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The prediction of soil surface displacements arising from elliptical shaft excavation in clay

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ABSTRACT
Shafts are used to allow access to subsurface infrastructure and generally comprise of a deep, vertical, narrow opening in the ground. Shafts may be constructed using a variety of methods and plan forms. An axisymmetric (cylindrical) geometry is often preferred due to the relatively simple structural analysis, construction method and for a number of approaches that are available to estimate the ground movements around such an excavation. In certain cases, particularly when there is restricted space both above and below surface, non-circular shafts could be a preferred solution. The assessment of surface movements around non-circular shafts (which engineers require for asset surveys) is difficult as little information exists and there are few empirical prediction methods available. In this study, a series of centrifuge tests have been conducted to investigate the effects of modifying the cross-sectional profile of a shaft (i.e. circular in plan compared with elliptical). Analysis of measurements obtained from centrifuge tests undertaken at City, University of London’s geotechnical centrifuge facility are presented and compared with existing predictive methods. An addendum to the empirical equations and procedures for predicting surface settlements arising from circular shafts is presented to allow for the assessment of movements around elliptical shafts in clay.

KEYWORDS
Shaft construction; Ground movements; Centrifuge modelling
LIST OF SYMBOLS

a  Constant indicates the depth at which maximum horizontal displacement occurs
b  Constant governs the height of the Gaussian curve
d  Distance from the shaft wall
D  Shaft diameter
H  Shaft depth
\( K_0 \)  The ratio between horizontal and vertical effective stresses at rest

OCR  Overconsolidation ratio

n  Multiple of shaft depth, \( H \), to a distance, \( d \), from the shaft wall where settlement becomes zero
S  Soil displacement
\( S_v \)  Vertical soil displacement
\( S_h \)  Horizontal soil displacement
\( S_u \)  Undrained shear strength of clay
\( \alpha \)  Empirical constant
\( \phi'_c \)  Critical state angle of shearing resistance
\( \sigma'_h \)  Horizontal effective stress
\( \sigma'_v \)  Vertical effective stress
\( \sigma'_{0v} \)  Maximum consolidation pressure for clay model in centrifuge test
INTRODUCTION

In a developed urban environment the surface space is heavily utilised leading engineers to develop tunnelling solutions for housing transport links, water services, sewage services, communication networks and electrical lines. Access to these tunnelling systems can be a considerable challenge, particularly for transportation systems where easy access is required for thousands of people daily. There are many solutions to this problem of access including the sinking of shafts to intersect with tunnels or other structures (such as stations) below. The construction of a deep shaft will generate ground movements, primarily arising from the horizontal stress relief that the soil around the shaft experiences. In a dense urban environment these movements have the potential to cause structural damage to existing surface and subsurface infrastructure and this must be, at the design stage, assessed.

The most common geometric form of a shaft is circular in plan cross-section. This shape is favoured due to the inherent advantage of radial symmetry. In this case the analysis of the lining can assume that loads are carried by the stiff hoop and that any ground movements generated during construction will be equal at any given distance from the shaft. These assumptions do not, of course, account for variations in the soil around the shaft (potentially leading to non-uniform pressures being applied to the lining and non-uniform ground movement) or the presence of any existing buildings which would also contribute to asymmetric behaviour.

In theory a shaft can be sunk with any cross-sectional geometry. There are obvious disadvantages to certain shapes (e.g. a square or rectangular shaft would require a stiff design at the corners of the lining to counter the bending moments generated by the pressure acting on the sides) but there are advantages to an elliptical cross-section particularly in cases of restricted surface space. Figure 1 shows a sketch of a hypothetical project to install two lifts for underground access to a metro station. The lifts are represented by the squares and the required circular or elliptical shaft to house them is shown. For this particular (notional) geometry the elliptical shaft has a plan area that is approximately 25% smaller which would have significant benefit in terms of removal of spoil from site. Additionally, the elliptical geometry could be aligned in such a way so as to avoid any surface or subsurface structures that may already exist. Taking into account
these potential benefits, the objective of this paper is to provide experimental data on elliptical shaft construction in clay to support current design methodologies.

SHAFT DESIGN AND CONSTRUCTION

Construction of a shaft in clay can be carried using a number of methods dependent on the strength of the clay. Allenby & Kilburn (2015) discuss shaft-sinking techniques divided into two general categories; underpinning and caisson sinking however Schwamb (2014) also highlights the use of piling and diaphragm walling as viable construction techniques. In an urban environment where there are limitations on available space, noise and vibrations, shafts are usually constructed by underpinning (e.g. Morrison et al., 2004). Underpinning is a construction technique which incrementally excavates the shaft followed by installation of a pre-cast concrete segmental lining and grouting behind the annulus (Allenby & Kilburn, 2015). There are also recent examples of shaft construction in stiff clays using a sprayed concrete lining (e.g. Rutty et al., 2015) which also use an underpinning method. It is worth highlighting this technique as its flexibility would make it most suitable for construction of non-circular geometries. When utilising sprayed concrete, excavation is followed by construction of a primary lining (using sprayed concrete) which is then supplemented by a secondary lining constructed soon after (usually Cast-in-place or pre-cast concrete). The primary lining can be assumed to carry none of the load in the long term (as in Rutty et al., 2015) or it can work with the secondary lining (as in Psomas et al., 2019).

Modern geotechnical engineering practice aims to reduce ground movements arising from construction to a minimum. BS EN 1997-2:2007 (BSI, 2007) specifies that the design of a shaft (of any cross-section) must include detailed assessments of the adjacent ground movements in order to assess any impact on existing structures. There is little guidance available to aid with these assessments although, most notably, New & Bowers (1994) give a prediction method for surface settlements arising from circular shaft sinking in London clay (recently updated; New, 2017). In this work it is asserted that predictions can only be made by referring to field data in similar soil conditions but these data are relatively limited in the literature, particularly so when compared with those of other geotechnical construction events (i.e. tunnelling). Le et al. (2019) extends this work to subsurface movements but again, the field data with which to validate these methods is limited.
When considering an elliptical shaft, the work of New (2017) may be applicable with additional modifications or assumptions. Alternatively, finite element methods could be used to make Class A predictions of ground movements (e.g. Pedro et al., 2019) but observational data are vital for validating any numerical analysis of elliptical shaft excavations. There are very few published case studies reporting ground movements arising from elliptical shafts (e.g. Topa Gomes et al., 2008) on which to base future assessments.

GROUND MOVEMENTS ARISING FROM SHAFT CONSTRUCTION

Ground movements generated by shaft construction will comprise vertical settlements and horizontal movements towards the shaft. These are primarily driven by reductions in horizontal and vertical earth pressures however, as Faustin (2017) identifies, there are many factors that contribute to the overall movements both in the short and the long term. These include (but are not limited to) the diameter and depth of the shaft, the construction method employed, workmanship, ground conditions and other processes such as dewatering or consolidation.

The vertical surface settlements arising from sinking a circular shaft in stiff London clay during the Heathrow Express Trial Tunnel were reported by New & Bowers (1994) and used to establish 

**Equation 1.**

\[ S_V = \alpha H \left(1 - \frac{d}{H}\right)^2 \]  

Where \( S_V \) is the surface settlement at a distance, \( d \), behind the wall. \( H \) is the depth of shaft and \( \alpha \) is an empirical constant that depends on ground conditions and construction method (in the original work \( \alpha \) had a value of \( 6 \times 10^{-4} \)). The limitations of **Equation 1** are that the diameter of excavation is not considered and there is a level of uncertainty surrounding the value of \( \alpha \).

Subsequently, New (2017) documented field data from thirteen case studies with a wide range of diameters (although predominantly in stiff London clay). An amendment to **Equation 1** was proposed with a new variable, \( n \), controlling the extent of the vertical settlements around the excavation (**Equation 2**).

\[ S_V = \alpha H \left(1 - \frac{d}{nH}\right)^2 \]  

(2)
Whilst there is still no explicit term considering the diameter of the shaft, the data presented by New (2017) clearly shows that larger shafts produce (as might be expected) larger settlements over a greater extent. It might also be logical that softer soils would produce larger movements, an observation supported by the data from Le et al. (2019).

As noted earlier, there is limited published data in the literature reporting either field measurements, experimental data or numerical analyses of shaft construction. When considering elliptical shafts the available literature is even more restricted however, Faustin et al. (2018) report a series of centrifuge tests on model elliptical shaft excavations in sand. These tests modelled a 1:80 scale elliptical shaft excavation (major axis length = 120mm, minor axis length = 180mm and excavation depth 193mm) in Fraction E Leighton Buzzard Sand with a stiff aluminium liner. The measurements during these tests were of the surface settlement and lining strains. The surface settlement data was compared with those from tests on circular shafts and showed that the maximum settlement was slightly higher in the elliptical shaft excavation (0.028%H compared with 0.02%H). However, it should be noted that these measurements may not be directly comparable as the plan area of the elliptical shaft modelled is larger than that of the circular shaft. Faustin et al. (2018) also state that the extent of the surface settlements is larger for the circular shaft when compared with the elliptical shaft (1.5H compared with 1.0H) however the data presented do not necessarily support this rather more measurements are reported for the circular tests at a greater distance from the shaft.

It is clear that, accepting that elliptical shaped shafts are likely to be utilised in future construction projects, there is a need to understand and predict the movements generated during their excavation. A series of centrifuge tests to examine this are now described.

CENTRIFUGE TESTING

Novel apparatus was developed to model the ground movements induced by a circular shaft excavation in overconsolidated clay (Divall & Goodey, 2016). Good agreement was shown between the data collected from experiments using this apparatus and the prediction methods of New (2017). Based on these designs, modifications were made to the set-up for modelling elliptical shafts whilst using an identical test procedure.
Test apparatus

A basic apparatus schematic of the shaft centrifuge models is given in Figure 2. As all excavations are modelled as half-space simulations; the shape of the cavity was cut into the clay and could be viewed through the 83mm Polymethyl methacrylate (PMMA) window during testing. Details of the model apparatus set-up for the equivalent circular shaft geometry is given in Le et al. (2019).

Essentially, the model shaft comprised a shaft liner, latex bag (the cavity between which is filled with a heavy fluid commercially known as Sodium Polytungstate or SPT), and the structural elements to support the model within the soil.

The two model elliptical shafts (shown in Figure 2) had plan cross-sectional areas equal to the circular shaft but had major and minor axes chosen to represent a similar aspect ratio to the elliptical shaft constructed at the Green Park station upgrade in London, UK (Feiersinger, 2011).

The lower section of the Green Park shaft had major axis minor axis dimensions of 10m and 6m, respectively. The tests were conducted at 100g and thus the model elliptical shaft had a minor axis of 64mm and a major axis of 100mm, the slight variation between this and the prototype size due to the requirement of the plan area being the same as the circular case. It should be noted that both apparatus representing the elliptical shafts have the same dimensions but have their plane of symmetry (in the model) corresponding with either the major or the minor axis. This approach allows a modelling of models scenario and enables investigation of the two different ground movement measurement techniques (detailed later).

The shaft liners were 200mm high and a cavity created in the underside to allow any basal movement (similar to Le et al., 2019). As in Divall & Goodey (2016) the latex bag had a thickness of 1.5mm with a void of 3mm to allow for soil movements analogous to a shaft excavation. The heavy fluid which supported this void, whilst the pore pressures in the soil reached hydrostatic equilibrium with a water table set by a standpipe outside the model, could be drained from the bottom of the liner to simulate the construction process.

Test series

A total of three tests were completed during this work. All three clay samples used in the tests were consolidated to 350kPa and swelled to 250kPa. All samples underwent further inflight consolidation on the centrifuge resulting in samples that had varying strength and
overconsolidation ratio with depth. The tests can be separated into two categories; CR, the reference circular shaft simulation and EL1 & EL2, the two different elliptical shaft simulations. Details of these test are summarised in Table 1. Where $H$ is the depth of excavation, $h$ is the horizontal axis length (i.e. the dimension across the box), $v$ is the vertical axis length (the dimension into the box) and $A$ is the cross-sectional area of the model shafts.

Test procedure and instrumentation

The soil samples were created by mixing Speswhite kaolin powder, a clay whose engineering properties are well-established for centrifuge modelling (Grant, 1998), with distilled water to form a slurry with a water content of 120% (twice the liquid limit). This slurry was placed within a soil container, known as a strongbox, and subjected to a vertical effective stress history as detailed previously. This process took approximately one week. During the swelling stage, two pore-water pressure transducers were installed via the back wall of the strongbox, the primary function of which is to ensure that pore water pressure within the soil achieves equilibrium with the standpipe during the inflight consolidation phase.

Once the clay sample is prepared, the model making procedure would begin more details on which can be found in Le et al. (2019). The main aspects are briefly described below:

- The front wall of the strongbox was removed and the exposed surfaces of the clay sample were sealed with silicone oil to prevent drying out,
- The soil sample was trimmed to the desired model height and semi-elliptical/circular cavity was cut into the front face of the clay sample,
- This front face of the model was sprayed with dyed blue Leighton Buzzard Sand (Fraction B) whereas the top of the model was sprinkled with Leighton Buzzard Sand (Fraction E) to create the texture necessary for post-test image analysis of soil movement,
- The 83mm thick PMMA window was bolted to the front of the strongbox which had the model shaft elements already attached, and finally,
- The drainage channels were connected and the gantry necessary for 3D topography (Le et al., 2016) was bolted to the top of the strongbox (Figure 2).

The model was placed on the centrifuge swing (City, University of London has access to an Acutronic 661 and a description of the main features can be found in Panchal, 2019) and
accelerated to 100g. The model was kept at this acceleration until the clay had reached hydrostatic equilibrium indicated by the stable readings from the aforementioned pore-water pressure transducers.

Simulation of the excavation process was achieved by draining the heavy fluid from the void between the liner and latex bag. The rate of flow of the heavy fluid was set such that the entire process took approximately three minutes. Data from the surface displacements, subsurface displacements, pore-water pressure and heavy fluid pressure was taken at a rate of one per second. Once all ground movements had stopped the model was decelerated and hand shear vane readings were taken at various depths on the laboratory floor. These readings could be used to determine the undrained shear strength, \( S_u \), for each model. These results can be found in Figure 3 and Table 2. Gorasia (2013) demonstrated that hand shear vane readings taken immediately after test completion were comparable with in-flight strength measurements and therefore this method was favoured due to space limitations on the model apparatus.

**RESULTS**

*Correlation of test data*

Before any comparison of settlement data can be undertaken, it is necessary to ascertain the similarity between each model. Aside from the differences in geometry, there are other experimental factors that may influence the results obtained such as inconsistencies in undrained soil strength and initial fluid level within the excavation (i.e. the horizontal pressure supporting the soil around the shaft). Table 2 shows the measured average \( S_u \) from all three tests with both Test CR and EL1 showing very similar undrained strength whereas Test EL2 is approximately 10% lower. Also shown in Table 2 is the initial fluid level within the excavation with again, Tests CR and EL1 being similar and Test EL2 being higher. These differences arise from the complex nature of the apparatus and model preparation process.

It is necessary to separate the effects on ground movements of these experimental variations from the differences that arise from changing the geometry of the shaft and a method was devised to account for the overall influence of the experimental variations. The presence of the stiff liner implies that the end position of the soil is known i.e. once the fluid is drained, the soil moves (generally) horizontally until it comes into contact with the liner. The effect of experimental
differences can therefore be quantified by measuring the horizontal movement of the soil immediately adjacent to the shaft liner as the fluid is drained. This movement must represent the distance between the soil’s initial position and the liner. Figure 4 shows this data, obtained from digital image analysis using geoPIV_RG (Stanier et al., 2015). It is clear that the horizontal movements in test EL2 are larger, indicating a bigger initial gap, consistent with the observations of lower strength soil and higher initial fluid support pressure. The area under each curve was obtained by numerical integration and it was found that (considering Test CR as the reference case) test EL1 had horizontal movements that were 3% lower than the reference case and test EL2 has movements that were 54% higher. This measurement can be considered to be analogous to the concept of volume loss used in tunnelling. The rate of excavation in the test is high and the event is essentially undrained. As such, the data for each test can be normalised to account for the fact that the movements driving the observed mechanisms (i.e. the initial gap between soil and liner at the end of in-flight consolidation) are greater or smaller than the circular reference case.

Accounting for the effect of friction at the clay model and PMMA window interface

In this paper, measurements of soil movements are presented from various areas of the model and comprise surface settlement measurements obtained from 3D topography (Le et al., 2016) and front face, subsurface measurements from geoPIV_RG (Stanier et al, 2015). Le et al. (2016) demonstrated that both of these techniques were capable of making measurements with comparable degrees of precision and accuracy. The (necessary) use of different measurement techniques means that come correlation must take place as front face measurements obtained from digital image analysis are influenced by friction between the soil and front window of the strongbox. Grant (1998) examined this phenomenon and determined that an offset of -0.1 mm was evident in the region of interest when comparing results from LVDTs and image analysis. Put another way, Grant (1998) accounted for the friction at the clay-window interface by adding 0.1 mm to the settlements taken from digital image analysis.

In the current work, the region of interest is larger than that considered by Grant (1998); his work considered the movements immediately above a tunnel excavation. The application of an offset was therefore deemed inappropriate in this case. The reported 0.1 mm correction correlates to a
scaling of about 10% and this was therefore applied to measurements made at the clay-window interface in the work presented here.

To summarise, all results obtained (i.e. from both measurement systems at all locations) were scaled to account for variations in the experimental technique as previously detailed. Subsequently, measurements made at the front face of the model were increased by 10% to account for interface friction.

Surface settlement data

Once the corrections detailed above have been applied to tests EL1 and EL2 it is possible to compare the surface settlements obtained parallel to the major and minor axes of the elliptical shaft and compare them with the (axisymmetric) settlements generated by the circular shaft. Figure 5 shows a sketch of the location of the measurement points and Figures 6a and 6b show the comparison along the major and minor axes respectively. In these figures it should be noted that those data labelled “P” (solid markers) are taken perpendicular to the front face of the centrifuge strong box using 3D topography and those labelled “F” (open markers) are taken at the front face both by geoPIV_RG and 3D topography (hence the larger number of data points).

The dashed lines are least squares best fits of Equation 2 to the data from the circular reference test and the elliptical shaft tests. Data from the elliptical tests show good agreement independent of the measuring technique used. Settlements along the minor axis are significantly smaller than those generated by the circular shaft excavation despite the major axis being 25% larger than the diameter of the circle (100mm vs 80mm). Conversely, settlements along the minor axis are comparable with those generated by the circular excavation despite the minor axis being 20% smaller than the diameter of the circle.

DISCUSSION

The nature of the modelled shaft

It should be noted that the normalised settlements presented from the current tests are very much larger (by an order of magnitude) than those observed in the field (New, 2017). This arises from the fact that, in these tests, there is a 300mm overcut (at prototype scale) between the soil and the liner into which the soil is allowed to move. This is very much larger than that which might be
encountered in practice where a 100mm overcut that is subsequently grouted might be more reasonable. The current work focusses on the patterns of movement generated and the large overcut is an artifact of the experiments deliberately chosen to ensure consistent movements that can be reliably detected by digital image correlation.

Comparison with empirical methods

Figure 7 shows that the surface settlements generated by the elliptical shaft excavation could be represented by Equation 1 (New, 2017). A least squares best fit to the combined data (i.e. from all tests and measurement methods) is carried out to determine values of $\alpha$ and $n$. Figure 7 shows the resulting curves and Table 3 gives the derived values of $\alpha$ and $n$.

Comparison with the results of Faustin et al. (2018)

As detailed earlier there is one previously published set of experimental data detailing a centrifuge test on an elliptical shaft constructed in dense sand. Despite the differences between this and the current work, Equation 2 is utilised to examine the patterns of movement generated. Figure 8 shows the results from Faustin et al. (2018) overlain with predicted curves generated by Equation 2. The curves are not mathematically fit to the data but rather placed to give an approximate upper bound to the data on the graph. The curve generated for the elliptical data has a value of $\alpha$ that is 10% larger than that used for the circular curve (the value of $n$ is constant at 1.5). This is commensurate with the observation that the plan area of the elliptical shaft is 10% larger in this work when compared with the circular. The curves give credence to the observation above that a suitable prediction can be generated for the maximum settlements caused by excavating an elliptical shaft from Equation 2 by considering a circular shaft of equivalent plan area. It should be noted that in the current work, the aspect ratio of the ellipse is 0.64 (and 0.67 in Faustin et al., 2018). Whether similar patterns of settlement would be observed for different aspect ratios remains a topic for future work.

CONCLUSION

A practical solution to the problem of restrictions on available surface space coupled with increasingly congested underground space is the utilisation of elliptical shafts for access to
underground infrastructure. It is clear that there is a requirement for estimating the ground
movements resulting from such constructions and data from a series of well-controlled centrifuge
tests carried out in overconsolidated clay have been presented in this paper.

The findings can be summarised below:

- The maximum settlements at the ground surface arising from elliptical shaft construction
  are apparent on line coincident with the minor axis of the ellipse. Conversely, the
  settlements generated on the line coincident with the major axis are significantly smaller
  in magnitude (in the order of 60% of the settlement seen on the minor axis).
- For the purposes of assessing the movements that might be generated by a proposed
  elliptical shaft construction in clay, an upper bound to the surface settlements can be
  generated from Equation 2 by modelling a circular shaft of equivalent plan area.

ACKNOWLEDGEMENT

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85).
REFERENCES


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Figure 6b: Comparison of surface settlements in elliptical shaft test (EL) along the minor axis direction with reference circular shaft data (CR).

Figure 7: Design lines for surface settlements arising for elliptical shaft construction in clay.

Figure 8: Comparison of Equation 2 with the results of Faustin (after Faustin et al., 2018)
### Table 1: Details of centrifuge tests

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Maximum consolidation pressure (kPa)</th>
<th>Swelling pressure (kPa)</th>
<th>Excavation dimensions (mm or mm²)</th>
<th>Shaft liner dimension (mm or mm²)</th>
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</thead>
<tbody>
<tr>
<td>CR (aspect ratio = 1.0)</td>
<td>350</td>
<td>250</td>
<td>h = v = 80</td>
<td>h = v = 71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H = 200</td>
<td>H = 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A = 5027</td>
<td>A = 3959</td>
</tr>
<tr>
<td>EL1 (aspect ratio = 0.6)</td>
<td>350</td>
<td>250</td>
<td>h = 64</td>
<td>h = 55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>v = 100</td>
<td>v = 45.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H = 200</td>
<td>H = 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A = 5027</td>
<td>A = 3959</td>
</tr>
<tr>
<td>EL2 (aspect ratio = 0.6)</td>
<td>350</td>
<td>250</td>
<td>h = 100</td>
<td>h = 91.6</td>
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<td></td>
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<td></td>
<td></td>
<td>A = 5027</td>
<td>A = 3959</td>
</tr>
</tbody>
</table>

### Table 2: Average undrained shear strength of the clay models and initial fluid levels.

<table>
<thead>
<tr>
<th>Test</th>
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<th>EL1</th>
<th>EL2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Su (kPa)</td>
<td>44.5</td>
<td>45.7</td>
<td>40.4</td>
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<tr>
<td>Initial fluid level (mm)</td>
<td>328</td>
<td>355</td>
<td>415</td>
</tr>
</tbody>
</table>

### Table 3. The values of $\alpha$ and $n$ derived from the tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>CR</th>
<th>EL1</th>
<th>EL2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$5.8 \times 10^{-3}$</td>
<td>$4.1 \times 10^{-3}$</td>
<td>$5.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>$n$</td>
<td>1.5</td>
<td>0.94</td>
<td>1.33</td>
</tr>
</tbody>
</table>
Figure 1: Sketch showing required circular and elliptical plan geometry to enclose two adjacent lift mechanisms.
Figure 2: Schematic of centrifuge test apparatus.

a) Test apparatus

b) Cross sections
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