FLIQ
Experimental Verification of Shallow Foundation Performance under Earthquake-Induced Liquefaction

- Final Report -

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ABSTRACT

The present document reports the experimental procedures and the results obtained during the SERIES Project “FLIC”. The project focused on the seismic performance of square footings, resting on a stratified soil profile that is commonly encountered in the field, namely a thick liquefiable sand layer overlaid by a thin over-consolidated clay crust. The scope of the performed experiments was to verify the beneficial effect of the existence of the surficial non-liquefiable layer on the dynamic and post-shaking response of the footing. Furthermore, the experiments aimed at exploring whether this non-liquefiable layer allows for a viable performance-based design methodology for shallow foundations, without the need of implementing any soil treatment on the underlying liquefiable sand. For this purpose, different thicknesses H of the clay crust were parametrically used, varying from H=0.65 to 1.50B, with B being the footing’s width (equal to 3m in prototype scale).

Each test was performed in three stages. The centrifugal acceleration was initially raised to 50g, in steps of 10g, allowing adequate time for the consolidation of the clay layer. A harmonic excitation was consequently applied to the base of the equivalent shear-beam container. During this stage, excess pore pressures developed in the sand layer, resulting in the accumulation of seismic settlements of the footing. Immediately after the end of shaking and before the dissipation of excess pore pressures, the square footing was pushed down using a vertical actuator via a load cell, until bearing capacity failure, in order to measure the (degraded) post-shaking bearing capacity.

Keywords: Shallow foundations, liquefaction, settlements, bearing capacity, two-layered soil profile, centrifuge
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Notation

ACRONYMS

ACC       ACCelerometer
CDAQS     Centrifuge Data AcQuisition System
CAM-SAT   CAMbridge SATuration (system)
ESB       Equivalent Shear Beam (box)
LC        Load Cell
LL        Liquid Limit
LVDT      Linear Variable Differential Transformer
MEMS      Micro-Electro-Mechanical System (accelerometer)
NC        Normally Consolidated
OC        Over-Consolidated
OCR       Over-Consolidation Ratio
PI        Plasticity Index
PL        Plastic Limit
SAM       Stored Angular Momentum (actuator)

SYMBOLS

a_{max}  Maximum applied acceleration
B        Footing width
c_u      Undrained shear strength
C_u      Uniformity coefficient
D_{10}   Grain diameter at which 10% of the soil sample is finer than
D_{50}   Grain diameter at which 50% of the soil sample is finer than
D_r      Relative density
e        Void ratio
e_{min}   Minimum void ratio
e_{max}   Maximum void ratio
G_s      Specific mass of sand grains
H_{crust}  Clay crust thickness
H_{liq}  Liquefiable sand thickness
k        Permeability
\( K_o \)  Horizontal earth pressure coefficient
\( m \)  Mass
\( M \)  Slope of the Critical State Line in the \( p'-q \) space (Cam-Clay)
\( n \)  Specific volume (Cam-Clay)
\( N \)  Model scale factor in a centrifuge model
\( p' \)  Mean effective stress
\( q \)  Deviatoric stress
\( V \)  Volume
\( \Gamma \)  Specific volume of the Critical State Line at unit pressure (Cam-Clay)
\( \kappa \)  Slope of the swelling line in the \( e-\ln p' \) space (Cam-Clay)
\( \lambda \)  Slope of the virgin consolidation line in the \( e-\ln p' \) space (Cam-Clay)
\( \rho \)  Density
\( \rho_d \)  Dry density
\( \rho_s \)  Density of sand grains
\( \sigma^{v'} \)  Vertical effective stress
1. Introduction

1.1. RESEARCH PROJECT

The present Data Report concerns the centrifuge tests performed in the Schofield Centre of the Cambridge University Engineering Department (CUED), under the Transnational Access (TA) Use Agreement made on 03/02/2010 between the

*Foundation Engineering Laboratory of the National Technical University of Athens (NTUA)*

and

*Cambridge University Technical Services (CUTS).*

The TA Use Project FLIC, entitled

*“Experimental Verification of Shallow Foundation Performance under Earthquake – Induced Liquefaction”,*

was part of the “Seismic Engineering Research Infrastructures for European Synergies” (SERIES) Project, funded by the “7th Framework Program of the European Community for Research, Technological Development and Demonstration Activities” (Grant Agreement No. 227887 with the European Commission).

1.2. SCOPE OF WORK

Liquefiable soils are currently categorized by all seismic codes as extreme ground conditions, where construction of shallow foundations is essentially not allowed without prior soil treatment. Alternatively, the use of deep foundations becomes mandatory with or without soil treatment, an alternative that generally increases the cost of construction. Yet, the use of shallow foundations may be still viable in the presence of a sufficiently thick and shear resistant non-liquefiable soil crust (e.g. clay, dense or dry sand and gravel, improved soil) between the foundation and the
liquefiable subsoil. In order to consider the beneficial effect of such a soil crust, one must be able resolve the following design issues: (a) what is the degraded bearing capacity of the shallow foundation at the end of shaking (before any excess pore pressure dissipation), and (b) what are the corresponding, liquefaction-induced settlements?

Consequently, the project’s objective is to perform a series of centrifuge experiments simulating the seismic response (settlement accumulation and static bearing capacity degradation) of a square footing resting upon a two layer soil profile: a thin top layer of non-liquefiable clay crust overlaying a thick layer of liquefiable sand. The base excitation will be harmonic, while the main problem variable will be the thickness of the non-liquefiable soil crust.

The scope of work is the verification of the extensive theoretical research on performance-based design criteria for surface foundations resting upon liquefiable soils, previously carried out by the proposing team (Bouckovalas & Dakoulas, 2007, Karamitros, 2010). This research has been based upon fully coupled, dynamic, elastoplastic numerical analyses, with critical state modeling of soil element response, properly calibrated against laboratory test (cyclic triaxial and simple shear tests). Nevertheless, the end results of this research (design charts and multi-variable relations) have never been verified against well-controlled physical models, but only case-studies from the literature with less than adequate documentation.

As a result, the main objectives of this TA Use Project are:

1. The experimental verification of the beneficial effect of increasing crust thickness, as well as the existence of a critical thickness of the non-liquefiable soil crust, beyond which there are no liquefaction effects on the foundation performance.

2. The experimental verification of the design methodology (multi-variable relations and design charts of Bouckovalas & Dakoulas, 2007) for the computation of foundation settlement.

3. The experimental verification of the design methodology (multi-variable relations and design charts of Bouckovalas & Dakoulas, 2007) for the computation of the degraded (end of shaking) bearing capacity.
1.3. MODEL OUTLINE

In order to attain the foregoing objectives, the project requires the execution of the following three (3) dynamic centrifuge experiments:

1.3.1. Centrifuge Test #1: MEDIUM soil crust

Centrifuge Test #1 will explore the seismic response of a square footing with a prototype width $B=3m$, resting on the surface of a medium thickness clay crust ($H_{\text{crust}}=3m$) overlying liquefiable sand with $H_{\text{liq}}=13.5m$ thickness.

Testing will be performed in three stages:

a. The centrifugal acceleration will be raised to 50g, in steps of 10g, allowing adequate time for consolidation of the clay layer.

b. Twenty (20) uniform cycles of harmonic excitation, with a peak acceleration of $a_{\text{max}}=0.25g$ will be consequently applied at the base of the container.

c. The static axial load applied on the footing will be finally increased until failure, immediately after the end of shaking.

1.3.2. Centrifuge Test #2: THIN soil crust

Centrifuge Test #2 is similar with Test #1, only that the square footing will rest on the surface of a relatively thin clay crust ($H_{\text{crust}}=2m$), overlying a liquefiable sand layer with $H_{\text{liq}}=14.5m$. Except from the thicknesses of the clay and sand layers, all other testing parameters (footing dimensions, total soil thickness, excitation characteristics, footing size and bearing pressure, loading sequence) should remain the same as in Centrifuge Test #1, described above.

1.3.3. Centrifuge Test #3: THICK soil crust

Centrifuge Test #3 will finally explore the seismic response of a square footing, resting on the surface of a relatively thick clay crust ($H_{\text{crust}}=5.0m$), overlying a liquefiable sand layer with $H_{\text{liq}}=11.5m$. Except from the thicknesses of the clay and sand layers, all other testing parameters (footing dimensions, total soil thickness,
excitation characteristics, footing size and bearing pressure, loading sequence) should remain the same as in Centrifuge Test #1, described above.

The model configuration and instrument positions are presented in Figure 1.1, while the geometrical parameters considered in the performed centrifuge tests are summarized in Table 1.1.

![Model Configuration Diagram](image.png)

**Figure 1.1.** Typical model configuration.

**Table 1.1.** Geometrical parameters (in prototype scale).

<table>
<thead>
<tr>
<th>Test Number</th>
<th>B (m)</th>
<th>H&lt;sub&gt;crust&lt;/sub&gt; (m)</th>
<th>H&lt;sub&gt;liq&lt;/sub&gt; (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.0</td>
<td>3.0</td>
<td>13.5</td>
</tr>
<tr>
<td>2</td>
<td>3.0</td>
<td>2.0</td>
<td>14.5</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>5.0</td>
<td>11.5</td>
</tr>
</tbody>
</table>
2. Facilities

2.1. THE PHILIP TURNER CENTRIFUGE INSTALLATION

Dynamic centrifuge experiments in the Schofield centre are carried out in its 10m beam centrifuge (Figure 2.1), named after the engineer P.W. Turner, who designed it in the early 1970’s (Schofield, 1980).

The machine has a 150g-tonne capacity, achieving a maximum centrifugal acceleration of approximately 130g at 4.125m radius. Dynamic centrifuge tests are normally carried out at centrifugal accelerations in the range of 50 to 80g. The tests presented herein were performed at 50g.

The centrifuge beam is mounted on a central spindle including a series of hydraulic, power and data slip-rings that allow in-flight control of actuators, instruments powering and data acquisition. Even though models can be carried at both ends of the arm, in the dynamic tests described herein, a swinging platform carrying the model and the actuator was installed on the beam’s “blue end” (Figure 2.2), while the required counterweight was attached to the “red end” (Figure 2.3).

![The Philip Turner Centrifuge](image.jpg)

**Figure 2.1.** The Philip Turner Centrifuge.
Figure 2.2. The centrifuge beam’s “blue end”, carrying the model and the actuator.

Figure 2.3. The centrifuge beam’s “red end”, carrying the counterweight.
2.2. SAM ACTUATOR

Earthquake excitations applied in the centrifuge tests are generated by the Stored Angular Momentum (SAM) Actuator (Figure 2.4 and Figure 2.5), developed at Cambridge University (Madabhushi et al., 1998). The SAM actuator can fire successive earthquakes at different amplitudes, durations and frequencies. In the tests presented herein, it was used to produce a single nearly sinusoidal motion, of known duration and controlled magnitude.

The input motion is generated by the energy stored in a pair of flywheels. The angular velocity of the fly-wheel determines the frequency of the motion transmitted to the base of the model. The motion is transmitted through a shaft via a fast acting clutch which triggers and stops the earthquake excitation. The magnitude of the earthquake excitation can be controlled by altering the pivot point of the lever.

Figure 2.6 illustrates one of the earthquake simulations generated as part of this research project, while Table 2.1 summarizes the capabilities of the SAM actuator.

Figure 2.4. The SAM Actuator (front).
Figure 2.5. The SAM Actuator (back).

Figure 2.6. Typical input motion generated by the SAM actuator: prototype acceleration time-history and fourier spectrum.

Table 2.1. SAM actuator characteristics (Haigh, 2002)

<table>
<thead>
<tr>
<th>Characteristics of input motion</th>
<th>Model scale</th>
<th>Prototype scale (at 50g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g-level</td>
<td>up to 100g</td>
<td>-</td>
</tr>
<tr>
<td>Peak acceleration (g)</td>
<td>up to 20</td>
<td>up to 0.4</td>
</tr>
<tr>
<td>Predominant frequency (Hz)</td>
<td>10 to 50</td>
<td>0.2 to 1.0</td>
</tr>
<tr>
<td>Duration (s)</td>
<td>0.05 to 2.00</td>
<td>2.5 to 100</td>
</tr>
<tr>
<td>No. consecutive earthquakes</td>
<td>&gt; 10&lt;sup&gt;(a)&lt;/sup&gt;</td>
<td>&gt; 10&lt;sup&gt;(a)&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>(a)</sup> Maximum number of consecutive earthquakes depending on the capacity of the accumulator used and the volume loss of fluid occurring in each earthquake fired.
2.3. EQUIVALENT SHEAR BEAM BOX

The tests were performed using an Equivalent Shear Beam (ESB) container shown in Figure 2.7 and Figure 2.8. The fundamental design principles of ESB containers were introduced by Zeng & Schofield (1996). More specifically, the box used herein consists of a series of alternating aluminium and rubber rings, whose geometry and stiffness were chosen so that the walls of the box have the same stiffness and natural frequency of vibration as an average soil placed inside (Teymur & Madabhushi, 2003). It should be taken into account, though, that during the investigation of liquefaction-related phenomena, the soil stiffness is cycle-dependent and consequently, it can not be matched by the stiffness of walls, which remains unchanged. Thus, boundary effects may exist, at later stages of the test, when liquefaction spreads wide over the soil volume.

The ESB container used as part of this research has internal dimensions of 673×253×427 mm$^3$ (L×B×H) and a weight of 101.5Kgr. A plate is placed at the base of the box to connect the container with the SAM actuator.

![Figure 2.7. The ESB box (inside).](image)
It must be stated here, that serious problems were faced during the preparation of the first test, regarding the leak-tightness of the ESB box, as significant leakage occurred between the rings. More specifically, during the saturation procedure, with the box being under vacuum, air entered inside the box, resulting in the formation of large air bubbles in the model pore fluid and consequently disturbing the model’s homogeneity.

In order to minimize this effect, previous researchers had covered both sides of the container’s walls with a plastic-type sealant (Figure 2.9). This sealant reduced the box’s inside plan area to 169,742mm² (from 673mm×253mm=170,269mm²).
However, during the first test of this project, it was found that the sealant had lost contact with the box walls, thus being unable to ensure leak-tightness. Hence, to improve the container’s performance, the old sealant was carefully removed after the end of the first test and the box was re-sealed, using aquarium silicone. Furthermore, both sides of the container’s walls were covered with three layers of a synthetic plastic coating, manufactured by Performix Plasti Dip International, which was applied by spraying.

The above procedure had a beneficial effect on the stability of the saturation procedure during the second test. Nevertheless, air bubbles still entered inside the box, while the box was under vacuum, resulting in settlement of the sand layer. Therefore, further improvements were made prior to the preparation of the third test. More specifically, the box was covered with a new plastic-type sealant, applied by painting. Furthermore, before sand pouring, the lateral boundaries of the box were covered on the inside, using cling film. At the bottom, the cling film was attached to the base of the box using metal tape, while at the top, it was only temporarily supported until the sand was poured, and subsequently held in place by the sand layer (Figure 2.10). This way, any air entering the box through its walls during the saturation procedure, would travel upwards, through the box walls – cling film interface, and would be then removed by the vacuum pump, which is connected to the top of the box. As described in the following, this modification significantly improved the stability of the saturation procedure, minimizing any disturbance to the model’s homogeneity.
**Figure 2.10.** Cling film used to seal the ESB Box walls during the third test.
2.4. DATA ACQUISITION SYSTEM

Data acquisition systems play a key role in centrifuge testing, especially when using the SAM actuator to investigate dynamic problems. Namely, the data acquired by the instruments can be seriously affected by noise introduced by SAM-generated electrical interference when being transmitted through the slip-rings. To avoid such effects, a special in-house data acquisition system, CDAQS (Centrifuge Data AcQuisition System), was devised in the Schofield Centre, to ensure the quality of recorded centrifuge data when carrying out dynamic experiments. This system allows a maximum of 16 accelerometers and 16 other transducers to be acquired simultaneously at a maximum sampling rate of 5 kHz.

CDAQS is a two-module data acquisition system, with module CD 198 flying with the centrifuge package and module CD_IF 198 sitting in the control room. Ruggedized CD 198 acquisition module digitizes the instruments readings onboard and stores the digital data in 2-Mb RAM.

The instruments are linked to the acquisition module via two (2) junction boxes, which have been previously set-up to the appropriate gain and excitation voltage. Hardware filtering can also be applied with the junction boxes. The CD_IF 198 interface module, which is connected to a central computer (running a terminal program) in the control room, uploads the data, in digital form, from the acquisition module, using an RS-485 link through 8 data slip rings. The CDAQS system capabilities are summarized in Table 2.2.
Table 2.2. Capabilities of CDAQS data acquisition system (modified from Haigh, 2002)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum number of channels</td>
<td>32</td>
</tr>
<tr>
<td>Simultaneous sampling rate (Hz)</td>
<td>4 to 5000</td>
</tr>
<tr>
<td>Sample resolution (bit)</td>
<td>16</td>
</tr>
<tr>
<td>Input sensitivity (V)</td>
<td>±10</td>
</tr>
<tr>
<td>Data buffer capacity (samples)</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Communications Duplex</td>
<td>RS485</td>
</tr>
<tr>
<td>Communications rate</td>
<td>19200 baud</td>
</tr>
<tr>
<td>Power required (V)</td>
<td>±15 , 0</td>
</tr>
<tr>
<td>Power consumption (W)</td>
<td>50</td>
</tr>
<tr>
<td>Trigger source</td>
<td>5V pulse</td>
</tr>
<tr>
<td>Minimum slip-rings requirements</td>
<td>8</td>
</tr>
<tr>
<td>Size (mm³)</td>
<td>120×225×100</td>
</tr>
<tr>
<td>Weight (Kgr)</td>
<td>2.4</td>
</tr>
<tr>
<td>Rating</td>
<td>IP65</td>
</tr>
</tbody>
</table>

Note that, although CDAQS succeeds in preventing the detrimental effects of electrical noise, it has the following limitations:

a) The sporadic crash of the terminal program, often due to power spikes in the electric system, may result in permanent data loss. Such a crash occurred during the consolidation procedure of the second test, resulting in loss of the relevant data. Fortunately, instrument readings had been taken by hand, at 5 to 10 min time intervals, thus allowing an overall evaluation of the model’s performance during this phase.

b) The amount of data acquired is limited by the CD 198 RAM capacity. Therefore, the following procedure had to be followed to acquire all necessary data:
   - First, the swing-up data were collected at a slow acquisition rate of 3 Hz. In parallel, instrument readings were taken by hand, at time intervals of 5 to 10 minutes. At the end of the consolidation phase, these data were uploaded to the computer terminal. No data were recorded during the uploading procedure.
At 50g centrifugal acceleration, a pre-defined data acquisition task was automatically triggered together with the earthquake excitation and the required data were recorded for 4sec, at a fast rate of 2kHz.

Immediately after the end of the above task (indicated on the screen of the computer terminal), a pre-defined and relatively slow acquisition rate (10Hz) task was manually imported, for about 100-150sec.

c) It is not possible to avoid a lag-time between each two successive tasks of data acquisition, during which no data is acquired. This problem is solved by adding the data files corresponding to the earthquake and post-earthquake response, after estimating the lag-time through the process illustrated in Figure 2.11.

![Figure 2.11](image.png)

**Figure 2.11.** Amplified plot of the experimental data recorded at different rates during the earthquake and post-earthquake data acquisition tasks, used to estimate the lag-time between successive changes in data acquisition rates.

d) The final limitation concerns the low data transmission speed of the RS-485 link. More specifically, uploading a data file using all the RAM space available can take more than 40 minutes. This results in a significant lag-time with no data acquisition, between the end of consolidation and the triggering of the seismic shaking. Nevertheless, this period is of minor importance for the entire test and consequently this last limitation results only to a time delay.
3. **Materials**

3.1. **SAND: LEIGHTON-BUZZARD FRACTION E**

The sand used for the models is dry Leighton Buzzard Fraction E fine silica sand henceforth termed Fraction-E sand.

3.1.1. **Selection Criteria**

Selecting of Fraction-E sand as the model sand took into account the following aspects:

- The most essential feature for the selection of the model sand was its susceptibility to liquefaction. Figure 3.1 shows that the grain size distribution of various batches of Fraction-E sand falls safely within the boundaries used to identify liquefiable soils (Tsuchida, 1970).

- The sand used in the tests was supplied by David Ball Group plc (Cambridge) and is industrially normalized, thus ensuring the similarity of the different batches of sand used in different experiments. More specifically, Fraction-E sand is extracted from the Lower Green formation of the Leighton Buzzard sand deposit, which was formed in a shallow sea that covered Bedfordshire more than 100 million years ago, as a result of the accumulation of sediments washed by local rivers. The natural sand has been washed, dried and graded to eliminate any silt, clay or organic matter and to conform to BS-EN-ISO-9002:1994 (David Ball, 2004).

- The sand is relatively uniform ($C_u = D_{60}/D_{10} \approx 2$), which ensures that no significant segregation will occur during the preparation of models using the air pluviation technique.
• The sand is relatively fine, which minimizes the detrimental scale effects that may possibly influence the behavior of centrifuge models.

• The sand’s laboratory behavior has been the subject of previous research (e.g. Jeyatharan, 1991).

![Grain size distribution of Fraction-E sand and boundaries for liquefiable soils (Tsuchida, 1970).](image)

**Figure 3.1.** Grain size distribution of Fraction-E sand and boundaries for liquefiable soils (Tsuchida, 1970).

### 3.1.2. Physical Properties

The main physical properties of Fraction-E sand are listed in Table 3.1. It is a light-brown natural and uncrushed silica sand, free from any silt, clay or organic matter components. It contains rounded and sub-angular particles, with a nominal grain size $D_{50}$ of 0.14mm and a specific gravity of 2.65Mgr/m$^3$.

**Table 3.1.** Basic properties of LBE sand

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{50}$ (mm)</td>
<td>0.12$^1$</td>
</tr>
<tr>
<td>$D_{10}$ (mm)</td>
<td>0.067-0.095$^1$</td>
</tr>
<tr>
<td>Roundness</td>
<td>0.30</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.81</td>
</tr>
<tr>
<td>$G_s$</td>
<td>2.65</td>
</tr>
<tr>
<td>$e_{\min}$</td>
<td>0.613$^1$</td>
</tr>
<tr>
<td>$e_{\max}$</td>
<td>1.014$^1$</td>
</tr>
</tbody>
</table>

$^1$ After Coelho (2007)
The sand’s permeability \( k \) may be fitted by Equation (3.1), originally proposed by Taylor (1948), using a coefficient \( C = 4 \times 10^{-4} \text{m/sec} \) (Jeyatharan, 1991). However, permeability may increase significantly once piping occurs in the tests.

\[
k = C \frac{e^3}{1+e}
\] (3.1)

Finally, Jeyatharan (1991) estimates the Critical State friction angle of Fraction-E sand, using data from drained and undrained triaxial compression tests, as 32°.

### 3.2. KAOLIN CLAY GRADE E

The clay used in the tests was over-consolidated Grade E Kaolin Clay, supplied by the Richard Baker Harrison Group.

#### 3.2.1. Physical Properties

Grade E Kaolin Clay has the Atterberg limits presented in Table 3.2, as quoted by Elmes (1985). In the Casagrande chart, it may be described as clayey silt of medium to high plasticity. Elmes also measured the specific gravity of the Kaolin particles, which was found equal to \( G_s = 2.6 \text{Mg}/\text{m}^3 \).

**Table 3.2.** Atterberg limits of Grade E Kaolin Clay.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit LL (%)</td>
<td>51</td>
</tr>
<tr>
<td>Plastic Limit PL (%)</td>
<td>30</td>
</tr>
<tr>
<td>Plasticity Index PI (%)</td>
<td>21</td>
</tr>
</tbody>
</table>

Various relations have been proposed for the computation of kaolin clay’s permeability, most of which involve a power equation relationship in terms of the corresponding void ratio. More specifically, Potter (1996) examined the experimental data from Elmes (1984) & Gronow et al. (1988), for 1-D normally consolidated E-grade kaolin clay, and fitted the following power equation curve:
k = 1.90 \times 10^{-9} \times e^{3.77} \quad (3.2)

Potter (1996) also back-calculated a similar relationship from the results of 5 centrifuge tests, at higher void ratios than those considered in the previous work, and the expression she proposed is:

k = 3.10 \times 10^{-9} \times e^{6.8} \quad (3.3)

A comparison of the permeabilities calculated from various expressions is given in Table 3.3.

### Table 3.3. E-Grade Kaolin Clay Permeability.

<table>
<thead>
<tr>
<th>Void ratio (e)</th>
<th>Permeability coefficient ((\times 10^{-9} \text{ m/sec})) according to:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>3.78</td>
</tr>
<tr>
<td>1.6</td>
<td>11.18</td>
</tr>
</tbody>
</table>

The undrained shear strength \(c_u\) of kaolin clay may be estimated from the following empirical equation:

\[ c_u = 0.18 \sigma'_v \text{OCR}^{0.8} \quad (3.4) \]

where OCR is the over-consolidation ratio.

This formula is based on Equations (3.5) and (3.6), proposed by Ladd et al (1977) and Skempton (1948, 1957), respectively:

\[ (c_u/\sigma'_v)_{NC} = (c_u/\sigma'_v)_{OC} \text{OCR}^{0.8} \quad (3.5) \]

\[ (c_u/\sigma'_v)_{NC} = 0.11 + 0.0037 I_P \quad (3.6) \]

where \((c_u/\sigma'_v)_{NC}\) and \((c_u/\sigma'_v)_{OC}\) are the undrained shear strength to vertical effective stress ratios of normally consolidated and over consolidated clays, respectively, while \(I_P\) is the plasticity index.

Table 3.4 summarizes the Cam-clay parameters for the E-Grade Kaolin, as estimated by Elmes (1984), Evans (1994) and Potter (1996). Cam-clay parameter values for the E-Grade Kaolin were initially determined by Elmes. Evans compared the results of
Elmes (1984) for speswhite clay with those of Clegg (1981), which were closer to the commonly accepted values, and used this comparison to factor Elmes results for E-grade Kaolin clay, accordingly. Potter also determined a value for the parameter $\Gamma_{1D}$ based on the work of Elmes (1984). She assumed $K_o=0.67$ and used the Elmes result so that the specific volume for one-dimensionally consolidated E-grade kaolin at $\sigma'_v=100$ kPa is $v=2.183$. It is reminded that the specific volume $v$ is the volume composed by unit volume of soil particles with their surrounding voids, and may be correlated to the void ratio $e$, using the following equation:

$$v=1+e$$  \hspace{1cm} (3.7)

**Table 3.4.** Cam-clay parameter values for E-Grade Kaolin Clay.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>0.124</td>
<td>0.21</td>
<td>0.124</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.02</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{iso}$</td>
<td>2.65</td>
<td>2.22</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{1D}$</td>
<td>-</td>
<td>2.16</td>
<td>2.723</td>
</tr>
<tr>
<td>$\Gamma_{cs}$</td>
<td>-</td>
<td>2.04</td>
<td>-</td>
</tr>
<tr>
<td>$M$</td>
<td>1.05</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3.3. MODEL FOOTING

The square footing that was used in the tests was made of steel (density $\rho=7.850$ Mgr/m$^3$). Its dimensions were $60\times60\times25$ mm$^3$ while its mass was equal to 0.690 Kgr. Hence, at 50-g centrifugal acceleration, it applied an average bearing pressure of 94 KPa (in prototype scale).
4. **Instrumentation and Calibration**

4.1. **INSTRUMENT POSITIONS**

A total of 27 transducers were used in each test, as described below:

- **11 Accelerometers**: 8 accelerometers were placed within the sand layer, namely: 1 near the base of the model, 3 at different depths in the free-field, 3 at different depths along the footing’s axis and 1 under the footing’s edge. Furthermore, 1 accelerometer was placed on the free-field surface of the clay layer and another 2 were attached to the bottom and to the top of the ESB box, respectively. All accelerometers were placed so as to measure the developing horizontal accelerations.

- **9 Pore Pressure Transducers (PPTs)**: 8 PPTs were placed within the sand layer, namely 1 near the base of the model, 3 at different depths in the free-field, 3 at different depths underneath the footing’s axis and 1 under the footing’s edge. In addition, 1 PPT was placed in the middle of the clay layer, in the free-field.

- **2 Linear Variable Differential Transformers (LVDTs)**: The LVDTs were placed on the clay’s surface, so as to measure free-field settlements at the two opposite sides of the footing.

- **1 Potentiometer**: The potentiometer was placed on a gantry, above the footing, and was consequently attached to one of the footing’s corners, so as to measure its settlements.

- **3 Micro-Electro-Mechanical System (MEMS) accelerometers**: The MEMS were attached to the footing’s corners, so as to measure its horizontal, transverse and vertical acceleration.
1 Load Cell (LC): The load cell was attached to the actuator for vertical load application, in order to measure the footing’s post-shaking bearing capacity.

4.1.1. Centrifuge Test #1

The instrument coordinates for Centrifuge Test #1 are presented in Table 4.1. All coordinates are in model scale. Axis x is the horizontal axis, in the direction of motion, y is the transverse horizontal axis and z is the vertical axis, pointing from the bottom and upwards. The instrument locations are also shown in Figure 4.1. To add clarity, Figure 4.2 and Figure 4.3 show plan views of the instrument positions at z=250mm and at the model’s surface, respectively.

Note that the above coordinates are the ones considered in the initially planned configuration. The final instrument positions during testing had to be slightly changed, due to a number of reasons (e.g. difficulties in placing the instruments, sand settlement during the placement of the overlying clay layer), which are thoroughly described in the following Chapter. The final instrument coordinates are also listed (in parentheses) in Table 4.1.
Table 4.1. Instrument coordinates (in model scale) for Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Number</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>z (mm)</th>
</tr>
</thead>
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<td>505</td>
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<td>90 (83)</td>
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<td>ACC 5</td>
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<td>127</td>
<td>180 (167)</td>
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<tr>
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<td>336 (344)</td>
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<td>376 (389)</td>
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<td>250 (231)</td>
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<tr>
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<td>505 (443)</td>
<td>127</td>
<td>330 (310)</td>
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<tr>
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<td>0</td>
<td></td>
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<tr>
<td>ACC 11</td>
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Figure 4.1. Instrument locations (in model scale) for Centrifuge Test #1.

Figure 4.2. Instrument locations (in model scale): plan view at z=250mm.

Figure 4.3. Instrument locations (in model scale): plan view at the model’s surface.
4.1.2. Centrifuge Test #2

The instrument coordinates for Centrifuge Test #2 are presented in Table 4.2, while the corresponding instrument locations are shown in Figure 4.4.

Table 4.2. Instrument coordinates (in model scale) for Centrifuge Test #2.

<table>
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<th>z (mm)</th>
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Figure 4.4. Instrument locations (in model scale) for Centrifuge Test #2.
4.1.3. Centrifuge Test #3

The instrument coordinates for Centrifuge Test #3 are presented in Table 4.3, while the corresponding instrument locations are shown in Figure 4.5 and Figure 4.6.

Table 4.3. Instrument coordinates (in model scale) for Centrifuge Test #3.

<table>
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<tr>
<th>Instrument</th>
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<th>x (mm)</th>
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<th>z (mm)</th>
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<td>127</td>
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<td>97</td>
<td>355 (347)</td>
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Figure 4.5. Instrument locations (in model scale) for Centrifuge Test #3.

Figure 4.6. Instrument locations (in model scale): plan view at the model’s surface.
4.2. ACCELEROMETERS

Seismic accelerations were recorded with miniature piezoelectric accelerometers (A23-S & TS), manufactured by D.J. Birchall Ltd, which rely on the piezoelectric effect of quartz to generate an electrical output proportional to the acceleration. The instruments are less than 20mm in length and 10mm in diameter, they weight about 5gr, have a resonant frequency of 50kHz and perform linearly for a wide range of temperatures (-25 to 100º) and frequencies (1 to 1,000Hz) (Birchall, 2002). The response is poor at very low frequencies, which may limit the use of recorded accelerations to calculate displacements (after double integration).

The accelerometers were calibrated before each test using a Brüel & Kjær’s calibrator (Figure 4.7), which excites the instrument with a sinusoidal input acceleration with amplitude of ±1g. The instrument readings corresponding to the minimum, maximum and average applied acceleration were acquired (in Volts), using a data logger with the software Dasylab 9.0. In this way, a constant calibration factor (C.F.) was obtained, assuming a linear response for the relevant acceleration range. The intercept of the determined linear function with the acceleration axis, hereafter denoted as acceleration offset, was also obtained.

Finally, note that all the accelerometers that were placed within the saturated sand and clay layers had been previously sealed with wax.
Figure 4.7. Accelerometer calibrator.

Figure 4.8. Accelerometer junction box.
4.2.1. Centrifuge Test #1

Starting with Centrifuge Test #1, Figure 4.9 presents the linear variation of the accelerometers output voltage with the applied input acceleration, while the corresponding calibration factors are listed in Table 4.4. This table also presents the numbers of the junction box channels, where each instrument was connected. Note that the junction box (Figure 4.8) used during the calibration procedure was the same one used for the centrifuge test.

Table 4.4. Accelerometer calibration factors for Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Accelerometer</th>
<th>Description</th>
<th>Calibration Factor (g/Volt)</th>
<th>Offset (g)</th>
</tr>
</thead>
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<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8838</td>
<td>ACC 6: Footing axis – high</td>
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<td>8</td>
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<td>ACC 2: Footing axis – low</td>
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Figure 4.9. Accelerometer calibration for Centrifuge Test #1.
4.2.2. Centrifuge Test #2

Figure 4.10 presents the linear variation of the accelerometers output voltage with the applied input acceleration, for Centrifuge Test #2. The corresponding calibration factors are listed in Table 4.5.

Table 4.5. Accelerometer calibration factors for Centrifuge Test #2.

<table>
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<th>Junction Box Channel</th>
<th>Accelerometer</th>
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<th>Offset (g)</th>
</tr>
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<td>0.0262</td>
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<tr>
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<td>7698</td>
<td>ACC 10: ESB Box – bottom</td>
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<td>0.0178</td>
</tr>
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<td>4</td>
<td>8932</td>
<td>ACC 3: Free-field – low</td>
<td>6.5724</td>
<td>0.0057</td>
</tr>
<tr>
<td>5</td>
<td>8858</td>
<td>ACC 2: Footing axis – low</td>
<td>6.5145</td>
<td>0.0122</td>
</tr>
<tr>
<td>6</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8883</td>
<td>ACC 4: Footing axis – middle</td>
<td>6.5402</td>
<td>0.0146</td>
</tr>
<tr>
<td>9</td>
<td>10190</td>
<td>ACC 5: Free-field – middle</td>
<td>5.9207</td>
<td>0.0087</td>
</tr>
<tr>
<td>10</td>
<td>8829</td>
<td>ACC 6: Footing axis – high</td>
<td>6.9203</td>
<td>0.0035</td>
</tr>
<tr>
<td>11</td>
<td>8859</td>
<td>ACC 7: Edge of footing</td>
<td>6.7159</td>
<td>0.0034</td>
</tr>
<tr>
<td>12</td>
<td>8895</td>
<td>ACC 8: Free-field – high</td>
<td>6.8259</td>
<td>-0.0005</td>
</tr>
<tr>
<td>13</td>
<td>10157</td>
<td>ACC 11: ESB Box – top</td>
<td>6.1824</td>
<td>0.0097</td>
</tr>
<tr>
<td>14</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.10.  Accelerometer calibration for Centrifuge Test #2.
4.2.3. Centrifuge Test #3

Figure 4.11 presents the linear variation of the accelerometers output voltage with the applied input acceleration, for Centrifuge Test #3. The corresponding calibration factors are listed in Table 4.6.

Table 4.6. Accelerometer calibration factors for Centrifuge Test #3.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Accelerometer</th>
<th>Description</th>
<th>Calibration Factor (g/Volt)</th>
<th>Offset (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8858</td>
<td>ACC 1: Footing axis - bottom</td>
<td>6.9276</td>
<td>0.0224</td>
</tr>
<tr>
<td>3</td>
<td>8888</td>
<td>ACC 2: Footing axis - low</td>
<td>6.8633</td>
<td>-0.0135</td>
</tr>
<tr>
<td>4</td>
<td>7340</td>
<td>ACC 3: Free-field - low</td>
<td>6.7340</td>
<td>0.0162</td>
</tr>
<tr>
<td>5</td>
<td>8827</td>
<td>ACC 4: Footing axis - middle</td>
<td>7.6893</td>
<td>0.0231</td>
</tr>
<tr>
<td>6</td>
<td>8895</td>
<td>ACC 5: Free-field - middle</td>
<td>6.5811</td>
<td>0.0270</td>
</tr>
<tr>
<td>7</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8829</td>
<td>ACC 6: Footing axis - high</td>
<td>7.0077</td>
<td>-0.0222</td>
</tr>
<tr>
<td>9</td>
<td>8904</td>
<td>ACC 7: Edge of footing</td>
<td>6.7911</td>
<td>0.0025</td>
</tr>
<tr>
<td>10</td>
<td>8836</td>
<td>ACC 8: Free-field - high</td>
<td>7.6746</td>
<td>0.0082</td>
</tr>
<tr>
<td>11</td>
<td>8894</td>
<td>ACC 9: Clay surface</td>
<td>6.8143</td>
<td>0.0200</td>
</tr>
<tr>
<td>12</td>
<td>10190</td>
<td>ACC 10: ESB Box - bottom</td>
<td>5.8823</td>
<td>0.0118</td>
</tr>
<tr>
<td>13</td>
<td>10223</td>
<td>ACC 11: ESB Box - top</td>
<td>5.9524</td>
<td>0.0417</td>
</tr>
<tr>
<td>14</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>CHANNEL NOT USED</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.11. Accelerometer calibration for Centrifuge Test #3.
4.3. MEMS ACCELEROMETERS

Horizontal and vertical acceleration of the footing were measured with single-axis, high-g MEMS accelerometers manufactured by Analog Devices. These devices have a resonant frequency of about 24 kHz, a maximum error of 5% while their dimensions are 5mm x 5mm x 2mm. They can measure both dynamic (vibration) and static (gravity) acceleration.

No calibration was performed for the MEMS and data processing was based on their factory calibration factors. More specifically, the calibration factor for the 120-g capacity MEMS that were used to measure the footing’s vertical acceleration is \( CF=18.1818 \text{g/Volt} \). The footing’s horizontal motion was measured with two 35-g capacity MEMS, which feature a calibration factor of \( C.F.=55.5555 \text{g/Volt} \).

The MEMS were attached to the footing with super-glue. It should be noted that before the performance of the second and third test, MEMS accelerometers were also covered with an epoxy adhesive, for sealing and protection. Figure 4.12 shows the sealed MEMS accelerometers attached to the footing, before execution of the second test.

![Figure 4.12. MEMS accelerometers attached to the footing prior to the test.](image)

4.4. PORE PRESSURE TRANSDUCERS

Miniature 700-kPa-range PDCR-81 PPTs (Figure 4.13) manufactured by Druck Ltd were placed in the soil to measure fluid-pore-pressure variations during testing, through a strain-gauged silicon diaphragm that deflects under pressure. Note that the
PPT used to measure pore pressures in the clay layer, in the third test, had a 100kPa range.

All these transducers are about 11mm in length and 7mm in diameter, they weight about 10g and work accurately under a wide frequency and temperature range (Druck, 2002).

![PPT diagram]

**Figure 4.13.** Druck PDCR-81 PPTs

To protect the fragile membrane of the PPTs placed in the sand layer, the entrance of the transducer is covered by a bronze porous stone, which is removed and cleaned between tests. A high air-entry filter with smaller pore diameter was used for the PPT that was placed in the clay layer, so that the silicon diaphragm is protected from clay particles. In this particular case, the filter was attached to the PPT’s casing using superglue, while a sealant was applied above the interface between the filter and its casing.

Calibration of the PPTs was carried out in the air pressure chamber, shown in Figure 4.14 and schematically illustrated in Figure 4.15. This chamber allows both positive and negative pressures to be applied to the PPTs. The calibration factor was computed by measuring the electric output for different applied pressures.

PPTs placed in the sand layer were subjected to positive pressures in the range between 0 and 400kPa, both in loading and in unloading. As far as the PPT placed in the clay is concerned, it was subjected to suction, up to about -75KPa.

Note that a special procedure was also followed for the saturation of the porous stone of this PPT. More specifically, the chamber was first vacuumed to a negative pressure of -100KPa. Then, it was filled with de-aired water and the water pressure was increased to about 200KPa. The PPT was consequently left in the chamber for about one day. During this period, the chamber pressure was cycled periodically from high
positive to low negative values, as it has been proposed by Ridley (1993), in order to reduce the time required for saturation. Note that, in the third test, where a 100KPa-range PPT was used, the pressure was cycled from -75KPa to 75KPa.

**Figure 4.14.** Air pressure chamber used for the simultaneous calibration of eight PPTs.

**Figure 4.15.** Air pressure chamber used for the simultaneous calibration of eight PPTs.
4.4.1. Centrifuge Test #1

The variation of the output voltage with applied pressure, for the PPTs used in Centrifuge Test #1 is presented in Figure 4.16, while the corresponding calibration factors are listed in Table 4.7.

Table 4.7. PPT calibration factors for Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>PPT</th>
<th>Description</th>
<th>Calibration Factor (KPa/Volt)</th>
<th>Offset (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11065</td>
<td>PPT 3: Footing axis – low</td>
<td>39.92</td>
<td>14.596</td>
</tr>
<tr>
<td>2</td>
<td>11267</td>
<td>PPT 6: Free-field – high</td>
<td>40.30</td>
<td>-32.173</td>
</tr>
<tr>
<td>3</td>
<td>11263</td>
<td>PPT 9: Clay</td>
<td>35.90</td>
<td>1.755</td>
</tr>
<tr>
<td>4</td>
<td>10950</td>
<td>PPT 1: Free-field – base</td>
<td>39.35</td>
<td>48.528</td>
</tr>
<tr>
<td>5</td>
<td>6797</td>
<td>PPT 8: Footing axis – high</td>
<td>37.49</td>
<td>-34.361</td>
</tr>
<tr>
<td>6</td>
<td>11269</td>
<td>PPT 2: Free-field – low</td>
<td>39.80</td>
<td>34.857</td>
</tr>
<tr>
<td>7</td>
<td>11264</td>
<td>PPT 5: Footing axis – middle</td>
<td>40.15</td>
<td>7.227</td>
</tr>
<tr>
<td>8</td>
<td>10948</td>
<td>PPT 7: Edge of footing</td>
<td>39.84</td>
<td>-17.405</td>
</tr>
<tr>
<td>9</td>
<td>11059</td>
<td>PPT 4: Free-field – middle</td>
<td>41.76</td>
<td>20.128</td>
</tr>
</tbody>
</table>
Figure 4.16. PPT calibration for Centrifuge Test #1.
4.4.2. Centrifuge Test #2

The variation of the PPT’s output voltage with the applied pressure, for the PPTs used in Centrifuge Test #2 is presented in Figure 4.17. The corresponding calibration factors are listed in Table 4.8.

Table 4.8. PPT calibration factors for Centrifuge Test #2.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>PPT</th>
<th>Description</th>
<th>Calibration Factor (KPa/Volt)</th>
<th>Offset (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11062</td>
<td>PPT 4: Free-field – middle</td>
<td>40.88</td>
<td>-78.422</td>
</tr>
<tr>
<td>2</td>
<td>11267</td>
<td>PPT 8: Footing axis – high</td>
<td>39.92</td>
<td>-35.017</td>
</tr>
<tr>
<td>3</td>
<td>11263</td>
<td>PPT 9: Clay</td>
<td>40.33</td>
<td>0.342</td>
</tr>
<tr>
<td>4</td>
<td>11262</td>
<td>PPT 2: Free-field – low</td>
<td>39.33</td>
<td>2.131</td>
</tr>
<tr>
<td>5</td>
<td>6797</td>
<td>PPT 5: Footing axis – middle</td>
<td>37.03</td>
<td>-38.807</td>
</tr>
<tr>
<td>6</td>
<td>11260</td>
<td>PPT 3: Footing axis – low</td>
<td>39.34</td>
<td>33.768</td>
</tr>
<tr>
<td>7</td>
<td>11264</td>
<td>PPT 1: Free-field – base</td>
<td>39.61</td>
<td>2.525</td>
</tr>
<tr>
<td>8</td>
<td>10948</td>
<td>PPT 6: Free-field – high</td>
<td>39.35</td>
<td>-95.262</td>
</tr>
<tr>
<td>9</td>
<td>11059</td>
<td>PPT 7: Edge of footing</td>
<td>43.66</td>
<td>25.045</td>
</tr>
</tbody>
</table>
Figure 4.17. PPT calibration for Centrifuge Test #2.
4.4.3. Centrifuge Test #3

The variation of the PPT’s output voltage with the applied pressure, for the PPTs used in Centrifuge Test #3 is presented in Figure 4.18. The corresponding calibration factors are listed in Table 4.9.

Table 4.9. PPT calibration factors for Centrifuge Test #3.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>PPT</th>
<th>Description</th>
<th>Calibration Factor (KPa/Volt)</th>
<th>Offset (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190</td>
<td>PPT 9: Clay</td>
<td>10.66</td>
<td>32.43</td>
</tr>
<tr>
<td>2</td>
<td>10945</td>
<td>PPT 1: Free-field - base</td>
<td>47.77</td>
<td>195.40</td>
</tr>
<tr>
<td>3</td>
<td>6797</td>
<td>PPT 2: Free-field - low</td>
<td>39.88</td>
<td>-30.44</td>
</tr>
<tr>
<td>4</td>
<td>11260</td>
<td>PPT 3: Footing axis - low</td>
<td>42.96</td>
<td>41.53</td>
</tr>
<tr>
<td>5</td>
<td>10944</td>
<td>PPT 4: Free-field - middle</td>
<td>41.84</td>
<td>20.60</td>
</tr>
<tr>
<td>6</td>
<td>10951</td>
<td>PPT 5: Footing axis - middle</td>
<td>41.77</td>
<td>7.64</td>
</tr>
<tr>
<td>7</td>
<td>3312</td>
<td>PPT 6: Free-field - high</td>
<td>44.32</td>
<td>1.85</td>
</tr>
<tr>
<td>8</td>
<td>11268</td>
<td>PPT 8: Footing axis - high</td>
<td>42.87</td>
<td>12.01</td>
</tr>
<tr>
<td>9</td>
<td>10948</td>
<td>PPT 7: Edge of footing</td>
<td>40.22</td>
<td>83.77</td>
</tr>
</tbody>
</table>
Figure 4.18. PPT calibration for Centrifuge Test #3.
4.5. LVDTS

Settlements of the free-field clay surface were measured by Linear Variable Differential Transformers (LVDTs), while specially-made small footings were used to acquire the required measurements during the tests (Figure 4.19).

Calibration of LVDTs is performed by creating a data base of readings against displacements, measured with a digital micrometer (Figure 4.20), over the full measuring range of the instrument.

Figure 4.19. Specially-made small footings connected to the LVDT, in order to acquire the settlements of the clay surface.
4.5.1. Centrifuge Test #1

The variation of the LVDTs output voltage with the applied displacement, for Centrifuge Test #1 is presented in Figure 4.21. The corresponding calibration factors are listed in Table 4.10.

Figure 4.21. LVDT calibration for Centrifuge Test #1.
Table 4.10. LVDT calibration factors for Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>LVDT</th>
<th>Description</th>
<th>Calibration Factor (mm/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>018</td>
<td>LVDT 2: Right</td>
<td>3.80</td>
</tr>
<tr>
<td>12</td>
<td>029</td>
<td>LVDT 1: Left</td>
<td>3.63</td>
</tr>
</tbody>
</table>

4.5.2. Centrifuge Test #2

The variation of the LVDTs output voltage with the applied displacement, for Centrifuge Test #2 is presented in Figure 4.22. The corresponding calibration factors are listed in Table 4.11.

Figure 4.22. LVDT calibration for Centrifuge Test #2.

Table 4.11. LVDT calibration factors for Centrifuge Test #2.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>LVDT</th>
<th>Description</th>
<th>Calibration Factor (mm/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Fc</td>
<td>LVDT 2: Right</td>
<td>3.74</td>
</tr>
<tr>
<td>13</td>
<td>Hn</td>
<td>LVDT 1: Left</td>
<td>3.67</td>
</tr>
</tbody>
</table>
4.5.3. **Centrifuge Test #3**

The variation of the LVDTs output voltage with the applied displacement, for Centrifuge Test #3 is presented in Figure 4.23. The corresponding calibration factors are listed in Table 4.12.

![Figure 4.23. LVDT calibration for Centrifuge Test #3.](image)

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>LVDT</th>
<th>Description</th>
<th>Calibration Factor (mm/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Fc</td>
<td>LVDT 1: Left</td>
<td>3.76</td>
</tr>
<tr>
<td>13</td>
<td>Hn</td>
<td>LVDT 1: Right</td>
<td>3.50</td>
</tr>
</tbody>
</table>
4.6. POTENTIOMETER

Foundation settlements in the tests were measured with a potentiometer (Figure 4.24), which was calibrated by creating a data base of readings against distances measured with a digital micrometer (Figure 4.25), over the full measuring range of the instrument.

Figure 4.24. Potentiometer.
4.6.1. Centrifuge Test #1

The variation of the potentiometer’s output voltage with the applied displacement, for Centrifuge Test #1 is presented in Figure 4.26. The corresponding calibration factor is listed in Table 4.13.

Figure 4.25. Potentiometer calibration.

Figure 4.26. Potentiometer calibration for Centrifuge Test #1.
Table 4.13. Potentiometer calibration factor for Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Calibration Factor (mm/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>55.98</td>
</tr>
</tbody>
</table>

4.6.2. Centrifuge Test #2

The variation of the potentiometer’s output voltage with the applied displacement, for Centrifuge Test #2 is presented in Figure 4.27. The corresponding calibration factor is listed in Table 4.14.

![Graph of Potentiometer Calibration for Centrifuge Test #2](image)

Figure 4.27. Potentiometer calibration for Centrifuge Test #2.

Table 4.14. Potentiometer calibration factors for Centrifuge Test #2.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Calibration Factor (mm/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>54.62</td>
</tr>
</tbody>
</table>
4.6.3. Centrifuge Test #3

The variation of the potentiometer’s output voltage with the applied displacement, for Centrifuge Test #3 is presented in Figure 4.28. The corresponding calibration factor is listed in Table 4.15.

Figure 4.28. Potentiometer calibration for Centrifuge Test #3.

Table 4.15. Potentiometer calibration factors for Centrifuge Test #3.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Calibration Factor (mm/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>56.18</td>
</tr>
</tbody>
</table>
4.7. LOAD CELL

A load cell was used in the centrifuge test to measure the post-shaking bearing capacity of the model foundation. The load cell was attached to an actuator, which applied the post-earthquake static load to the footing, as shown in Figure 4.29.

![Load cell connected to the actuator.](image)

**Figure 4.29.** Load cell connected to the actuator.

4.7.1. Centrifuge Test #1

Before the first test, the load cell was calibrated by first placing the load cell against the floor and then applying plates of known weight on top of it to obtain its output voltage. The variation of the load cell’s output voltage with the force applied by the weight plates is presented in Figure 4.30, while the corresponding calibration factor is given in Table 4.16.
Figure 4.30. Load cell calibration for Centrifuge Test #1.

Table 4.16. Load cell calibration factor for Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Calibration Factor (N/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>707.39</td>
</tr>
</tbody>
</table>

4.7.2. Centrifuge Test #2

A more accurate calibration procedure was followed for the second test, with the load cell used in the test (hereafter called “testing load cell”) being calibrated against another load cell (hereafter denoted as “prototype load cell”). More specifically, the load cell was placed between two metal plates, as shown in Figure 4.31 and schematically illustrated in Figure 4.32. An actuator, placed above the top plate, applied pressure to the testing load cell. The prototype load cell was placed below the bottom plate.

The prototype load cell was initially calibrated by removing the top plate and the actuator and placing weights on the bottom plate. Then, the testing load cell was placed between the two plates and air pressure was added to the actuator. The calibration procedure was accomplished by increasing this pressure and obtaining readings from both the prototype and the testing load cell.

Figure 4.33 presents the variation of the prototype cell’s output voltage with the applied weight, as well as the readings from both the load cells during the external
application of air pressure. The calibration factor for the testing load cell is given in Table 4.17.

Figure 4.31. Load cell calibration.
Figure 4.32. Load cell calibration (schematic).

Figure 4.33. Load cell calibration for Centrifuge Test #2.

Table 4.17. Load cell calibration factor for Centrifuge Test #2.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Calibration Factor (N/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>726.71</td>
</tr>
</tbody>
</table>
4.7.3. Centrifuge Test #3

The procedure that was followed for the third test is the same as for Test #2. Nevertheless, while checking the instrument readings, before the performance of the test, an unexpected, significant change of the load cell’s offset (i.e. voltage reading for zero input force) was observed. Therefore, the load cell was recalibrated after the end of the test. Figure 4.34 presents the variation of the prototype cell’s output voltage with the applied weight, as well as the readings from both the load cells during the external application of air pressure, for both the pre-test and post-test calibrations. The corresponding calibration factors for the testing load cell are given in Table 4.18.

Observe that the load cell’s calibration factor had also significantly changed! As this change occurred prior to testing, the post-test calibration factor is used for the following interpretation of the test data.

![Load cell calibration for Centrifuge Test #3](image)

**Table 4.18.** Load cell calibration factor for Centrifuge Test #3.

<table>
<thead>
<tr>
<th>Junction Box Channel</th>
<th>Calibration Factor Pre-test (N/Volt)</th>
<th>Calibration Factor Post-test (N/Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>717.93</td>
<td>1740.0</td>
</tr>
</tbody>
</table>
5. **Model Set-up**

5.1. **SAND POURING**

5.1.1. **General**

As mentioned previously, the centrifuge tests described herein were performed on a reconstituted Leighton-Buzzard Grade-E sand specimen. In order to achieve uniform deposition, as well as repeatability of the reconstitution method, the air pluviation technique was applied, using the robotic apparatus of Figure 5.1.

![Figure 5.1. Robotic apparatus used for sand pluviation.](image)

The air pluviation technique consists of pouring dry sand through the air, so that the flow rate and the fall height determine the density of the sample. The flow rate is controlled by the diameter of the nozzle through which the sand is poured. More specifically, a large nozzle diameter results in a large flow rate, which in turn leads to
a low relative density, due to the minimal bouncing and subsequent rearrangement of the sand particles. Similar to the increase in flow rate, a low drop height leads to a low fall velocity, which in turn results in a loosely packed arrangement.

Taking into account that manual pouring may not ensure a consistent flow rate and drop height, a robotic sand pourer was employed, designed to be fully automated and requiring no intervention from the operator. The components of the apparatus were constructed in the University of Cambridge, using available off-the-shelf units and commercial computer control software so as to lower development costs.

The apparatus consists of a travelling hopper (Figure 5.2) that can move both horizontally and vertically. The sand is poured through a nozzle of variable diameter (Figure 5.3), as the hopper moves across the container’s axes, following the travel path illustrated in Figure 5.4. Two pouring cycles are considered when the hopper has travelled from a to b and consequently from c to d, so that the plan area is covered once within each cycle. After each cycle, the hopper is raised vertically by the thickness of the deposited sand, in order to maintain a constant flow height. As the travelling hopper is rather small, it needs to be (automatically) refilled from a larger hopper, placed at a given location in the Model Preparation Room (Figure 5.5).

**Figure 5.2.** Travelling hopper.
Figure 5.3. Nozzle through which the sand is poured.

Figure 5.4. Sand pouring travel paths.
Figure 5.5. Automatic refilling of the travelling hopper.

5.1.2. Calibration

The sand pourer is calibrated by filling a small cylinder of 202mm diameter and 200mm height (Figure 5.6). Since flow irregularities may arise at the edges of the hopper’s travel path, the travel paths were extended over the boundary of the container to avoid such irregularities. Furthermore, the rim of the container was tapered outwards, in order to minimize disturbances from the boundary effects, as suggested by Zhao et al. (2006). After filling, the cylinder is weighted and the dry unit weight of the sand is calculated and consequently used to obtain the associated average void ratio and relative density. The above procedure is consequently repeated for different flow heights and nozzle diameters, until the target relative density is obtained.
During preparation of the centrifuge tests, the target relative density of 50% was achieved after two trials. In the first trial, a flow height of 785mm and a nozzle diameter of 7mm were selected. After pouring the first pair of cycles, it was found that the sand pouring rate was 1.9mm per cycle. This measurement was used to define, in the computer control software, the hopper’s vertical movement after the execution of each pouring cycle, in order to maintain a constant flow height. The pouring procedure was also interrupted before filling the container, in order to measure the flow height and make fine readjustments to this vertical travel speed.

After the end of this procedure, the total mass of the container filled with sand was found equal to 14.880Kgr, which corresponds to 9.215Kgr of sand (the container’s mass is equal to 5.665Kgr). Therefore, the sand’s dry density was equal to:

\[
\rho_d = \frac{m}{V} = \frac{9.215\text{Kgr}}{\frac{\pi(202\text{mm})^2}{4} \cdot 200\text{mm}} = 1.438\frac{\text{Mg}}{\text{m}^3}
\]

The above dry density corresponds to a void ratio of

\[
e = \frac{\rho_s}{\rho_d} - 1 = \frac{2.65\frac{\text{Mg}}{\text{m}^3}}{1.438\frac{\text{Mg}}{\text{m}^3}} - 1 = 0.843
\]

and a relative density of:
\[ D_r = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}} = \frac{1.014 - 0.843}{1.014 - 0.613} = 42.6\% \]  

(5.3)

Since the above relative density is lower than 50\%, the above procedure was repeated with a smaller nozzle diameter of 6mm and a flow height of 775mm. This configuration resulted in a sand pouring rate of 2mm per cycle. After the completion of the procedure, the total mass of the filled container was found equal to 15.065Kgr, corresponding to 9.400Kgr of sand. Therefore, the obtained sand’s dry density was equal to \( \rho_d = 1.467 \text{Mg/m}^3 \), corresponding to a void ratio of \( e = 0.806 \) and a relative density of \( D_r = 51.6\% \).

This relative density is quite close to the target value of 50\%, thus the configuration of a nozzle diameter of 6mm and a flow height of 775mm was selected for the sand pouring procedure.

*Note: The above direct calibration of the sand pouring apparatus does not agree with the findings of Chian et al (2010), who have proposed the design chart of Figure 5.7, for air pluviation of LBE Sand with the same apparatus. Namely, this chart predicts that the relative density corresponding to the chosen sand pouring configuration is about 38\% (instead of 51.6\%).*

![Figure 5.7](image-url)  
*Figure 5.7.* Design chart to achieve specific relative density with LBE Sand, after Chian et al (2010).
5.1.3. Centrifuge Test #1

Having chosen the flow height and rate required, the air pluviation technique was applied to fill the ESB box with a total of 270mm of sand. Before starting the sand pouring process, thin metal plates were placed at the box’s top edge, so as to minimize boundary effects (Figure 5.8).

![ESB box prepared for sand pluviation.](image)

In order to measure the mass of the sand placed in the ESB box, the model preparation room was cleaned, and the sand placed in the hoppers was weighed and found equal to 121.005Kgr.

The process of sand pouring was interrupted at 4mm, 92mm, 182mm and 252mm, in order to place the instruments (Accelerometers and PPTs). Excess care was given so as to minimize any disturbance to the sample. Deviations of the order of 2mm from the initially planned instrumentation levels (4mm, 90mm, 180mm and 250mm) are due to the fact that the sand pluviation could only be interrupted after the completion of an even number of pouring cycles, with 2mm of sand being poured in each cycle.

In certain cases, the stiffness of the instrument cables made it difficult to accurately position the instruments. Therefore, deviations of the order of 5 to 10mm, from the initially planned positions, could not be avoided, as already discussed in Section 4.1.
of this Report. Photographs from the instrumentation, placed at each one of the above sand levels, are shown in Figure 5.9.

It should also be noted that, during each of the above interruptions, the distance of the nozzle from the pluviated sand was measured, and fine adjustments were made to the computer control software, so as to maintain a constant flow height. In all cases, deviations from the required height of 775mm did not exceed 5mm.

![Photographs from the instrumentation](image1)

![Photographs from the instrumentation](image2)

![Photographs from the instrumentation](image3)

![Photographs from the instrumentation](image4)

**Figure 5.9.** Instrumentation placed at a) 4mm, b) 92mm, c) 182mm and d) 250mm.

The sand pluviation should have stopped when the total thickness of the sand layer reached the initially planned value of 270mm. Nevertheless, when this thickness was achieved at the middle of the sand sample, it was observed that it was shallower at certain corners, as shown in Figure 5.10. Therefore, another 20mm of sand were poured, and the sand surface was consequently leveled by removing the excess sand with a modified vacuum cleaner. This vacuum cleaner had a sand trap that allowed weighting the removed sand.
The sand which was removed from the model, the sand that fell out of the box during the pouring procedure, as well as the sand that had remained in the hoppers, were weighed and found equal to 55.470Kgr. Therefore, the sand used for the model had a total mass of \[121.005\text{Kgr} - 55.470\text{Kgr} = 65.535\text{Kgr} \].

Taking into account that the ESB box’s internal plan area is 169,742mm\(^2\), the sample’s dry density may be computed equal to 1.430Mgr/m\(^3\), which corresponds to a void ratio of \(e = 0.853\) and a relative density of \(D_r = 40.1\%\). This value is quite lower than the one obtained during the calibration procedure, with the same configuration, in terms of flow height and rate, but is in fairly good agreement with the Chian et al (2010) diagram in Figure 5.7.

### 5.1.4. Centrifuge Test #2

The same procedure was applied for Centrifuge Test #2, where the total sand layer thickness was equal to 290mm. In this case, a total of 108.975Kgr of sand was placed in the hoppers. The sand removed from the box during leveling with a modified vacuum cleaner, as well as the sand that fell out of the box, weighed 37.755Kgr. As a result, a total mass of 71.220Kgr of sand was used for the sand layer, corresponding to
a dry density of $1.442\text{Mg/m}^3$, a void ratio of $e=0.837$ and a relative density of $D_r=44.1\%$. Note that in this case, the thick old sealant covering the ESB box sides had been removed, and replaced with a thin layer of plastic coating, as described in Section 2.3.

The process of sand pouring was interrupted at 4mm, 100mm, 200mm and 269mm, in order for the instruments (Accelerometers and PPTs) to be placed. Photographs from the instrumentation, placed at each one of the above sand levels, are shown in Figure 5.11.

![Figure 5.11. Instrumentation placed at a) 4mm, b) 100mm, c) 200mm and d) 269mm.](image)

### 5.1.5 Centrifuge Test #3

In Centrifuge Test #3, the total sand layer thickness was equal to 230mm. In this case, a total of 92.250Kgr of sand was placed in the hoppers. The sand that was removed
from the box during leveling with a modified vacuum cleaner, as well as the sand that fell out of the box, weighed 35.875Kgr. As a result, a total mass of 56.375Kgr of sand was used for the sand layer, corresponding to a dry density of $1.440 \text{Mg}/\text{m}^3$, a void ratio of $e = 0.840$ and a relative density of $D_r = 43.4\%$.

The process of sand pouring was interrupted at 4mm, 70mm, 140mm and 211mm, in order for the instruments (accelerometers and PPTs) to be installed. Photographs from the instrumentation, installed at each one of the above sand levels, are shown in Figure 5.12.

![Image of instrumentation at different levels](image)

**Figure 5.12.** Instrumentation placed at a) 4mm, b) 70mm, c) 140mm and d) 211mm.
5.2.  MODEL SATURATION

5.2.1.  Viscosity Scaling

The study of liquefaction-related centrifuge problems requires that the sand specimens are saturated with pore fluid. The scaling laws presented by Schofield (1981) highlight a discrepancy between the time scaling of consolidation time and loading time period of dynamic events. Hence, a commonly used approach to correct for this discrepancy is to use a pore fluid with an appropriately elevated viscosity.

In the centrifuge tests presented herein, methylcellulose (hydroxypropyl methylcellulose – HPMC) was used to implement this viscosity scaling. Methylcellulose is a water-soluble polymer derived from cellulose (Dow, 1997), which is supplied by the Dow Chemical Company in large containers of dry powder. The viscous fluid is prepared by adding the correct amount of powder to the required amount of water. The effect of methylcellulose concentration to the kinematic viscosity, as well as to the specific gravity of water, is presented in Figure 5.15. As all dynamic centrifuge tests were carried out at an average centrifuge acceleration of 50g, the pore-fluid used to saturate the models was prepared with a viscosity of 50cSt.

![Figure 5.13. Effect of methylcellulose concentration to the kinematic viscosity and the specific gravity of water.](image)

The methylcellulose powder takes some time to dissolve in water, but the process is normally completed within 48 h, using the mixing tank shown in Figure 5.16. Taking into account the long time period needed for the methylcellulose dissolution, as well as any uncertainties involved in the correlation of the kinematic viscosity with the methylcellulose concentration, the following procedure was followed: a larger amount of methylcellulose was added to the water and, when it had dissolved, the viscosity
was measured using the device of Figure 5.17. Water was consequently added to the mixture, until the desired viscosity of 50cSt was achieved. Note that adding water to the mixture to decrease viscosity is much faster than the opposite, i.e. increase viscosity by adding methylcellulose powder to the mixture and wait for it to dissolve.

Figure 5.14. Methylcellulose mixing tank.

Figure 5.15. Measurement of the kinematic viscosity of the model’s pore fluid.
5.2.2. Model Saturation using the CAM-SAT system

Using a viscous fluid poses a number of challenges for the saturation process. In an ideal situation, models should be saturated at high speeds, while still achieving a final saturation ratio of $S_r=100\%$. In a first order approximation, Darcy's law governs the flow of the pore fluid during the saturation process and therefore, if the flow rate is increased beyond a critical level, then the model can become unacceptably disturbed. Examples of the model disturbance which can occur include fluidization of the model, piping and upward displacement of embedded instruments.

In order to minimize these effects, the CAM-Sat automated system was used for the saturation process (Stringer & Madabhushi, 2009 and Stringer & Madabhushi, 2010). This system aims to improve model quality by continually monitoring the mass flux into the model and maintaining it within user-defined tolerances which are low enough to avoid model disturbance, but not so low that the saturation process takes an unnecessary length of time.

The CAM-Sat system is schematically illustrated in Figure 5.16. Having closed all the valves shown in this figure, a vacuum of about -95KPa was initially applied to the model for about an hour. In order to apply the vacuum, the instruments connectors were placed in two plastic bowls, resting on the sand surface, and the ESB box was sealed with a special lid (Figure 5.17). Then, vacuum was applied with the pump shown in Figure 5.18.

![Schematic illustration of the CAM-SAT system layout.](#)

Figure 5.16. Schematic illustration of the CAM-SAT system layout.
In order to enhance the saturation process, the model was consequently flushed with CO₂ (Takahashi et al, 2006). Three holes were opened to the lid, for this purpose. The first hole was used to attach a pressure gauge, capable of both vacuum and positive pressures. The second opening was used to attach a 0.5bar pressure release valve, to ensure that the model container is not subjected to high pressures, which could either
damage the model container or in the worst case cause an accident to the researchers. Finally, a T-piece was attached to the third hole. A pressure transducer was connected to one of the openings of the T-piece, in order to transfer pressure measurements to a data-logging computer system, powered with the DasyLab 9.0 Software. The other opening was connected (via valves) to the carbon dioxide bottle (Figure 5.19). A 0-2bar regulator was also attached to the carbon dioxide bottle, in order to ensure that low pressures are delivered to the model. This regulator was set to a very small positive value of about 0.2bar, and the valve was opened to allow the package to return to atmospheric pressure (and slightly over). The carbon dioxide was consequently switched off and disconnected from the ESB box lid. The vacuum pump was then connected to this opening, vacuum was re-applied and left for another hour. The same process could have been repeated, in order to remove any traces of air left within the sand voids. Nevertheless, due to time limitations, CO2 flushing was only performed once.

![Carbon dioxide bottle](image)

**Figure 5.19.** Carbon dioxide bottle.

Having the ESB box under vacuum, the viscous fluid that had been prepared was placed in the container holding tank shown in Figure 5.20. This tank was placed on an electronic scale, used to transmit the container’s mass to the datalogging system. The bottom of the container was connected (with a valve), through the green pipe of Figure 5.20, to four openings at the base of the ESB box (Figure 5.17). Finally, the container was sealed with a lid, and vacuum was applied, using the same vacuum
pump (Figure 5.18) used for the ESB box. Nevertheless, in this case, a computer controlled pressure regulator (Figure 5.21) was placed, between the vacuum pump and the fluid container to enable the automatic control of the saturation process.

**Figure 5.20.** Pore fluid holding tank.

**Figure 5.21.** Pressure regulator.
Using the DasyLab computer programs “Cam-sat Prep” and “Cam-Sat v3” and the pressure regulator, the vacuum applied to the reservoir is automatically controlled and adjusted to a proper value, so that a positive pressure difference causes fluid flow from the reservoir into the model. The rate of saturation is consequently monitored through the electronic scales of Figure 5.20 and maintained within a user-defined allowable range, by altering the vacuum applied to the reservoir.

According to Stringer & Madabhushi (2009), for Fraction E sand, model cross-sectional dimensions of 250mm x 500mm and a pore fluid viscosity of 50cSt, the saturation rate should not exceed 0.5Kgr/hour. However, due to the time restrictions defined by the TNA agreement, a maximum rate of 0.6Kgr/hour was used, so that the saturation process could be accelerated. Note that the ESB box used for the tests had larger cross-sectional dimensions (i.e. 253mm x 673mm) than the reference container of Stringer & Madabhushi (2009). Considering a linear variation of the allowable saturation rate with the model’s cross-sectional area, a rate of 0.68Kgr/hour could have been also considered as acceptable.

Finally, note that in order for the system to be able to control the flow rate, an allowable range should be defined, with the minimum value typically being 0.1Kgr/hour lower than the maximum flow rate.

### 5.2.3. Centrifuge Test #1

A number of technical difficulties were faced during the saturation procedure for Centrifuge Test #1. More specifically, vacuum was initially applied to the ESB box, but a significant pressure drop was observed, indicating the existence of leaks at the lid’s connection to the box. Therefore, the box had to be opened, in order to add silicon grease to the interface. The vacuum was consequently disconnected from the lid and the valve was opened. However, this resulted in abrupt flow of atmospheric air towards the inside of the box, creating a crater in the sand, underneath the lid’s opening. The crater had a depth of about 15 to 20mm.

The ESB box was consequently moved back to the model preparation room, and the sand surface was leveled by removing 20mm of sand. This amount of sand was weighed and found equal to 2.640Kgr. The hopper of the robotic sand pouring system was filled with 13.695Kgr of sand and 20mm of sand were pluviated, using the same
flow height and rate configuration as described in Section 5.1. The remaining sand in the hopper, and the sand that fell out of the box had a total mass of 10.580Kgr. Therefore, a total of 3.115Kgr of sand was added to the model. Note that this mass is 0.475Kgr larger than the one removed from the ESB box.

Having finished the above procedure, the model was moved back to the saturation room and the saturation process was restarted. Still, during the CO₂ flushing, it was impossible to avoid the formation of a crater, even though extra care was given to open the corresponding valve slowly (Figure 5.22).

![Crater formed in the sand layer, underneath the lid’s opening.](image)

**Figure 5.22.** Crater formed in the sand layer, underneath the lid’s opening.

Furthermore, the ESB box suffered from leaks between its alternating aluminum and rubber rings. As the model was under vacuum, atmospheric air entered the box through these leaks, forming air bubbles in the viscous pore fluid, possibly disturbing the model’s homogeneity. This disturbance resulted in a non-uniform rise of the water table in the sand layer, as it may be observed in Figure 5.22. Note that since the model is under vacuum, these bubbles are significantly expanded.

When the water table reached the sand surface, the box filled with air bubbles, which started breaking and filling the plastic bowls with the instrument connectors with water. Therefore, as the weight of these bowls increased, they settled in the saturated sand layer, as shown in Figure 5.23.
Figure 5.23. Sand settlement, due to the plastic bowls filling with water.

Taking into account that the air bubbles that existed inside the pore fluid would shrink, when the applied vacuum was removed, an excess amount of pore fluid had to be added to the model. To accomplish this, the vacuum pump was turned off and disconnected from the box. Since a negative pressure was still present in the box, pore fluid was added from the lid opening, as shown in Figure 5.24. Note that the corresponding valve was only slightly opened, in order for the fluid to drip slowly inside the box, so that no further disturbance was caused.

Having raised the water table to about 10mm above the sand surface, the ESB box was opened, the bowls were removed and the sand surface was leveled using a small metallic ruler. The excess fluid above the sand surface was consequently removed using a large syringe.

All above may have resulted in disturbance of the model. For instance, note in Figure 5.25 that one of the PPT cables (probably PPT 6) emerged on the model’s surface, while it had been placed 20mm below. Furthermore, the sand surface was found to have settled by 10mm. This corresponds to a volumetric strain of:

$$\Delta e_{\text{vol}} = \frac{10\text{mm}}{270\text{mm}} = 3.7\%$$

(5.4)
Assuming an initial void ratio of $e_0 = 0.853$, this settlement corresponds to a void ratio decrease of:

$$\Delta e = (1 + e_0) \Delta e_{vol} = 0.069$$  \hspace{1cm} (5.5)

and a relative density increase of:

$$\Delta D_r = \frac{\Delta e}{e_{max} - e_{min}} = \frac{0.069}{1.014 - 0.613} = 17.1\%$$  \hspace{1cm} (5.6)

Hence, the relative density of the sand at the end of the saturation process has increased to about 57.2% (from 40.1%). It is not clear to what extent this increase of relative density was uniform over the entire volume of the sand.

To make a rough estimate of the fluid’s weight, it is noted that the initial mass of the filled fluid holding tank was equal to 35.355Kgr. The fluid added from the lid’s opening was taken from the same container, leaving a final total mass of 9.895Kgr. Furthermore, 4.940Kgr of fluid was removed from the model (fluid in the bowls and fluid removed from the surface). In addition, note that during this procedure, it was inevitable to avoid some small amount of fluid to fall on the floor, while another small amount remained in the piping system. Therefore, the total amount of pore fluid added to the model did not exceed 20.520Kgr.

Figure 5.24. Addition of pore fluid from the ESB box lid opening.
5.2.4. Centrifuge Test #2

Taking into account the technical difficulties faced during the saturation procedure of Centrifuge Test #1, a number of measures were taken to minimize the disturbance of the sand model in the second test.

Firstly, the old plastic sealant was removed from the ESB box, and resealing was attempted using aquarium silicone, as well as a synthetic plastic coating spray, as described in Section 2.3.

Secondly, the bowls used for the placement of the cable connectors inside the box, were sealed with clean-film, as shown in Figure 5.26, so that they could not be filled with water and settle into the sand layer.

Furthermore, a protective metal plate was added to the box’s lid (Figure 5.27), in order to avoid the formation of a crater in the sand’s surface, while flushing the sand layer with CO₂.

Finally, the ESB box was externally wrapped with clean-film, as shown in Figure 5.28, to limit as much as possible any air leaks between the alternating aluminum and rubber frames.

Figure 5.25. Centrifuge model #1, after the end of the saturation process.
Figure 5.26. Instrument connectors placed inside sealed bowls, in the ESB box, prior to model saturation.

Figure 5.27. ESB box lid, with protective metal plate.
Figure 5.28. ESB box covered with clean-film, during the saturation process of Centrifuge Test #2.

Figure 5.29. Air bubbles on the water surface, during the saturation of Centrifuge Model #2.
The above measures significantly improved the saturation procedure for Centrifuge Test #2. Air bubbles still formed on the water surface (Figure 5.29), but they were significantly less than in the first test. Figure 5.30 presents the centrifuge model after the end of the saturation procedure.

Even with the previously described precautions, settlement of the sand layer during saturation was not avoided. The settlement was found equal to 7mm at the left side of the box (Figure 5.30) and 6mm at the right side.

Assuming an initial void ratio of $e_0 = 0.837$, the average settlement of 6.5mm corresponds to a volumetric strain of $\Delta e_{vol} = 2.24\%$, a void ratio decrease of $\Delta e = 0.041$ and a relative density increase of $\Delta D_r = 10.3\%$. Hence, in this case the relative density of the sand has increased to 54.4% (from 44.1%).

As far as the added water mass is concerned, the initial total mass of the filled fluid holding tank was equal to 28.725Kgr, while the corresponding final mass was equal to 8.800Kgr, while a small amount of fluid remained in the piping system.

The CAM-SAT System incorporates a soft-stop function (Stringer & Madabhushi, 2010) which allows the user to reduce the rate of saturation at the final stages. Nevertheless, when the water table exceeded the sand surface, air bubbles started to form and the procedure was manually stopped.
It should be taken into account that the sand layer should always be covered with water, so that when the vacuum is released and any air pockets existing in the sand collapse, more fluid can be drawn into the sand layer. In order to avoid such effects, when the saturation procedure was stopped, 1.750Kgr of fluid were carefully added on the surface. After about one hour, when equilibrium was reached, a total of 1.755Kgr of fluid was removed from the surface, using a syringe.

As a result, the total mass of fluid added to the model is estimated to 19.920Kgr.

5.2.5. Centrifuge Test #3

As described in Section 2.3, extra care was taken in order to minimize the disturbance of the sand model, during the saturation procedure of Centrifuge Test #3. More specifically, the box was covered with a new plastic-type sealant, which was applied with a painting brush. Furthermore, the inner side of the box’s lateral boundaries was covered with cling film. At the bottom, the cling film was attached to the base of the box using metal tape, while at the top, it was only temporarily supported until the sand was poured, and was subsequently held in place by the sand layer itself. This way, any air entering the box through its walls, during the saturation procedure, would travel upwards, through the box walls – cling film interface, and would be then removed by the vacuum pump at the top of the box, without forming any bubbles in the saturated sand layer and affecting its homogeneity.

Similar to Centrifuge Test #2, the bowls used for the placement of the cable connectors inside the box were sealed with cling-film (Figure 5.31). Furthermore, a protective metal plate had been added to the box’s lid, as described in Section 5.2.4. Taking all the above into account, it was considered unnecessary to cover the external walls of the box with cling-film.

The above measures were proved quite effective for the saturation procedure. No bubbles were observed on the water surface, while the settlement of the sand layer was minimized to 1mm. Figure 5.32 presents the centrifuge model after the end of the saturation procedure.
Figure 5.31. Instrument connectors placed inside a sealed bowl, in the ESB box, prior to model saturation.

Figure 5.32. Centrifuge model #3 after the saturation procedure.

As far as the added water mass is concerned, the initial total mass of the filled fluid holding tank was equal to 26.740Kgr. When its mass was equal to 13.360Kgr, the saturation procedure was interrupted and another 11.560Kgr of water was added to the tank. After the end of the saturation procedure, the final total mass of the fluid
holding tank was equal to 18.080Kgr, with a small amount of fluid remaining in the piping system.

At the end of the saturation procedure, the saturated sand layer was covered with about 12mm of water. This action ensured that, when the vacuum was released and any air pockets existing in the sand collapsed, there would be enough fluid on the surface to be drawn into the sand layer so that it would remain saturated. Several hours later, when equilibrium was reached, the excess fluid was removed from the surface using a syringe. Its weight was measured to 1.965Kgr, so that the total mass of fluid added to the model is estimated to 18.255Kgr.
5.3. CONSOLIDATION AND PLACEMENT OF CLAY CAP

5.3.1. Consolidation procedure

According to the test specifications, a clay crust with an undrained shear strength of $c_u = 40\text{KPa}$ should be placed on top of the saturated sand layer. In order to obtain this high shear strength value, the clay was over-consolidated to $400\text{KPa}$. Assuming a unit weight of $\gamma = 20\text{KN/m}^3$, Equation (3.4) indicates that at a depth of 1m from the ground surface, the clay’s undrained shear strength would be approximately equal to:

$$c_u = 0.18 \cdot 1\cdot \frac{20\text{KN}}{\text{m}^3} \left( \frac{400\text{KPa}}{1\cdot 20\frac{\text{KN}}{\text{m}^3}} \right)^{0.8} = 39.5\text{KPa}$$  \hspace{1cm} (5.7)

while at a depth of 1.5m, the undrained shear strength can be estimated as:

$$c_u = 0.18 \cdot 1.5\cdot \frac{20\text{KN}}{\text{m}^3} \left( \frac{400\text{KPa}}{1.5\cdot 20\frac{\text{KN}}{\text{m}^3}} \right)^{0.8} = 42.9\text{KPa}$$  \hspace{1cm} (5.8)

Note that the depth of a Prandtl-type failure mechanism within the clay layer is theoretically equal to $0.7B$, where $B$ is the footing width, which, in this particular case, is equal to 3m (in prototype scale). Therefore, the depth of 1m corresponds to the average depth of the failure region, if the failure mechanism develops within the clay layer. In case that a composite, punch-through the clay failure mechanism develops, as expected in centrifuge tests #1 and #2, an average undrained shear strength should be considered, for the whole clay layer. For centrifuge test #1, where the thickness of the clay layer is equal to 3m (in prototype scale), the depth of 1.5m may be regarded as a representative depth for the computation of the punch-through resistance of the clay crust. In centrifuge test #2, the clay crust thickness is 2m, thus the depth of 1m is the representative value.

The consolidation procedure was performed in a metal tub, with an internal diameter of 850mm. About 250mm of slurry were initially placed in the tub, followed by an additional 85mm after two days. The slurry was created by mixing kaolin powder...
with enough water, so that the initial water content was above the liquid limit (LL). The clay was covered with a metal lid and the consolidation pressure was applied incrementally, through an electronically controlled hydraulic piston (Figure 5.33). Note that between the application of successive increments, adequate time was allowed for the excess pore pressures to dissipate.

![Clay consolidation](image)

**Figure 5.33.** Clay consolidation.

The time history of the applied load increments, as well as the corresponding thickness of the clay layer, are presented in Figure 5.34. Note that an unexpected decrease of the applied pressure occurred on 4/12/2010, due to an electric power breakdown. The variation of the thickness of the clay layer with the applied load is shown in Figure 5.35.

As shown in these figures, after the end of consolidation, the applied pressure was decreased to 80KPa. This corresponds to an undrained shear strength of:

$$c_u = 0.18 \times 80\text{KPa} \times \left(\frac{400\text{KPa}}{80\text{KPa}}\right)^{0.8} = 52.2\text{KPa}$$  \hspace{1cm} (5.9)

This undrained shear strength was selected so as to allow for the clay pieces required for the test to be easily cut and manipulated. Furthermore, note that the pressure of
80KPa is lower than the air entry value of kaolin clay, which is about 100KPa. As a result, when the clay is taken out of the consolidation tub, it would remain under suction, thus maintaining its shear strength.

Figure 5.34. Applied pressure time history and corresponding clay layer thickness.
5.3.2. Placement of clay: Centrifuge Test #1

According to the initial plan, the clay should be taken out of the tub and placed in the ESB box one day prior to testing. Nevertheless, the clay was placed in the ESB box on 16/11/2010, while the test was performed 6 days later, on 22/11/2010, due to a number of unexpected delays.

The placement procedure was performed as follows:

Firstly, the tub’s lid was removed (Figure 5.36) and the clay layer was lifted to the top of the tub, by applying an upward pressure to a metal plate, at the tub’s bottom. A thin slice of clay (about 10mm) was consequently removed from the top of the clay layer. Then, three blocks were marked on the clay surface (Figure 5.37), namely one large piece (450mm x 230mm x 60mm) that would be placed underneath the model footing, as well as two smaller pieces (100mm x 230mm x 60mm) that would be placed on each side of the larger central piece. Note that, for practical reasons, the dimensions of the clay blocks are somewhat smaller than the internal dimensions of the ESB box (673mm x 253mm), thus leaving a small gap of about 10mm around each block. This gap would be filled with slurry, after placement of the clay pieces.

Having marked the blocks, the clay layer was lifted 60mm above the top edge of the consolidation tub (Figure 5.39) and was cut using a wire (Figure 5.40 & Figure 5.41).

Figure 5.35. Variation of clay thickness with the applied pressure.
Figure 5.36. Kaoling clay in the consolidation tub.

Figure 5.37. Blocks marked on the clay surface.
**Figure 5.38.** Clay layer lifted 60mm above the edge of the consolidation tub.

**Figure 5.39.** Wooden blocks placed underneath the consolidation tub, in order to lift the clay layer 60mm above the tub’s edges.
Figure 5.40. Cutting a clay slice with wire.

Figure 5.41. Clay block before placement in the ESB box.
Figure 5.42. Placement of clay blocks in the ESB box.

The clay blocks were consequently placed on top of the saturated sand, as shown in Figure 5.42. Nevertheless, this resulted in a significant settlement of 10mm of the sand layer, due to the weight of the clay cap. Hence, the final thickness of the settled sand layer was equal to 250mm (in model scale).

Furthermore, assuming an initial void ratio of $e_o = 0.784$, this settlement corresponds to a volumetric strain of $\Delta e_{vol} = 3.85\%$, a void ratio decrease of $\Delta e = 0.069$ and a relative density increase of $\Delta D_r = 17.1\%$. As a result, the final void ratio of the sand became $e = 0.715$, which corresponds to a relative density of $D_r = 74.3\%$.

As the sand layer was settling, pore fluid and sand came out to the model’s surface through the gaps, around the clay blocks. These were consequently removed with cloth, thus inducing some uncertainty with regard to the final mass of the saturated sand layer. After completion of the settlement, slurry was grouted with a syringe at several positions along the gap, thus forming a clayey-sandy mixture around the clay blocks, with the excessive sand being pushed upwards and consequently removed from the top of the model. After completion of this process, the model was carefully covered with clean-film, in order to prevent the clay layer from drying.

Due to the uncertainties in the total mass of the model, the ESB box was weighed after placing the clay cap and perimetrically sealing the gaps with slurry. The total
mass was found equal to 206.5Kgr. Subtracting the mass of the ESB box (105.5Kgr), the total mass of the saturated sand and the overlying clay layer may be estimated as 101.0Kgr.

As far as the properties of the clay layer are concerned, numerous lab-vane tests were performed on the surface of clay blocks (Figure 5.43), taken from the consolidation tub and an undrained shear strength of 37-38KPa was measured. Furthermore, a clay block of 225mm x 448mm x 59mm was weighed and its mass was found equal to 11.025Kgr. The clay density may be consequently estimated as \( \rho = 1.85 \text{Mg}/\text{m}^3 \).

**Figure 5.43.** Performance of lab-vane tests on the clay.

Before execution of centrifuge test #1, a special tool (Figure 5.44) was used to vertically drill a 30mm deep hole, inside the clay layer, for the placement of PPT #9. A few drops of water were poured in the hole and the PPT was placed, using the tool shown in Figure 5.45. A second, larger, hole was also opened on the clay surface, for placing Accelerometer #9. Both holes were consequently sealed with slurry.
5.3.3. Centrifuge Test #2

After cutting off the clay blocks for the first test, the remaining clay cake was placed back in the consolidation tub. The tub was reopened on the 29/11/2010 and the same
procedure was repeated for the second test. Note that the second test was performed three days later, on 3/12/2010.

More specifically, three blocks of clay were cut: one large block, with dimensions of 450mm x 230mm x 40mm and a mass of 7.335Kgr, as well as two smaller blocks, with dimensions of 100mm x 230mm x 40mm and a total mass of 3.360Kgr (both pieces together).

After placement of the central clay block, a significant settlement of 18mm was observed, combined with uplifting of the saturated sand, near the model edges (Figure 5.46). The black color of the pore fluid, shown in this figure, is due to colored sand grains existing in the sand layer. Note that the sand of Test #2 had been reused for dry centrifuge experiments, where some sand grains had been colored to aid the PIV (Particle Image Velocity) analysis.

![Figure 5.46. Placement of the central clay block.](image)

As a result, 2.180Kgr of saturated sand, as well as 0.795Kgr of water had to be removed from the perimeter of this block, in order for the two smaller blocks to be placed. The gaps between the clay blocks were consequently filled with 0.750Kgr of slurry.
The total soil thickness was estimated after the end of the above procedure, for 15 points on the ground surface, and the results are shown in Figure 5.46. A cross-section of the soil profile is also shown in Figure 5.47.

**Figure 5.47.** Total soil thickness, after the placement of the clay layer.

**Figure 5.48.** Soil profile, after the placement of the clay layer.

As it may be observed in the above figure, the average settlement after the placement of the clay cap was equal to 20mm. Assuming an initial void ratio of $e_o = 0.796$, this settlement corresponds to a volumetric strain of $\Delta e_{vol} = 7.04\%$, a void ratio decrease of $\Delta e = 0.126$ and a relative density increase of $\Delta D_r = 31.5\%$. Thus, the final void ratio of the sand layer may be estimated as $e = 0.670$, which corresponds to a relative density of $D_r = 85.8\%$. 


Due to the uncertainties in the total mass of the model, the ESB box was weighed after placing the clay cap and perimetrically sealing the gaps with slurry. The total mass was found equal to 203.0Kgr. Subtracting the mass of the ESB box (105.5Kgr), the total mass of the saturated sand and the overlying clay layer may be estimated as 97.5Kgr.

5.3.4. Centrifuge Test #3

Since the third test was performed several months after the first two ones, a new clay layer had to be prepared in the consolidation tub. Similar to the previous tests, this layer was over-consolidated to 400KPa and the applied pressure was consequently decreased to 80KPa. Both loading and unloading stages were applied incrementally, allowing adequate time between the application of successive increments. The consolidation procedure was finished and the clay layer was placed on the model on 10/05/2011, while the test was performed two days later, on 12/05/2010.

Three blocks of clay were cut: a large one, with dimensions of about 440mm x 220mm x 100mm and a mass of 18.105Kgr, as well as two smaller ones, with dimensions of about 90mm x 220mm x 100mm and a total mass of 7.590Kgr (both pieces together). Note that the plan dimensions of the clay blocks were slightly smaller than in the previous tests. This was considered necessary, in order to facilitate the placement of the thicker and heavier blocks on top of the sand layer.

In order to avoid the problems faced during the preparation of Centrifuge Test #2 (significant settlement of the central clay block, before the placement of the smaller blocks at the sides), all three blocks were placed on top of the sand layer as quickly as possible, one after the other.

As it was expected, significant settlements were observed after the placement of the clay layer, similar to the previous tests. More specifically, the central clay block settled by 8mm, while the smaller ones settled by 5mm. If the settlement during the saturation procedure is also taken into account, the total average settlement of the sand layer was equal to 7mm. Assuming an initial void ratio of $e_o = 0.840$, this settlement corresponds to a volumetric strain of $\Delta e_{vol} = 3.04\%$, a void ratio decrease of $\Delta e = 0.056$ and a relative density increase of $\Delta D_r = 14.0\%$. Thus, the final void ratio of the sand layer may be estimated as $e = 0.784$, which corresponds to a relative
density of $D_r = 57.4\%$. It is noted that, after the completion of sand settlements, the model surface remained level (Figure 5.49).

As sand settlement occurred, the gaps between the clay blocks were filled with water, as well as with a small amount of sand. A standpipe was also connected to the ESB box (Figure 5.50), allowing for excess pore pressures to dissipate from the model’s base. Nevertheless, the amount of water that flew out of the standpipe was minimal, compared to the water flowing upwards, which was subsequently removed with a syringe. The total mass of water removed from the model was equal to 0.360Kgr. Finally, the gaps between the clay blocks were filled with 2.750Kgr of slurry.

Figure 5.49. Centrifuge model after the placement of the clay layer.
Figure 5.50. Centrifuge model, after filling the gaps with slurry.
6. Centrifuge Preparation

6.1. BALANCE CALCULATIONS

Detailed balance calculations preceded the execution of each centrifuge test, listing the masses and centers of gravity of every component of the centrifuge package and indicating the necessary counterweight that needs to be attached to the centrifuge’s “red end” before spinning. The tests were only carried out if the total mass of the package, which was checked just before loading, matched these calculations.

The balance calculation worksheets for each Centrifuge Test are shown in Figure 6.1 to Figure 6.6.
Balance Calculations for new SAM ACTUATOR Beam Centrifuge Tests

Test Id: TNA1 / Test 1  Date: 17/11/2010

Brief Description of the test:
TNA Bouckovalas

Origin O is taken at the center of the surface of the swinging platform (in plan view)

Include all items you have with the closest mass and centroid distances under bold columns only

You are allowed to leave extra rows free with 0 in the Mass column

SAM + Swing should be 672.3kg

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Figure 6.2. Balance Calculations for Centrifuge Test #1 (Part b).
## Balance Calculations for new SAM ACTUATOR Beam Centrifuge Tests

**Test Id:** TNA1 / Test 2  
**Date:** 30/11/2010

**Brief Description of the test:** TNA Bouckovalas  
**SAM only**

---

SAM + Swing should be 550.90 kg

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<td>20</td>
<td>Gantry</td>
<td>8.425</td>
<td>633.5</td>
<td>447.5</td>
<td>31.5</td>
<td>5337.2375</td>
<td>3770.188</td>
<td>265.3875</td>
<td>285.67 kg</td>
</tr>
<tr>
<td>21</td>
<td>Piston + spacers + connector (including load cell)</td>
<td>10.01</td>
<td>1041</td>
<td>157.5</td>
<td>0</td>
<td>10420.41</td>
<td>1576.575</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>22</td>
<td>Foundation</td>
<td>0.69</td>
<td>704</td>
<td>157.5</td>
<td>0</td>
<td>485.76</td>
<td>108.675</td>
<td>25.9875</td>
<td>285.67 kg</td>
</tr>
<tr>
<td>23</td>
<td>Potentiometer</td>
<td>0.165</td>
<td>914</td>
<td>157.5</td>
<td>0</td>
<td>150.81</td>
<td>25.9875</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>24</td>
<td>Solenoid Valve for the drainage</td>
<td>0.245</td>
<td>350</td>
<td>157.5</td>
<td>0</td>
<td>85.75</td>
<td>38.5875</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Mass</strong></td>
<td><strong>836.57 kg</strong></td>
<td><strong>SUM</strong> =</td>
<td><strong>302896.34 kg</strong></td>
<td><strong>-1009.71 kg</strong></td>
<td><strong>-11859.02 kg</strong></td>
<td><strong>Calculations set up by:</strong> Dr. Gopal Madabhushi, Asst. Director, GCC ; 27-8-98</td>
<td><strong>Swing</strong> =</td>
<td><strong>550.90 kg</strong></td>
<td><strong>Swing</strong> =</td>
</tr>
</tbody>
</table>
### Centroidal distances of the payload only

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
<th>Xpay (mm)</th>
<th>Ypay (mm)</th>
<th>Zpay (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing</td>
<td>125.1</td>
<td>72.6</td>
<td>-1.6</td>
<td>0</td>
</tr>
</tbody>
</table>

### Centroidal distances of the swing only

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
<th>Xswing (mm)</th>
<th>Yswing (mm)</th>
<th>Zswing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing</td>
<td>125.1</td>
<td>72.6</td>
<td>-1.6</td>
<td>0</td>
</tr>
</tbody>
</table>

### Combined centroidal distances of payload and swing

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
<th>M.X</th>
<th>M.Y</th>
<th>M.Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing</td>
<td>125.1</td>
<td>72.6</td>
<td>-1.6</td>
<td>0</td>
<td>9082.26</td>
<td>-200.16</td>
<td>0</td>
</tr>
<tr>
<td>Payload</td>
<td>836.57</td>
<td>362.0717244</td>
<td>-1.206964</td>
<td>-14.17577</td>
<td>302898.34</td>
<td>-1009.71</td>
<td>-11859.02</td>
</tr>
</tbody>
</table>

**Sum =** 961.67

**Sum =** 311980.6

**Sum =** -1209.87

**Sum =** -11859.02

### Combined C.G of the payload and swing

**Xcomb =** 324.415446

**Ycomb =** -1.258092693

**Zcomb =** -12.33169642

**n =** (808.4 - Xcomb) / (98.4 - Ycomb) = 4.85645

**Swing up RPM =** w = \[60/(2*3.14)\]*\sqrt{\text{n} \cdot g \cdot 1000/(4125-\text{Xcomb})} = 33.8

### Counter Weight Calculation

**Mass of the counter weight =** 3.557 (kg/mm)

From earlier calculations Moment due to payload = 3147952.9

Lower moment due to lighter new blue swing = 9174

\[3.557 \cdot (808.4 - \text{Xcomb}) = 3138780\]

Solving for 't' we have

\[t = 8030.224484\] or \[t = 219.7755159\]

Selecting the smaller counterweight at larger distance we have

**t = 219.7755159**

**Centroid Radius Red End =** 4.015112

**Mass of the counter weight (Mcw) =** 781.7415 (kg-mm)

**Moment at the Red end =** 3138780

**Moment at the Blue end =** 3147953

Including moment due to difference in swings = 3138779.9

### Swing Up of the RED End with Counter weight

**Centroidal distance along X axis =** \[127 \cdot 61 + Mcw/2]/(127 + Mcw) = 103.05551

**n =** (808.4 - Xred) / 98.4 = 7.168135

**Swing up RPM =** w = \[60/(2*3.14)\]*\sqrt{\text{n} \cdot g \cdot 1000/(4125-\text{Xred})} = 39.9

---

**Figure 6.4.** Balance Calculations for Centrifuge Test #2 (Part b).
Figure 6.5 Balance Calculations for new SAM ACTUATOR Beam Centrifuge Tests

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Description</th>
<th>Mass (kg)</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
<th>M.X (kg-mm)</th>
<th>M.Y (kg-mm)</th>
<th>M.Z (kg-mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T-Plate (fabricated unit)</td>
<td>123.62</td>
<td>163</td>
<td>-133</td>
<td>-28</td>
<td>20150.06</td>
<td>-16441.46</td>
<td>-3461.36</td>
</tr>
<tr>
<td>2</td>
<td>Blue Face Plate</td>
<td>208.21</td>
<td>120</td>
<td>145</td>
<td>0</td>
<td>24985.20</td>
<td>30190.45</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Clutch</td>
<td>19.15</td>
<td>270</td>
<td>-215</td>
<td>50</td>
<td>5170.50</td>
<td>-4117.25</td>
<td>957.5</td>
</tr>
<tr>
<td>4</td>
<td>Motor</td>
<td>66.00</td>
<td>555</td>
<td>-315</td>
<td>-250</td>
<td>36630</td>
<td>-20790</td>
<td>-16500</td>
</tr>
<tr>
<td>5</td>
<td>Aluminium flywheel</td>
<td>5.00</td>
<td>555</td>
<td>-525</td>
<td>-250</td>
<td>2775</td>
<td>-2625</td>
<td>-1250</td>
</tr>
<tr>
<td>6</td>
<td>SAM Actuator</td>
<td>73.00</td>
<td>570</td>
<td>-290</td>
<td>50</td>
<td>41610</td>
<td>-21170</td>
<td>3650</td>
</tr>
<tr>
<td>7</td>
<td>Accumulator (Full)*</td>
<td>18.98</td>
<td>220</td>
<td>-435</td>
<td>120</td>
<td>4175.6</td>
<td>-8256.3</td>
<td>2277.6</td>
</tr>
<tr>
<td>8</td>
<td>Balance Mass</td>
<td>3.74</td>
<td>100</td>
<td>-215</td>
<td>0</td>
<td>374</td>
<td>-804.1</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>Control Systems</td>
<td>4.5</td>
<td>45</td>
<td>-315</td>
<td>300</td>
<td>202.5</td>
<td>-1417.5</td>
<td>1350</td>
</tr>
<tr>
<td>10</td>
<td>Pneumatic Cylinder</td>
<td>1.5</td>
<td>145</td>
<td>-215</td>
<td>110</td>
<td>217.5</td>
<td>-322.5</td>
<td>165</td>
</tr>
<tr>
<td>11</td>
<td>Junction box support</td>
<td>11</td>
<td>773.75</td>
<td>-235</td>
<td>50</td>
<td>8511.25</td>
<td>-2585</td>
<td>550</td>
</tr>
<tr>
<td>12</td>
<td>CDAQS+3 Junc. Box</td>
<td>9.6</td>
<td>813.75</td>
<td>-230</td>
<td>-35</td>
<td>7812</td>
<td>-2208</td>
<td>-336</td>
</tr>
<tr>
<td>13</td>
<td>CPT Gantry Supports</td>
<td>6.6</td>
<td>550</td>
<td>100</td>
<td>50</td>
<td>3630</td>
<td>660</td>
<td>330</td>
</tr>
<tr>
<td>14</td>
<td>Webcam</td>
<td>0.55</td>
<td>838</td>
<td>-50</td>
<td>125</td>
<td>460.9</td>
<td>-27.5</td>
<td>68.75</td>
</tr>
<tr>
<td>15</td>
<td>Shaking Table</td>
<td>58</td>
<td>275</td>
<td>190</td>
<td>0</td>
<td>15950</td>
<td>11020</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>Deep ESB Box</td>
<td>101</td>
<td>554</td>
<td>157.5</td>
<td>0</td>
<td>55954</td>
<td>15907.5</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>Sand + MC (incl instruments)</td>
<td>103.3</td>
<td>529</td>
<td>157.5</td>
<td>0</td>
<td>54645.7</td>
<td>16269.75</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>LVDT Ga nties (incl 2 LVDT)</td>
<td>3.315</td>
<td>788.5</td>
<td>157.5</td>
<td>0</td>
<td>2613.8775</td>
<td>522.1125</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>Power Supply</td>
<td>1.025</td>
<td>886.5</td>
<td>-102.5</td>
<td>95</td>
<td>908.6625</td>
<td>-105.0625</td>
<td>97.375</td>
</tr>
<tr>
<td>20</td>
<td>Solenoid Valve for the cylinder</td>
<td>0.245</td>
<td>885</td>
<td>-102.5</td>
<td>-95</td>
<td>216.825</td>
<td>-251125</td>
<td>-23275</td>
</tr>
<tr>
<td>21</td>
<td>Gantry</td>
<td>8.425</td>
<td>633.5</td>
<td>447.5</td>
<td>31.5</td>
<td>5337.2375</td>
<td>3770.188</td>
<td>2653875</td>
</tr>
<tr>
<td>22</td>
<td>Piston + spacers + connector (incl load cell)</td>
<td>10.01</td>
<td>1041</td>
<td>157.5</td>
<td>0</td>
<td>10420.41</td>
<td>1576575</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>Foundation</td>
<td>0.69</td>
<td>704</td>
<td>157.5</td>
<td>0</td>
<td>485.76</td>
<td>108675</td>
<td>0</td>
</tr>
<tr>
<td>24</td>
<td>Potentiometer</td>
<td>0.165</td>
<td>914</td>
<td>157.5</td>
<td>0</td>
<td>150.81</td>
<td>259875</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>Solenoid Valve for the drainage</td>
<td>0.245</td>
<td>350</td>
<td>157.5</td>
<td>0</td>
<td>85.75</td>
<td>385875</td>
<td>0</td>
</tr>
</tbody>
</table>

**Total Mass =**

**SUM =**

Calculations set up by: Dr. Gopal Madabhushi, Asst. Director, GCC; 27-8-98

*Note: The calculations are set up to ensure the balance of the system during the centrifuge test.*
Figure 6.6. Balance Calculations for Centrifuge Test #3 (Part b).
6.2. PRE-FLIGHT OPERATIONS

Once the total mass of the package was confirmed, the centrifuge package and counterweight were loaded (Figure 6.7) on the corresponding ends of the rotating arm. Since sand models saturated with viscous fluid can easily liquefy due to even small vibrations, the ESB box was loaded last, only after the swing and the SAM actuator were fitted to the beam. In order to avoid undesired displacements, the footing was placed on the soil surface just prior to testing. The junction boxes were bolted to the SAM’s gantries and the instrumentation was consequently connected to them, with all the cables being firmly tied. A web-cam was also placed on the ESB box (Figure 6.12), in order to monitor the model’s behavior on flight.

The actuator was installed on a specially designed gantry and its height was adjusted, so that the actuator’s tip would leave a 3mm gap from the top of the footing. The piston’s pressure lines were connected to the centrifuge’s main air pressure system, through a pressure switch, that would allow the actuator to either be held up, or to push the footing downwards. The corresponding pressure was set to 650KPa.

Furthermore, a standpipe was installed (Figure 6.13), that would allow drainage of the saturated sand through the bottom of the ESB box. The standpipe was configured so that the water table could be fixed at about 5mm above the initial sand-clay interface. Note that if the water table was set above the soil surface, the effective stresses in the clay layer would be lower and its undrained shear strength would be consequently decreased. During centrifuge swinging-up, the bearing pressure applied by the footing would increase instantly. However, the effective stresses in the clay layer would not increase until the excess pore pressure had dissipated. As a result, failure would have occurred within the clay layer, which would have not developed an adequate shear strength.

An electromagnetic valve was added to the standpipe, allowing water flow to be switched on or off from the control room. In this way, as the sand layer would consolidate, during swinging-up, excess pore pressures would be allowed to dissipate, in order to avoid the formation of sand boils through the clay layer. The valve would be turned off before shaking, so that the liquefaction-induced excess pore pressures do not dissipate through the standpipe. Note that the valve remained closed during the post-shaking loading of the foundation.
Prior to testing, lab vane tests were performed on the surface of the two clay blocks near the model’s edges (Figure 6.14). An undrained shear strength of \( c_u = 18 \pm 3 \text{KPa} \) was measured for Test #1, while the corresponding value for Tests #2 and #3 were \( c_u = 23 \pm 2 \text{KPa} \) and \( c_u = 11 \pm 1 \text{KPa} \), respectively. Note that these values are considerably less than the lab vane measurements taken at the consolidation tub.

Once the model was finalized (Figure 6.8 & Figure 6.11), the CDAQS Data Acquisition System was set-up and the pressure in the accumulator required to activate SAM’s fast-acting hydraulic clutch was checked. Finally, a last safety check of all the package and centrifuge components and the counterweight mass was performed.

### 6.2.1. Photos from Centrifuge Model #1

*Figure 6.7.* Centrifuge model being loaded to the centrifuge.
Figure 6.8. Centrifuge model #1.
6.2.2. Photos from Centrifuge Model #2

Figure 6.9. Centrifuge model ready to be loaded.

Figure 6.10. Weighing of centrifuge model before loading.
Figure 6.11. Centrifuge model #2.

Figure 6.12. Webcam placed on the ESB box.
Figure 6.13. Stand-pipe system.

Figure 6.14. Lab vane measurements prior to testing.
6.2.3. Photos from Centrifuge Model #3

![Image of Centrifuge Model #3 (model footing and actuator)](image1.png)

**Figure 6.15.** Centrifuge model #3 (model footing and actuator).

![Image of Centrifuge Model #3 (footing close-up)](image2.png)

**Figure 6.16.** Centrifuge model #3 (footing close-up).
Figure 6.17. Centrifuge model #3.
Figure 6.18. Centrifuge model #3 (stand-pipe).
7. Test Procedures

Once centrifuge operators and researchers were satisfied with pre-flight checks, the centrifuge was started and accelerated up to 50g, in five increments of 10g each. At each stage, a time of about 25mins was allowed for the clay layer to consolidate, as well as for (static settlement-induced) excess pore pressures in the sand layer to dissipate through the standpipe system. Furthermore, the readings of transducers were manually recorded every 5mins. During this phase, the model was permanently monitored through a camera installed near the beam’s axis, as well as through the webcam placed on the ESB box (Figure 6.12).

When a centrifugal acceleration of 50g was reached (at the base of the model), and after consolidation had finished, the drainage valve was switched off and the data acquired during this phase were uploaded from the data acquisition system to the computer terminal (Section 2.4).

CDAQS was consequently prepared for data acquisition during the earthquake and after the end of shaking, as described in Section 2.4. An electronic timer triggering the data acquisition system and controlling the solid-state relays on the SAM actuator was also set-up, in order to define the initial countdown, the duration of the earthquake and the piston’s movement for the post-shaking loading of the foundation.

To fire the earthquake excitation, the motor of the SAM actuator was turned on and the magnitude of the earthquake was selected by adjusting, through the readings of an LVDT, the length of the lever arm that connects the package to the rotating shaft. The clutch was then forced into a central position, by supplying compressed air to the clutch centering mechanism. After starting the SAM motor, and after taking it to the desired speed, defined in relation to the frequency of the seismic excitation, the timer was started and an earthquake simulation was fired after 20s. Immediately after the end of the earthquake excitation, the previously set-up electronic timer triggered the pressure switch that controlled the piston’s movement, so that the post-shaking loading of the footing was performed.
The data were automatically collected for the short period of seismic shaking and post-shaking loading of the foundation and long-term readings started after the end of this period. After stopping the SAM motor, the data were uploaded to the computer terminal and the centrifuge was slowed down slowly, until complete stop.

Figure 7.1. Control Room.
7.1.1. Photos from Centrifuge Test #1

1. 

5. 

2. 

6. 

3. 

7. 

4. 

8. 

Figure 7.2. Webcam photos from Centrifuge Test #1.
7.1.2. Photos from Centrifuge Test #2

Figure 7.3. Webcam photos from Centrifuge Test #2.
7.1.3. Photos from Centrifuge Test #3

Figure 7.4. Webcam photos from Centrifuge Test #3.
8. Test Data

A total of 27 channels were recorded by the data acquisition system, through two different junction boxes. The first junction box accommodated 11 channels, recording the accelerometers’ response. The second junction box accommodated 9 channels for PPTs, 1 channel for the Load Cell, 2 channels for the LVDTs, 1 channel for the Potentiometer and 3 channels for the MEMS accelerometers. As explained in Section 2.4, swing-up data were recorded at a slow acquisition rate of 3Hz, earthquake data were consequently recorded for 4sec, at a fast rate of 2kHz, and post-shaking data were finally recorded at a relatively slow acquisition rate of 10Hz.

8.1.1. Centrifuge Test #1

Figure 8.1 to Figure 8.5 present the time histories of the instrument recordings during spin-up. All data records were appropriately corrected, so that the corresponding time histories start from zero, and the calibration factors presented in Section 4 were consequently applied. Note that the time-histories in the following figures are presented in model scale.
Figure 8.1. Pore-pressures during spin-up (model scale) – Test #1.
Figure 8.2. Pore-pressures during spin-up (model scale) – Test #1.
Figure 8.3. Free field and foundation settlements during spin-up (model scale) – Test #1.

Figure 8.4. Load cell recordings during spin-up (model scale) – Test #1.
Figure 8.5. MEMS accelerometer recordings during spin-up (model scale) – Test #1.

The pore pressures recorded by the PPTs in the end of the spin-up phase are summarized in Table 8.1.

Table 8.1. Pore pressures in the end of the spin-up phase – Test #1.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Pore Pressure (KPa)</th>
<th>Instrument</th>
<th>Pore Pressure (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPT 1</td>
<td>-</td>
<td>PPT 5</td>
<td>39.5</td>
</tr>
<tr>
<td>PPT 2</td>
<td>-</td>
<td>PPT 6</td>
<td>13.4</td>
</tr>
<tr>
<td>PPT 3</td>
<td>-</td>
<td>PPT 7</td>
<td>5.1</td>
</tr>
<tr>
<td>PPT 4</td>
<td>48.8</td>
<td>PPT 8</td>
<td>18.0</td>
</tr>
</tbody>
</table>
Figure 8.6 to Figure 8.13 present the instrument recordings during shaking, as well as during the post-shaking loading of the foundation. All recordings are presented in prototype scale. Details of the acceleration, excess-pore pressure and settlement time-histories, during shaking, are presented in Figure 8.14 to Figure 8.20.

**Figure 8.6.** Acceleration time-histories (prototype scale) – Test #1.
Figure 8.7. Acceleration time-histories (prototype scale) – Test #1.
Figure 8.8. Acceleration time-histories (prototype scale) – Test #1.

Figure 8.9. Acceleration time-histories (prototype scale) – Test #1.
Figure 8.10. Excess pore pressure time-histories (prototype scale) – Test #1.
Figure 8.11. Excess pore pressure time-histories (prototype scale) – Test #1.
Figure 8.12. Free-field and foundation time-histories (prototype scale) – Test #1.

Figure 8.13. Time-history of the load applied by the actuator to the footing (prototype scale) – Test #1.
Figure 8.14. Accelerations during earthquake (prototype scale) – Test #1.
Figure 8.15. Accelerations during earthquake (prototype scale) – Test #1.
Figure 8.16. Accelerations during earthquake (prototype scale) – Test #1.

Figure 8.17. Accelerations during earthquake (prototype scale) – Test #1.
Figure 8.18. Excess pore pressure during earthquake (prototype scale) – Test #1.
Figure 8.19. Excess pore pressure during earthquake (prototype scale) – Test #1.
Figure 8.20. Free-field and foundation settlements during earthquake (prototype scale) – Test #1.
Figure 8.21 to Figure 8.24 present the post-shaking instrument recordings, until the centrifuge was spinned-down. The recordings are presented in prototype scale.

**Figure 8.21.** Post-shaking excess pore pressure time-histories (prototype scale) – Test #1.
Figure 8.22. Post-shaking excess pore pressure time-histories (prototype scale) – Test #1.
Figure 8.23. Post-shaking settlement time-histories (prototype scale) – Test #1.

Figure 8.24. Post-shaking time-history of pressure applied by the actuator to the footing (prototype scale) – Test #1.
The excess pore pressures recorded by the PPTs in the end of the test are summarized in Table 8.2.

**Table 8.2.** Excess pore pressures in the end of Test #1.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Excess Pore Pressure (KPa)</th>
<th>Instrument</th>
<th>Excess Pore Pressure (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPT 1</td>
<td>-</td>
<td>PPT 5</td>
<td>32.8</td>
</tr>
<tr>
<td>PPT 2</td>
<td>-</td>
<td>PPT 6</td>
<td>28.8</td>
</tr>
<tr>
<td>PPT 3</td>
<td>-</td>
<td>PPT 7</td>
<td>32.9</td>
</tr>
<tr>
<td>PPT 4</td>
<td>29.2</td>
<td>PPT 8</td>
<td>34.0</td>
</tr>
</tbody>
</table>
8.1.2. Centrifuge Test #2

Figure 8.25 to Figure 8.29 present the time histories of the instrument recordings during spin-up. Note that due to a failure of the data acquisition system, the data presented herein are the ones obtained manually, at time intervals of about 5 to 10 minutes. The recordings were appropriately corrected, so that the corresponding time histories start from zero, and the calibration factors presented in Section 4 were consequently applied. Note that the time-histories in the following figures are presented in model scale.
Figure 8.25. Pore-pressures during spin-up (model scale) – Test #2.
Figure 8.26. Pore-pressures during spin-up (model scale) – Test #2.
Figure 8.27. Free field and foundation settlements during spin-up (model scale) – Test #2.

Figure 8.28. Load cell recordings during spin-up (model scale) – Test #2.
Figure 8.29. MEMS accelerometer recordings during spin-up (model scale) – Test #2.

The pore pressures recorded by the PPTs in the end of the spin-up phase are summarized in Table 8.3.

Table 8.3. Pore pressures in the end of the spin-up phase – Test #2.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Pore Pressure (KPa)</th>
<th>Instrument</th>
<th>Pore Pressure (KPa)</th>
</tr>
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<tbody>
<tr>
<td>PPT 1</td>
<td>115.6</td>
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<td>PPT 2</td>
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<td>19.2</td>
</tr>
<tr>
<td>PPT 3</td>
<td>77.3</td>
<td>PPT 7</td>
<td>12.4</td>
</tr>
<tr>
<td>PPT 4</td>
<td>38.3</td>
<td>PPT 8</td>
<td>46.6</td>
</tr>
</tbody>
</table>
Figure 8.30 to Figure 8.37 present the instrument recordings during shaking, as well as during the post-shaking loading of the foundation. All recordings are presented in prototype scale. Details of the acceleration, excess-pore pressure and settlement time-histories, during shaking, are presented in Figure 8.38 to Figure 8.44.

![Graphs showing acceleration time-histories](image)

**Figure 8.30.** Acceleration time-histories (prototype scale) – Test #2.
Figure 8.31. Acceleration time-histories (prototype scale) – Test #2.
Figure 8.32. Acceleration time-histories (prototype scale) – Test #2.

Figure 8.33. Acceleration time-histories (prototype scale) – Test #2.
Figure 8.34. Excess pore pressure time-histories (prototype scale) – Test #2.
Figure 8.35. Excess pore pressure time-histories (prototype scale) – Test #2.
Figure 8.36. Free-field and foundation time-histories (prototype scale) – Test #2.

Figure 8.37. Time-history of the load applied by the actuator to the footing (prototype scale) – Test #2.
Figure 8.38. Accelerations during earthquake (prototype scale) – Test #2.
Figure 8.39. Accelerations during earthquake (prototype scale) – Test #2.
Figure 8.40. Accelerations during earthquake (prototype scale) – Test #2.

Figure 8.41. Accelerations during earthquake (prototype scale) – Test #2.
Figure 8.42. Excess pore pressure during earthquake (prototype scale) – Test #2.
Figure 8.43. Excess pore pressure during earthquake (prototype scale) – Test #2.
Figure 8.44. Free-field and foundation settlements during earthquake (prototype scale) – Test #2.
Figure 8.45 to Figure 8.48 present the post-shaking instrument recordings, until the centrifuge was spun down. The recordings are presented in prototype scale.

**Figure 8.45.** Post-shaking excess pore pressure time-histories (prototype scale) – Test #2.
**Figure 8.46.** Post-shaking excess pore pressure time-histories (prototype scale) – Test #2.
**Figure 8.47.** Post-shaking settlement time-histories (prototype scale) – Test #2.

**Figure 8.48.** Post-shaking time-history of pressure applied by the actuator to the footing (prototype scale) – Test #2.
The excess pore pressures recorded by the PPTs in the end of the test are summarized in Table 8.4.

**Table 8.4.** Excess pore pressures in the end of Test #2.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Excess Pore Pressure (KPa)</th>
<th>Instrument</th>
<th>Excess Pore Pressure (KPa)</th>
</tr>
</thead>
<tbody>
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<td>PPT 3</td>
<td>21.0</td>
<td>PPT 7</td>
<td>23.2</td>
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<tr>
<td>PPT 4</td>
<td>16.0</td>
<td>PPT 8</td>
<td>23.1</td>
</tr>
</tbody>
</table>
8.1.3. Centrifuge Test #3

Figure 8.49 to Figure 8.53 present the time histories of the instrument recordings during spin-up. The recordings were appropriately corrected, so that the corresponding time histories start from zero, and the calibration factors presented in Section 4 were consequently applied. All the time-histories in the following figures are presented in model scale.
**Figure 8.49.** Pore-pressures during spin-up (model scale) – Test #3.
Figure 8.50. Pore-pressures during spin-up (model scale) – Test #3.
Figure 8.51. Free field and foundation settlements during spin-up (model scale) – Test #3.

Figure 8.52. Load cell recordings during spin-up (model scale) – Test #3.
Figure 8.53. MEMS accelerometer recordings during spin-up (model scale) – Test #3.

The pore pressures recorded by the PPTs at the end of the spin-up phase are summarized in Table 8.5.

Table 8.5. Pore pressures in the end of the spin-up phase – Test #3.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Pore Pressure (KPa)</th>
<th>Instrument</th>
<th>Pore Pressure (KPa)</th>
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<td>PPT 3</td>
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<td>-</td>
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<tr>
<td>PPT 4</td>
<td>39.5</td>
<td>PPT 8</td>
<td>11.8</td>
</tr>
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</table>
Figure 8.54 to Figure 8.61 present the instrument recordings during shaking, as well as during the post-shaking loading of the foundation. All recordings are presented in prototype scale. Details of the acceleration, excess-pore pressure and settlement time-histories, during shaking, are presented in Figure 8.62 to Figure 8.68.

**Figure 8.54.** Acceleration time-histories (prototype scale) – Test #3.
Figure 8.55. Acceleration time-histories (prototype scale) – Test #3.
Figure 8.56. Acceleration time-histories (prototype scale) – Test #3.

Figure 8.57. Acceleration time-histories (prototype scale) – Test #3.
Figure 8.58. Excess pore pressure time-histories (prototype scale) – Test #3.
Figure 8.59. Excess pore pressure time-histories (prototype scale) – Test #3.
Figure 8.60. Free-field and foundation time-histories (prototype scale) – Test #3.

Figure 8.61. Time-history of the load applied by the actuator to the footing (prototype scale) – Test #3.
Figure 8.62. Accelerations during earthquake (prototype scale) – Test #3.
Figure 8.63. Accelerations during earthquake (prototype scale) – Test #3.
Figure 8.64. Accelerations during earthquake (prototype scale) – Test #3.

Figure 8.65. Accelerations during earthquake (prototype scale) – Test #3.
Figure 8.66. Excess pore pressure during earthquake (prototype scale) – Test #3.
Figure 8.67. Excess pore pressure during earthquake (prototype scale) – Test #3.
Figure 8.68. Free-field and foundation settlements during earthquake (prototype scale) – Test #3.
Figure 8.69 to Figure 8.72 present the post-shaking instrument recordings, until the centrifuge was spinned-down. The recordings are presented in prototype scale.

**Figure 8.69.** Post-shaking excess pore pressure time-histories (prototype scale) – Test #3.
Figure 8.70. Post-shaking excess pore pressure time-histories (prototype scale) – Test #3.
Figure 8.71. Post-shaking settlement time-histories (prototype scale) – Test #3.

Figure 8.72. Post-shaking time-history of pressure applied by the actuator to the footing (prototype scale) – Test #3.
The excess pore pressures recorded by the PPTs in the end of the test are summarized in Table 8.6.

**Table 8.6.** Excess pore pressures in the end of Test #3.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Excess Pore Pressure (KPa)</th>
<th>Instrument</th>
<th>Excess Pore Pressure (KPa)</th>
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<td>PPT 2</td>
<td>41.8</td>
<td>PPT 6</td>
<td>44.1</td>
</tr>
<tr>
<td>PPT 3</td>
<td>43.0</td>
<td>PPT 7</td>
<td>-</td>
</tr>
<tr>
<td>PPT 4</td>
<td>42.5</td>
<td>PPT 8</td>
<td>46.6</td>
</tr>
</tbody>
</table>
9. Post-testing observations & measurements

When centrifuge testing was completed, a preliminary inspection of the model was carried out at the centrifuge beam. During this first phase, lab shear vane tests were performed on the clay surface and measurements of the soil surface settlement were obtained.

The ESB box was unloaded one day later, after disconnecting the cables and disassembling the gantries where the actuator had been placed. The model was consequently inspected again and carefully excavated. During this second phase, detailed measurements were obtained for both the soil surface and the sand-clay interface elevations. Lab shear vane tests were also performed at the bottom, as well as at the middle of the clay layer, after taking clay blocks out of the ESB box, and cutting them with a metal knife, lubricated with silicon oil. The post-test instrument positions were also established and the excavated sand and clay were re-weighted.

9.1.1. Centrifuge Test #1

Figure 9.1 to Figure 9.4 present Centrifuge Model #1, immediately after the end of testing. As shown in Figure 9.2 to Figure 9.4, three (3) sand-boils were observed on the clay surface, with diameters of 50mm, 55mm and 65mm. These sand-boils were located at the connection joints between the central clay block and the two side clay blocks (see Section 5.3).
**Figure 9.1.** Post-test view of Centrifuge Model #1.

**Figure 9.2.** Post-test view of Centrifuge Model #1.
Figure 9.3. Sand-boil observed on the clay surface, at the junction between the central and the side clay blocks.

Figure 9.4. Sand-boils observed on the clay surface, at the junction between the central and the side clay blocks.

Shear vane tests were performed on the clay surface, immediately after the end of testing and an undrained shear strength of $c_u = 35 \pm 3$KPa was measured. When the
model was unloaded from the centrifuge beam, more shear vane tests were performed, giving the following average measurements:

- Top of central clay block: $c_u = 39 \pm 3$ KPa
- Top of side clay blocks: $c_u = 24 \pm 1$ KPa
- Bottom of central clay block: $c_u = 34 \pm 4$ KPa
- Bottom of side clay blocks: $c_u = 38 \pm 3$ KPa
- Middle of central clay block: $c_u = 18 \pm 2$ KPa
- Middle of side clay blocks: $c_u = 18 \pm 2$ KPa

The total thickness of both the sand and clay layers, after the end of Centrifuge Test #1 are illustrated in model scale, in Figure 9.5, while the thickness of the sand layer is presented in Figure 9.6. Finally, a cross-section of the soil profile along the model’s x-axis is shown in Figure 9.7.

![Figure 9.5](image-url)  
*Figure 9.5.* Post-testing total soil thickness (in model scale).
Figure 9.6. Post-testing thickness of sand layer (in model scale)

Figure 9.7. Cross-section of the deformed soil profile (in model scale).

Photos taken during the model’s excavation are presented in Figure 9.8 to Figure 9.12. More specifically, the location and size of the aforementioned sand-boils may be observed in the plan-view of Figure 9.8. Figure 9.9 presents one of the edges, around the central clay block, which was filled with sand, as described in Section 5.3. Figure 9.10 and Figure 9.11 present the deformation mode of the clay layer, underneath the footing. Note that the crack observed in these figures developed during the excavation procedure and not during testing. Finally, Figure 9.12 is indicative of the high negative pore pressure (suction) existing in the over-consolidated clay layer.
Figure 9.8. Post-test plan-view of Centrifuge Model #1.

Figure 9.9. Edge around the central clay block.
Figure 9.10. Clay deformation underneath the footing.

Figure 9.11. Central clay block, indicating the failure mechanism underneath the footing.
Figure 9.12. Negative pore pressure (suction) in the over-consolidated clay layer.
The post-test instrument positions were measured during the excavation procedure and are presented in Table 9.1. Figure 9.13 and Figure 9.14 present a plan view of the higher level of instruments. A significant inclination was observed in all these instruments, due to soil settlement, both during the model’s preparation and during the subsequent shaking and post-shaking vertical loading.

**Table 9.1.** Post-test instrument positions (in model scale) in Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC 1</td>
<td>338</td>
<td>130</td>
<td>16</td>
</tr>
<tr>
<td>ACC 2</td>
<td>335</td>
<td>125</td>
<td>72</td>
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<tr>
<td>ACC 3</td>
<td>505</td>
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<td>70</td>
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<tr>
<td>ACC 4</td>
<td>345</td>
<td>118</td>
<td>149</td>
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<td>ACC 5</td>
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<td>ACC 6</td>
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<td>PPT 3</td>
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<td>154</td>
</tr>
<tr>
<td>PPT 5</td>
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<td>108</td>
<td>155</td>
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<tr>
<td>PPT 6</td>
<td>162</td>
<td>121</td>
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</tr>
<tr>
<td>PPT 7</td>
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<tr>
<td>PPT 8</td>
<td>327</td>
<td>104</td>
<td>197</td>
</tr>
</tbody>
</table>
Figure 9.13.  Post-test plan view of the higher level of instruments, within the sand layer.

Figure 9.14.  Post-test position of the higher level of instruments, within the sand layer.

After the excavation, the total mass of the clay (including the slurry) was found equal to 17.420Kgr, while the mass of the saturated sand and of the water removed from the model’s surface was found equal to 82.180Kgr.
9.1.2. Centrifuge Test #2

Figure 9.15 and Figure 9.16 present Centrifuge Model #2, immediately after the end of testing.

Figure 9.15. Post-test view of Centrifuge Model #2.

Figure 9.16. Post-test view of Centrifuge Model #2.
Shear vane tests were performed on the clay surface, immediately after the end of testing and gave an average undrained shear strength of $c_u = 33 \pm 2$ KPa. When the model was unloaded from the centrifuge beam, more shear vane tests were performed and gave the following average measurements:

- Top of central clay block: $c_u = 28 \pm 1$ KPa
- Bottom of central clay block: $c_u = 23 \pm 5$ KPa
- Bottom of side clay blocks: $c_u = 26 \pm 1$ KPa
- Middle of central clay block: $c_u = 13 \pm 3$ KPa
- Middle of side clay blocks: $c_u = 19 \pm 2$ KPa

The total thickness of both the sand and clay layers, after the end of Centrifuge Test #2 is illustrated in model scale, in Figure 9.17. A detail of this figure is shown in Figure 9.18. Furthermore, the thickness of the sand layer is presented in Figure 9.19, while a cross-section of the soil profile along the model’s x-axis is shown in Figure 9.20.

![Figure 9.17](image_url)  
**Figure 9.17.** Post-testing total soil thickness (in model scale).
Figure 9.18. Post-testing total soil thickness (in model scale).

Figure 9.19. Post-testing thickness of sand layer (in model scale)
Figure 9.20. Cross-section of the deformed soil profile (in model scale).

Photos taken during the model’s excavation are presented in Figure 9.21 to Figure 9.26. More specifically, Figure 9.21 shows the centrifuge model immediately after unloading from the centrifuge beam. A plan view of the deformed clay surface is presented in Figure 9.22, while Figure 9.23 and Figure 9.24 show different views of the model’s surface, in order to demonstrate its mode of deformation. During the excavation procedure, efforts were made to obtain cross-sections of the deformed model, in hope of observing the failure mechanism underneath the foundation. These cross-sections are presented in Figure 9.25 and Figure 9.26.
Figure 9.21. Centrifuge Model #2 after unloading from the centrifuge beam.

Figure 9.22. Post-test plan-view of Centrifuge Model #2.
Figure 9.23. Post-test view of the deformed surface of Centrifuge Test #2.

Figure 9.24. Post-test view of the deformed surface of Centrifuge Test #2.
Figure 9.25. Failure mechanism underneath the footing.

Figure 9.26. Failure mechanism underneath the footing.

The post-test instrument positions were measured during the excavation procedure and are presented in Table 9.2.
After the excavation, the total mass of the clay (including the slurry) was found equal to 11.375Kgr, while the mass of the saturated sand and of the water removed from the model’s surface was found equal to 83.125Kgr.
9.1.3. Centrifuge Test #3

Figure 9.27 to Figure 9.29 present Centrifuge Model #3, immediately after the end of testing. As shown in Figure 9.29, large cracks were observed on the clay surface, far away from the footing. Three (3) small sand-boils were also observed at the model’s edges.

Figure 9.27. Post-test view of Centrifuge Model #3.
Shear vane tests were performed on the clay surface, immediately after the end of testing and an undrained shear strength of $c_u = 19 \pm 2$ kPa was measured. When the model was unloaded from the centrifuge beam, more shear vane tests were performed, giving the following average measurements:
- Top of central clay block: $c_u = 20 \pm 2\text{KPa}$
- Bottom of central clay block: $c_u = 28 \pm 2\text{KPa}$
- Middle of central clay block: $c_u = 11 \pm 1\text{KPa}$

The total thickness of both the sand and clay layers, after the end of Centrifuge Test #3 are illustrated in model scale, in Figure 9.30, while the thickness of the sand layer is presented in Figure 9.31. Finally, a cross-section of the soil profile along the model’s x-axis is shown in Figure 9.32.

![Figure 9.30. Post-testing total soil thickness (in model scale).](image)

![Figure 9.31. Post-testing thickness of sand layer (in model scale)](image)
Figure 9.32. Cross-section of the deformed soil profile (in model scale).

Photos taken during the model’s excavation are presented in Figure 9.33 to Figure 9.36. More specifically, the location and size of the aforementioned sand-boils may be observed in the plan-view of Figure 9.33. Figure 9.34 shows the gap, between the central clay block and the smaller side block, which is partially filled with sand. Note that this occurred during the placement of the clay layer, as described in Section 5.3 and not during testing. Furthermore, efforts were made to obtain cross-sections of the deformed model, underneath the foundations. These cross-sections are presented in Figure 9.35 and Figure 9.36.
Figure 9.33. Post-test plan-view of Centrifuge Model #1.

Figure 9.34. Sand filling the lower part of the gaps, between the clay blocks.
Figure 9.35. Clay deformation underneath the footing.

Figure 9.36. Clay deformation underneath the footing.
Finally, the post-test instrument positions were measured during the excavation procedure and they are presented in Table 9.3.

Table 9.3. Post-test instrument positions (in model scale) in Centrifuge Test #1.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>x (mm)</th>
<th>y (mm)</th>
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10. References


