*Physical Modelling in Geotechnics – McNamara et al. (Eds)*


# A new shared miniature cone penetrometer for centrifuge testing

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ABSTRACT: Cone penetrometers (CPTs) are commonly used for characterising the soil properties of centrifuge models; CPT data is useful for interpretation and quality control. This paper describes the development and design of a new robust CPT device for centrifuge testing. The new device consists of a 6 mm cone, an outer sleeve, and an inner rod that transmits cone tip forces to a load cell above the ground surface. The design eliminates the need for a custom submerged strain gauge bridge near the tip, significantly reducing cost. A direct comparison was performed between this CPT device and another similar device developed at the University of Cambridge. CPT's were manufactured using the new design and then shipped to eight different centrifuge facilities, for quality control of similar experiments performed for LEAP (Liquefaction Experiments and Analysis Projects). All the centrifuge tests simulated a 4 m deep deposit of soil, all consisting of Ottawa F-65 sand with relative densities ranging between about 45 to 80%. The results obtained have been extremely valuable as an independent assessment of the density calculated from mass and volume measurements at different laboratories.

## 1 INTRODUCTION

The ability of a cone penetrometer (CPT) to characterise the mechanical properties of geomaterials (Robertson and Cabal 2010) makes it an important tool for soil characterisation. Cone penetrometers have been used in centrifuge models by a number of researchers in the past (Bolton et al. 1999, Kim et al. 2015, Zhou et al. 2015 & Darby et al. 2016) for this reason.

The LEAP project, (Manzari et al. 2015) is an international collaboration to verify and validate numerical models that predict soil liquefaction. The current phase of the project, LEAP-UCD-2017, involves roughly 24 centrifuge experiments performed at 9 different research facilities. The LEAP tests were designed to determine the median response and the uncertainty of results. To assess the importance and influence of the uncertainty on the median response, it is also a goal of LEAP to quantify the sensitivity of test results to intended and unintended variations of input parameters. CPT results are especially valuable as an independent check of centrifuge model densities. To reduce variability due to differences in CPT equipment at each facility, it was decided to produce one economical design, fabricate the devices at one machine shop, and distribute them to the various centrifuge laboratories.

One of the challenges encountered following the previous phase of the LEAP project, LEAP-GWU-2015, was determining the achieved densities of the centrifuge models by mass and volume measurements (Kutter et al. 2016). Most researchers reported the achieved model density as the specified value and no independent checks were performed to evaluate the uncertainty of the mass and volume measurements. Therefore, it was considered critical for future LEAP exercises to have an independent check of model density. In flight CPTs were selected as a quality control check on prepared specimen density.

This paper describes the design, calibration, and provides a direct and cross comparison of the newly developed LEAP CPT device.

## 2 DESIGN

The new CPT, sketched in Figure 1, is 6 mm in diameter and is fabricated from stock stainless steel tubing and rod. This device measures tip forces using a load cell at the top of the cone, avoiding use of a costly custom submerged strain gauge near the tip. As shown in Figure 1, the inner rod is protected by a hollow sleeve and transmits tip forces to a load cell located in a rigid aluminium block. The yield stress of the Type 316 Stainless Steel inner rod is specified to be 200 MPa. Using an allowable yield stress of 130 MPa and considering the cross section of the inner rod is reduced by the presence of O-ring grooves, corresponds to a maximum tip force rating of 900 N (200 lbf). The relative density of a sand can be estimated with an expression proposed by Jamiolkowski et al. (1985):

$$D_r(\%) = 68\left[\log\left(\frac{q_c}{\sqrt{p_a \sigma_v}}\right) - 1\right] \tag{1}$$

where $q_c$ is the cone tip resistance, $P_a$ is atmospheric pressure, and $\sigma_v$ is overburden vertical effective stress. For an overburden vertical effective stress of 100 kPa and $q_c = 900$ N/(area of the 6 mm diameter cone), it was estimated the cone could safely penetrate sand with relative density of 100%.

A guiding philosophy of the CPT design was to minimise use of components that require specialty machining. The completed manufacturing and assembly cost, including the load cell, is roughly $US 1,300. All the components of the device use 316 stainless steel, unless otherwise noted. The main components of the device are described herein.

### 2.1 *Rod and sleeve*

To avoid buckling, the unsupported length of the rod was reduced by a series of O-rings spaced at 100 mm; to minimise friction, the outer diameter of the O-rings were designed to be slightly smaller than the 5 mm inner diameter of the sleeve. The O-rings rest in grooves cut into the rod to prevent them from sliding while the rod is inserted into the sleeve. To align the rod in the centre of the sleeve, larger diameter "snug-fitting" O-rings are used at each end of the rod. To prevent sand and fluid from entering the gap between the rod and sleeve, a tip O-ring with a 4 mm diameter and 1 mm cross section is used. During final assembly, the inner cone rod is clamped to the slotted cone rod bolt by a M8 Jam nut, and is threaded into the load cell until 4 to 9 N of preload on the tip O-ring is achieved;

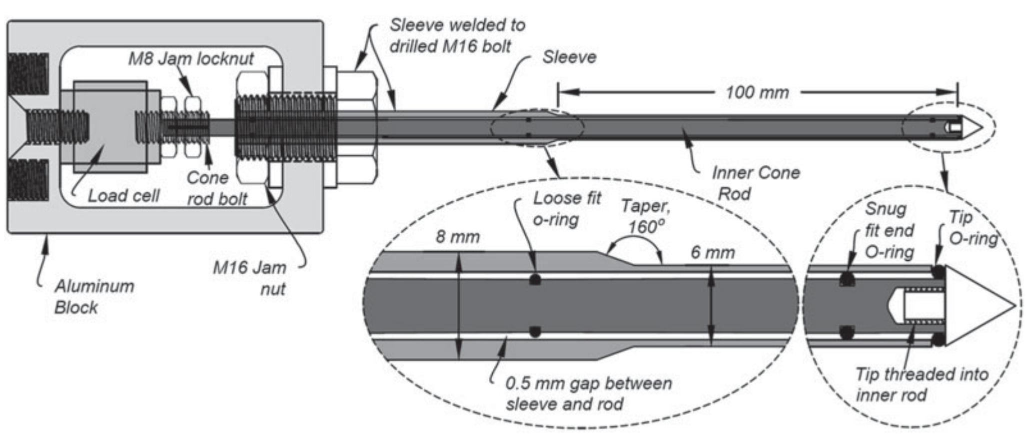


Figure 1. LEAP-UCD-2017 CPT design, illustrating cone tip, taper, and aluminium reaction block details.

the preload is easily measured by monitoring the load cell during assembly. Preloading the end O-ring to a specified small value ensures the gap between the cone shoulder and sleeve is closed and minimises potential inconsistencies of results caused by variable preloads.

The sleeve was manufactured from 8 mm outer diameter, 5 mm inner diameter tubing. Within 100 mm of the cone tip, the sleeve is machined down to 0.5 mm wall thickness, with an OD of 6 mm. 100 mm above the tip, the sleeve is tapered at 20 degrees to transition from 6 mm to 8 mm diameter. The location of the taper and the taper angle were selected to minimise increases in overburden stress at the cone tip from bearing loads produced at the transition. An abrupt 20 degree taper between the 6 mm and 8 mm diameters was chosen based on results by LeBlanc and Randolph (2008), who showed that resultant bearing loads on the tapered section would, perhaps counterintuitively, be larger on a gentler taper.

### 2.2 *Reaction block and load cell*

The aluminium block allows for simultaneous pushing of both the cone rod and sleeve. The block is 78 mm tall by 53 mm wide and 39 mm deep.

A M16 bolt connects the sleeve to the aluminium block. This is accomplished by thru drilling a bolt 25 mm in length, and welding the sleeve to the bolt. The bolt sleeve assembly is attached to the aluminium block using a jam nut. This connection is illustrated in Figure 1.

The load cell is attached to the block with a M8 bolt. The slotted cone rod bolt with a tapered jam nut clamps the cone rod to the load cell.

The load cell used for the CPT design is a 4500 N capacity, SML Mini Low Height S-Type Interface load cell. The SML line was selected for its small size and high capacity. To provide attachment for the completed device to an actuator, or an external load cell, four M6 threaded inserts are located atop the aluminium block.

## 3 CALIBRATION

Three calibration tests were performed prior to using the device on centrifuge models.

### 3.1 *Friction between rod and sleeve*

The first test measured the undesirable transfer of tip loads to the sleeve via the O-rings. A reference load cell was attached to the top of the aluminium block of the assembled device and measured total force while the cone tip was pushed into a block of plastic. The difference between the readings of the tip load and the external reference load cell is attributed to friction from the bracing O-rings. Under 425 N of axial load, the difference between the internal and external reference load cell was 13 N. This 3% difference is small and is accounted for by adjusting the calibration factor of the CPT load cell. In other words, the tip load measured by the CPT load cell should be multiplied by 1.03 to estimate the total tip load. This correction factor should be checked for each device in the calibration process.

### 3.2 *Lateral force*

The second test subjected the device to a 15 N lateral load at the tip, to determine if lateral loads would influence the load cell reading. Several cycles of lateral loading were applied, and no tip forces were measured. While lateral loads are expected to be small for a properly aligned device, this test shows unintended lateral loads should have negligible effect on the cone tip force reading.

### 3.3 *Cyclic loading*

The final test applied a sequence of several cycles of loading to determine the extent of the hysteresis of the completed device from friction of the O-rings. After five cycles of loading to 425 N, and back to zero load the peak difference between the internal tip and external reference load cell was measured at 13 N. The maximum and minimum widths between the loading and unloading paths of the hysteresis loops at 200 N of external loading is 1.3 N and 0.9 N respectively. The minimal change in the width of the hysteresis loops during successive loading and unloading suggests the friction contact between the sleeve and the O-rings is small and remains almost constant.

## 4 DIRECT COMPARISON

A direct comparison was performed with a CPT device developed at the University of Cambridge's Schofield Centre. Both CPT devices were pushed into the same tub of uniform sand, eliminating many sources of uncertain variability such as operator error during testing, placement method of sand, or different properties amongst sand batches. The container was filled with Hostun sand, dry pluviated to about 100% relative density to a depth that represented 14.5 m prototype at 50 g.

The University of Cambridge's CPT device is 6.35 mm in diameter and has a 60-degree cone tip. Similar to the new device, the Cambridge design uses an outer sleeve and has an inner rod that transmits tip forces to a load cell. As shown in Figure 4, the Cambridge CPT device uses a PTFE bushing behind the cone shoulder instead of the tip O-ring.

### 4.1 *Results*

Shown in Figure 2 are four cone resistances versus depth profiles for each device. In Figure 3 the cone tip load is isolated for depths of 2, 4, 6, 8, and 10 meters for each design. Overall, it can be concluded that the two devices produce comparable trends both in terms of stress magnitude and distinguishing characteristics. The device-to-device variability is similar to the profile-to-profile variability, but the average $q_c$ of the LEAP CPT is about 5 to 10% larger than that from the Cambridge CPT.

The difference in average $q_c$ values might be attributed to the different tip designs. It is also suspected that the details of the tip geometry can have significant effect on the tip resistance. In Figure 4 the PTFE bushing leaves a small (0.1 mm) gap before the sleeve, while the O-ring design results in a small ledge behind the cone shoulder.

## 5 CROSS COMPARISON

Twenty-four centrifuge experiments have been conducted so far at nine centrifuge facilities. Eight of these (UC Davis, Ehime, IFSTTAR, Kyoto, KAIST, NCU, RPI, and Zhejiang) used the LEAP-UCD-2017 CPT and Cambridge used their own, very similar design discussed above. Each facility has a custom rod and sleeve length due to unique container sizes, but all LEAP-UCD-2017 CPTs were manufactured at UC Davis to reduce variably of machinists and manufacturing tools.

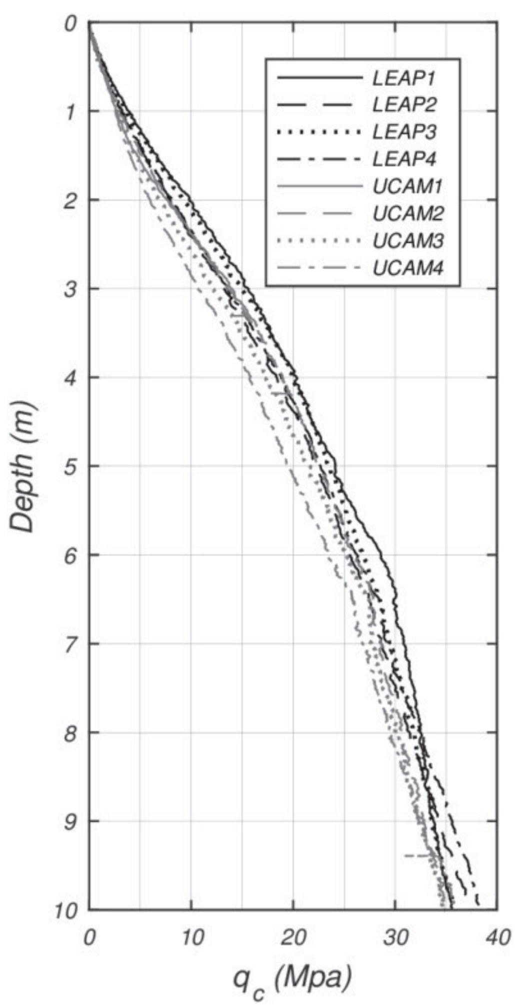


Figure 2. Stress profiles vs depth for the LEAP and the University of Cambridge CPT.

### 5.1 *LEAP-UCD-2017 experiment*

The LEAP-UCD-2017 centrifuge experiment consists of a saturated Ottawa F-65 sand profile inclined with a five-degree slope in a rigid container. Each experiment used sand that was from the same batch that was shipped to UC Davis and then forwarded to participating facilities. Different facilities, with different box dimensions used different scale factors ($L^* = L_{model}/L_{prototype}$ between 1/20 and 1/50), but all the models represented 4 m deep (prototype scale) sand layers.

Shown in Figure 5 is the sensor layout for the LEAP-UCD-2017 experiment with accelerometers shown as triangles, and pore pressure transductors as circles.

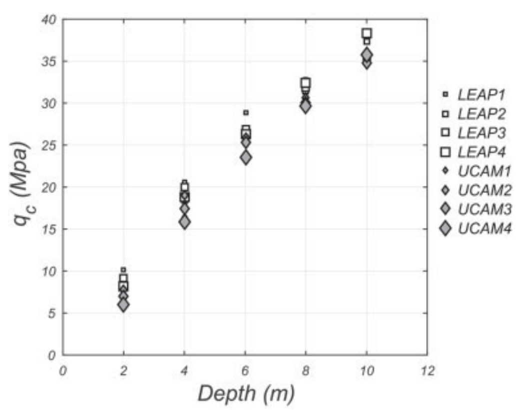


Figure 3. Cone tip resistance at 2, 4, 6, 8 and 10 m depths for the LEAP and Cambridge CPT.

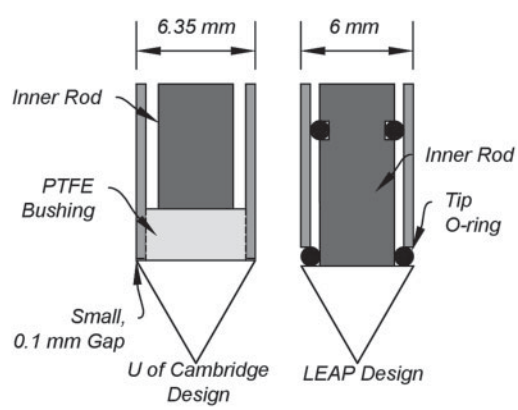


Figure 4. Different in tip design between the Cambridge and LEAP CPT.

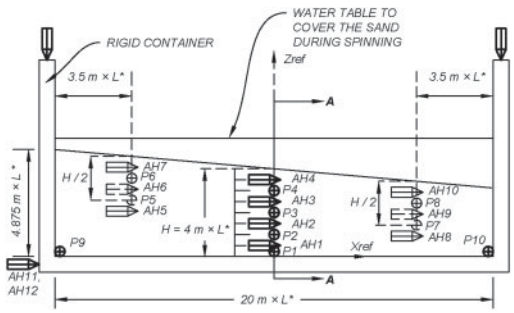


Figure 5. Sensor layout and test geometry for LEAP-UCD-2017.

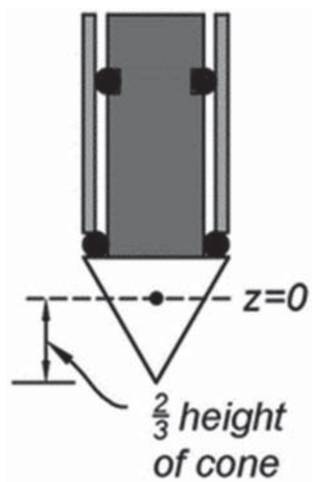


Figure 6. All CPT profiles were adjusted so zero depth coincided at 2/3 the height of the cone.

To ensure consistent drainage conditions for all penetration tests, the desired rate of cone penetration, in model scale, was specified for LEAP-UCD-2017 to depend on the pore fluid viscosity in the model:

$$V_{cpt,modelScale} = (100mm/s)/\mu^* \quad (2)$$

where $\mu^* = \mu_{model}/\mu_{water}$. Thus, if the test is done at 1/20 scale and according to scaling laws for dynamic testing ($\mu^* = 20$), the velocity of penetration should be 5 mm/s, model scale.

Kutter et al. (2016) presents a detailed discussion on the test geometry, sensor location and scaling laws for the LEAP-GWU-2015, which are similar to LEAP-UCD-2017. The detailed specifications for the LEAP-UCD-2017 centrifuge tests will be published prior to the ICPMG conference in London.

One goal of LEAP-UCD-2017 was to test models with a range of relative densities between about 50% (about 1599 kg/m$^3$) to 80% (1703 kg/m$^3$) to determine the sensitivity of the model response to relative density.

In centrifuge testing, the cone depth to diameter ratio is significant and hence a standard method for calculating the depth of cone penetration is important. Consistent with industry standards, the depth of zero penetration is adjusted to the 2/3 height of the cone tip, which is illustrated in Figure 6. In Figure 7 the recorded qc is given for depths of 1.5, 2, 2.5, and 3 m respectively versus the reported density of the model after the initial spin up. The solid lines in Figure 7 represent a linear regression, and the area between the dashed lines is the 95% confidence interval for the linear mean fit.

In Figure 8, the theoretical steady-state tip resistance, calculated from Idriss & Boulanger (2008), is compared with the $q_c$ data at 1.5, 2, 2.5, and 3 m depths.

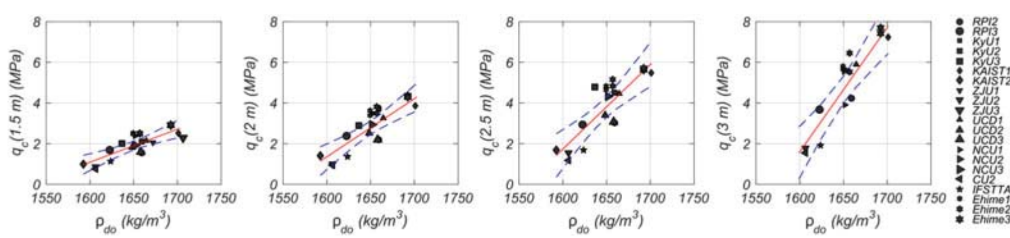


Figure 7. $q_c$ vs reported dry density at and confidence intervals for 1.5, 2, 2.5 and 3 m depths for LEAP-UCD-2017 experiments prior to destructive shaking.

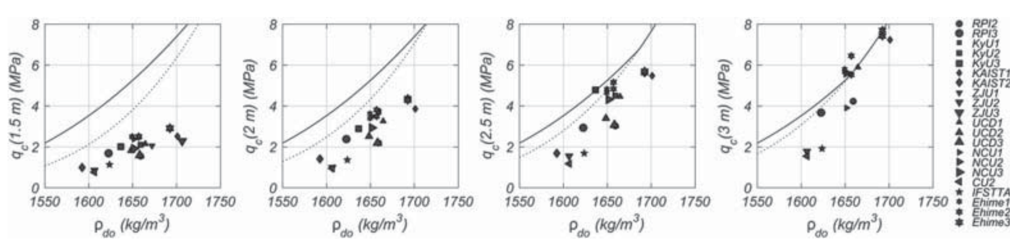


Figure 8. $q_c$ vs reported dry density at and theoretical steady-state tip resistance for 1.5, 2, 2.5 and 3 m depths for LEAP-UCD-2017 experiments prior to shaking.

The dashed line assumes the overburden correction factor ($C_n$) is unbounded, and the solid line assumes the correction factor is capped at 1.7. The $C_{dq}$ factor for the curves is 0.65. At shallower depths, the theoretical cone tip resistance exceeds the recorded data significantly. One possible reason for this discrepancy is the lateral flexibility and limited distance to the walls of the model container. Another explanation could be that the model cones, being 120 to 250 mm in diameter prototype scale (depending on the g-level used in the LEAP experiments), were not sufficiently deep relative to their diameter to assume a deep failure mechanism.

## 6 CONCLUSION

A new, low cost, CPT device was developed. The device consists of an outer sleeve and an inner rod that transmitted cone tip forces to a load cell. A series of calibration tests were conducted, showing the device performed as expected. A direct comparison experiment was performed with the device at the University of Cambridge's Schofield Centre. Good agreement was observed with the Cambridge CPT and the LEAP-UCD-2017 CPT.

LEAP-UCD-2017 CPT's were used in similar models on eight different centrifuges. CPT results from all the LEAP facilities, especially at shallow depths, deviate from trends observed in large calibration chamber tests at 1 g. For tests at 3 m depth (Fig. 8(d)), agreement with correlations from calibration chamber tests is improved.

The use of a standard CPT on different centrifuges and standard methods of interpreting the depth of penetration are valuable, especially for comparing results of centrifuge tests performed at different facilities. It might be the case that tip resistance measurements using a standardised centrifuge CPT are more reliable for soil characterisation than direct density calculations based on mass and volume measurements.

## ACKNOWLEDGMENTS

Funding for this work was provided by the National Science Foundation under the following CMMI grants: 1635307, 1635524 and 1635040, and the National Science Foundation of China (Nos. 51578501, 51778573). Thank you to Kate Darby for providing data during the initial design process. Design suggestions from professor Jason DeJong were very helpful. Barry Zheng's help during data processing was much appreciated. The authors would also like to thank Andy Cobb at UCD's BAE shop for providing construction recommendations and manufacturing each device.

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