = 0.01897 \text{ m} = 18.97 \text{ mm} \approx 19 \text{ mm}.
\]

Due to the fact that the final calibration chamber height will be 300 mm, and it is not a round number, the emptying hole diameter chosen is of 20 mm; moreover it will help to empty faster the quantity of water of the calibration chamber.

3.1.3. Determination of the number of holes in the inner house

In the same way as before, the number of holes will depend on the calibration chamber’s height (inner house), so that:

Case a)

Height= 250 mm → the useful calibration chamber’s height is 238 mm due to the fact that there will be 5 mm free since the rounded edge (ratio of 1 mm) (up and down) to make the holes. Moreover, these other considerations must be taken into account:

Hole diameter → 6 mm
Distance between holes (since centers) → 12 mm

Therefore → \[\frac{238 \text{ mm}}{12 \text{ mm}} = 19.83 \approx 20 \text{ rows} \rightarrow 21 \text{ rows}.
\]

(It’s necessary to add 1 more row due to the fact that in 12 mm there is space for 2 holes)

Now the number of holes per row must be determinated. The number of holes per row will be known taking into account the inner house’s circumference length. As the inner house’s diameter is 120 mm (ratio = 60 mm) and the holes must be separated between them by 12 mm:
Circumference length formula:

\[ CL = 2\pi \cdot r \]  

\[
\frac{2\pi \cdot r}{12 \text{ mm}} = \frac{2\pi \cdot 60 \text{ mm}}{12 \text{ mm}} = \frac{31,4159 \text{ holes}}{\text{row}} \approx \frac{32 \text{ holes}}{\text{row}}
\]

The \( \frac{32 \text{ holes}}{\text{row}} \) will be a common data for any of the 2 possible choices.

Then, having 21 rows and 32 holes per row:

\[
21 \text{ rows} \cdot \frac{32 \text{ holes}}{\text{row}} = 672 \text{ holes}.
\]

Case b)

Height = 300 mm \( \rightarrow \) the useful calibration chamber’s height is 288 mm due to the fact that there will be 5 mm free since the rounded edge (ratio of 1 mm)(up and down) to make the holes.

Moreover, these other considerations must be taken into account:

Hole diameter \( \rightarrow \) 6 mm

Distance between holes (since centers) \( \rightarrow \) 12 mm

Therefore \( \rightarrow \frac{288 \text{ mm}}{12 \text{ mm}} = 24 \text{ rows} \rightarrow 25 \text{ rows.} \)

(It’s necessary to add 1 more row due to the fact that in 12 mm there is space for 2 holes)

Taking into account the common data of 32 holes per row and having 25 rows and 32 holes per row:

\[
25 \text{ rows} \cdot \frac{32 \text{ holes}}{\text{row}} = 800 \text{ holes}.
\]

3.1.4. Determination of the volume excelled in each hole

Below there are summarized the cone volume, rod volume, and both together, with the 3 different diameter size, respectively. When the cone and the rod penetrate into the calibration chamber, produce a volume change and the sample tends to excel through the holes.
CONE

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGTH [mm]</th>
<th>VOLUM [mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>6,928</td>
<td>116,08</td>
</tr>
<tr>
<td>5</td>
<td>8,66</td>
<td>226,72</td>
</tr>
<tr>
<td>6</td>
<td>10,392</td>
<td>391,78</td>
</tr>
</tbody>
</table>

Table 8: Volume change due to the cone

ROD

<table>
<thead>
<tr>
<th>ROD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATIO [mm]</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

Table 9: Volume change due to the rod

CONE & ROD

<table>
<thead>
<tr>
<th>CONE &amp; ROD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATIO [mm]</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

Table 10: Volume change due to the cone & rod
VOLUM EXCELLED

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>VOLUM EXCELLED [m₃]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8158,56</td>
</tr>
<tr>
<td>5</td>
<td>15934,68</td>
</tr>
<tr>
<td>6</td>
<td>27535,14</td>
</tr>
</tbody>
</table>

Table 11: Excelled volume through the holes

What is going to be calculated now, is the sample amount which excels from these holes, finding finally the excelling amount sample ratio. This data will be useful to choose the suitable kind of latex membrane.

There will be 6 different results, depending on the cone & rod ratio and the calibration chamber’s height.

For 250 mm calibration’s chamber height there will be 3 volumes excelled:

- Ratio = 4 mm → 8158,56 m₃

\[
\frac{8158,56 \text{ mm}^3}{672 \text{ holes}} = \frac{12,14 \text{ mm}^3}{\text{hole}}
\]

As is wished to know the excelled volume, it will be only half sphere volume:

\[
\frac{12,14 \text{ mm}^3}{\text{hole}} \div 2 = 6,07 \text{ mm}^3 \text{ hole}
\]

Now with the half sphere volume known, is possible to find the amount sample’s ratio (the length) which excels from the inner house, through the sphere volume formula:

\[
V_{Sphere} = \frac{4}{3} \pi \cdot r^3 \tag{5}
\]

Therefore the only unknown is the ratio:

\[
6,07 \text{ mm}^3 = \frac{4}{3} \pi \cdot r^3
\]

\[r = 1,13 \text{ mm}\]
• Ratio = 5 mm → 15934,68 mm³

\[
\frac{15934,68 \text{ mm}^3}{672 \text{ holes}} = \frac{23,71 \text{ mm}^3}{\text{ hole}}
\]

As is wished to know the excelled volume, it will be only half sphere volume:

\[
\frac{23,71 \text{ mm}^3}{\text{ hole}} \times \frac{1}{2} = 11,85 \text{ mm}^3
\]

Now with the half sphere volume known, is possible to find the amount sample’s ratio (the length) which excels from the inner house, through the sphere volume formula:

\[
V_{\text{sphere}} = \frac{4}{3} \pi \cdot r^3
\]

Therefore the only unknown is the ratio:

\[
11,85 \text{ mm}^3 = \frac{4}{3} \pi \cdot r^3
\]

\[r = 1,414550 \text{ mm}\]

• Ratio = 6 mm → 27535,14 mm³

\[
\frac{27535,14 \text{ mm}^3}{672 \text{ holes}} = \frac{40,97 \text{ mm}^3}{\text{ hole}}
\]

As is wished to know the excelled volume, it will be only half sphere volume:

\[
\frac{40,97 \text{ mm}^3}{\text{ hole}} \times \frac{1}{2} = 20,48 \text{ mm}^3
\]

Now with the half sphere volume known is possible to find the amount sample’s ratio (the length) which excels from the inner house, through the sphere volume formula:

\[
V_{\text{sphere}} = \frac{4}{3} \pi \cdot r^3
\]
Therefore the only unknown is the ratio:

\[ 20,48 \text{ mm}^3 = \frac{4}{3} \pi \cdot r^3 \]

\[ r = 1,697461 \text{ mm} \]

For 300 mm calibration’s chamber height we have 3 volumes excelled:

- Ratio = 4 mm → 8158,560298 mm³

\[ \frac{8158,56 \text{ mm}^3}{800 \text{ holes}} = \frac{10,20 \text{ mm}^3}{\text{hole}} \]

As is wished to know the excelled volume, it will be only half sphere volume:

\[ \frac{10,20 \text{ mm}^3}{\frac{\text{hole}}{2}} = 5,10 \text{ mm}^3 \frac{\text{hole}}{\text{hole}} \]

Now with the half sphere volume known is possible to find the amount sample’s ratio (the length) which excels from the inner house, through the sphere volume formula:

\[ V_{sphere} = \frac{4}{3} \pi \cdot r^3 \]

Therefore the only unknown is the ratio:

\[ 5,10 \text{ mm}^3 = \frac{4}{3} \pi \cdot r^3 \]

\[ r = 1,06 \text{ mm} \]

- Ratio = 5 mm → 15934,68154 mm³

\[ \frac{15934,68 \text{ mm}^3}{800 \text{ holes}} = \frac{19,91 \text{ mm}^3}{\text{hole}} \]
As is wished to know the excelled volume, it will be only half sphere volume:

\[
\frac{19.91 \text{ mm}^3}{\text{hole}} \div 2 = 9.96 \text{ mm}^3/\text{hole}
\]

Now with the half sphere volume known is possible to find the amount sample’s ratio (the length) which excels from the inner house, through the sphere volume formula:

\[
V_{sphere} = \frac{4}{3} \pi \cdot r^3
\]

Therefore the only unknown is the ratio:

\[
9.96 \text{ mm}^3 = \frac{4}{3} \pi \cdot r^3
\]

\[
r = 1,334683 \text{ mm}
\]

- Ratio = 6 mm → 27535,14101 mm³

\[
\frac{27535,14 \text{ mm}^3}{800 \text{ holes}} = \frac{34,42 \text{ mm}^3}{\text{hole}}
\]

As is wished to know the excelled volume, it will be only half sphere volume:

\[
\frac{34,42 \text{ mm}^3}{\text{hole}} \div 2 = 17,21 \text{ mm}^3/\text{hole}
\]

Now with the half sphere volume known is possible to find the amount sample’s ratio (the length) which excels from the inner house, through the sphere volume formula:

\[
V_{sphere} = \frac{4}{3} \pi \cdot r^3
\]

Therefore the only unknown is the ratio:

\[
17,21 \text{ mm}^3 = \frac{4}{3} \pi \cdot r^3
\]
In this paragraph is going to be explained the necessary calculations for the minimum outer house wall thickness, in order to ensure a good calibration chamber working, and avoid any possible fracture or fissure in the outer house, due to pressure that it is going to be subjected.

Following is the formula that relates the minimum wall thickness as a function of pressure, considering other factors that also influence in the wall thickness; this formula is also known as “The boiler formula”:

\[
\begin{align*}
t_w &= \frac{d_{ou} \cdot P}{2 \cdot \frac{\sigma}{S} \cdot v_N} \\
\end{align*}
\]

\( t_w \) = minimum outer house wall thickness (mm).
\( d_{ou} \) = outer house’s outer diameter (mm).
\( P \) = pressure which is subjected the outer house (N/mm²).
\( \sigma \) = steel elastic limit (N/mm²).
\( S \) = Safety factor according to DIN 2413-1
\( v_N \) = Joint efficiency

Before applying this formula must be defined the initial conditions to get a suitable (and safe) outer house’s wall thickness. The initial conditions are the next:

The outer house’s outer diameter will be of 280 mm.
The outer house will be subjected up to 20 bars. Taking into account that:

\[
1 \text{ bar} = 1 \cdot 10^5 \frac{\text{N}}{\text{m}^2} \rightarrow 20 \text{ bars} = 20 \cdot 10^5 \frac{\text{N}}{\text{m}^2} = 2.000.000 \frac{\text{N}}{\text{m}^2} = 2 \cdot \frac{\text{N}}{\text{mm}^2}
\]

The steel that is going to be used is the V2A stainless steel (or also known as stainless steel 304) with a standard austenitic grade of 1.4301 and an elastic limit of 210 \( \frac{\text{N}}{\text{mm}^2} \). Moreover this kind of steel has an ultimate tensile strength of 520-720 \( \frac{\text{N}}{\text{mm}^2} \) and an elongation at break of 45%. Its density is 7900 \( \frac{\text{Kg}}{\text{m}^3} \).

The safety factor will be about 1,6 according DIN 2413-1; as its name says, it’s just a precautionary measure against any error or determined pressure excess.

The joint efficiency is defined as the lowest efficiency of any joint in a boiler’s head; considering the calibration chamber as a special case of boiler, because of there is not any welding, the maximum value for this coefficient will be taken, which will be of 1,0.

So once defined all the formula’s parameters, is possible to apply it:
\[ t_w = \frac{d_{ou} \cdot P}{2 \cdot \sigma \cdot u_N} \rightarrow t_w = \frac{176 \text{ mm} \cdot 2 \cdot \frac{N}{\text{mm}^2}}{2 \cdot \frac{210 \text{ N}}{1,6 \cdot 1,0}} \rightarrow t_w \geq 1,34 \text{ mm}. \]

The inner house’s wall has been designed with 3 mm thickness, taking into account that into it would be the latex membrane with the sample and the rod pushing down and compressing thus the sample; however, who must endure the highest pressure by water is the outer house, and this is the reason which the thickness calculation has been necessarily designed.

In this sense, the outer house will be built with a 3 mm thickness, since it would not be logical that it was less than the inner house; in addition, there have not been any space restriction, as occurred with the inner house (since has been necessary to leave space enough between the inner and outer house for the air pressure exit). Anyway, 3 mm thickness is not at all any madness, and in this way a good consistency in the outer house is managed.

### 3.2. Final calibration chamber design

This last calibration chamber design, has been an evolution of the first design, and had been necessary doing some changes, according to the needs required for the completion of the CPT, in a satisfactory manner and with a high degree of reliability.

Among these changes are the rubber membrane’s diameter increase (where the sample will be deposited), measuring now 240 mm instead of 120 mm. Another change, the latter directly related to, is the disappearance of the inner house. Instead of the inner house, a closing has been designed, in order to give shape to the rubber membrane during the filling, and it is taken away once the rubber membrane is filled and fixed to the lower base and upper cover. The frame screws have been placed into the outer house, accordingly to the diameter increase.

Also visible is the hole for the measurement of the side pressure membrane, as well as the screw holes, the holes piston, the bearing housing, the vertical in & out water pressure (in the lower base), the conic air pressure exit and the conic hole for the measurement of the pressure pore.
Figure 16: Final calibration chamber design

Figure 17: Final calibration chamber design
3.2.1. Determination of the volume change

For this final calibration chamber design, the same calculations as in the first design have been required, but now with a calibration chamber ratio of 120 mm.

ROD

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGHT [mm]</th>
<th>VOLUM [mm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>160</td>
<td>8042.48</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>15707.97</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
<td>27143.36</td>
</tr>
</tbody>
</table>

Table 12: Volume change due to the rod

CONE

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGHT [mm]</th>
<th>VOLUM [mm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>6.9282</td>
<td>116.08</td>
</tr>
<tr>
<td>5</td>
<td>8.66</td>
<td>226.72</td>
</tr>
<tr>
<td>6</td>
<td>10.3923</td>
<td>391.78</td>
</tr>
</tbody>
</table>

Table 13: Volume change due to the cone

To get the cone’s height, is necessary to use some trigonometric rules, exactly, the Pythagora’s theorem:

Figure 18: Cone height calculation
h = x \cdot \sin 60^\circ
\begin{align*}
r &= x \cdot \sin 60^\circ \\
x &= \frac{4}{\cos 60^\circ} = 8 \\
\Rightarrow h &= 6.92
\end{align*}
\begin{align*}
x &= \frac{5}{\cos 60^\circ} = 10 \\
\Rightarrow h &= 8.66
\end{align*}
\begin{align*}
x &= \frac{6}{\cos 60^\circ} = 12 \\
\Rightarrow h &= 10.39
\end{align*}

This table summarizes the cone & rod volume change:

<table>
<thead>
<tr>
<th>RATIO [mm]</th>
<th>HEIGHT [mm]</th>
<th>TOTAL VOLUM [mm³]</th>
<th>TOTAL VOLUME [litters]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>160</td>
<td>8158.56</td>
<td>0.008</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>15934.68</td>
<td>0.016</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
<td>27535.14</td>
<td>0.027</td>
</tr>
</tbody>
</table>

**Table 14**: Volume change due to the cone & rod

**CALIBRATION CHAMBER**

The following calculation shows the calibration chamber volume, in order to know the new volume change managed in the calibration chamber.

<table>
<thead>
<tr>
<th>CALIBRATION CHAMBER</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RATIO [mm]</td>
<td>HEIGHT [mm]</td>
<td>VOLUM [mm³]</td>
<td>TOTAL VOLUME [liters]</td>
</tr>
<tr>
<td>120</td>
<td>300</td>
<td>13571680.26</td>
<td>13.57</td>
</tr>
</tbody>
</table>

**Table 15**: Calibration chamber volume
NEW VOLUME [litters]

<table>
<thead>
<tr>
<th>NEW VOLUME [litters]</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RATIO [mm]</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>HEIGTH [mm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>11,318</td>
<td>11,325</td>
<td>11,337</td>
</tr>
<tr>
<td>300</td>
<td>13,579</td>
<td>13,587</td>
<td>13,60</td>
</tr>
</tbody>
</table>

Table 16: New volume change managed in the calibration chamber

PISTON SURFACE

Knowing the piston’s surface, it is possible to know the height achieved by the piston due to the new volume, and so, the maximum piston movement, taking into account that the new piston ratio is 120 mm.

<table>
<thead>
<tr>
<th>PISTON SURFACE</th>
<th>RATIO [mm]</th>
<th>SURFACE [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td></td>
<td>45238,93</td>
</tr>
</tbody>
</table>

Table 17: Piston surface
ACHIEVED HEIGHT BY THE NEW VOLUME [mm]

<table>
<thead>
<tr>
<th>NEW VOLUME</th>
<th>ACHIEVED HEIGHT</th>
<th>INCREASED HEIGHT</th>
<th>MAXIMUM INCREASED HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>[litters]</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[mm]</td>
</tr>
<tr>
<td>11,318</td>
<td>250,18</td>
<td>0,18</td>
<td></td>
</tr>
<tr>
<td>11,325</td>
<td>250,35</td>
<td>0,35</td>
<td></td>
</tr>
<tr>
<td>11,337</td>
<td>250,60</td>
<td>0,60</td>
<td>0,60</td>
</tr>
<tr>
<td>13,579</td>
<td>300,18</td>
<td>0,18</td>
<td></td>
</tr>
<tr>
<td>13,587</td>
<td>300,35</td>
<td>0,35</td>
<td></td>
</tr>
<tr>
<td>13,60</td>
<td>300,60</td>
<td>0,60</td>
<td>0,60</td>
</tr>
</tbody>
</table>

Table 18: Achieved height by the piston due to the new volume

MAXIMUM MOVEMENT BY THE PISTON

55 mm + 0,60 = 55,60 ≈ 56 mm

In spite of having less piston’s movement in this final calibration chamber design, the same distance will be kept, since it will be useful to us as a security margin. So it will continue being of 58 mm.

3.2.2. Determination of the in & out pore water hole

As is known, is possible to link the pipe flow with its surface and the speed in it, through the next formula:

\[ Q = v \cdot s \]

Q : flow \([m^3/s]\)
v: speed \([m/s]\)
s: surface \([m^2]\)

First at all, the flow must be calculated with this other formula:
\[ Q = \frac{V}{t} \]

\( V: \text{volume} \quad \text{[m}^3\text{]} \)
\( t: \text{time} \quad \text{[seconds]} \)

Taking into account that it is wished to empty the calibration chamber in a maximum time of 10 minutes, saying, 600 seconds, and a height of 300 mm:

Height = 300 mm → \( V = 13571680,2635 \text{ mm}^3 = 13,57\cdot10^{-3} \text{ m}^3 \)

\[ Q = \frac{V}{t} = \frac{13,57\cdot10^{-3} \text{ m}^3}{600 \text{ s}} = 22,62\cdot10^{-6} \text{ m}^3/\text{s} \]

Also it is known that the cone penetrating rate is constant, with a speed of \( 2 \frac{\text{cm}}{\text{s}}, \text{saying,} \ 0,02 \frac{\text{m}}{\text{s}} \).

Now with the cone penetrating speed and the flow, it is possible to find out the hole diameter that is necessary to empty the water calibration chamber in 10 minutes.

Knowing that the hole surface is:

\[ S \left(A_2\right) = \frac{\pi}{4} \cdot d^4 \]

\[ Q = \nu \cdot S \rightarrow S = \frac{Q}{\nu} \]

\[ \frac{\pi}{4} \cdot d^4 = \frac{22,62 \cdot 10^{-6} \text{ m}^3}{0,02 \frac{\text{m}}{\text{s}}} \]

\( d = 0,03794\text{m} = 37,94 \text{ mm} \approx 40 \text{ mm}. \)

In one hand, and due to the fact that the final calibration chamber height will be 300 mm, and it is not a round number, we will choose an emptying hole diameter of 40 mm; moreover it will help to empty faster the quantity of water of the calibration chamber.

After thinking about the in & out pore water hole’s dimensions, we think that is better to have a smaller hole (like in the first version), although the emptying time is longer, since the hole dimensions are too big for the design. So the in & out pore water hole will be 20 mm wide, and the emptying time will be double.
In this paragraph is going to be explained the necessary calculations for the minimum outer house wall thickness, in order to ensure a good calibration chamber working, and avoid any possible fracture or fissure in the outer house, due to pressure that it is going to be subjected.

Following is the formula that relates the minimum wall thickness as a function of pressure, considering other factors that also influence in the wall thickness; this formula is also known as “The boiler formula”:

\[
t_w = \frac{d_{ou} \cdot P}{2 \cdot \frac{\sigma}{S} \cdot u_N}
\]

\(t_w\) = minimum outer house wall thickness (mm).
\(d_{ou}\) = outer house’s outer diameter (mm).
\(P\) = pressure which is subjected the outer house (N/mm²).
\(\sigma\) = steel elastic limit (N/mm²).
\(S\) = Safety factor according to DIN 2413-1
\(u_N\) = Joint efficiency

Before applying this formula must be defined the initial conditions to get a suitable (and safe) outer house’s wall thickness. The initial conditions are the next:

The outer house’s outer diameter will be of 584 mm.

The outer house will be subjected up to 20 bars. Taking into account that:

\[
1\text{ bar} = 1 \cdot 10^5 \frac{N}{m^2} \rightarrow 20\text{ bars} = 20 \cdot 10^5 \frac{N}{m^2} = 2.000.000 \frac{N}{m^2} = 2 \cdot \frac{N}{mm^2}
\]

The steel that is going to be used is the V2A stainless steel (or also known as stainless steel 304) with a standard austenitic grade of 1.4301 and an elastic limit of 210 \(\frac{N}{mm^2}\). Moreover this kind of steel has an ultimate tensile strength of 520-720 \(\frac{N}{mm^2}\) and an elongation at break of 45%. Its density is 7900 \(\frac{kg}{m^3}\).

The safety factor will be about 1.6 according DIN 2413-1; as its name says, it’s just a precautionary measure against any error or determined pressure excess.

The joint efficiency is defined as the lowest efficiency of any joint in a boiler’s head; considering the calibration chamber as a special case of boiler, because of there is not any welding, the maximum value for this coefficient will be taken, which will be of 1.0.

So once defined all the formula’s parameters, is possible to apply it:
\[ t_w = \frac{d_{ou} \cdot P}{2 \cdot \frac{\sigma}{S} \cdot \sigma} \rightarrow t_w = \frac{584 \text{ mm} \cdot 2 \cdot \frac{N}{\text{mm}^2}}{2 \cdot \frac{210 \text{ mm}^2}{1,0}} \rightarrow t_w \geq 4,4495238 \text{ mm.} \]

The inner house’s wall has been designed with 3 mm thickness, taking into account that into it would be the latex membrane with the sample and the rod pushing down and compressing thus the sample; however, who must endure the highest pressure by water is the outer house, and this is the reason which the thickness calculation has been necessarily designed.

In this sense, the outer house will be built with a 3 mm thickness, since it would not be logical that it was less than the inner house; in addition, there have not been any space restriction, as occurred with the inner house (since has been necessary to leave space enough between the inner and outer house for the air pressure exit). Anyway, 3 mm thickness is not at all any madness, and in this way a good consistency in the outer house is managed.

After making a feedback in the design, it would be necessary to modify the outer house, constructing it with 5 mm thickness instead of 3 mm, due to the fact that the outer house’s dimensions have been increased, and consequently, also the wall thickness; despite having 3 mm thickness in the outer house (as the technical drawings show), it would be very important to modify this measure, so as other calibration chamber parts:

The upper lip of the upper cover should be 17 mm wide instead of 15 mm.

The lower base’s grooving should be 5 mm wide, instead of 3 mm, in order to fit in the outer house.
4. Technical drawings

4.1. Break-down of the set

4.1.1. Centering

Figure 19: Centering
4.1.2. Cover

Figure 20: Cover

Figure 21: Cover
4.1.3. Upper base

Figure 22: Upper base

Figure 23: Upper base
4.1.4. Upper cover

Figure 24: Upper cover

Figure 25: Upper cover
4.1.5. Outer house

Figure 26: Outer house
4.1.6. Closing team

4.1.6.1. Closing A

Figure 27: Closing A
4.1.6.2. Closing B

Figure 28: Closing B
4.1.6.3. Closing female

Figure 29: Closing female

4.1.6.4. Closing male

Figure 30: Closing male
4.1.7. Lower base

Figure 31: Lower base
Figure 32: Lower base
4.1.8. Piston

Figure 33: Piston

4.1.9. Stopper piston

Figure 34: Stopper piston
4.1.10. Interchangeable lower cover

Figure 35: Interchangeable lower cover
Figure 36: Interchangeable lower cover
4.2. Plan assembly

Figure 37: Plan assembly 1

Figure 38: Plan assembly 2
Figure 39: Plan assembly 3

Figure 40: Plan assembly 4
5. Not pirating declaration

In this paragraph I want to state that the only maker for the accomplishment of this project, he has been it is me, Enrique García Herráiz, and for whose accomplishment I have helped myself with bibliography, catalogues and information about CPT, without including works realized on this field with any previous calibration chamber design.
6. BIBLIOGRAPHY

6.1. Books

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6.2. Webs

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- http://www.barinox.com/
- http://www.tindsa.com/
- http://www.applycarsl.com/
- http://pdf.directindustry.es/
- http://lacasadeltrenes.site11.com/
- http://www.parker.com
7. ANNEXA

7.1. Catalogs

The catalogs needed to do this project are added in paragraph 2.2, as well as all the calibration chamber pictures are in 4.1.