PART 3: CALIBRATION OF GEOTECHNICAL INSTRUMENTS

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Overview: This new 5 part series has been written to explain the hardware, software and instrumentation used in the testing of soil and rock. The series comprises of 5 chapters (see below). The series is aimed at people interested in gaining a better understanding of geotechnical laboratory equipment.

1. Key Terminology and Engineering Parameters for Geotechnical Engineering,
2. Principles of Instrumentation Measurement – Error, Accuracy and Resolution,
3. **Calibration of Geotechnical Instruments**
4. Selecting Ideal Transducer Range,
5. Principles of Testing Machine Control Feedback.

INTRODUCTION

As we have seen, the accuracy of transducers is transferred to them by the process of calibration against (or comparison with) some standard. The standard will itself have a specified accuracy. Doebelin (2003) points out that the standard must have an accuracy higher than the accuracy of the instrument being calibrated, and that the standard itself must have been established by acceptable means. Sydenham et al. (1989) make the important point that "… *Associated with the calibration are two costs – that of making it and that of not making it*".

It is evident that the calibration means of transferring the accuracy must encompass the whole measurement system involved and will be affected by resolution, stability and repeatability – and above all be part of the laboratory culture.

It is desirable that transducers have a near-linear relationship between the set standard and the measured quantity so that the relationship can be expressed as a parameter in engineering units per transducer output which is usually in mV e.g. kPa/mV. The variability in this relationship can be expressed as an accuracy or linearity such as say 0.1%. But it is not always possible, and indeed with modern software, not always necessary for linearity to be achieved.

There follows three examples of calibration methods. The use of the dead-weight tester for calibrating pressure transducers, pressure sources and load cells is probably common to most large soil mechanics laboratories. The use of laser interferometry to calibrate LVDTs (Linear Variable Displacement Transformers) and measure small strains on triaxial test specimens of stiff soils and soft rocks, however, will be very much a glimpse of the future of advanced soil testing. There also follows an example of how machines can be calibrated too and how this can be important for loading frames, particularly when testing hard soils and soft rocks. Finally we comment on the importance of *verification*.

Budenberg Dead-weight Tester

The calibration of pressure transducers, pressure sources and load cells can be carried out using the Budenberg dead-weight tester. This is shown in Fig. 3. The principle of operation is a screw pump that pressurises low viscosity oil. Oil can be drawn into the screw pump via a set of valves from an oil reservoir. The pressurised oil causes a vertical piston to float up through an open vertical cylinder. The top of the piston where it emerges from the piston is provided with a platen that fits into an interlocking vertical stack of nested plate-like weights. The stack of plates and the piston together are lifted by operation of the screw pump so that they float above the rest position. In this floating state, the weights can be slowly set spinning by hand or by an electric motor. Oil slowly flows past the piston and into an overflow cup. The operation of the piston is therefore virtually frictionless much like a rotating bushing except here the piston rotates and the bushing or cylinder is stationary. Stops come into action if the pressure is too high or too low and it is essential that the weights should be spinning freely when taking readings.

Fig. 3 Budenberg dead-weight tester showing stack of standard calibrating weights, oil-water change-over pot, and load cell calibrating frame (permission of DH-Budenberg Ltd).

Fig. 4 Calibration of "slave" pressure controllers from a production batch by a "master" pressure controller calibrated by the Budenberg dead-weight tester.

The masses of the weights together with the mass of the piston and the piston area are so arranged as to give a number of increments in the calibrating pressure. The pressure datum of the tester is at the base of the piston and is marked on the piston units. The tester is certified by the manufacturer to be balanced against an assembly calibrated by the National Physical Laboratory whence they certify that the error of the tester when used at standard temperature of 20°C ± 1°C does not exceed 0.05% of the pressure being measured. The manufacturer provides equations and software for correcting for variations in temperature (e.g. deducting 0.0027% from the nominal pressure for each 1°C rise in temperature and adding correspondingly for each 1°C fall) and gravity (e.g. the calibration for the tester is only exact at a place where the acceleration due to gravity is $9.80665 m/s^2$).

For example, the set-up for calibrating pressure sources such as pressure controllers is shown in Fig. 4. The oil outlet of the tester is connected to an oil-water change-over pot made of clear acrylic polymer so the oil-water interface can be seen. This enables the pressure connection to the controllers to be filled with water. At GDS, when calibrating a production run of say 20 controllers, one of the controllers is selected that has a very high linearity on-board pressure transducer (pressure transducers are typically specified by the manufacturer as having a minimum linearity of 0.5% but when supplied in batches will typically range from 0.4% to 0.1%). This is designated the "master" controller and is calibrated using the dead weight tester. First, the master controller "hard" zero is set in hardware (by adjusting a small potentiometer on the controller printed circuit board) against the zero of the dead-weight tester by holding a water-filled open tube that is connected to the controller so the open end of the water-filled tube is at the same elevation as the tester zero. The tube is then connected into the outlet of the tester oil-water pot. The full range is set on the tester, say 2000kPa, and the "hard" range of the master controller is also set in hardware (again by adjusting a small potentiometer on the controller printed circuit board). The master is then calibrated by increasing the pressure of the tester in steps of 100kPa in the range from 0 to 2000kPa and in steps back to zero again. At each step, the pressure measured by the master controller is stored in computer and a calibration table is made in software. The master controller is then connected by small bore nylon tubing to a manifold connecting the remaining 19 "slave" controllers of the production batch. A water-filled open tube is connected to the manifold, the open end held at the elevation of the dead-weight tester zero, and the slave controllers are also hard-zeroed. The open tube of water is then disconnected from the manifold and the master controller is set to full range, say 2000kPa, and the hard ranges set on the slaves, by adjusting another small potentiometer on the controller printed circuit board. The calibration software is then run and the computer calibrates the slave controllers against the master controller by setting target pressures on the master and measuring the corresponding pressures for each slave and thus producing a calibration certificate with a table of readings and linear regression analyses for each controller of the batch.

Calibration of machines – Virtual Infinite Stiffness (VIS)

Machines can be calibrated too. This can very useful to correct machines or machine generated readings for machine compliance. At GDS this has lead to the development of Virtual Infinite Stiffness (VIS) applied to loading systems. To the observer, and in terms of the test specimen, it allows the axial loading system to appear to have infinite stiffness.

Loading frames have a display of platen displacement. This is usually derived from the loading system mechanical characteristics such as counting steps for the driving stepping motor. This does not take into account the machine compliance that includes strain in the load cell and side columns, bending flexure of the cross beams, and distortion within the motorised mechanical transmission. For testing hard soils and soft rocks (and particularly for medium to hard rocks) the machine itself can have a stiffness comparable to the material being tested – the so-called "soft machine". This leads to the machine overestimating the displacement that occurs between the load cell and machine platen i.e. within the domain of the test cell.

To overcome this, for the entire loading range, both the measurement and control of platen displacement is automatically corrected so that it corresponds to the deformation that occurs between the platen and the load button of the load cell. In this way, the platen displacement is corrected for machine compliance. These measurements are made with the adjustable upper cross beam in the maximum and minimum positions. For each position, measurements are made with the platen at each end of its travel.

The calibration data is loaded into the read only memory (ROM) of the system which constantly monitors the axial load and uses the calibration to apply a correction to the platen displacement. Therefore, it appears to the observer (or controlling computer) that the measurement of platen displacement (resolved to 0.1µ) is derived from a machine with infinite stiffness. In this way the system has the characteristic of “Virtual Infinite Stiffness”. Of course, the loading frame (or loading assembly in the case of a force actuator used in direct shear tests for example) is not infinitely stiff – it only *appears* to be infinitely stiff by having the machine displacement corrected for machine compliance both on the display and at the computer interface.

Verification

Following the calibrations of all test equipment and transducers (and machines) *using the measurement systems of the test*, it might seem that the testing programme can begin. Indeed it can. But what if on subsequent tests and before the next calendar date of re-calibration one of the transducers malfunctions? With modern transducers monitored by computer logging with on-line test data presentation, a malfunctioning transducer might not be immediately obvious or it might be misunderstood, for example, as anomalous soil behaviour. This is why *verification* is important. For example, a GDS digital pressure controller can be easily provided with a Bourdon tube type *mechanical* pressure gauge that can readily be checked *during the test* against the display of pressure on the controller and on the computer screen and GDS can supply their controllers with pressure gauges (for example in Hong Kong – see HOKLAS requirements below). While the performance of load cells and displacement transducers, however, cannot usually be checked during a test, they can be *verified before each test*. A displacement transducer can easily be moved by either a set amount (say by inserting a small block of known size to cause a displacement of the armature) or by an approximate amount “by eye” (say $\approx$10mm) and the corresponding movement recorded by the logger can be compared to verify that the readings make sense (this can only confirm that the transducer does or does not work – not that the calibration is OK). With a load cell it is a little more complicated and less precise. A rough check can be made by extracting the submersible load cell and ram from a triaxial cell, or by removing the external load cell from a triaxial loading frame say, and loading it manually by pushing it against the floor by hand. About half one’s weight or more can easily be applied in this way corresponding to an approximate force somewhere in the range of about half to one kN. By noting the output of the load cell it can soon be seen if the reading is about right i.e. a rough verification has been made (which is better than none at all). Of course if the laboratory has a Budenberg dead-weight tester and load cell calibration rig. In-house verification (and calibration) means and procedures are a necessary requirement for laboratory accreditation. In the UK there is the United Kingdom Accreditation Service (UKAS). UKAS is a member of the European co-operation for Accreditation (EA), the International Accreditation Forum (IAF) and the International Laboratory Accreditation Cooperation (ILAC). A search on the UKAS web site under “construction/soils and stabilised soils/effective shear strength tests” returns seven company names.

The Hong Kong Laboratory Accreditation Scheme (HOKLAS) publish detailed guidelines. For example, in their on-line publication “HOKLAS Supplementary Criteria No. 18. Calibration/verification procedure or guidance documents and equipment requirements. General soil and rock tests[1]” they state clearly (and most helpfully):

“Pressure transducers – transducer types (for triaxial testing only).

Check against calibrated values of the pressure gauge Bourdon tube type at three points, one at the middle of the range, one at the lower (not less than 200kPa) and one at the uppermost range. Carry out a full calibration if the drift of the gauge exceeds the test requirement.”

In their on-line publication on measurement uncertainty[1] (or *error*), UKAS make the very important point that uncertainty of measurement has particular implications for specification, regulation and simply for comparison of test results from different laboratories. They make the point that:

“Uncertainty is an unavoidable part of any measurement and it starts to matter when results are close to a specified limit. A proper evaluation of uncertainty is good professional practice and can provide laboratories and customers with valuable information about the quality and reliability of the result. Although common practice in calibration, there is some way to go with expression of uncertainty in testing, but there is growing activity in the area and, in time, *uncertainty statements will be the norm*.”

Reference:

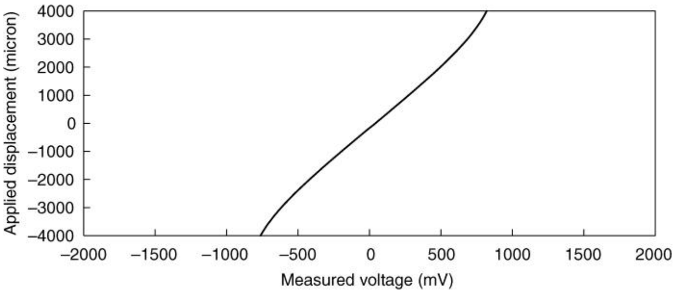
Doebelin, E. O. (1983). *Measurement systems – application and design*. McGraw-Hill, 1078p.

Sydenham, P. H., Hancock, N. H. and Thorn, R. (1989). *Introduction to measurement science and engineering.* Chichester: Wiley, 327p.

Case Study: Hall Effect Local Strain Transducer calibration and look-up table

Hall Effect local strain transducers are used for measuring small strain stiffness of stiff soils because they are light and small and can easily be attached to triaxial test specimens (Fig. 5). Hall Effect semiconductors that are used widely as sensing elements in a range of applications including computers, machine tools, and medical equipment (Clayton et al., 1989) can be deployed in such sensors. The devices register a change in voltage output when a small magnet (with pole pieces to concentrate the magnetic field) is moved relative to the surface of the Hall Effect semiconductor.

Fig. 5 One radial and two axial Hall Effect local strain transducers on a 100mm dia. Triaxial test specimen



For ±2 mm range: The equation of the calibration line in the format $y = mx + c$
$y = 4.31496047973633x + -172.494644165039$
Correlation coefficient =1.000

For ±2.5 mm range: The equation of the calibration line in the format $y = mx + c$
$y = 4.36894702911377x + -171.713790893555$
Correlation coefficient =1.000

For ±3 mm range: The equation of the calibration line in the format $y = mx + c$
$y = 4.44091987609863x + -171.151992797852$
Correlation coefficient =1.000

Fig. 6 Calibration curve for a Hall Effect local strain transducer showing S-shape

Fig. 7 Set-up of the rig used to calibrate Hall Effect transducers against displacement of a vernier micrometer. To avoid backlash the micrometer drum is turned in one direction (usually clockwise) during calibration.

A calibration certificate and curve for a Hall Effect local strain transducer is shown in Fig. 6. The calibration rig is shown in Fig. 7. It can easily be seen that the curve is slightly curved at each end in an S-shape. Any straight-line relationship will be imperfect and so liner regression lines fitted to the curve have different parameters for the ±2mm, ±2.5mm and ±3mm ranges about the mid-point. Whether these slopes are sufficiently accurate for the purpose they are being used for (measuring small movements over short gauge lengths to give local axial and radial strain) is for the user to decide. As an aid, Table 1 (Fig 6.1) tabulates the errors that would arise if the slope of the liner regression line was used as the sensitivity of the gauge. On the one hand, the user may be tempted to use the shorter range relationship but then discover that range is exceeded in a test. On the other hand, the user may play safe and use the greater range relationship only to find that movements were less that the shorter range and so accuracy was unnecessarily reduced. It may not matter a great deal, but if it does the dilemma of which range relationship between voltage and movement to use can be overcome by using a *look-up table* like the calibration tables shown in Table 6.1.

In software, the user can use the look-up table which is the actual tabulated numbers of displacement in µm and corresponding output in mV given in the calibration certificate (the manufacturer will also provide this on CD). Since output in mV is being read continually by the logging system, the computer can locate the look-up table values of say the 2 (or more) values greater than and less than the read value with the corresponding displacement being found by linear interpolation. So it can be seen that the calibration relationship between the standard and the transducer output need not be linear if a look-up table is used or a non-linear relationship fitted.

Standard displacement micron	*Output millivolts*	*Error micron on ±2 mm equation*	*Error micron on ±2.5 mm equation*	*Error micron on ±3 mm equation*
4500	859.513	223.347	209.787	192.331
4400	853.000	206.684	193.411	176.325
4300	846.013	190.496	177.510	160.795
4200	838.356	174.977	162.277	145.934
4100	829.500	160.658	148.244	132.272
4000	819.500	147.483	135.356	119.754
3900	809.500	134.308	122.467	107.236
3800	798.500	122.133	110.578	95.718
3700	786.856	110.601	99.333	84.844
3600	774.000	100.283	89.300	75.183
3500	760.500	90.607	79.912	66.165
3400	747.013	80.920	70.510	57.134
3300	732.112	72.645	62.521	49.517
3200	717.500	64.082	54.245	41.611
3100	702.000	56.407	46.856	34.593
3000	685.500	49.731	40.468	28.575
2900	668.063	43.994	35.016	23.495
2800	650.500	38.381	29.690	18.540
2700	632.500	33.206	24.801	14.022
2600	614.469	28.062	19.944	9.535
2500	595.500	23.856	16.024	5.986
2400	575.513	20.668	13.122	3.456
2300	556.000	17.005	9.746	0.450
2200	536.500	13.330	6.357	−2.567
2100	516.000	10.655	3.968	−4.585
2000	495.500	7.980	1.579	−6.603
1900	474.269	6.036	−0.078	−7.890
1800	452.969	4.160	−1.667	−9.108
1700	431.000	2.954	−2.587	−9.657
1600	409.006	1.773	−3.482	−10.181
1500	387.000	0.604	−4.365	−10.692
1400	364.288	0.141	−4.541	−10.498
1300	342.000	−0.747	−5.142	−10.728
1200	319.500	−1.422	−5.531	−10.746
1100	296.969	−2.066	−5.889	−10.733
1000	273.875	−2.147	−5.684	−10.157
900	251.000	−2.447	−5.697	−9.800
800	227.819	−2.441	−5.405	−9.136
700	204.500	−2.298	−4.975	−8.335
600	181.194	−2.167	−4.558	−7.547
500	158.000	−2.148	−4.253	−6.871
400	135.000	−2.323	−4.142	−6.389
300	111.588	−2.086	−3.618	−5.494
200	88.125	−1.799	−3.044	−4.550
100	64.500	−1.349	−2.308	−3.442

Standard displacement micron	*Output millivolts*	*Error micron on ±2 mm equation*	*Error micron on ±2.5 mm equation*	*Error micron on ±3 mm equation*
0	41.031	−1.055	−1.728	−2.491
−100	17.288	−0.487	−0.873	−1.266
−200	−8.494	2.119	2.019	1.998
−300	−32.213	2.663	2.849	3.199
−400	−55.656	2.931	3.404	4.125
−500	−79.287	3.388	4.147	5.238
−600	−103.000	3.925	4.970	6.433
−700	−126.000	3.750	5.082	6.915
−800	−149.063	3.637	5.255	7.459
−900	−172.988	4.387	6.291	8.867
−1000	−196.000	4.224	6.415	9.361
−1100	−219.000	4.049	6.526	9.843
−1200	−242.000	3.874	6.638	10.325
−1300	−264.769	3.467	6.517	10.576
−1400	−287.919	3.442	6.779	11.209
−1500	−310.000	2.348	5.971	10.772
−1600	−332.919	2.092	6.001	11.173
−1700	−354.000	−0.002	4.193	9.736
−1800	−376.288	−0.890	3.592	9.506
−1900	−398.000	−2.353	2.416	8.700
−2000	−419.788	−3.740	1.315	7.970
−2100	−441.000	−5.703	−0.362	6.665
−2200	−462.000	−7.878	−2.251	5.147
−2300	−483.000	−10.053	−4.139	3.629
−2400	−503.413	−12.816	−6.616	1.524
−2500	−523.975	−15.429	−8.942	−0.432
−2600	−543.000	−19.579	−12.806	−3.925
−2700	−562.525	−23.229	−16.170	−6.917
−2800	−581.125	−27.804	−20.458	−10.835
−2900	−600.000	−32.104	−24.472	−14.478
−3000	−617.156	−38.123	−30.205	−19.840
−3100	−634.969	−43.486	−35.281	−24.545
−3200	−651.494	−50.136	−41.645	−30.538
−3300	−667.944	−56.861	−48.084	−36.606
−3400	−683.000	−64.980	−55.916	−44.067
−3500	−698.000	−73.155	−63.805	−51.585
−3600	−712.944	−81.387	−71.750	−59.159
−3700	−726.394	−91.112	−81.189	−68.227
−3800	−739.000	−101.681	−91.472	−78.139
−3900	−751.556	−112.300	−101.804	−88.100
−4000	−763.000	−124.031	−113.249	−99.175
−4100	−774.000	−136.207	−125.138	−110.692
−4200	−784.000	−149.382	−138.027	−123.210
−4300	−793.000	−163.557	−151.916	−136.728
−4400	−801.944	−177.788	−165.861	−150.302
−4500	−809.000	−193.907	−181.693	−165.764

Fig 6.1. Look-up tables showing the relationship between electrical output in mV with standard displacement in µm for a Hall Effect local strain transducer, one table for each side of the zero or null point. Also shown are errors in µm that would be returned using the three fitted linear regression line relationships from Fig. 6.

Reference:

Clayton, C. R. I. and Khatrush, S. A. (1986). A new device for measuring local axial strains on triaxial specimens. *Géotechnique* **36**, No.4, 593-597.