THE HONG KONG
UNIVERSITY OF SCIENCE
AND TECHNOLOGY

Geotechnical Centrifuge Facility

HKUST GCF
USER MANUAL

Model preparation, Sensors, Balance calculations

Foreword

The Geotechnical Centrifuge Facility (GCF) User Manual is an essential guide for users of the GCF. This manual has been meticulously designed to provide comprehensive information on model preparation, sensors, and balance calculations before conducting tests at our state-of-the-art facility. It is of utmost importance that users thoroughly read and understand this manual before embarking on any testing procedures.

The GCF User Manual is an all-inclusive resource that encompasses the HKUST GCF Learning Series, aimed at educating students on the calibration and proper usage of various sensors employed at the HKUST Geotechnical Centrifuge Facility. Our facility is equipped with a wide range of sensors, including pore-pressure transducers (PPTs), displacement sensors, load and pressure cells, and strain gauges, all of which are covered in this manual. The structure of this manual is designed to provide users with fundamental calibration procedures and best practices for utilizing the sensors in the GCF. In addition to the written guidelines, the Learning Series includes instructional videos, which serve as a valuable visual aid for users. We extend our sincere gratitude to Dr. Andre Archer for his invaluable contribution to the Learning Series and Mr Arno Crous for his contribution to the development of the in-house GCF-PPT.

By adhering to the guidelines and procedures outlined in this manual and utilizing the Learning Series videos, users can maximize the potential of the Geotechnical Centrifuge Facility, ensuring accurate and efficient testing outcomes. We wish you a successful and productive experience as you delve into the world of geotechnical testing at the GCF.

Sina Baghbanrezvan, Ph.D.

Engineer

Geotechnical Centrifuge Facility

ABOUT

The Geotechnical Centrifuge Facility (GCF) at The Hong Kong University of Science and Technology (HKUST) serves as an advanced laboratory for physically modelling a wide range of engineering-related challenges. These include rain-induced landslides, consolidation settlement of reclaimed lands, seismic ground response, earthquake-induced liquefaction and deformations, offshore structure response to wave loading, seabed pipeline instability, pollutant transport in porous media, tunnelling, deep excavations, piles, and numerous other soil-structure interaction issues under both static and dynamic loading conditions. The centrifuge has a maximum modelling capacity of 400g-ton, and geotechnical structures can be constructed in model boxes with dimensions up to 1.5m x 1.5m in plan and 1.0m in height.

Over the past 15 years, geotechnical centrifuge modelling techniques have experienced rapid development and gained worldwide popularity. The fundamental principle of centrifuge modelling involves recreating stress conditions that would be present in a full-scale construction (prototype) by using a significantly smaller-scale model. This is achieved by subjecting the model components to an enhanced body force, supplied by a centripetal acceleration of a magnitude appropriate for the model's scale. Consequently, centrifuges are well-suited for modelling gravity and time-dependent problems.

Plate 1. The 8.5 m-diameter (400g-ton) beam centrifuge at the HKUST

Table of Contents

1 Duties and responsibilities of student

It is the responsibility of the student to ensure that they familiarise themselves with the terminology used in this manual. This manual assumes that the student has a basic understanding of soil mechanics and the principles of centrifuge modelling and calibration. The student should also be able to use the Data Acquisition (DAQ) system employed in the GCF. This manual also does not elaborate on the working principle of the sensors as it assumes that the student is familiar with relevant working principles.

In order to maintain a clean, safe, and efficient working environment at the Geotechnical Centrifuge Facility (GCF), all students utilizing the facility are expected to adhere to the following duties. If users do not adhere to these responsibilities, they may face a temporary ban from using the GCF, with the duration determined by the engineer and management.

1.1 Maintain a Clean and Safe Environment

I. Keep the centrifuge area clean and organized by promptly disposing of any waste materials, wiping down equipment after use, and returning tools and equipment to their designated storage areas.

II. Ensure that all cables, hoses, and other potential tripping hazards are properly secured and managed to prevent accidents.

III. Store hazardous materials and chemicals according to facility guidelines and dispose of them in designated waste containers.

IV. Wear appropriate personal protective equipment as required, including safety glasses, gloves, and hearing protection when necessary.

1.2 Communication and Collaboration

I. Regularly communicate with the engineer and technicians to discuss any potential issues, concerns, or questions related to the centrifuge and its operation.

II. Work closely with the GCF staff to troubleshoot and resolve any technical issues that arise during the course of your research.

III. Attend facility meetings and training sessions as required to stay informed about changes to policies, procedures, and best practices within the GCF.

1.3 Borrowing Sensors and Equipment

I. Review and sign the declaration form prior to borrowing any sensors or equipment from the GCF. This form outlines the user's responsibility to return borrowed items in good working condition and within the specified time frame.

II. Inspect equipment and sensors before and after use to ensure they are in proper working order. Report any damage or malfunctions to the GCF staff immediately.

III. The users are required to watch tutorial videos before using each instrument to get reliable measurements without damaging the instruments. The tutorial videos for calibrating and using different sensors such as pore-pressure transducer(PPT), displacement sensors, load and pressure cells, and strain gauges are uploaded on the GCF website server and can be accessed through the link below: ftp://wgy033.ust.hk/Andre/HKUST%20GCF%20Learning%20Series%20Videos/

    a. Username: gcfstudent
    b. Password: gcfst2005

By adhering to these duties, students will contribute to a clean, safe, and collaborative environment at the Geotechnical Centrifuge Facility, promoting the success of their own research as well as the research of their colleagues.

2 MODEL CONTAINERS

Before beginning a centrifuge testing program, it is essential to have a well-designed model container suited to the specific needs of the experiment. At the GCF, there is a variety of model containers available to accommodate different types of experimental problems. Generally, these containers can be categorized into three main types: one-dimensional, two-dimensional, and three-dimensional containers.

In addition to the primary container types, the GCF has developed several specialized chambers and equipment to enhance experimental capabilities. These include an environmental chamber, an energy harvesting chamber, a wave tank, and an SCR model container. Although these specialized chambers offer unique benefits, this manual will focus solely on the three main container types mentioned earlier.

By understanding the characteristics and applications of each container type, users can select the most appropriate option for their centrifuge testing program.

2.1 Containers for one-dimensional models

When modeling a prototype or examining an event that occurs in a single direction, one-dimensional (1-D) model containers are an appropriate choice. These simple containers are well-suited for experiments such as cone penetration tests (CPT) in layered soil. For instance, consider a scenario where the consolidation of clay layers interspersed with thick sand layers is being investigated, and the goal is to determine the immediate settlement in sand layers and consolidation settlement in clay layers. In such cases, centrifuge testing can be an effective method, and employing a 1-D model container is a practical and straightforward approach. An example of a 1-D model container is depicted in Plate 2.

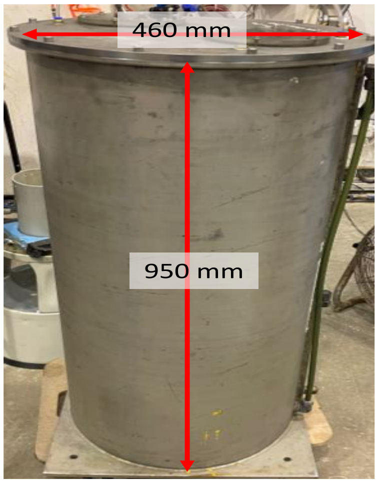


Plate 2. 1-D model container

2.2 Containers for two-dimensional plane strain models

Many civil engineering problems can be simplified under the assumption of plane strain conditions. Examples of such situations include wide earth dams, embankments, and retaining walls, where the height of the structure is relatively small compared to its width. By assuming plane strain conditions, it is implied that all vertical cross-sections through the structure are identical, and no lateral strains are allowed.

To model plane strain problems, specially designed two-dimensional (2-D) model containers are employed in centrifuge modeling. These containers typically feature thick, Perspex sides that allow for in-flight viewing or Particle Image Velocimetry (PIV) analysis of the model cross-section during testing. Additionally, 2-D plane strain model containers are equipped with high-pressure hydraulic fittings to facilitate pore fluid connections.

An example of a 2-D plane strain model container is shown in Plate 3. By using these containers, researchers can accurately model and analyze engineering problems under plane strain conditions, leading to valuable insights and solutions.

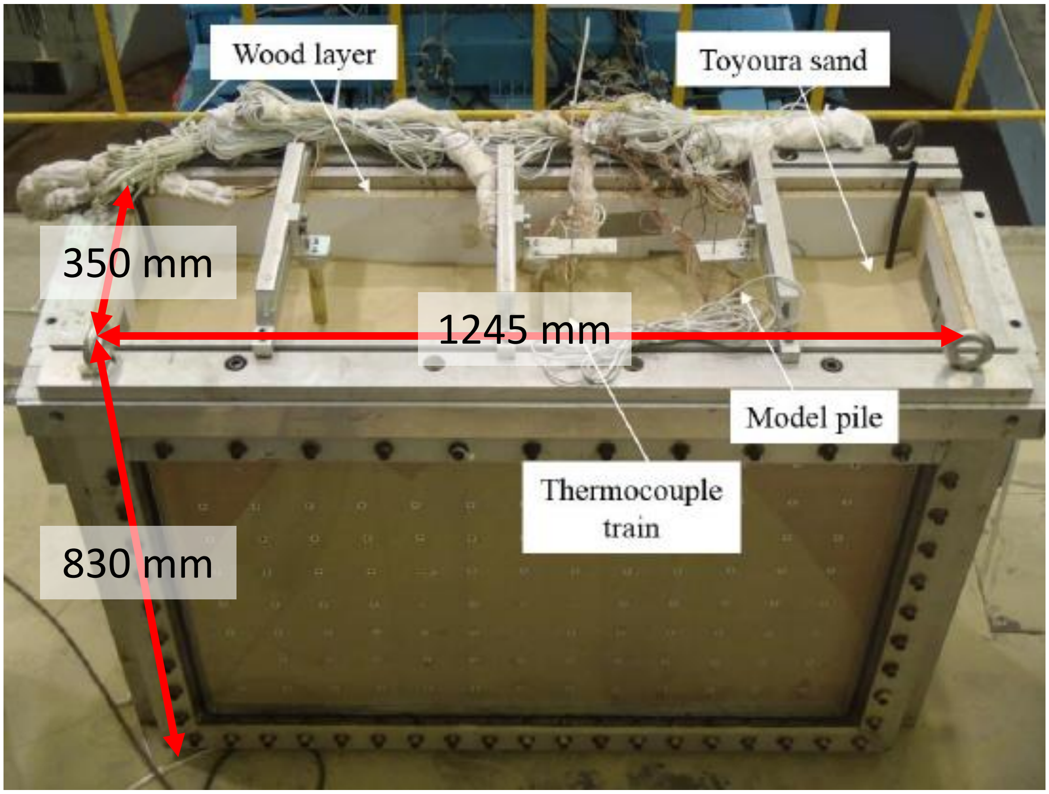


Plate 3. 2-D plane strain model container

2.3 Containers for three-dimensional models

In geotechnical engineering, the most comprehensive category of problems is inherently three-dimensional (3-D) due to the geometry or loading involved. For instance, a pile foundation subjected to axial loading can be considered a 2-D axisymmetric problem. However, when lateral loads are applied to the pile, it transforms into a 3-D issue. Similarly, modeling a tunnel with a vertical shaft extending to the ground surface in a centrifuge naturally results in a 3-D representation. By addressing these complex problems through 3-D analysis, engineers can better understand and design solutions for real-world scenarios. An example of the 3-D model container is shown in Plate 4.

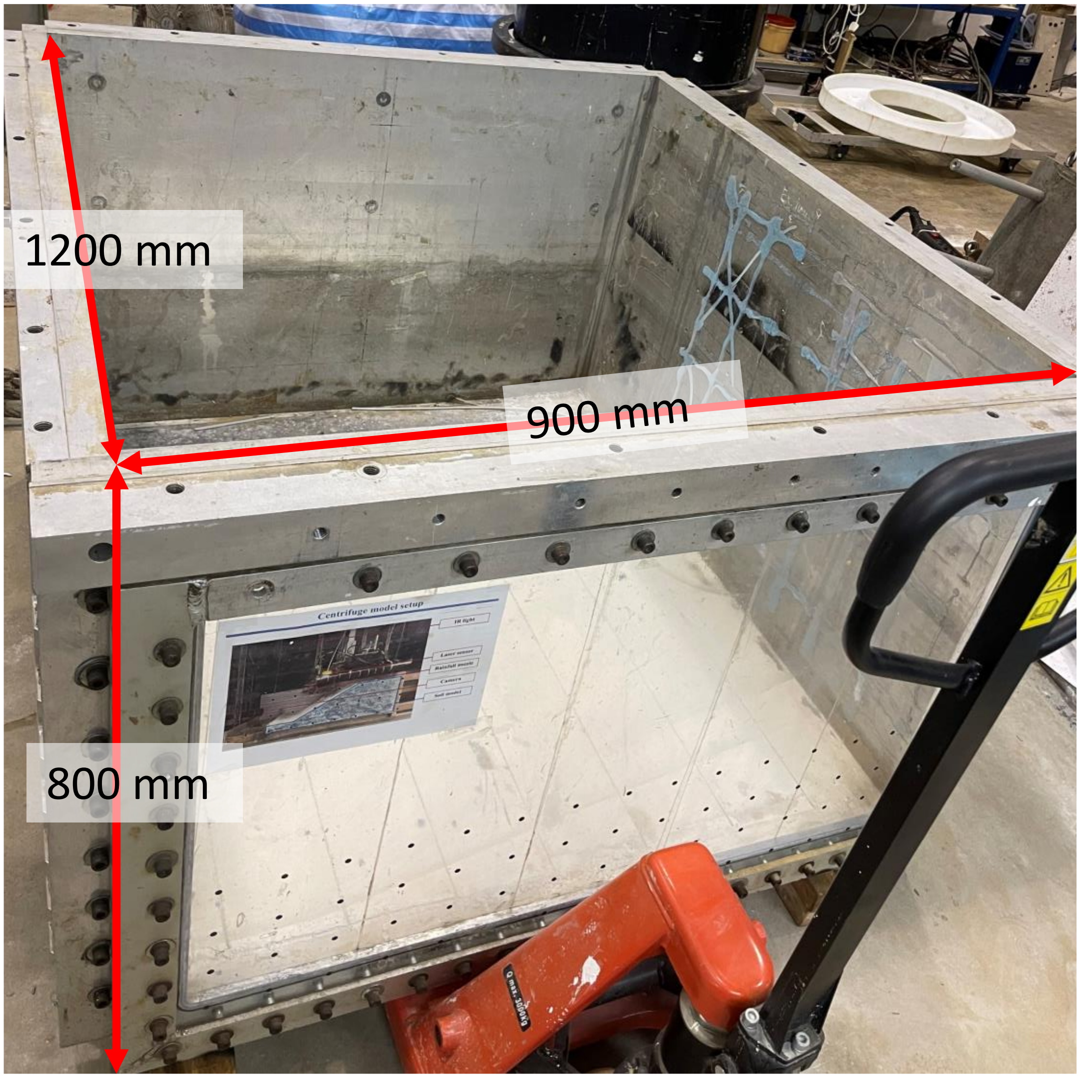


Plate 4. 3-D model container

3 MODEL PREPARATION TECHNIQUES

Centrifuge models can be created using either undisturbed soil samples collected from the field or reconstituted soil samples prepared in the laboratory. Although undisturbed samples are occasionally utilized for significant projects where the expense of obtaining large, undisturbed soil samples is justifiable, reconstituted soil samples are more commonly employed. One advantage of using reconstituted samples is the ability to effectively control soil properties and stress history. As a result, models with highly similar or even identical properties can be produced repeatedly, making them suitable for parametric studies.

Several model preparation techniques have been developed to ensure the repeatability of centrifuge models. In the subsequent sections, the methods used for preparing sand and clay samples will be discussed.

3.1 Air pluviation of sand samples

Air pluviation is a widely accepted technique for preparing sand models in geotechnical centrifuge testing. The primary components of the air pluviation setup include a hopper (as shown in Plate 5. (a)) filled with sand and an adjustable nozzle positioned above the model container. The nozzle size can be modified to control the flow rate of sand particles, while the drop height can be altered to achieve different relative densities. To evenly cover the model container's area, the user must move the nozzle accordingly. Typically, uniformly graded sands such as Toyoura sand are used for sand models.

To prepare a sand model using the air pluviation technique, follow these steps:

1. Fill the hopper with clean and dry sand, ensuring that the selected sand meets the requirements of the specific experiment.
2. Adjust the nozzle size and drop height based on the desired relative density of the sand model. For example, a drop height of 650 mm above the temporal ground surface (as shown in Plate 5(b)) may achieve a relative density of about 71% for dry Toyoura sand.

3. Gradually open the hopper to release sand particles through the nozzle, moving the nozzle systematically to ensure even coverage of the model container's area.
4. Monitor the deposition process to maintain a consistent flow rate and adjust the nozzle or drop height if necessary.
5. Once the desired model thickness is achieved, carefully level the sand surface.

During the model preparation, users should wear protective face masks to avoid inhalation of fine silica particles.

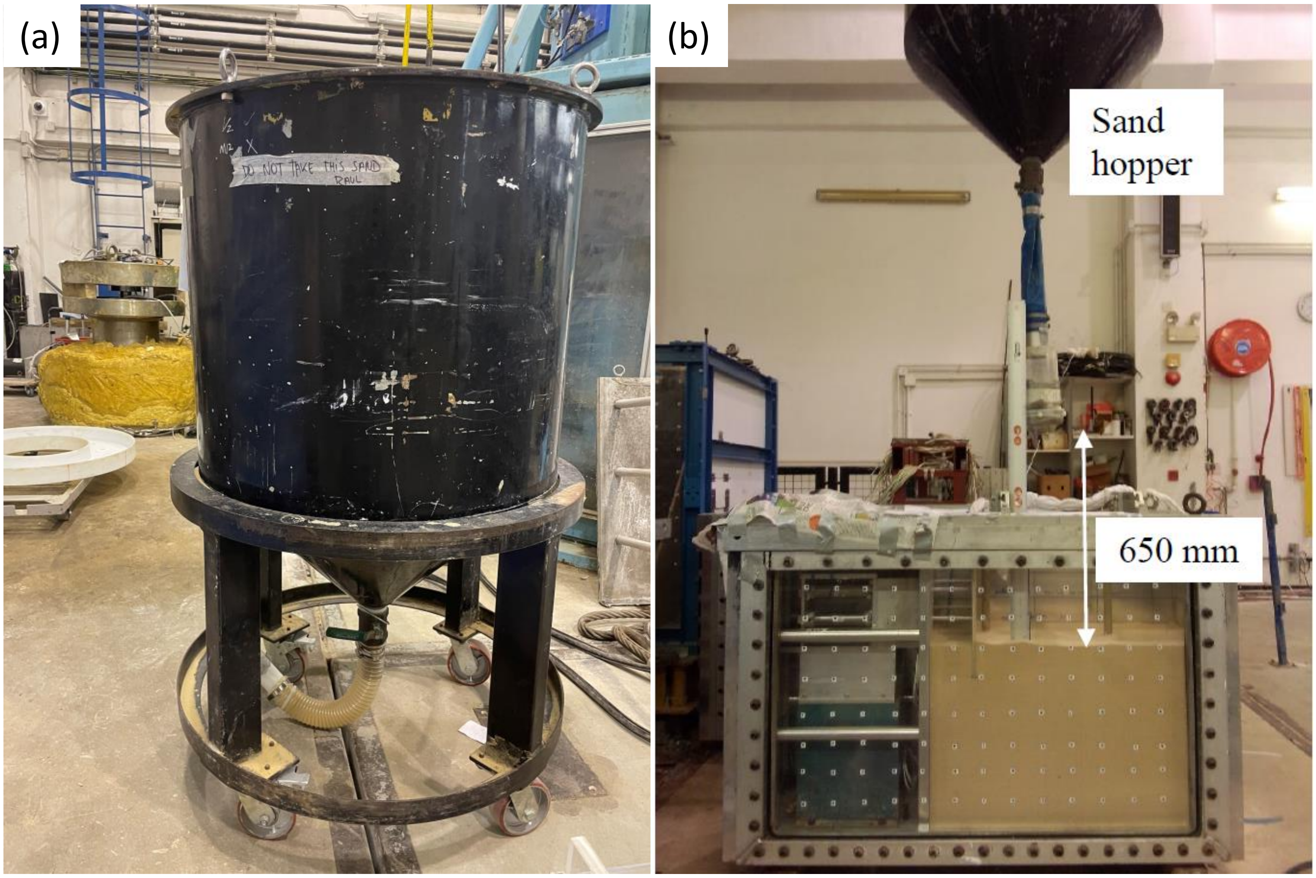


Plate 5. (a) sand hopper; (b) an example of sand pluviation

3.1.1 Saturation of sand models

Dry sand models, prepared using the techniques outlined in Section 3.1, may need to be saturated. If de-aired water is used for saturation, this can be achieved by applying a vacuum to the sand surface and carefully introducing water from the base of the model.

The vacuum application ensures that no air pockets remain within the sand, allowing for complete saturation.

Alternatively, permeable drains can be established at the far boundaries of the centrifuge model, and water can be introduced through these drains. This method also facilitates the saturation of the soil, providing the desired conditions for the experiment.

3.2 Consolidation of clay samples

In the absence of undisturbed samples, reconstituted clay samples can be prepared and tested in a centrifuge. These samples can have the advantage of having a completely known and well-controlled stress history. The reconstituted clay samples are often made using kaolin clay. It is possible to consolidate the clay layer in the centrifuge directly. However, this will take quite a long time (even with the scaling law for which time of consolidation is $1/N^2$). For example, for a 400-mm-thick clay layer to reach a normally consolidated state, we may have to run the centrifuge for 16 to 18 hours at 100 *g* depending on the properties of the clay. Furthermore, lots of water will be drained in the primary consolidation and the user would require stopping the centrifuge and re-fill the container at different steps. This leads to imposing stress history on the clay layers as well resulting in layering of the final prepared sample. It would be much easier to consolidate the clay at 1g to remove the water by applying load via a piston or dead load. Once the clay is consolidated and reaches its normally consolidated state, we can remove the load putting the clay into a temporary suction. The clay is then moved onto the centrifuge as quickly as possible and subjected to high gravities. The clay will then lose its suction and will return to its fully consolidated state. This process will only take a few hours. This way we can reduce the running time on the centrifuge.

The normal procedure employed in making a reconstituted clay sample begins with mixing the kaolin powder with deionized water at 120 percent of its liquid limit. The mixing is carried out under a vacuum to remove any air bubbles trapped in the clay. A view of the clay mixer is shown in Plate 6. This produces clay in a slurry form that is poured into the centrifuge model container. To allow for two-way consolidation of clay from the top and from the bottom of the model container, 50 mm thickness of Toyoura sand can be poured at the bottom of the container.

Plate 6. Clay mixer at the GCF

To facilitate drainage, the perforated tubes can be installed within the bottom sand layer and connected to the outlet of the container. The perforated tubes are covered with geotextile to prevent any blockage by sand particles. The outlet can be connected to a standpipe out of the container with the same water table as on the soil surface to keep the drainage conditions similar on the two surfaces based on the same total head. For this purpose, four vertical pipes should be installed inside the container at the corners to connect the two drainage surfaces providing the same total head at the top and bottom drainage surfaces. Internal walls of the model container should be coated with silicon grease to minimise the boundary effects by reducing the friction between the container and soil. A piston or dead load (as shown in Plate. 7) is then can be placed on top of the clay slurry which is left to consolidate for a day or so, under the weight of the piston or dead load. Further consolidation is achieved by applying a load from the piston acting on the surface of the clay layer. The load on the piston can be created by using a hydraulic pump. Samples consolidated in the above fashion will give a strength profile for the clay that increases with depth. After reaching the desired degree of consolidation, models can be placed on the centrifuge platform with a desired dead load on the model surface for high-g consolidation.

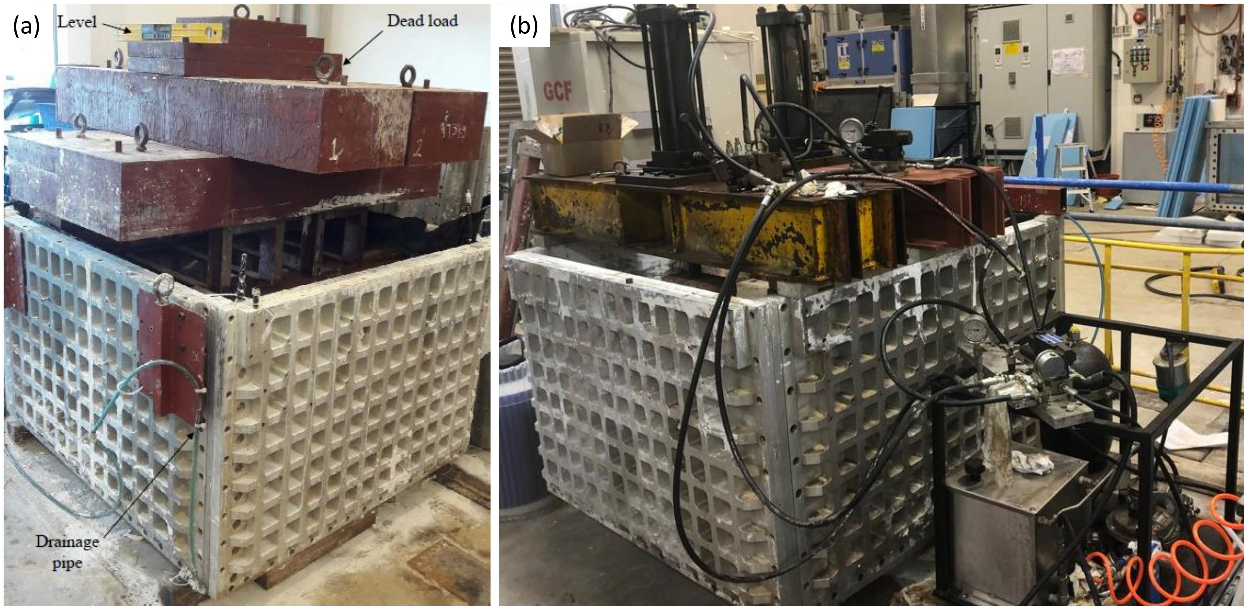


Plate 7. (a) 1g consolidation under dead load; (b) 1g consolidation using hydraulic jacks

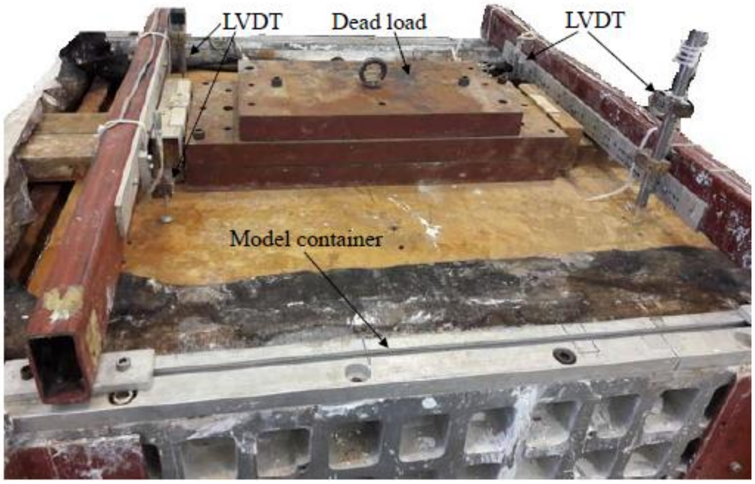


Plate 8. Top view of the model setup for high-g consolidation with required dead load

4 Sensors at the GCF and their calibration process

In this section, some typical sensors used in experiments at the GCF are introduced and the calibration process for the sensors is outlined. In addition to this manual, the users are required to watch tutorial videos before using each instrument to get reliable measurements without damaging the instruments. The tutorial videos for calibrating and using different sensors such as pore-pressure transducer (PPT), displacement sensors, load and pressure cells, and strain gauges are uploaded on the GCF website server and can be accessed through the link below:

ftp://wgy033.ust.hk/Andre/HKUST%20GCF%20Learning%20Series%20Videos/

Username: gcfstudent

Password: gcfst2005

4.1 GCF Pore-pressure transducers

The GCF employs commercial miniature pore-pressure transducers sold by TE Connectivity[1] as well as the in-house developed GCF-PPT as shown in Plate9. This document assumes that the student is familiar with these PPTs and the detail will not be discussed in this manual. Only the saturation and calibration procedures will be discussed. Most parts of the saturation and calibration procedure of the commercial and in-house GCF-PPT are similar. The parts which they have differences are highlighted in the following sections.

The typical setup required for saturation and calibration is shown in Plate10 and 11 for the commercial and in-house GCF-PPTs, respectively. Note that the vacuum pressure supple and data logger are same for both PPTs. However, the in-house GCF-PPT requires an additional interface box to be connected to the data logger as shown in Plate 11. In addition, larger capacity air supply is required for saturation of the high-capacity models of GCF-PPTs since they employ high-capacity ceramic disks.

---

[1] https://www.te.com/global-en/product-CAT-PTT0004.html

The different components required as shown is:

i. Pore-pressure transducer
ii. Vacuum supply
iii. Air pressure supply
iv. Pressure meter
v. Data logger
vi. Saturation/Calibration chambers (herein referred to as pressure chambers)
vii. De-aired water

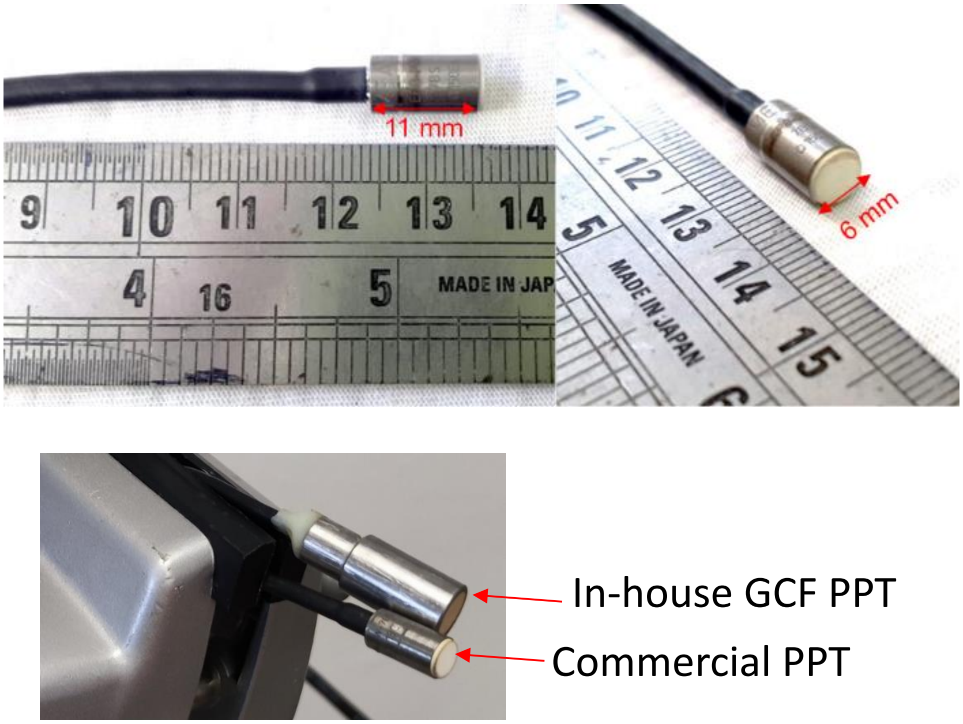


Plate 9. Overview of commercial PPT and in-house developed GCF-PPT

4.1.1 Saturation

A rigorous saturation procedure is required in order to effectively use the PTTs and facilitate measuring negative pore-water pressures. The saturation procedure is as follows:

i. Oven dry the PPT at 40-50°C for 4 hours to ensure that any dissolved-air water in the porous filter can be removed.

ii. Fill a pressure chamber with one-third de-aired water.

iii. Connect the PPT to the pressure chamber through the compression fitting (Plate. 12Figure). Ensure the PPT fits properly and is sealed completely. Do not over-tighten the compression fitting to avoid damaging the PPT. For the in-house GCF-PPT, there is no need for compression fitting since the compression fitting is pre-installed in the calibration chamber.

iv. Place the pressure chamber horizontally as shown in Plate13. The PPT should not be in contact with the water when it was placed horizontally. Note that similar action is required for the in-house GCF-PPT.

v. Apply vacuum of approximately -100 kPa (gauge pressure) at the other end of the pressure chamber for 1 hour. This step is to further de-air the water as well as remove any water trapped in the ceramic tip. This is the most important step and if the PPT gets in contact with water before applying the vacuum, it requires to be oven dried again and repeat the process.

vi. After an hour of initial vacuum, rotate the pressure chamber approximately 45° (see Plate 14), while maintaining the applied vacuum for 30 min.

vii. Remove the vacuum and apply positive pressure for 30 min, while the PPT remains submerged in the de-aired water and the pressure chamber remains in the rotated state. This is necessary to allow water to flow into the filter. The positive pressure applied is user defined and is typically governed by the maximum pressure the PPT can withstand, the maximum pressure that can be supplied, or the maximum pressure at which the PPT will be used.

viii. Apply the vacuum for 30 min, while keeping the PPT submerged.

ix. Steps vii and viii are repeated at least four more times to end the saturation procedure.

x. After saturated, first calibrate the PPT, where after it is removed and placed in de-aired water until used.

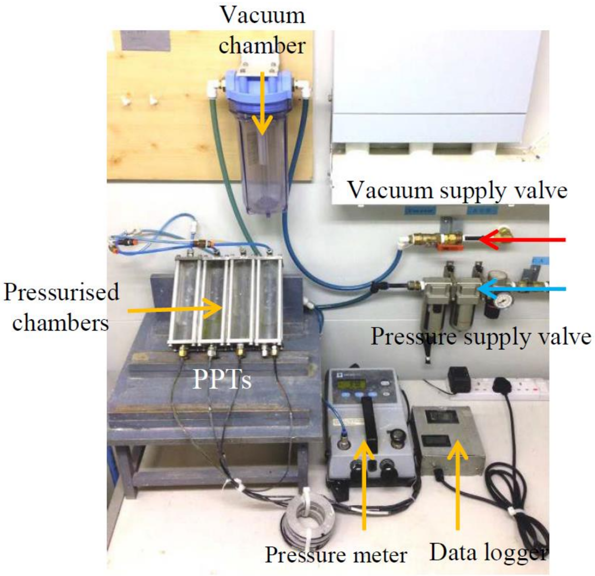
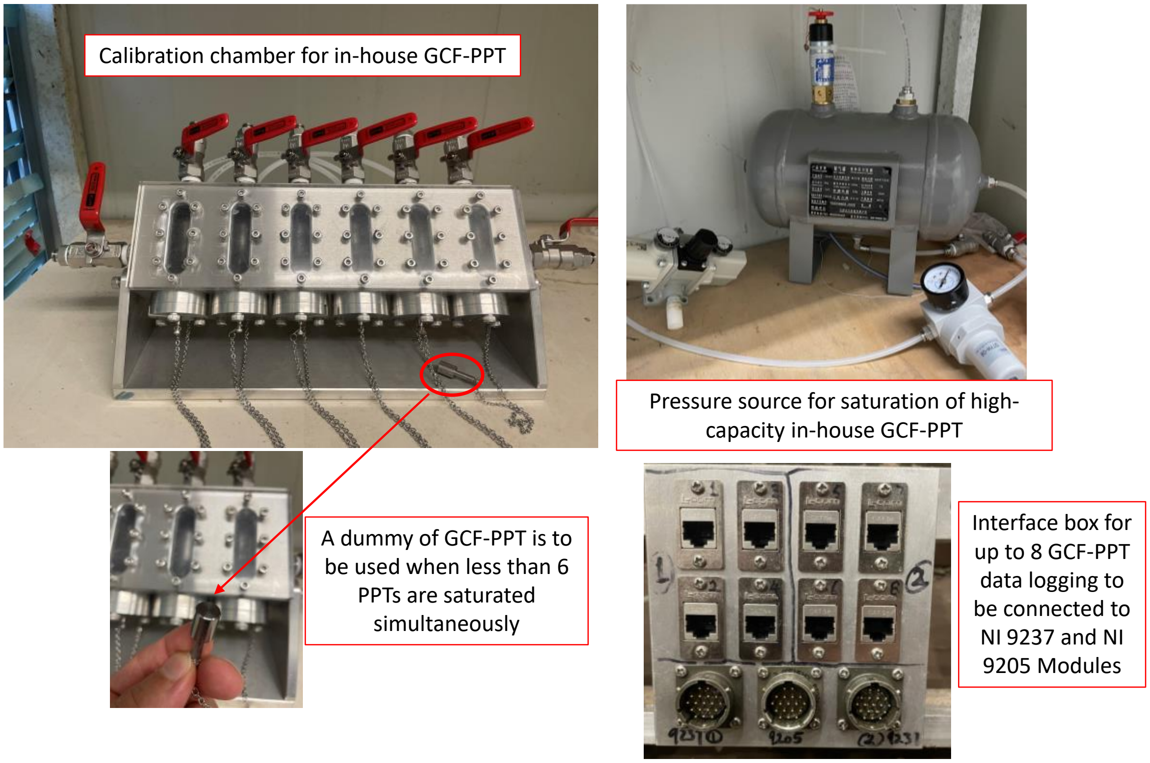


Plate 10: Saturation and calibration setup for commercial PPTs



Calibration chamber for in-house GCF-PPT

Pressure source for saturation of high-capacity in-house GCF-PPT

A dummy of GCF-PPT is to be used when less than 6 PPTs are saturated simultaneously

Interface box for up to 8 GCF-PPT data logging to be connected to NI 9237 and NI 9205 Modules

Plate 11: Saturation and calibration setup for in-house GCF-PPTs

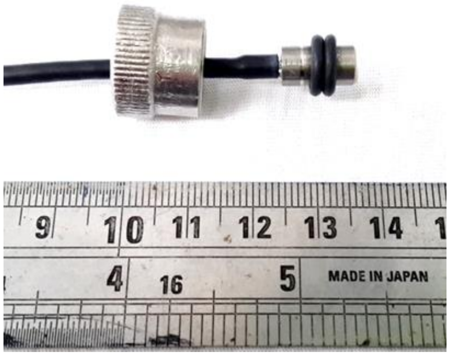


Plate 12. Overview of PPT and compression fitting

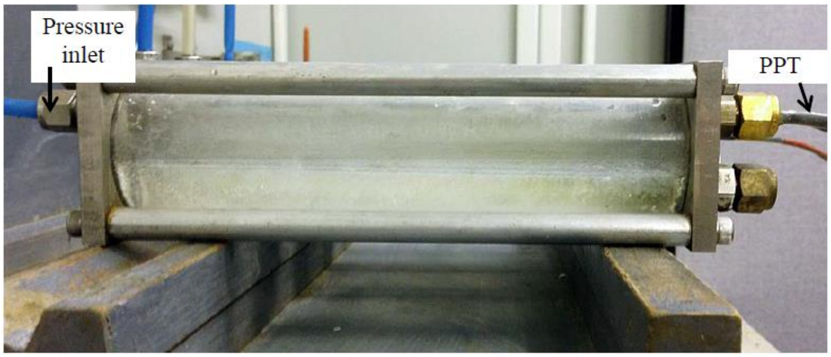


Plate 13. Pressure chamber for saturation of PPT filled with de-aired water placed horizontally

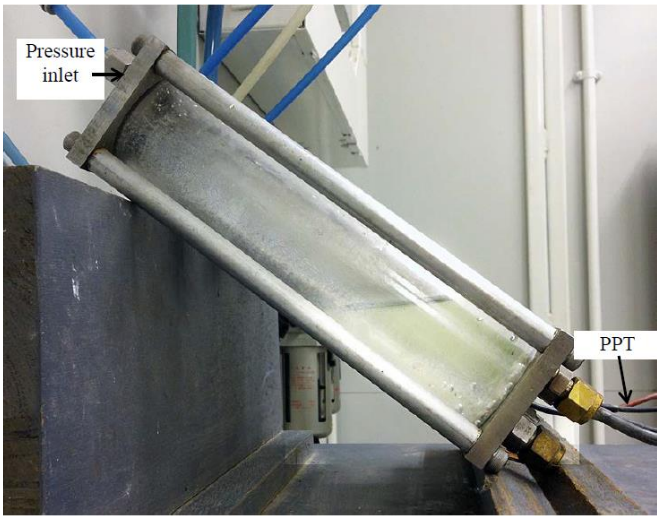


Plate 14. Pressure chamber filled with de-aired water and rotated for saturation and calibration of PPT

4.1.2 Calibration

In general, the PPTs measure a change in voltage, which is the output signal. The relationship between the applied pressure and the output signal is obtained through calibration. PPTs typically produce a linear relationship between the applied pressure and the output voltage. The range and voltage output are dependent on the sensor and the manual for the particular sensor should be consulted.

After saturation, while the PPT is still in the pressure chamber, connect the PPT to the data logger or DAQ system.

Apply a vacuum of approximately -80 kPa (gauge pressure), which is the starting point of the calibration. Allow the PPT to reach equilibrium before taking a voltage reading. If the PPT is correctly saturated, the response should be immediate.

Record the initial voltage (typically mV) value at the initial vacuum pressure (this is the first calibration point).

Increase the applied pressure from the initial vacuum pressure by the desired calibration interval (e.g. 50 kPa) and record the corresponding output voltage.

Repeat step 4 until the maximum desired calibration pressure is reached. Record the corresponding voltage for the different pressure steps.

Once the maximum desired calibration pressure is reached, reverse the process (with the same calibration pressure interval) until the initial vacuum pressure (or as close as possible) is reached. Reversing the process will allow the linearity and hysteresis to be assessed. The recorded voltage values for each applied pressure is the calibration curve. An example of a typical displacement sensor calibration curve is shown in Figure 1. Furthermore, the response time of each increase in pressure should be less than 1 second as shown in Fugure 2. Otherwise, the PPTs are not saturated well.

Unlike other sensors, the absolute value from the calibration curve trendline is required. Therefore, the complete equation should be used and not only the slope of the best-fit line through the calibration points. Thus, during centrifuge tests the PPT voltage is measured and the pore-water pressure is obtained by calculating the absolute pressure from the calibration curve using a linear function.

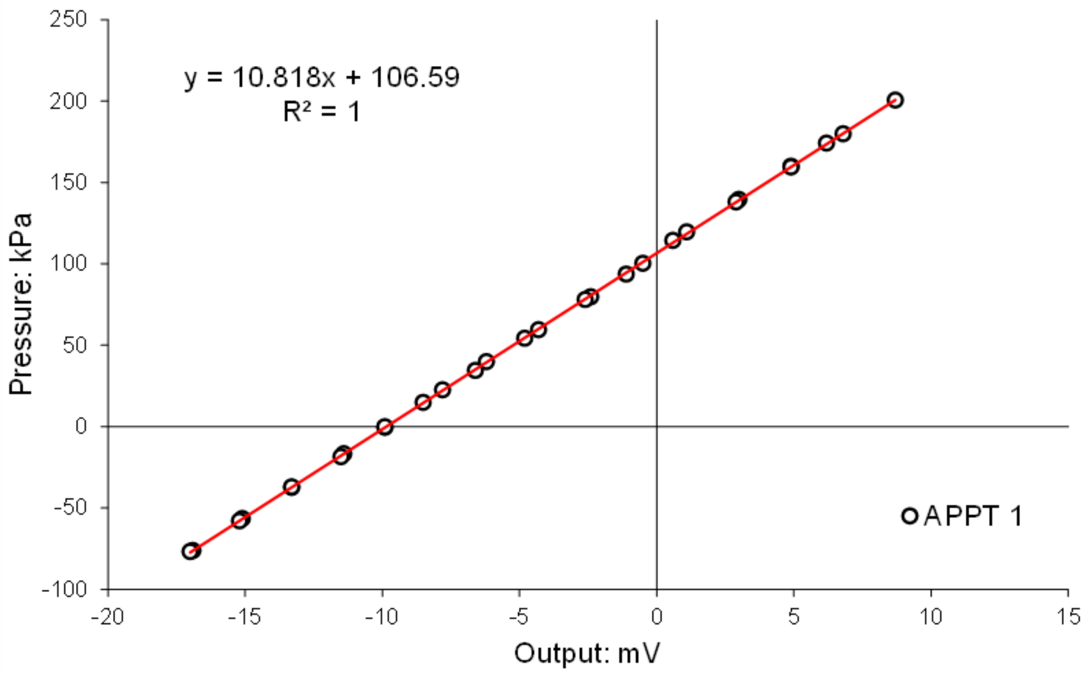


Figure1. Typical PPT calibration curve

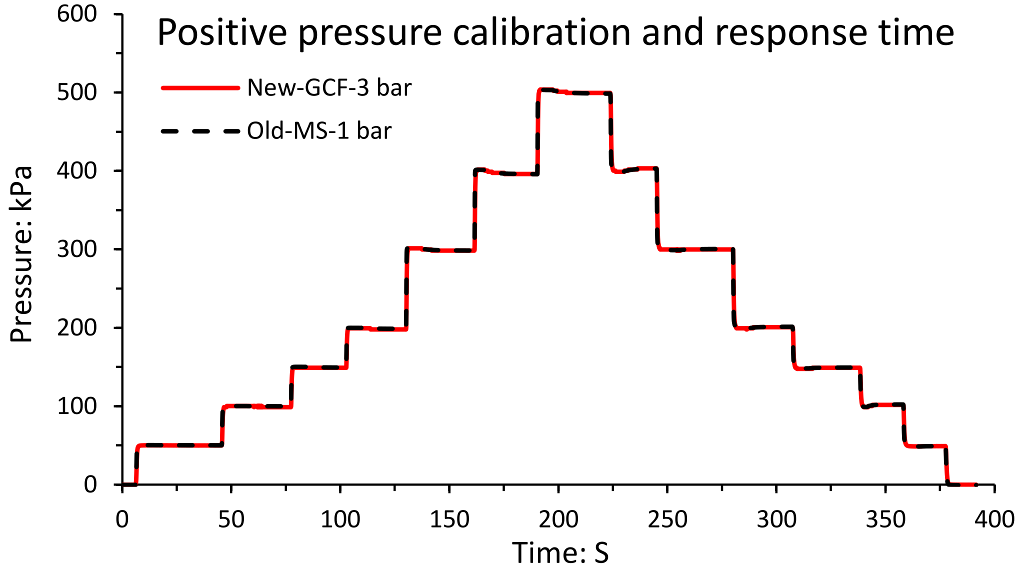


Figure 2. The response time if the commercial (Old-MS-1 bar) and GCF-PPT

4.2 GCF Displacement sensors

The GCF employs two types of displacement sensors: 1) linear variable differential transformers (LVDT), and 2) laser displacement sensors.

The typical setup required for calibration requires the following components:

viii. LVDT or laser sensor
ix. Calibration plate with Vernier calliper.
x. Data logger

4.2.1 General calibration principle

In general, the displacement sensors measure a change in voltage, which is the output signal. The relationship between the measured displacement and the output signal is obtained through calibration. Displacement sensors typically produce a linear relationship between the displacement and output voltage. The range and voltage output are dependent on the sensor and the manual for the particular sensor should be consulted.

4.2.2 Calibration Procedure

Install the LVDT on the calibration device, which is a Vernier calliper fixed to a plate, onto which the LVDT can be connected.

Setup the core of LVDT at its centre or at the maximum measurement location.

“Zero” the Vernier calliper to start the calibration.

Record the initial voltage (either mV or V) value at the zero displacement (this is the first calibration point).

Change the core displacement by the desired calibration interval (e.g. 1 mm) in one direction and record the corresponding output voltage.

Repeat step 5 until the maximum desired displacement or the limit of the LVDT is reached. Record the corresponding voltage for various the displacement steps.

Once the maximum desired displacement or the limit of the LVDT is reached, reverse the process until the initial zero location (or as close as possible).

The recorded voltage values at each set displacement is the calibration curve. An example of a typical displacement sensor calibration curve is shown in Figure .

The slope of the best-fit line through the calibration points is the calibration factor for the sensor (e.g. 12.322 in Figure 3).

The calibration setup and procedure are the same for the LVDT and laser sensors.

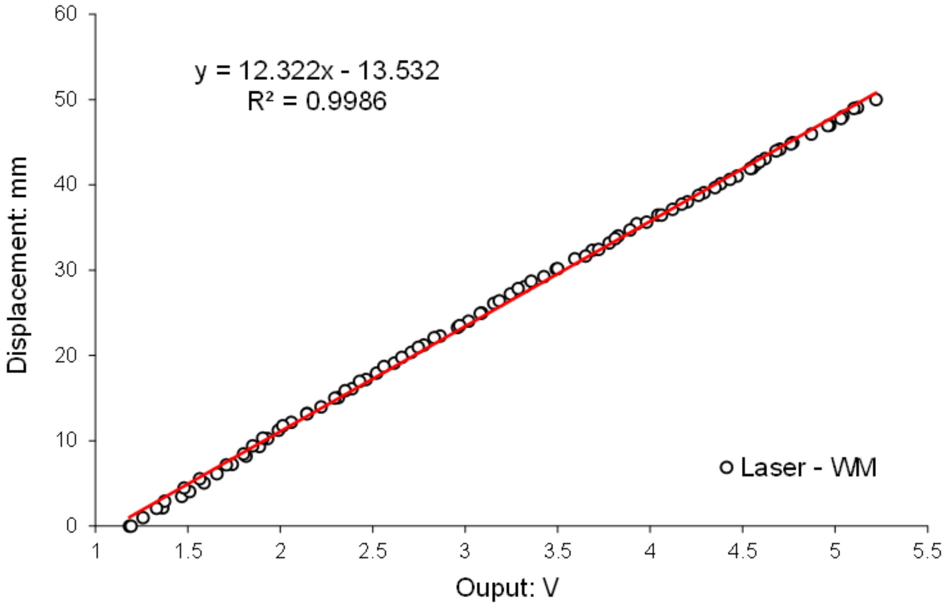


Figure 3: Typical displacement sensor calibration curve

4.2.3 Usage instruction

Always handle the sensors with care as they need to be used by other students as well and are expensive.

A minimum of one cycle, but preferably three, should be carried out for a sensor. This will allow the linearity and hysteresis of the sensor to be determined.

Place marks on the LVDT extension rod to show the range of the particular LVDT.

Be careful when you cut cables ties used to fix the sensor wire so that you do not accidentally cut a wire and damage the sensor.

Clean the sensors thoroughly after use, especially when used in clay.

Always return the sensors to proper storage with one the technicians after use.

4.3 GCF Strain gauges

The GCF employs commercial strain gauges or various resistances. The strain gauge to be used by a student is usually user dependent and is chosen based on the type of test to be carried out. This document assumes that the student is familiar the working principle of the strain gauges as it will not be elaborated on in this manual. Only the bonding and calibration procedure will be discussed.

The different components required for bonding is as follows:

xi. Strain gauges
xii. Bonding adhesive
xiii. Connecting terminals (is used)
xiv. Test specimen
xv. Solvent
xvi. Cleaning tissue
xvii. Soldering iron and solder
xviii. Abrasive paper (100 – 300 grit)
xix. Marking pencil
xx. Tweezer
xxi. Extension wire
xxii. Polyethylene sheet
xxiii. Wire cutter

4.3.1 Bonding

When bonding a strain gauge, the most suitable adhesive should be selected for each application. The typical bonding procedure is as follows:

xi. Determine the location on the test specimen where the strain gauge is to be bonded.

xii. Surface preparation:

  - Remove grease, scale, dust, paint etc. from the bonding area to provide a shiny metallic surface.
  - Use abrasive paper to abrade an area slightly larger than the strain gauge bonding area.
  - Clean the abraded surface with cleaning tissue or cloth dampened with a small amount of solvent such as acetone or pure alcohol. Cleaning should be continued until the tissue or cloth comes away clean.
  - After surface cleaning, immediately attach the strain gauge before the surface becomes newly contaminated.

xiii. General bonding:

  - Carefully mark the position for the strain gauge installation.
  - Take out the strain gauge form the plastic binder.
  - Apply the required amount of adhesive to the back of the strain gauge base. One drop of adhesive is normally sufficient, while additional adhesive might be needed for large strain gauges.
  - Use the adhesive nozzle to spread the adhesive uniformly over the back for the strain gauge.

- Align the strain gauge to the guide mark, place the polyethylene sheet over the strain gauge, press down and apply constant pressure with your thumb. This step should be done quickly as the adhesive cures fast. The curing time depends on the strain gauge, test specimen, temperature, humidity and applied pressure.

xiv. Soldering:

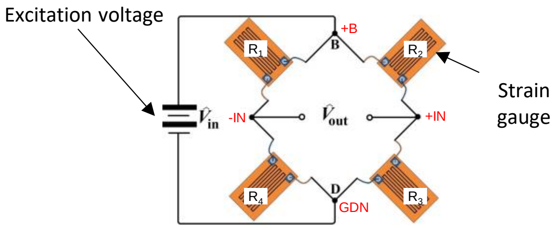
- Place the strain gauge leads on the connecting terminal with a little slack and apply solder so that the metal foil of the terminal is covered with solder. Any excess strain gauge leads should be cut off. If a connecting terminal is not used, the strain gauge leads are soldered directly to the extension wire.
- Solder the end of the extension wires to the connecting terminal. It is recommended to plate the exposed core of the extension wire with solder to aid the soldering process.

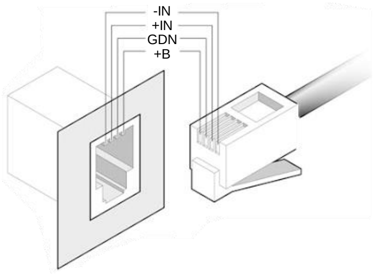
xv. Apply a coating after soldering, if required, with consideration of the following with regard to the type of coating used:

- Coatings should have excellent resistance to moisture and water and good electrical insulation.
- Coatings should have good adhesion to the strain gauge, lead wires and the test specimen surface.
- Coatings should not restrict the test specimen in any way.

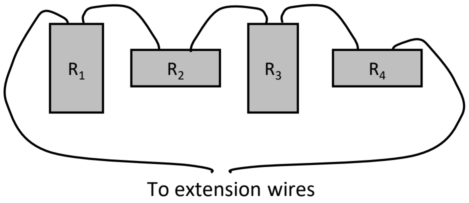
Figure 4.4 shows typical connections for a full Wheatstone bridge assembly measuring axial force or bending moment. The typical connections shown are only a guide and the student should ensure that the connections employed are correct for their application. The connection shown is also for a 4-pin connector. If a connector with more pins is used, the student should ensure that the correct pin is used.

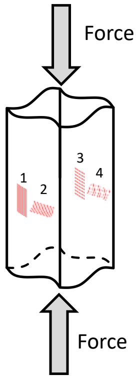
Full Wheatstone bridge



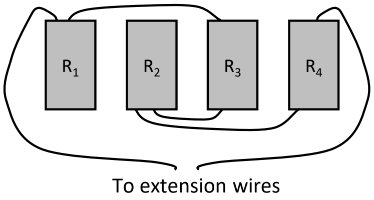


Connection to measure axial force





Connection to measure bending moment



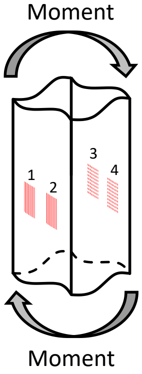


Figure 4. Typical strain gauge connections

4.3.2 Calibration

In general, strain gauges produce a voltage output when subject to strain. The strain can be either bending or axial strain, which is the most common in the GCF. The output voltage is compared with a known moment or axial force, typically obtained by subjecting a test specimen to different weights. The user should, therefore, calculate the known bending moment or axial force for their specific applications before calibration. This is typically a bending moment or axial force diagram over the length of the test specimen.

The relationship between the applied moment or force and the output voltage is obtained through calibration. Strain gauges typically produce a linear relationship between the applied moment or force and the output voltage. The range and voltage output are dependent on the strain gauge type and the manual for the particular strain gauge should be consulted.

Set up the test specimen to measure the desired axial force or bending moment and connect the strain gauges to the DAQ system. At this stage the bending moment or axial force to applied to the test specimen should have been calculated (i.e. the bending moment or axial force diagram).

Apply the first weight (corresponding to known bending moment or axial force) to the test specimen, which is the start of the calibration. Allow the measurement to reach equilibrium before taking the voltage reading.

Record the initial voltage (typically mV) value at the initial weight (this is the first calibration point).

Increase the weights from the initial weight by the desired calibration interval (e.g. 5 kg or the known bending moment or axial force) and record the corresponding output voltage at each weight applied.

Repeat step 4 until the maximum desired calibration load is reached. Record the corresponding voltage for each applied weight.

Once the maximum desired calibration load is reached, reverse the process (with the same weight calibration interval) until the initial weight is reached. Reversing the process will allow the linearity and hysteresis to be assessed.

The recorded voltage values for each applied weight (or known bending moment or axial force) is the calibration curve. An example of a typical strain gauge calibration curve is shown in Figure 5. The slope of the best-fit line through the calibration points is the calibration factor for the sensor.

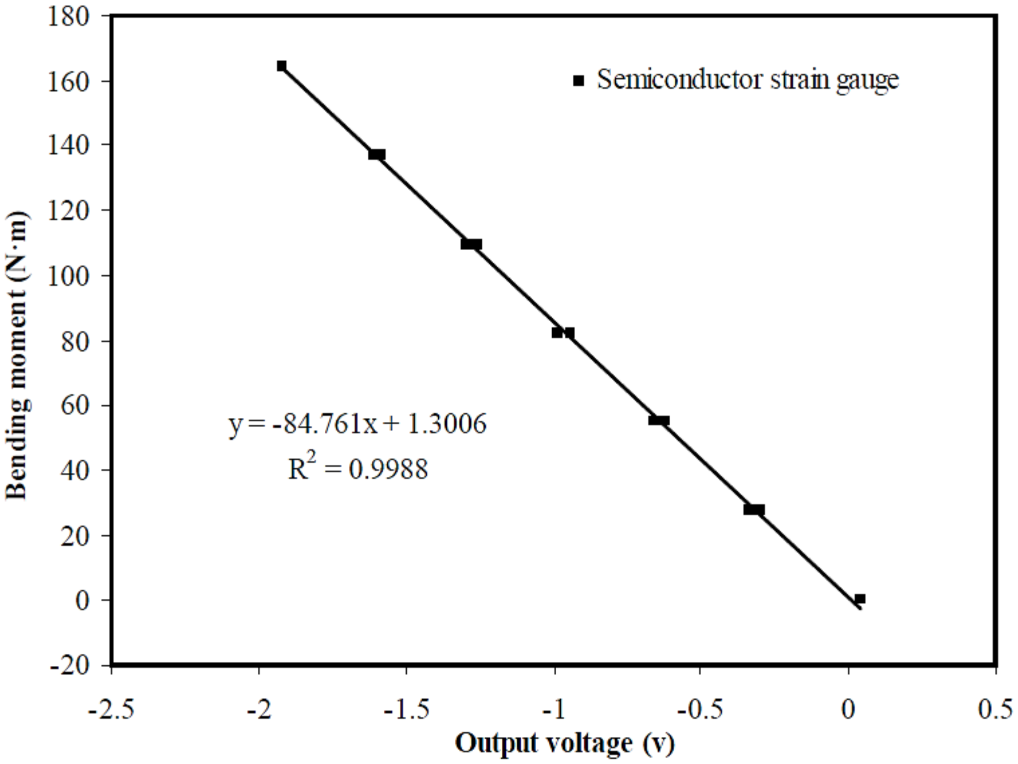


Figure 5. Typical strain gauge calibration curve

4.3.3 Usage instruction

Always handle the sensors with care as strain gauges are fragile and can break easily.

A minimum of one calibration cycle, preferably three, should be carried out. This will allow the linearity and hysteresis of the sensor to be determined.

After bonding the strain gauge and before calibration, check the resistance and connections of the strain gauges to ensure they work and that your bridge circuit is correctly connected. This can easily be done with a multimeter.

Most strain gauges come with alignment marks than be used to guide the user during bonding.

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor (GF). This factor should be obtained from the strain gauge manual and can be used to assess the sensitivity to temperature as well. Please consult the strain gauge manual for more details.

The output of strain gauges and bridges is relatively small. In practice, most strain gauge bridges will produce less than 10 mV/V (10 mV of output per volt of excitation voltage). With a 10 V excitation voltage, the output signal will be 100 mV. Therefore, depending on the DAQ system, the signal should be amplified.

Be careful when you cut cables ties used to fix the sensor wire so that you do not accidentally cut a wire and damage the sensor.

4.4 GCF Load- and pressure cells

The GCF employs commercial load- and pressure cells. Load cells are typically used to measure the force on or from a structural component. Pressure cells are used to measure soil pressure, typically at some depth within a soil profile. Load cells can be loaded in either tension or compression, while pressure sensors can only be loaded in compression.

The typical setup required for calibration requires the following components:

xxiv. Load- or pressure cell
xxv. Calibration weights (Load cell calibration)
xxvi. Pressure chamber filled with water (Pressure cell calibration)
xxvii. Pressure meter (Pressure cell calibration)
xxviii. Data logger

4.4.1 General calibration principle

In general, forces are applied to the force transducer in increments over its rated capacity or user defined capacity. The electrical output of the force transducer is compared to the known force applied at each force increment, and the linearity, hysteresis, repeatability, and creep of the transducer. The forces applied to load cells are typically in the form of weights (in kg), which can be converted to a force (in N). When pressure transducers are calibration, pressure is applied rather than a force.

The relationship between the measured force or pressure and the output signal is obtained through calibration. Load- and pressure transducers typically produce a linear relationship between the applied force or pressure and output voltage. The range and voltage output are dependent on the sensor and the manual for the particular sensor should be consulted.

Install the load cell on any calibration setup, which is typically a loading frame to which the load cell can be fixed, and weights can be applied to the load cell. For the pressure cells, the typical calibration setup requires a pressure chamber, filled with water, in which the pressure cell is sealed (similar to the pressure chambers used for calibration of the pore-pressure transducers).

Add an initial weight to the load cell or apply an initial pressure to the pressure cell.

Record the initial voltage (typically mV) value at the initial weight or pressure (this is the first calibration point).

Increase the weight or applied pressure from the initial value by the desired calibration interval (e.g. 1 kg or 50 kPa) and record the corresponding output voltage.

Repeat step 4 until the maximum desired calibration weight (i.e. force) or pressure is reached. Record the corresponding voltage for the different steps.

Once the maximum desired calibration force or pressure is reached, reverse the process until the initial force or pressure (or as close as possible) is reached. Reversing the process will allow the linearity and hysteresis to be assessed.

The recorded voltage values for each applied force or pressure is the calibration curve. An example of a typical load or pressure sensor calibration curve is shown in Figure .

The slope of the best-fit line through the calibration points is the calibration factor for the sensor (in Figure 6).

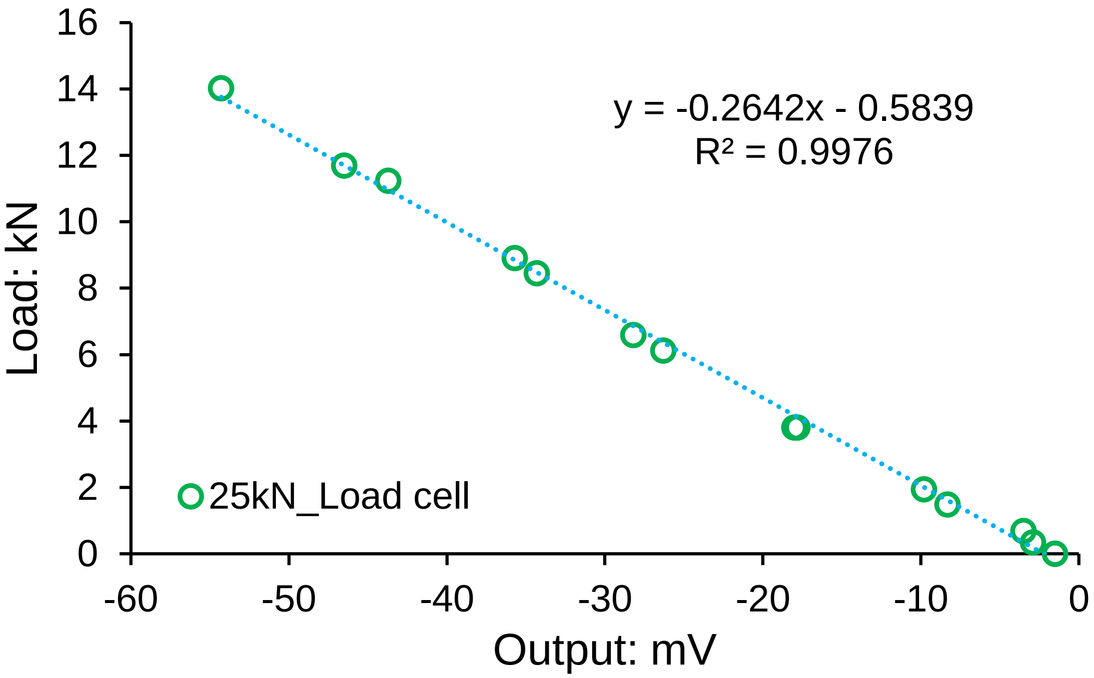


Figure 6: Typical load sensor calibration curve

4.4.2 Usage instruction

Always handle the sensors with care as they need to be used by other students as well and are expensive.

A minimum of one cycle, but preferably three, should be carried for a sensor. This will allow the linearity and hysteresis of the sensor to be comprehensively assessed.

When removing the pressure cells from the soil, do not pull on the wire. Carefully excavate to expose the pressure cell and gently remove it from the soil.

Be careful when you cut cable ties used to fix the sensor wire so that you do not accidentally cut a wire and damage the sensor.

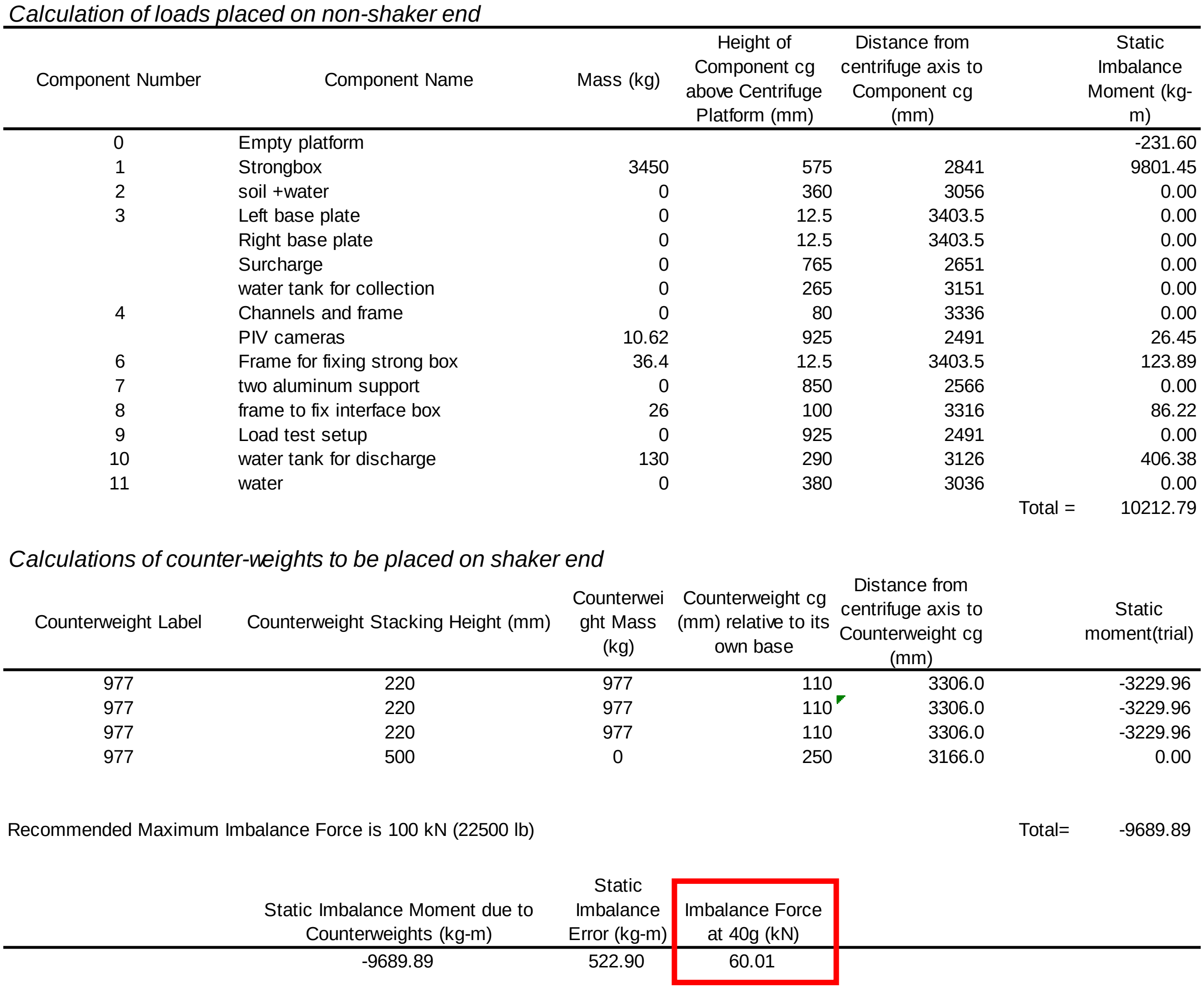
Clean the sensors thoroughly after use, especially when used in clay.

Always return the sensors to proper storage with one of the technicians after use.

5 Balance calculations

In standard procedures, the soil model, which forms the payload, is positioned on a swiveling platform at one end of the horizontal beam. To balance the mass of the model, a counterweight is placed on a similar swiveling platform at the opposite end of the beam. During each centrifuge test, these counterweights are adjusted to maintain equilibrium with the soil model being evaluated.

An example Excel spreadsheet is prepared for some of the tests conducted before and the users can employ the same format in their experiments. Please make sure that you get the Excel spreadsheet from the users or the engineer and understand it thoroughly prior to calculations of the imbalance in your tests. An example of this spreadsheet is shown in Figure 7. The most important point in the calculation of imbalance force is measuring the weight and center of gravity of the mass placed on the centrifuge platform. You have to make sure that the total imbalance force at the g-level of your experiment DO NOT exceed ±100 kN.



Calculation of loads placed on non-shaker end

Component Number	Component Name	Mass (kg)	Height of Component cg above Centrifuge Platform (mm)	Distance from centrifuge axis to Component cg (mm)		Static Imbalance Moment (kg-m)
0	Empty platform					-231.60
1	Strongbox	3450	575	2841		9801.45
2	soil +water	0	360	3056		0.00
3	Left base plate	0	12.5	3403.5		0.00
	Right base plate	0	12.5	3403.5		0.00
	Surcharge	0	765	2651		0.00
	water tank for collection	0	265	3151		0.00
4	Channels and frame	0	80	3336		0.00
	PIV cameras	10.62	925	2491		26.45
6	Frame for fixing strong box	36.4	12.5	3403.5		123.89
7	two aluminum support	0	850	2566		0.00
8	frame to fix interface box	26	100	3316		86.22
9	Load test setup	0	925	2491		0.00
10	water tank for discharge	130	290	3126		406.38
11	water	0	380	3036		0.00
					Total =	10212.79

Calculations of counter-weights to be placed on shaker end

Counterweight Label	Counterweight Stacking Height (mm)	Counterweight Mass (kg)	Counterweight cg (mm) relative to its own base	Distance from centrifuge axis to Counterweight cg (mm)		Static moment(trial)
977	220	977	110	3306.0		-3229.96
977	220	977	110	3306.0		-3229.96
977	220	977	110	3306.0		-3229.96
977	500	0	250	3166.0		0.00

Recommended Maximum Imbalance Force is 100 kN (22500 lb) Total= -9689.89

Static Imbalance Moment due to Counterweights (kg-m)	Static Imbalance Error (kg-m)	Imbalance Force at 40g (kN)
-9689.89	522.90	60.01

Figure 7. View of the Excel spreadsheet used for imbalance calculations in energy harvesting chamber test at 40g.