PART 4: SELECTING IDEAL TRANSDUCER RANGE

Prepared by the GDS Instruments Technical Team

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 saw at the beginning of this series, the 1m rule had a range of 1m! This may seem to be a statement of the obvious but when dealing with transducers, their range is of paramount importance. Range is crucially important for two main reasons. Firstly the resolution of the signal conditioning is a proportion of the range it is set to which is fixed by the A/D converter's bit range. For 12 bit A/D the range is divided into about 4000 steps. Secondly, and just as importantly, the transducer accuracy is specified by the manufacturer as a percentage of full range e.g. 0.05% FRO is common for pressure transducers. Thus range is the key element, not only in the specification of transducers and measuring systems, but also how these specifications work out in practice. These practical outcomes are best illustrated with some examples.

Example: using a high range load cell to make low range measurements in the triaxial test

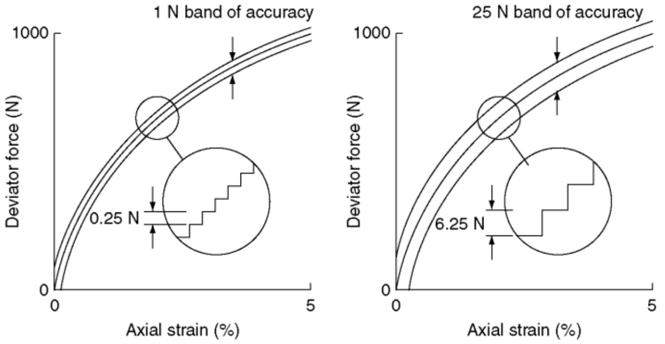
Consider a test on soft soil where the maximum deviator force will be 1000N. Imagine that two tests are carried out on identical test specimens made from the same sample, one using a 1kN load cell and one using a 25kN load cell. Assume the signal conditioning system for the load cells use a 12 bit A/D converter where the Full Range Output (FRO) of the load cell is resolved to 1 in 2^{12} or very nearly 1 in 4,000. Also imagine the load cells are specified by the manufacturer as having the same accuracy of 0.1% FRO. The resolutions of measurements and the bands of accuracy are summarised in Table 3.

Load cell range	Resolution of measurement assuming 12 bit A/D (1 in 4000)	Accuracy band assuming accuracy is 0.1% FRO
1kN	0.25N	1N
25kN	6.25N	25N

Table 3. Range, resolution and accuracy for two ranges of load cell.

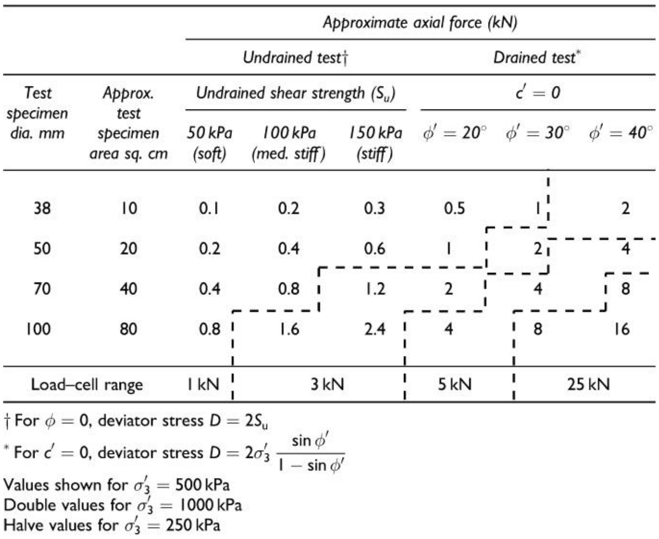
Naturally, geotechnical engineers want to see plotted results from their triaxial tests. These are shown in Fig. 8. The plot of deviator force against axial strain would look something like Fig. 8(a) for the 1kN range load cell and something like Fig. 8(b) for the 25kN range load cell. The implications of choosing a high range load cell to carry out low range measurements are immediately clear. For the low range load cell, the resolution is sufficient for most purposes. More importantly, the results lie within an acceptable band of accuracy of 1N. For the high range load cell, however, the resolution is poorer and may give a saw-tooth appearance that is the diagnostic presentation for inappropriately high ranges of transducer where the resolution is all too apparent. Most importantly, however, the accuracy band is now degraded to 25N or a massive 2.5% of the range being measured!

Shown in Table 4 is a guide for the selection of load cell range for triaxial testing of soft to hard soils. As Simons and Menzies (2000) comment *"Do not use high range transducers to carry out low range measurements – The Golden Rule of Instrumentation!"*



(a) 1 kN load cell (b) 25 kN load cell

Fig. 8 Diagrammatic deviator force vs. axial strain plots for triaxial tests on soft soil using (a) low range (1kN) and (b) high range (25kN) load cells. Note the "saw-tooth" effect in (b) typical of plotted results when low range measurements are carried out using a high range transducer.



		Approximate axial force (kN)					
		Undrained test†			Drained test*		
Test specimen dia. mm	Approx. test specimen area sq. cm	Undrained shear strength (S_u)			$c' = 0$		
		50 kPa (soft)	100 kPa (med. stiff)	150 kPa (stiff)	$\phi' = 20°$	$\phi' = 30°$	$\phi' = 40°$
38	10	0.1	0.2	0.3	0.5	1	2
50	20	0.2	0.4	0.6	1	2	4
70	40	0.4	0.8	1.2	2	4	8
100	80	0.8	1.6	2.4	4	8	16
Load–cell range		1 kN	3 kN		5 kN	25 kN	

† For $\phi = 0$, deviator stress $D = 2S_u$

* For $c' = 0$, deviator stress $D = 2\sigma'_3 \dfrac{\sin\phi'}{1 - \sin\phi'}$

Values shown for $\sigma'_3 = 500$ kPa
Double values for $\sigma'_3 = 1000$ kPa
Halve values for $\sigma'_3 = 250$ kPa

Table 4 Load cell range selection chart for triaxial testing of soils (permission of GDS Instruments).

Case study: wet-wet differential pressure transducer to control consolidation pressure

Sometimes in triaxial testing it is necessary to test at very low effective stresses for soft soils but at very high cell pressure and back pressure to ensure or restore saturation to the test specimen. This is important because if a triaxial test specimen can be restored to its original or near original saturated state (perhaps the soil was sampled from below the water table) then measurement of pore pressure is more straight forward and area correction is valid when based on volume change and axial deformation. Imagine, therefore, that a small consolidation pressure of 20kPa is required but saturation requirements mean that the back pressure should be say 1000kPa. This means the cell pressure would be 1020kPa so that the isotropic state of effective stress or consolidation pressure is 20kPa. Also imagine that the pressures are applied using GDS pressure controllers having a range of 2000kPa, 12 bit A/D resolution, with the on-board pressure transducers having an accuracy of 0.05% FRO at 100mV. Pressure can be controlled to ± 2 bits or ±1kPa. The accuracies mean that the pressure measurement is accurate to 1kPa. The cell pressure controller set to 1020kPa could actually be applying 1020±2kPa while the back pressure controller could be applying 1000±2kPa, in other words the accuracy to which the consolidation pressure was known would be ±4kPa or ±20%!

These figures are the simple consequence of using pressure sources of the appropriate ranges for high back pressure. What is required of course is some means of controlling the *difference* between cell pressure and back pressure. This can be done using a wet-wet differential pressure transducer of suitable range (say, 50kPa) and switching the feedback from the on-board pressure transducer to the output of the wet-wet differential pressure transducer that is connected hydraulically between the cell pressure and back pressure lines as shown in Fig.9. On the back pressure controller, the set target would be 20kPa.

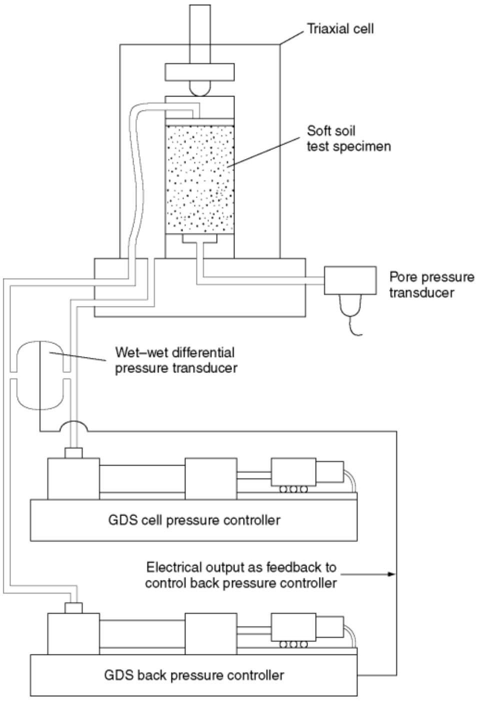


Fig. 9 Set-up schematic diagram for using a wet-wet differential pressure transducer to control consolidation pressure in the triaxial test.

The wet-wet differential pressure transducer assembly is shown in Fig.10. Zero volume change valves (that do not cause pressure changes when opened or closed) are used to connect the transducer between the cell pressure and back pressure lines. While the device is being connected in place, the valves are set so that the cell pressure is applied to both sides of the diaphragm – the “zero” condition.

Fig. 10 Wet-wet differential pressure transducer assembly to enable connection between the cell pressure and back-pressure lines in the triaxial test. Note the pipe-work gives a "safe" position for initial set up whereby both sides of the central diaphragm of the transducer are connected to the same pressure giving a null or zero condition (permission of GDS Instruments).

Assuming the wet-wet differential pressure transducer also has an accuracy of 0.05% FRO, the pressure difference between the cell pressure controller and back pressure controller will be maintained to a resolution of ±1 in 4000 (±0.01kPa) with an accuracy of ±0.025kPa. In other words, the set consolidation pressure is now 20±0.035 i.e. 20.035kPa or 19.965kPa – a vast improvement over 24kPa or 16kPa! An alternative approach is now to use 1MPa pressure controllers with 16 bit A/D. This would reduce the ±4kPa variation by 1/32 to ±0.13kPa or 0.6% of 20kPa.

Datum

In the soil mechanics laboratory there are many transducers for measuring displacement, force and pressure (see "Transducers" below). We have seen how these can be calibrated and have the accuracy of the calibrator standard transferred to them. We have also seen how measurement of the output of transducers is subject to resolution. Above all, we have seen that the sum of the transducer accuracy and the resolution of the measurement means combine to give an error to the readings made. But of equal importance is the question of the datum of measurement. While it might seem obvious that load cells, displacement transducers and pressure transducers have ranges and are calibrated within that range, nevertheless it is all too easy to overlook ensuring they have the correct datum of measurement or their "zero". The computer will perhaps prompt for the operative to set to zero all transducers connected to a logger and it is all too easy to check the "yes" box without first comprehending what actually is going on. Clearly, at this stage the load cell, displacement transducer and pressure transducer should be at zero load, displacement and pressure. But are they? It is fairly simple to ensure zero conditions for the load cell and displacement transducer. Often, however, the zeros of all pressure transducers, connected directly to the test rig or in pressure controllers, are set to different zero conditions and not a common datum. Consider the following example.

Example: Influence of datum of pressure measurement in the triaxial test

In the triaxial test, pressure transducers can be used to measure cell pressure, back-pressure, pore pressure in the base pedestal and pore pressure in the mid-plane of the test specimen. In the hydraulic stress path triaxial cell (such as the Bishop and Wesley, 1975 design), lower chamber pressure will also be measured. In this extreme example, there will be up to five pressure transducers. Naturally, there will be small differences between measurements of the same pressure by these transducers. This is because they will have slightly different accuracies (their specified deviation from a standard value). This is quite normal and should be taken into account when interpreting test results because we do not have any control over these inherent discrepancies. We do, however, have control over setting the common zero or datum of pressure measurement. This is essential for all four or five pressure measuring systems (i.e. the transducers and their associated analogue-digital conversion) to ensure that we measure pressure from the same "base line" of total head.

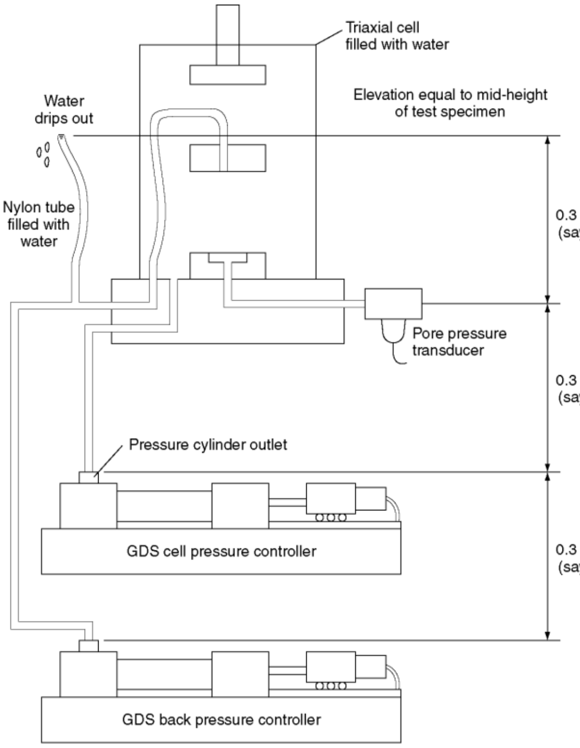


Fig. 11 Set-up schematic diagram for setting the datum of pressure measurement to the mid-height (or base if preferred) of the test specimen in the triaxial test when various pressure sensors are at different elevations.

The first thing to do is to set up the datum of pressure measurement. Normally this will be an elevation equal to the mid-height of the test specimen. Probably the best way of doing this is to connect a short length (say 300mm) of small bore nylon tubing with an open end to the back pressure connector of the cell. This is the connector to the top drain. Fill the cell with water. *There will not be a test specimen in place for this procedure*. Any mid-plane pressure transducer will be laid in the bottom of the inside of the cell together with the top cap and back pressure connection to it.

Consider the triaxial set-up shown in Fig. 11. The cell pressure and back pressure are applied using GDS digital pressure controllers. These might be mounted on a bench alongside the triaxial frame or mounted on the wall near the frame. Either way they will probably be at different *elevations* to the triaxial cell. Fill the cell with water. Apply a small positive cell pressure using the cell pressure controller. Open the valve to the back pressure line. Water will flow out of the cell into the short tube. Stop the controller from pumping when the tube is full of water and drips out of the open end. Fix the open end of the water-filled tube at an elevation corresponding to the mid-height of the test specimen (or the base of the test specimen if you prefer to use that elevation as the datum).

Now the water in the cell is at a pressure corresponding to this elevation head. Connect the back-pressure controller to the base pedestal pore water port and open the valve. Now the cell pressure controller, back-pressure controller and pore pressure transducers all share the same pressure head set by the external tube and would deliver the same zero pressure as at the mid-sample elevation. The displays of the pressure controllers and the pore pressure transducers can be zeroed at this time. Now all four (or five) displays of pressure are zeroed to the same datum of pressure measurement. For the stress path cell the lower chamber pressure controller can be zeroed at this time also. The zeroing process is a soft (as in software) zero offset – the hardware zero is not touched.

What if the different pressure transducers were zeroed at different times during the set up of the test with corresponding discrepancies? For example, consider the set up shown in Fig.11. Remember that 10kPa corresponds to a head of very nearly 1m of fresh water. If the zero offset for the pore pressure transducer is applied, the actual pressure at the pore pressure transducer will be 3kPa (this is the head of water) but because a zero offset is applied (by zeroing the corresponding channel of the logging system) this will be read as 0kPa. But consider now if the zeros had been set on the cell pressure and back pressure controllers when they were open to the atmosphere before being connected to the cell pressure and back pressure lines. Then the pressure datum for each of them will be the respective elevations of the outlets of the controller pressure cylinders. Now, for the set up shown in Fig.11, the cell pressure controller will measure (3 + 3 = 6kPa), the back pressure controller will measure (3 + 3 + 3 = 9kPa), but the pore pressure transducer will read zero because it has been zeroed in this condition. Therefore the two controllers will have a 6kPa or 9kPa difference from the pore pressure measurement due to their different zeros of pressure measurement. To overcome this discrepancy, *it is essential to zero all devices at the same time using the same datum as described in this section*.

Reference:

Simons, N. E. and Menzies, B. K. (2000). *A short course in foundation engineering*, 2nd ed. Thomas Telford, London, 244p.