INNOVATIVE DATA ACQUISITION FOR THE FALL CONE TEST IN TEACHING AND RESEARCH

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ABSTRACT

The fall cone device may be preferable to the Casagrande cup for the determination of liquid limits because it is based on a firm theoretical background and maintains a high degree of operator independence. This makes the fall cone device a superior tool for measuring consistency limits for research and for teaching soil mechanics. Two inexpensive data acquisition techniques are developed for the fall cone device that seek to make the fall cone equipment less expensive, better for teaching, and provide unique time-displacement data of cone motion. The first data acquisition technique uses an inexpensive USB camera and image processing to analyze cone motion, and the second method uses a commonly available linearly variable differential transformer (LVDT) to track cone motion. The techniques are validated by comparing measured liquid limit to the liquid limit measured with an unmodified fall cone and the Casagrande cup of several different soils. Details of the data acquisition techniques are presented along with typical time-displacement data of the cone motion.

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INTRODUCTION

In the United States the Casagrande cup and thread-rolling procedures (i.e., ASTM D4318-10) are the primary means for measuring two of the consistency limits (liquid limit, LL; plastic limit, PL) of soils (shrinkage limit, SL, is the third). While these procedures have the benefits of a significant historic record of use, they can be difficult for new users to perform correctly (Bowles 1992). Furthermore, repeatability across users or laboratories can sometimes be an issue (Sowers et al. 1960; Feng 2004; Verastegui-Flores and Emidio 2014). Sherwood and Ryley (1970, Figure 1) report results of a UK study showing that the spread of liquid limits [= $(LL_{max} - LL_{min})/LL_{mean}$] measured in the Casagrande cup for three soils across multiple laboratories can range from 30-45% with a coefficient of variation (COV) of 7–8% and state that an unreferenced study in the United States showed even more scatter. These issues are potentially exacerbated by the effects of the Casagrande device itself on measurements (e.g., cup roughness and base hardness may vary with use), by the dynamic nature of the test (e.g., low-plasticity soils may liquefy in the cup rather than flowing plastically; J. David Frost, personal communication, August 31, 2001), and by the difficulty associated with maintaining constant pressure during thread rolling. Thus, while these tests have a long history of successful use, they are not perfect.

The fall cone test provides an alternative means for measuring the LL and PL of soils and is already preferred by some researchers (e.g., Casagrande 1958; Wasti 1987; Feng 2000). Standards for fall cone testing currently exist in many regions (e.g., United Kingdom BS 1377-2, Europe CEN ISO/TS 17892-6, and Canada CAN/BNQ 2501-092/2006), but not in the United States. The fall cone benefits from a firm theoretical background, a higher degree of operator independence, and the ability to measure both LL and PL (or, plasticity index, PI) with a single device. In addition, the fall cone may also be used to determine undrained shear strength at a given water content (e.g., Hansbo 1957; Youssef et al 1965; Wood and Wroth 1978; Houlsby 1982; Koumoto and Houlsby 2001;) and the shear viscosity of clays (Mahajan and Budhu 2009; Cevikbilen and Budhu 2011), all simultaneously with the Atterberg Limits. In a single-laboratory, multiple-user study, Sherwood and Ryley (1970, Table 3) found that for eight users measuring the LL of three soils, the spread for the Casagrande cup ranged from 5-23% but only from 3-11% for the fall cone (COVs were 1.6-7.5% and 0.9-3.3%, respectively). The spread and the COV for all three soils were lower for the fall cone than for the Casagrande cup. However, the fall cone does have several drawbacks: (1) the fall cone test does not always result in the same liquid limit as a Casagrande cup test for the same material; however the measured liquid limits are uniformly inconsistent (Littleton and Farmilo 1977, Wasti 1987); (2) the initial economic investment in the apparatus is more for a fall cone test than a Casagrande test; and (3) cone surface roughness and tip bluntness can also affect cone penetration (Hansbo 1957; Houlsby 1982), thus machine wear is still an issue.

Hansbo (1957) published some of the first experimental results and theoretical analyses of the fall cone test. Sherwood and Ryley (1970) note that the Casagrande test is too variable and posit that the fall cone test is an acceptable alternative to the Casagrande test. Using concepts from critical state soil mechanics, Wood and Wroth (1978) suggest that the fall cone can also be used to measure the plasticity index of soils. Others have provided alternative cone designs and data acquisition techniques, such as the MIT cone which is a variable mass cable-hung cone that makes use of an LVDT to track motion (Zreik et al. 1995), and particle image velocimetry (PIV) to track cone motion (Hazell 2008).

In order to minimize the initial economic impact of using the fall cone device and to provide additional data from the test for research and education, two inexpensive data acquisition techniques have been developed and validated. These techniques use (1) a camera and image processing software; or (2) a linearly variable differential transformer (LVDT) on a standard base-model fall cone device to collect time-history data. Validation has resulted in similar measured liquid limits and time-histories between the new techniques, conventional fall cone, Casagrande device, and Hansbo's (1957) theoretical analysis.

THEORETICAL BASIS OF THE FALL CONE TEST

The undrained shear strength of a remolded plastic soil at its liquid limit is essentially a constant, narrowly ranging from 1.47 – 2.45 kPa (Youssef et al. 1965). Equation 1 shows that this is the basis for determination of the liquid limit with the fall cone (Hansbo 1957, Wood and Wroth 1978):

$$\frac{s_u d^2}{W} = \lambda \tag{1}$$

where s_u is the undrained shear strength, d is the cone penetration, W is the weight of the cone, and λ is a constant depending on cone angle. If s_u is constant for all remolded soils at the liquid limit, then the penetration depth is the same for all remolded soils using the same cone weight and geometry. The dynamic nature of the traditional percussion cup method does not readily imply this fundamental soil behavior at the liquid limit, so: (1) using the fall cone in an educational environment supplements soil consistency theory; and (2) its use for research is supported by basic theory and well-correlated to other measurable soil properties.

DATA ACQUISITION FOR FALL CONE TESTS

In the current work, an ELE International (Loveland, CO) fall cone device (≈$700 in March 2013) was used for all of the tests. An off-the-shelf fall cone apparatus is prone to an avoidable problem: affordable devices leave the judgment of a predefined duration of penetration up to the user. Fall cone apparatuses are available with a solenoid to precisely control duration of penetration, but these are significantly more expensive than a user-operated mechanical device. Two inexpensive data collection techniques were developed to retrofit the fall cone devices which eliminate the user judgment problem and provide unique time-displacement data. The first is a fall cone image processing technique (hereinafter referred to as the FCIP method) which uses inexpensive image sensing and processing technology. The second is the use of an LVDT and a digital multimeter to measure cone displacement (hereinafter referred to as the LVDT method). Both of these techniques produce accurate displacement measurements at a precise duration (within ± 0.04 s for FCIP and within ± 0.002 s for LVDT using the hardware systems described subsequently) resulting in accurate liquid limit measurements.

The FCIP Method

FCIP uses particle image velocimetry (PIV) to track the motion of the cone. GeoPIV (White et al. 2003) is the suite of MATLAB® scripts used for image processing. The FCIP method requires a PC with MATLAB® and a USB webcam. (Note: while a high-speed camera would result in higher temporal resolution, a goal of the current work was to develop low-cost options for automated data acquisition.) The webcam used to collect data was a Microsoft LifeCam Studio (≈$60 retail in March 2013); however, any webcam compatible with MATLAB® and capable of 30 fps capture rate at 1280 x 720 pixels (high definition) resolution or better would be sufficient. While a research-grade high speed camera may yield improvements in measurement density, the authors believe that the additional costs associated therewith (as much as tens of thousands of dollars) are not justified. The webcam is controlled using a MATLAB® script that records image files with a simultaneous timestamp. The MATLAB® script is presented in Appendix A. A paper target is attached to the cone, and a scale grid is positioned to be in-frame and in the same plane as the target motion. At the conclusion of the test, GeoPIV is used to track the frame-by-frame motion of the target, resulting in pixel displacements. To transform pixel displacements to physical displacements, a scale factor is determined using the scale grid. The displacements from each image are then plotted versus time, allowing the user to determine displacement at a desired time (typically 5 seconds) within a tolerance of ±0.04 seconds. A flowchart conceptualization of the FCIP method is shown in Figure 1(*a*) and the modifications and camera positioning are shown in Figure 2. (Note: The fall cone device shown in Figure 2 has been modified to allow for simultaneous implementation of both the LVDT and FCIP approaches so that the results may be compared directly. In practice, only one method of data acquisition is necessary.)

Depending on the frame rate and shutter speed of the camera used, some images at the beginning of the test may be blurry due to the rapid motion of the cone (approximately 0.5 m/s; Hansbo 1957). In order to accurately track the target using GeoPIV, the blurry images are manually omitted. The timestamps from these images must also be omitted to ensure proper data alignment. This results in data sparsity at the beginning of the test (within the first 0.2 seconds), but does not affect later measurements. In order to minimize the effects of camera lens distortion, the camera is positioned so that the entire range of target motion remains in the middle third of the camera's field of view.

The LVDT Method

The LVDT method uses an LVDT to measure displacement of the cone rod during penetration (Figure 2). The LVDT used in the current work is a Sangalmo-Schlumberger ACR50. An AC excitation was supplied by a Validyne CD148 Carrier Demodulator, which outputs a DC signal. The CD148 is mounted in a Validyne MC1 Chassis and powered by a Validyne PM212.

The DC output is measured and recorded by an Agilent 34925A multiplexer installed in a 34980A digital multimeter (DMM). The authors compiled this system using equipment that was already available in the laboratory, but any system with an LVDT of sufficient displacement capacity ($\gtrapprox$40 mm) that does not increase system mass to a point at which depth of penetration is too large (see Equation 2), and a DMM with at least 5 digits of accuracy would be adequate. The components necessary to assemble a system meeting these specifications (i.e., a multimeter, an LVDT, and a power supply) can be found online for less than $1400 (in March 2013), but it is likely that any well-equipped laboratory will have them already on hand. A schematic of the data acquisition (DAQ) system is shown in Figure 1(*b*). The LVDT displacement and a timestamp are recorded by the DMM, and a plot of displacement versus time is generated. The additional mass of the LVDT shaft and bolt spacer give a total falling mass of 116.3 g. This deviation from the standard 80-g mass is accounted for by redefining the depth of penetration at the liquid limit after Wood and Wroth (1978):

$$\frac{s_u(20mm)^2}{80gm} = \frac{s_u(d_{LVDT})^2}{116.3gm} \rightarrow d_{LVDT} = 24.1mm \qquad (2)$$

TECHNIQUE VALIDATION

The LVDT method was calibrated by first stacking several precision metal spacers of known thickness beneath the cone. Spacers were then removed individually and the corresponding voltage outputs measured. The last spacer was left beneath the cone to ensure a level landing spot for the cone tip and a final voltage reading was made. The voltage output was then scaled to displacement. The resulting fit is shown in Figure 3(*a*) and Equation 3:

$$d = 14.657 - 7.8743 \cdot V \qquad (3)$$

where V is the voltage measured by the DMM, and d is the displacement of the cone in millimeters. The FCIP method was checked for accuracy in a similar fashion: the known displacements caused by removal of the metal spacers were plotted against the displacement measured by the FCIP method and compared to a 1:1 line. This comparison can be seen in Figure 3(*b*).

The LVDT and FCIP techniques were validated by testing several materials with an unmodified fall cone and with the traditional percussion method and comparing these results with LVDT and FCIP results. The materials used for validation were kaolinite (G_s = 2.65, trade name Snobrite Industrial Kaolin) supplied by Unimin Corporation, sodium bentonite (G_s = 2.45 – 2.55; trade name Envirogel 200) supplied by WyoBen, Willamette silt (a low-plasticity potentially liquefiable silt; 100% and 98% passing the #40 and #200 sieves, respectively), and mixtures of kaolinite with Ottawa 50/70 silica sand from U.S. Silica. The Ottawa 50/70 sand was selected because it is 100% passing the #40 sieve (Figure 4) and both ASTM 4318-10 and BS 1377 require that consistency limit tests be performed on the fraction of material passing the #40 sieve. Thus, the sand-clay mixtures could be tested as-prepared, as opposed to sieving out the coarser material.

For each material considered, four specimens at different water contents were prepared: two dry of the anticipated liquid limit and two wet of the anticipated liquid limit. Samples were mixed with de-ionized water, placed in sealed containers, and allowed to cure for at least 24 hours prior to testing. Each specimen was first tested in a Casagrande apparatus in accordance with the multi-point method outlined in ASTM D 4318-10. After testing with the percussion cup method, a small amount of water was added to each of the four specimens to replace that which was lost due to evaporation during testing. The specimens were again allowed to cure for 24 hours.

For fall cone testing, specimens were prepared in the standard 40 mm × 55 mm cylindrical brass cup by a combination of spooning material into and tapping of the cup. Specimens were tested in the modified fall cone with penetration duration longer than 5 seconds, obtaining data from both the LVDT and FCIP methods simultaneously. After two consecutive tests were completed with final penetrations within 0.5 mm, or three consecutive tests with final penetrations within 1 mm (cf. BS 1377-2), a sample was removed from the cup for water content determination. If a consecutive trial resulted in penetration greater than 1 mm difference from the previous trial, the specimen was removed from the cup and remixed with its host water content sample, and then retested. After a successful test at a given water content with the modified fall cone, that water content sample was then tested in accordance with BS 1377 using an unmodified fall cone device. Penetration duration was manually limited to 5 s using a stopwatch. Care was taken to prevent excessive desiccation of the specimens by keeping material in sealed containers when not being tested.

Because of the different liquid limits as determined by the dynamic Casagrande method and the quasi-static fall cone method (Wasti and Bezirci 1986, Wasti 1987, Leroueil and Le Bihan 1996), it was sometimes necessary to prepare separate specimens (generally wetter for the Casagrande cup method) for testing in the Casagrande cup.

RESULTS

Liquid limit was determined by plotting water content on the abscissa and cone penetration on the ordinate, fitting a straight line, and calculating water content at either 20 mm of penetration (unmodified fall cone device, British Standards Institute 1990) or 24.1 mm of penetration (modified fall cone, see equation 2). Feng (2000) suggests that the relationship between cone penetration and water content is better represented by a power law and fitted with an equation of the form:

$$\log(w) = \log(c) + m\log(d) \tag{4}$$

where *w* is water content, *d* is cone penetration, and *m* and *c* are slope and intercept, respectively, on a log-log plot. Flow curves (i.e. the best-fit to the penetration-water content data pairs) from each fall cone test method are shown in Figure 5.

The liquid limits are also calculated using the Casagrande cup per ASTM D 4318 where number of drops are plotted on a logarithmic abscissa and water content on a linear ordinate, and then liquid limit is taken as the water content at 25 blows. The measured liquid limit for each method and material is presented in Table 1. The liquid limit measured with the fall cone device is generally not the same as with the Casagrande cup, however similar differences between the fall cone liquid limit and the Casagrande liquid limit are also observed in the literature (Littleton and Farmilo 1977, Wasti and Bezirci 1986). For most soils, this variance is only a few percentage points. For problem soils (e.g. bentonite and Willamette Silt), this variance is slightly larger. Deviations are a result of factors such as Casagrande cup base hardness, cup roughness, cone roughness, and cone bluntness (Wasti and Bezirci 1986, Wasti 1987, Leroueil and Le Bihan 1996). Wasti and Bezirci (1986) show disagreement between percussion cup and fall cone LL for natural soils of low plasticity and soil where LL is above approximately 100.

Another significant advantage of the fall cone test is that it may also be used to determine the plastic limit (PL) of a soil using the same set of measurements as is used for LL determination (Feng 2001). Specifically, equation (4) may be re-cast as:

$$w = c \cdot d^m \quad (5)$$

where all terms are as previously defined. Since the undrained shear strength of a remolded clay at the plastic limit is approximately 100 times the undrained shear strength at the liquid limit (Skempton and Northey 1953; Wood and Wroth 1978; Feng 2001; Sharma and Bora 2003), equation (1) implies that the penetration depth at the plastic limit should be 1/10th of that at the liquid limit (i.e., $d_{PL} = d_{LL}/10$). Thus, the water content at the PL may be calculated as:

$$PL = c \cdot \left(\frac{d_{LL}}{10} \right)^m \quad (6)$$

Feng (2001) showed that the ratio of PL calculated using this approach and that from traditional thread rolling generally varied from 0.8 to 1.2. Measured and computed PL values for the soils considered herein are presented in Table 2.

The results presented in Tables 1 and 2 show that while there is some difference between the consistency limits measured with the modified fall cone device and the procedures outlined in ASTM D 4318, the values are internally consistent and also consistent with results previously reported in the literature. Specifically, for "well-behaved" soils such as kaolinite and the sand/kaolinite mixture, measurements with the fall cone and the percussion cup are quite similar while for problem or non-textbook soils (e.g., bentonite and Willamette silt) results from the two methods can vary from 5-20% (Table 1). An interesting outcome of this observation is that existing correlations of other engineering properties to the consistency limits may still be applicable for measurements made with the modified fall cone device but that the engineer must use best judgment when employing any relationships originally developed using data from Casagrande cup or thread rolling tests. However, when faced with particularly difficult soil conditions, it is unlikely that an engineer would rely solely on empirical correlations for final design, and thus, the divergence of response between the two methods has few practical implications beyond initial site characterization and soil classification work. We hypothesize that the differences between the two methods are a function of the vagaries of the percussion cup and thread rolling procedures, but further work is clearly needed.

Each test performed with the modified fall cone device also yielded two time-displacement data sets. A typical set of these data (time-truncated to show in detail the cone motion) are shown in Figure 6. As a final method of technique validation, the time-displacement data from the FCIP and LVDT methods are compared to the analytical solution to cone motion derived by Hansbo (1957):

$$t = \int_0^z \frac{d\xi}{\sqrt{2g\xi\left[1-\left(\xi/h\right)^2\right]}} \tag{7}$$

where t is time, g is acceleration due to gravity, z is penetration at time t, h is total depth of penetration, and ξ is a dummy variable of integration. Note that the data sparsity in the FCIP method only allows comparison after initial cone motion, but the LVDT method shows the same cone motion as Hansbo's (1957) solution.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Two inexpensive automated data collection methods for the fall cone test are proposed. These methods provide a new opportunity for students to explore soil consistency theory and for researchers to characterize and classify soils in a robust, repeatable, theory-based manner. In practice, the measurements can be automated using simple data acquisition procedures implemented with modular equipment that is likely already available even in modest laboratories.

This leads to better exposure to modern laboratory equipment for students and more reliable, repeatable measurements for researchers and practitioners. By limiting cone penetration to a precise duration using a rapid sequence of measurements, strict adherence to testing standards can be achieved. The new methods presented herein prevent the need for expensive solenoid-controlled fall cone devices by collecting time-displacement data and then back-calculating penetration at a desired duration.

The Casagrande cup and thread rolling procedures (ASTM D4318-10) are the well-accepted approaches for determining the LL and PL of soils. Over their long history of use, results from these tests have been used in soil classification schemes (e.g., USCS) and as inputs for empirical correlations between soil consistency and engineering properties. However, these tests can be imprecise and operator dependent and thus, repeatability is a concern. The fall cone test provides an alternative mechanics-based approach for measuring LL and PL. Results from fall cone tests have historically been reported as “consistent” with results from the ASTM D4318-10 procedures, but they are not the same. The same can be said for the modified procedures presented herein. Thus, if the fall cone test is to be widely adopted by practitioners, it must be done with the understanding that existing classification schemes and empirical relations may require modification. This seems not unreasonable if the fall cone is capable of providing consistently robust measurements and may result in improved empirical relationships due to potential decreases in data scatter.

Based on the results presented herein – and in the historical literature – the authors encourage ASTM Committee D18 on Soil and Rock to consider developing a U.S. standard for fall cone testing. Such a standard would serve to encourage the timely adoption of the fall cone test by educators, researchers, and practitioners, all to the benefit of the profession.

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FIGURE CAPTIONS

Figure 1. (a) Conceptual flowchart for the FCIP method; and (b) conceptual flowchart for the LVDT method.

Figure 2. Modified fall cone device (note standard 40 mm × 55 mm cylindrical brass cup for scale).

Figure 3. Calibration curves for (a) the LVDT method and (b) the FCIP method.

Figure 4. Grain size distribution and index properties of Ottawa 50-70 sand. Inset image from optical microscope. *After Hryciw and Thomann (1993). [†]ASTM D 854.

Figure 5. Flow curves for (a) kaolinite; (b) 50% kaolinite 50% sand; (c) bentonite; and (d) Willamette silt. Linear fit to LVDT is shown. Note change of horizontal axis on (c).

Figure 6. Typical time-history from single fall cone measurements for (a) a 50% kaolinite specimen; and (b) a bentonite specimen. Note time has been truncated to show cone motion in detail, total test duration is typically 6-8 seconds.

Table 1. Comparison of liquid limits measured with four different methods for all materials tested. The liquid limits measured with the fall cone are calculated after BS 1377-2 and after Feng (2000, 2001). Casagrande cup liquid limits were measured in accordance with ASTM D 4318.

	Kaolinite		**50/50 Kaolinite/Sand**		**Bentonite**		**Willamette Silt**	
Method	**BS 1377**	**Feng**	**BS 1377**	**Feng**	**BS 1377**	**Feng**	**BS 1377**	**Feng**
FCIP	48	49	27	27	538	559	36	37
LVDT	49	49	27	27	556	556	37	37
Unmod.	49	49	27	27	521	521	40	40
ASTM	42		24		526		31	

Table 2. Comparison of plastic limits measured using ASTM D 4318 and the Feng (2001) approach for all materials tested.

	Kaolinite	**50/50 Kaolinite/Sand**	**Bentonite**	**Willamette Silt**
FCIP	24	13	65	21
LVDT	24	13	69	21
Unmod.	25	13	74	18
ASTM	29	16	90	27

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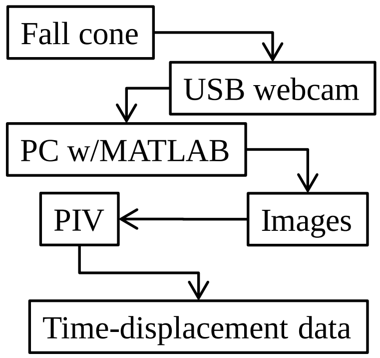
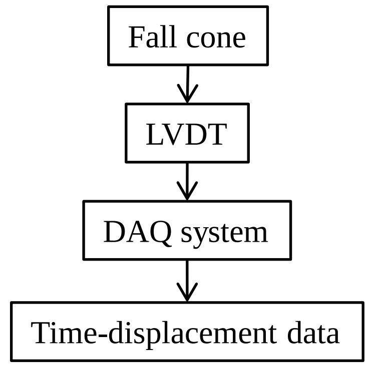
APPENDIX A

```
% This MATLAB file runs a webcam and creates .tif images of each frame
% by Daniel Simpson and T. Matthew Evans
% Oregon State University
% September 2013 and June 2014

clear;
clc;

% Make a location for test data
PID=input('Enter a project ID, surrounded by single quotes: ');
foldername=['fallcone_' PID];
mkdir(foldername);
disp(['A new folder called ' foldername ' has been created in the CWD where
test data will be stored.']);
disp(' ');
disp('Searching for devices...');
cd(foldername);

% Set device ID
temp=imaqhwinfo('winvideo');
j=length(temp.DeviceIDs);
for i=1:j
      imaqhwinfo('winvideo',temp.DeviceIDs{i})
end
devID=input('Enter ID of desired device from answers above: ')

% Set device resolution
temp=imaqhwinfo('winvideo',devID);
temp.SupportedFormats
format=input('Enter desired format, with quotes, from answers above: ')
disp('Measuring frame rate...');
vid=videoinput('winvideo',devID,format);

% Measure frame rate
vid.FramesPerTrigger=100;
start(vid);
wait(vid,Inf);
numframes=get(vid,'FramesAvailable');
[frames,time]=getdata(vid,numframes);
framerate=mean(1./diff(time));
src.FrameRate=framerate;
FPS=framerate

% Configure capture time
vid.TriggerFrameDelay=5;
duration=input('Enter the desired capture length in seconds (recommend 9 s or
more): ')
vid.FramesPerTrigger=FPS*duration;

% Set up camera and target location
```

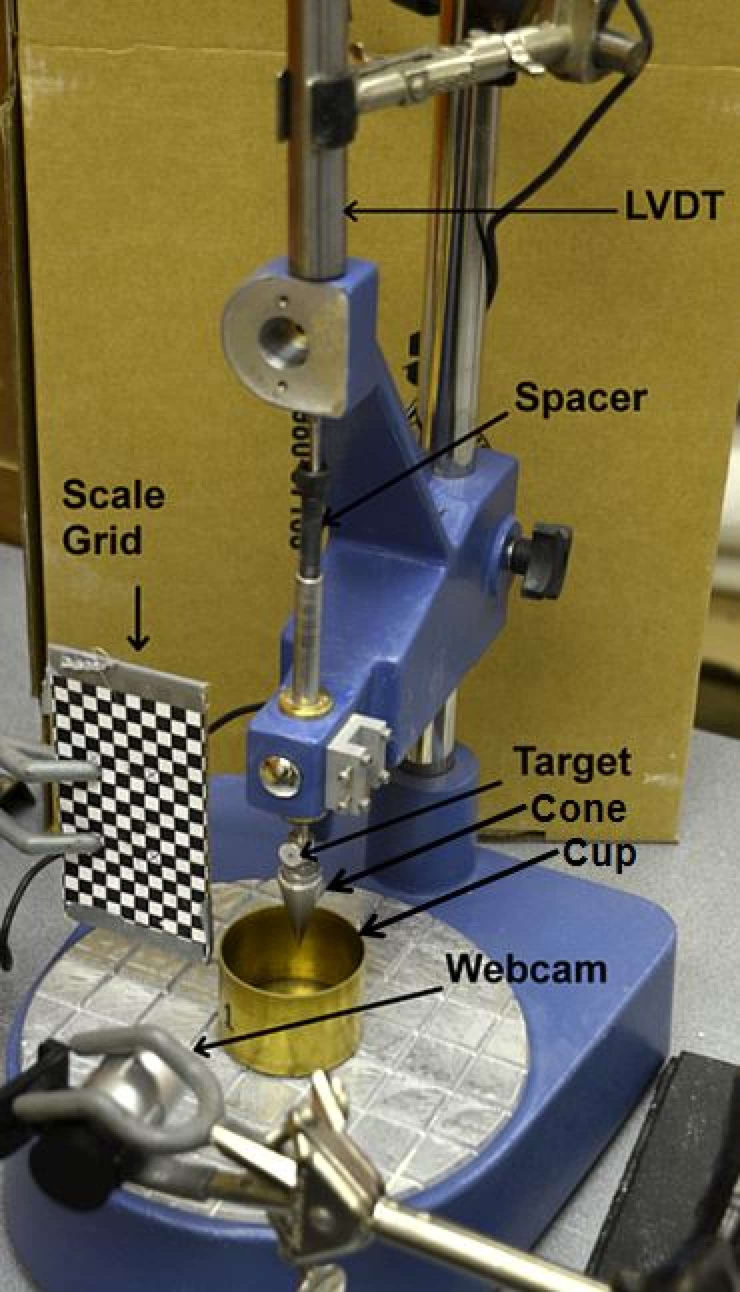
```
preview(vid)

% Initiate capture
choice=menu('Are you ready to begin recording? If yes, capture begins
immediately.','yes');
if choice>0
      start(vid)
      wait(vid,Inf);
end

% Retrieve data
[frames, timeStamp]=getdata(vid);
stop(vid);

% View FPS data
subplot(2,1,1)
plot(timeStamp,'x')
xlabel('Frame Index')
ylabel('Time (s)')
subplot(2,1,2)
plot(diff(timeStamp),'x')
xlabel('Frame Index')
ylabel('Time Difference (s)')

% Create image files from frames
for j = 1:size(frames,4)
      img =  frames(:,:,:,j);
      if j < 10
            imnum = ['00' num2str(j)];
      elseif j < 100
            imnum = ['0' num2str(j)];
      else
            imnum = num2str(j);
      end
      imwrite(img,['c_image' imnum '.tif'],'tif');
end

% Confirmation
menu('Finished!','OK');

% eof
```

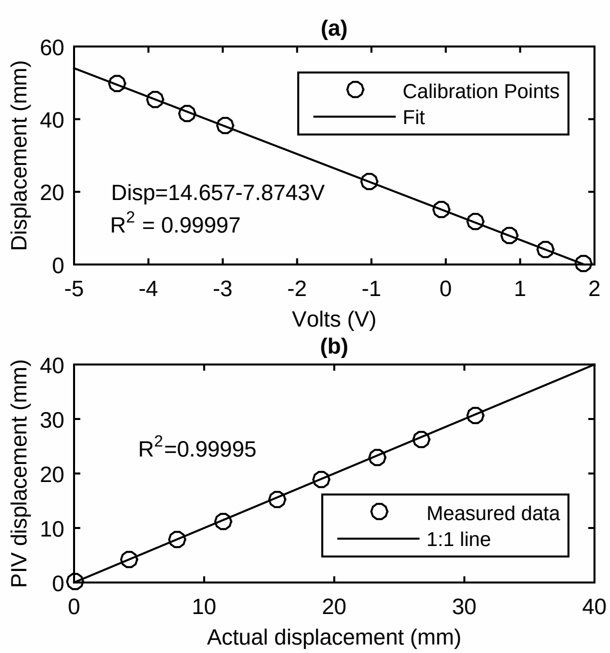

Fall cone
USB webcam
PC w/MATLAB
Images
PIV
Time-displacement data

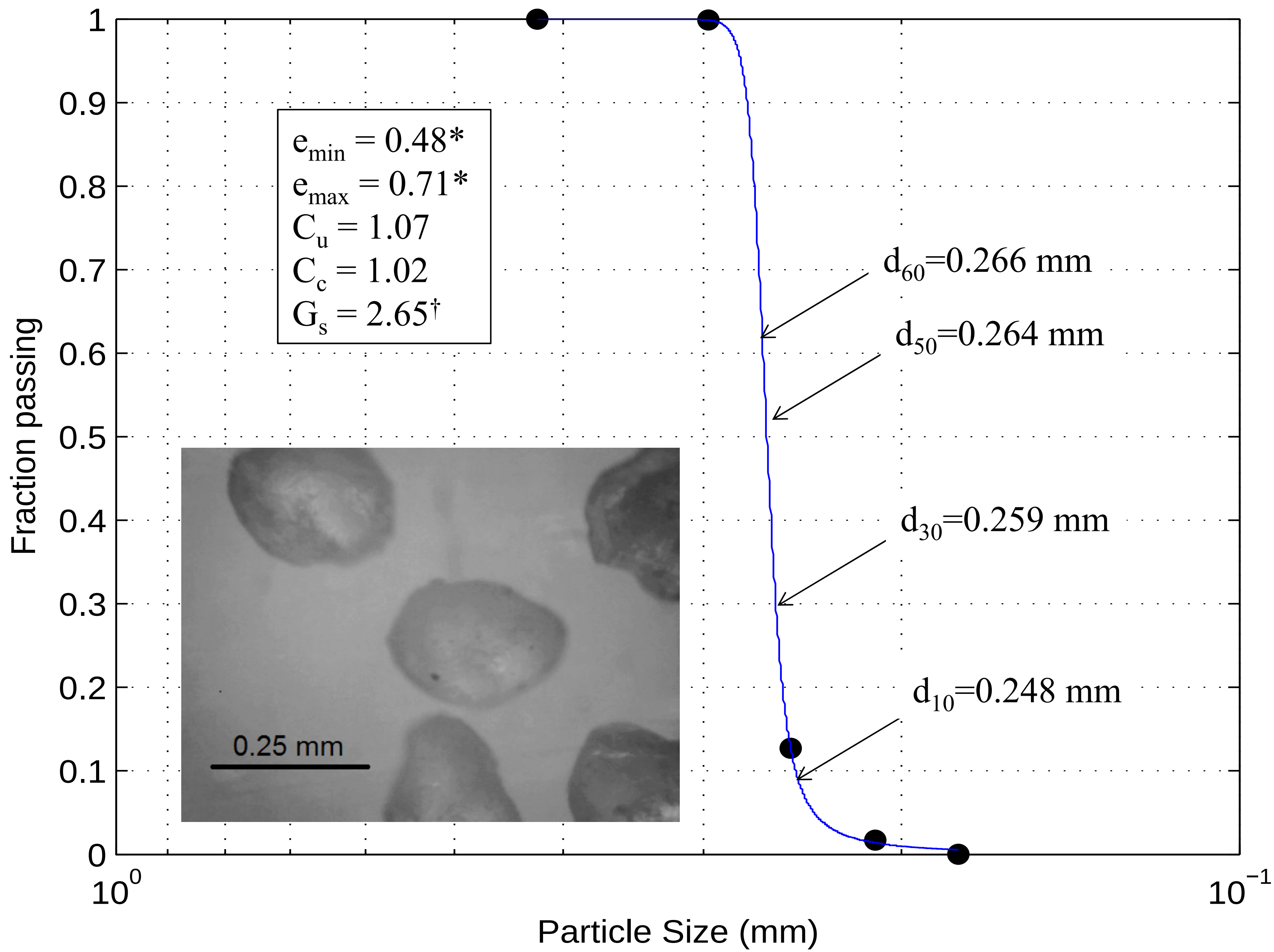
(a)


Fall cone
LVDT
DAQ system
Time-displacement data

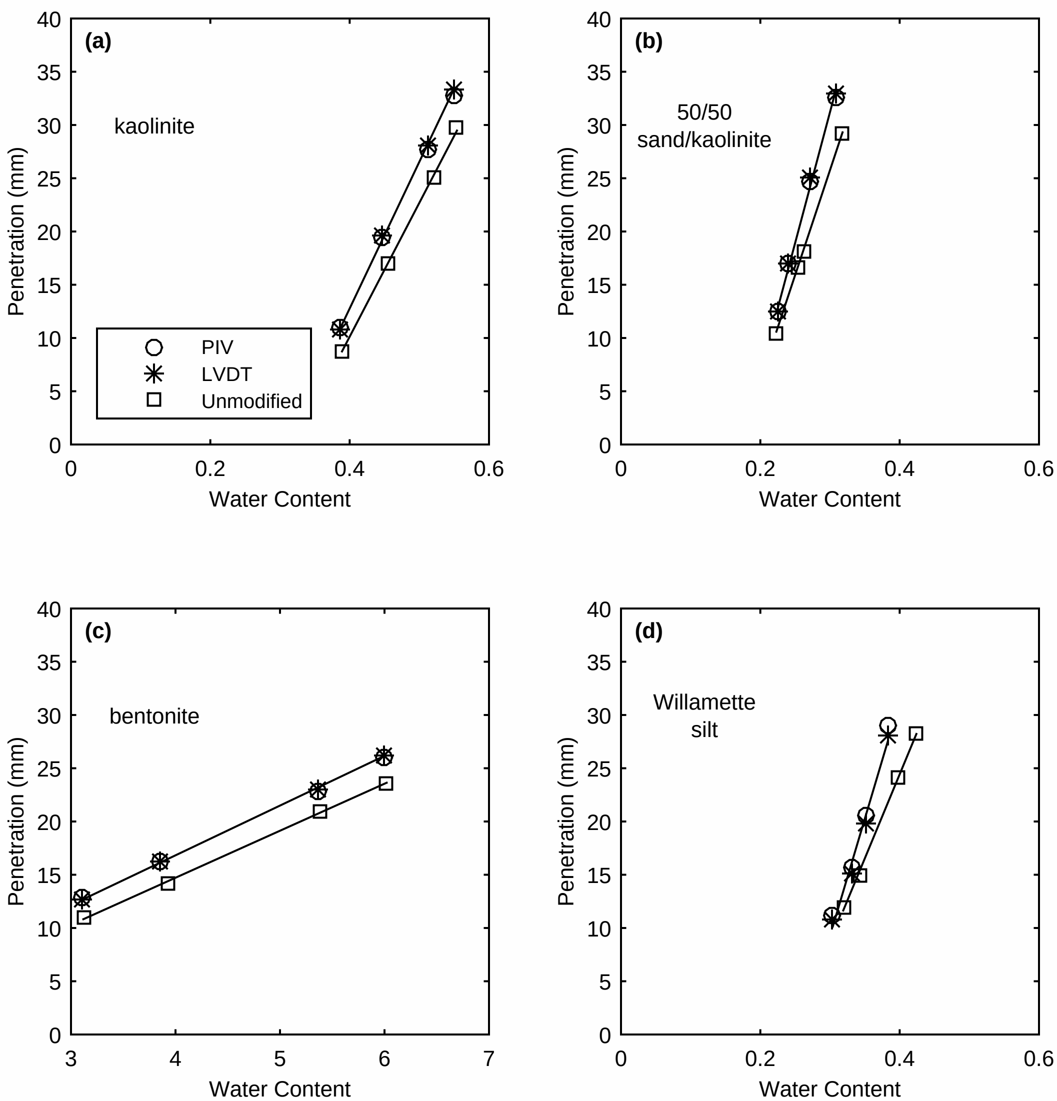
(b)

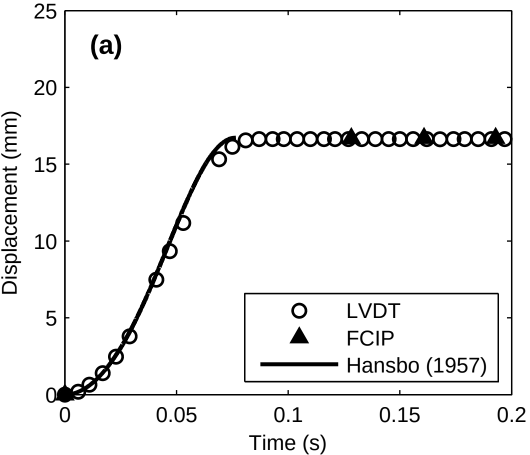

LVDT
Spacer
Scale
Grid
Target
Cone
Cup
Webcam

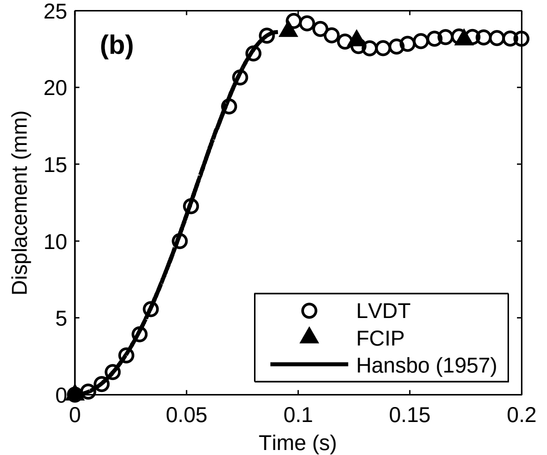

(a)
Displacement (mm)
60
40
20
0
-5
-4
-3
-2
-1
0
1
2
Volts (V)
Calibration Points
Fit
Disp=14.657-7.8743V
R2 = 0.99997
(b)
PIV displacement (mm)
40
30
20
10
0
0
10
20
30
40
Actual displacement (mm)
R2=0.99995
Measured data
1:1 line



Fraction passing
Particle Size (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^0
10^{-1}
e_{min} = 0.48*
e_{max} = 0.71*
C_u = 1.07
C_c = 1.02
G_s = 2.65†
d_{60}=0.266 mm
d_{50}=0.264 mm
d_{30}=0.259 mm
d_{10}=0.248 mm
0.25 mm


(a)
kaolinite
PIV
LVDT
Unmodified
Penetration (mm)
Water Content
(b)
50/50
sand/kaolinite
Penetration (mm)
Water Content
(c)
bentonite
Penetration (mm)
Water Content
(d)
Willamette
silt
Penetration (mm)
Water Content


(a)
Displacement (mm)
Time (s)
LVDT
FCIP
Hansbo (1957)
0
5
10
15
20
25
0
0.05
0.1
0.15
0.2



(b)
Displacement (mm)
Time (s)
0
5
10
15
20
25
0
0.05
0.1
0.15
0.2
LVDT
FCIP
Hansbo (1957)