Using cavity contraction creep displacements to identify principal stress boundaries in competent rock.

Y. Byrne

Cambridge Insitu, Little Eversden, Cambridge, UK

yasmin@cambridge-insitu.com

Abstract. The insitu cavity expansion test is often used to determine the elastic stiffness of competent rock. Such material will be put into tension but is unlikely to fail in shear at the loads that commercially available equipment can apply. In the absence of observable yield in shear, many of the analytical tools deployed to identify the principal stress boundaries cannot be used. Instead, fracture development and creep movement can allow some insight into the insitu state of stress. This paper considers the development and application of a cavity contraction creep assessment to determine the principal stress boundaries. It is essential that equipment can determine sub µm movements and demonstrate that such displacements are material behaviour, not instrument effects.

1. Introduction

The cavity expansion test is used to determine the engineering properties of soils and rocks. The experimental data are presented as a plot of cavity expansion against total pressure. Only in exceptional circumstances does this response give a direct indication of the insitu horizontal stresses. Most techniques for identifying the insitu horizontal stress rely on failure in shear being apparent.

In rock that does not fail in shear at the pressures that can be applied by commercial equipment (typically 20MPa), the options for identifying the initial stress state are limited. The entire test is an elastic process, but the expansion is influenced by tensile failure and fracture development. If the onset of such behaviour can be recognised, then it is possible to apply simple models of rock behaviour to identify the principal stress boundaries.

This behaviour can be observed through the assessment of creep variation with stress level. Throughout the cavity expansion pressure holds of a fixed duration are applied at set increments, giving the expansion a stepped appearance (see Figure 1). This pressure hold data can be expressed as a creep[1] displacement for a given pressure, which can be used to identify tensile failure and principal stress boundaries. This paper discusses the application of a similar process to the final part of the contraction phase of a cavity loading test.

Figure 1 presents a test in sandstone carried out using a High Pressure Dilatometer (HPD) placed in a pocket formed by rotary coring. The load at the cavity wall extends to 17MPa before being unloaded and the resulting movement of the rock is a radial strain of 1.3%. This is a combination of rock mass displacement and fracture displacement. Four unload/reload cycles for determining shear modulus (G)

[1] 'Creep' is used here in a highly specialised sense and is more akin to instantaneous creep preceding the primary creep behaviour that is a characteristic of all rock under load. Because the observation period is short and identical, it is a near instantaneous stress related elastic creep movement that is entirely recoverable.

have been taken during the loading phase and a further cycle on the contraction phase. On these axes, the slope of the cycles is expected to be 2G. This is not the case for cycles 1 and 4.

Cycle 1 has a dog-leg form or ‘banana’ shape. One of the conditions for a successful unload/reload event is that the stress at the cavity wall always stays above any of the primary lateral and vertical stress boundaries. The deviation towards asymmetry indicates that this condition has been violated, which invalidates the data for the determination of shear modulus. However, it is helpful as an indication of one of the primary stresses. Cycle 4 is invalid for a different reason. Beyond about 7MPa on the expansion, the test is dominated by fracture development. When the material is cycled the response is a combination of induced fracture movement and rock mass movement, with an apparent decrease in stiffness. Cycle 4 is hysteretic and less stiff than cycle 3 due to this effect.

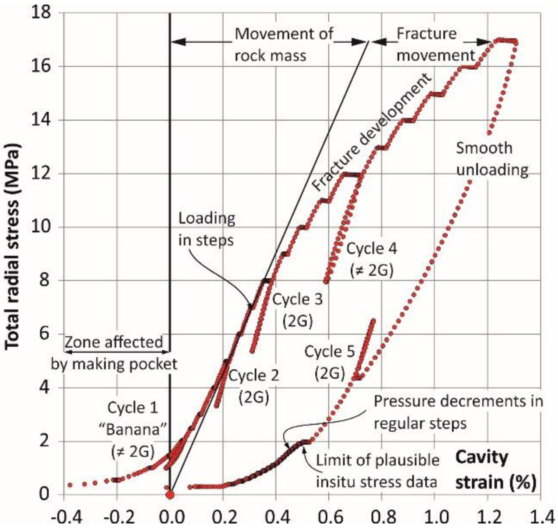

Figure 1. Example HPD test in sandstone with multiple unload/reload cycles.

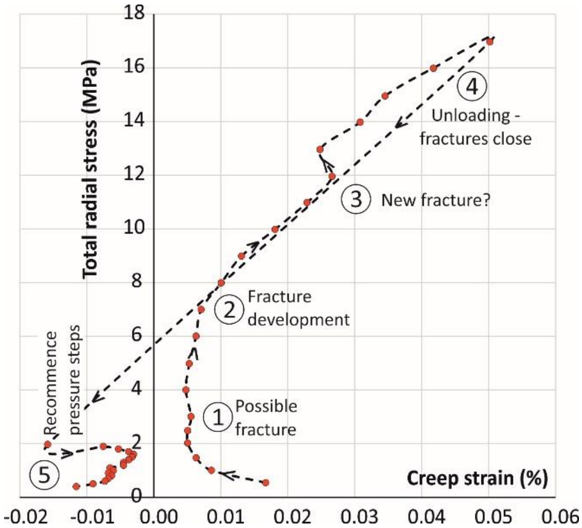

Figure 2. Creep strain against stress response for test in Figure 1.

The fracture development becomes clearer if the creep data from the pressure holds taken during expansion are extracted and examined (Figure 2). Initially the creep is substantial but reduces in a regular manner during the first 2MPa of the loading. This phase is assumed to be a consequence of pocket formation, subsequent unloading, and the probe deforming to fit the pocket. Between 2MPa and 7MPa the creep is almost constant; this can only occur when the stress at the cavity wall is greater than any primary stress boundary. There is a possible fracture initiation indicated at 3MPa, with increased creep strain indicating crack opening rather than an intact material where everything is in equilibrium.

As a consequence of controlled crack growth, the creep increases at a consistent rate that is stress dependent after 7MPa. There is an additional deflection at 12MPa. This may be a new fracture developing or the intersection of fractures.

Loading is terminated at 17MPa and the cavity is unloaded down to 2MPa. Creep readings at these points gives a result co-linear with loading data between 7 and 17MPa. This confirms that all behavior is elastic, the creep strain change is the consequence of fractures opening and closing. Observations indicate that all fracture closure terminates slightly below 2MPa in contraction. It is then possible to recommence testing in very small pressure decrements to explore the creep response in material free of fracture movement. Figure 3 is an expanded view of this critical part of the test; the loading and contraction data are shown together with the creep movements from the final phase.

2. Identifying principal stress boundaries using cavity contraction data

In competent rock, the zone of the test below the stress at which all testing induced fractures have closed can be inspected for primary stress boundaries during contraction. The Cavity Contraction Creep (CCC) assessment comprises of a series of stress holds at regular pressure decrements, each held for a fixed duration (at least 90 seconds is recommended) as the cavity contracts. A minimum of 10 fixed pressure increments are recommended to provide adequate detail. The magnitude, rate and direction of creep movement can then be assessed. Points of inflection and deviation from the general creep trend are significant indicators (Figure 3 and 5) of principal stress boundaries. In some cases, it is possible to see all three principal stresses despite the loading being in the horizontal plane. It is common to see creep magnitude decreasing for the first few holds of the CCC. This is an effect of ongoing crack closure and the rate of cavity contraction prior to the CCC.

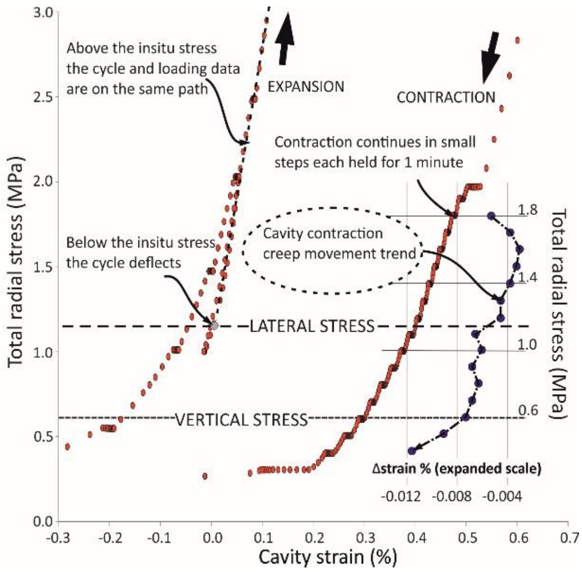

Figure 3. Expanded view of the critical part of the test shown in Figure 1 and 2.

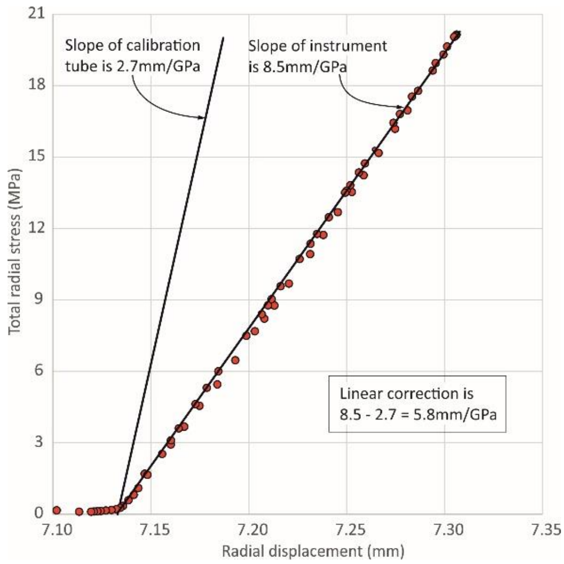

Figure 4. Calibration curve inside calibration cylinder of known properties.

This technique depends on the observed movement being that of the rock mass and not random noise. Prior to any testing, the equipment must be calibrated. The probe is expanded inside a calibration cylinder of known properties. The system compliance is calculated from difference between instrument slope and the known response of the calibration cylinder. A smooth, regular and repeatable response is required. Figure 4 shows an example HPD calibration, where the system compliance is a linear response and highly repeatable.

The CCC assessment is analogous to the Balance Pressure Check (BPC) technique [1]. The BPC can be incorporated into the cavity contraction phase in cohesive soils to observe the insitu horizontal stress. This technique only applicable to a material that has suffered significant plastic deformation. It assumes the soil retains memory of the initial stress which is indicated by a point of minimum creep and a change of creep direction.

3. Application and validation

The CCC assessment is used in combination with other methods to identify the principal stress boundaries, making use of all parts of the cavity expansion and contraction. This approach supports the determination of the credible range for principal stress boundaries, with the CCC assessment deciding specific values. This process permits data redundancy and validation of the CCC.

One such method is the assessment of unload/reload cycles. As discussed in Section 1 and shown in Figure 1 and 3, if an unload/reload cycle is taken below any of the primary lateral and vertical stress boundaries a shape change occurs. It is not always possible to target this effect.

In the example presented in Figure 3, a CCC assessment was undertaken. There is a clear zone where the creep magnitude and rate deviate from the general trend. This indicates a principal stress boundary. Within this zone there is significant point of inflection, which is inferred to be the major horizontal stress and occurs at the same stress level as the shape change within the loop presented in Figure 3. There also appears to be a creep rate change within the CCC trend, occurring at the expected vertical stress boundary.

As mentioned in Section 2 recognising stress anisotropy in a CCC is sometimes possible. Figure 5 is an example of this, where inflection points and direction changes in the creep magnitude and rate have been used to determine the major (σ_H) and minor (σ_h) horizontal stresses and their ratio σ_H/σ_h. Indications of this can also be seen in Figure 3.

For a vertically installed test, the ratio (but not the individual magnitudes) can be compared with the ratio derived from anisotropic stiffness. This concept was first developed by Dalton & Hawkins [2] and there has been recent experimental work (for example Liu et al [3]). The technique relies on applying a Mohr's circle calculation to three equally spaced stress vectors in the same plane. This information can be obtained from instrumentation with regularly and suitably spaced displacement sensors, such as a six arm HPD. Unload/reload cycles should be used as the stiffness data source to ensure minimal influence of probe movement and disturbance.

When compared with the stress ratio from the anisotropic stiffness, there is generally good agreement with the stress ratio identified in the CCC assessment, as in Figure 5. It is vital that the instrumentation used is appropriately calibrated to eliminate any bias in the individual sensors. Inspection of anisotropic stiffness can be challenging to interpret if the stress ratio tends towards isotropy. The orientation of the major stress can be expressed as a bearing if the probe is fitted with a compass. It is not possible to derive stress magnitude from anisotropic stiffness.

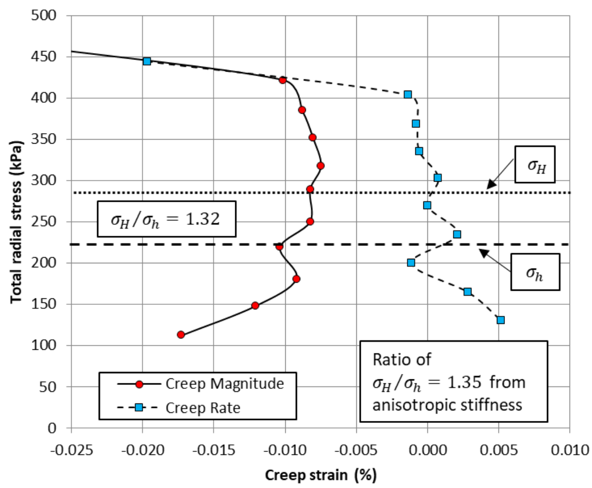

Figure 5. A CCC assessment compared with the ratio found by anisotropic stiffness.

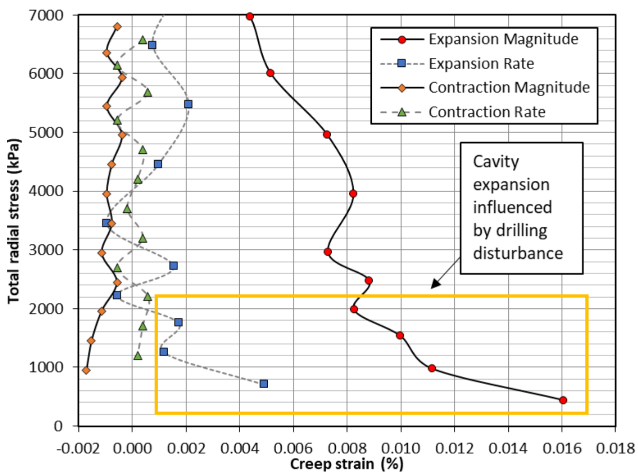

Figure 6. Comparing creep data from the cavity expansion phase and cavity contraction phase.

Section 1 touches on the standard practice for pressure holds taken during cavity expansion and the possible interpretations of this creep data. These pressure holds serve two purposes, they allow the rapid removal of any damage that occurred during pocket formation and identify fracture initiation and opening. Theoretically this first fracture will occur at the tensile stress limit and can be used to approximate the upper limit of a principal stress boundary based on Kirsch equations [4] for the equilibrium of stress: $P_T = 2\sigma_n + T$ where P_T is the tensile stress limit, T is the tensile strength and σ_n is the principle stress normal to fracture orientation. If T is not known, the calculation gives an upper limit for the insitu stress.

An example of this can be seen in Figure 3 where a potential fracture occurs at 3MPa, therefore the insitu stress can be no more than 1.5MPa. CCC assessment and other methods show the insitu stress to be 1.2MPa. This is a reasonably close agreement but suggestive that tensile strength is influencing the test. This technique is approximate due to unknowns such as fracture orientation and relaxation but can reduce the uncertainty.

4. Conclusions

The CCC assessment appears to be a useful and valid means to determine the principal stress boundary conditions. Not only can the magnitude be identified but cross hole anisotropy can also be determined in some cases. Selecting the best estimates of the principal stress boundaries can be subjective. The influence of pocket formation damage and fracture growth caused by cavity expansion do not impact the CCC assessment. This can be observed in Figure 6, which shows that the magnitude of creep in the CCC assessment is significantly smaller than that from the initial cavity expansion.

The preliminary validation of the method has been successful, however all validation techniques used have compared the CCC assessment to other parts of the pressuremeter curve. The next stage of validation is comparing CCC results with alternative methods of determining the insitu stress, for example hydraulic fracturing or over-coring.

Additionally, it must be noted that the CCC assessment, along with all cavity expansion principal stress determination techniques, is reliant on scrupulous calibration of the equipment. Significance is being attributed to very small displacements, so the resolution must be less than a µm for the results to have validity.

References

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