A new ring shear apparatus for determination of the residual shear resistance of remoulded brown coal

R, Mackay[1], J. Xue[1], W. Powrie[1] and B. Dent[1]

[1]Geotechnical and Hydrogeological Engineering Research Group, Monash University, Gippsland Campus, Building 4W, Northways Avenue, Churchill,Victoria 3842, Australia; PH +61 3 9902 7191 ; email: rae.mackay@monash.edu

ABSTRACT

Victorian brown coal is a typical intermediate geomaterial, whose behaviour falls between that of soft rock and engineering clay. The intact material exhibits lower permeability and higher tensile strength compared to over-consolidated clay. Large, shallow open cuts are used to mine the coal in the Latrobe Valley, Victoria, Australia, predominantly as fuel for Victoria's power stations. For batter design the brown coal is treated as clay with high values of cohesion and friction angle. Composite rotational and block sliding is a recognised failure mode for this material and it is apparent from recent observations that failure risk increases with time. During long-term movements of the brown coal behind and below the batters it is anticipated that the material will be crushed and remoulded along sliding surfaces as a result of progressive pre-failure displacements. After periods of decades, the assumption is that for large sections along any incipient failure surface, shear strength will be at or close to the residual shear strength of the material. Thus. it is important to understand whether this assertion is correct and the processes leading to the weakened state. A new ring-shear test apparatus has been designed to determine the variation of shear strength of this material for a range of shear strains under essentially drained conditions. In this paper the design considerations and the resulting form of the test apparatus are presented. The equipment is also applicable to the testing of the interseam clays, silts and fine sands that are also found in the mines.

Keywords: Ring Shear, Intermediate Geotechnical Material, Brown Coal, Residual Shear Strength, Large Strain.

1 INTRODUCTION

The Latrobe Valley, Victoria, Australia is underlain by the world's largest deposits of brown coal. Since the 1920's, these have been exploited for electricity power generation even though the energy value of the coal is relatively low. The thickness of the deposits, and the very low overburden to coal ratios, permit economic extraction of the coal and current production is greater than 65 Mt/year. Coal is extracted from deep open cuts and transported directly on conveyor to the power stations located adjacent to the mines. The three operating open cuts are Yallourn, Morwell and Loy Yang, with Yallourn the oldest and Loy Yang the most recent and deepest. Significant dewatering is required to prevent heave of the mine floor and to maintain stability of the mine batters. Relaxation and depressurisation of the materials adjacent to the open cut induces significant movements horizontally and vertically behind the batters. The brown coal is a soft rock and a typical intermediate geomaterial. Analysis of its geotechnical behaviour has usually assumed it can be treated in the same manner as clay but with higher values of cohesion and friction angle. As with old slopes in clay (Chandler and Skempton, 1974), long term slope stability in brown coal is an issue given the decadal periods over which the mines are operating.

This issue was brought into focus with a failure of the northern batter of the Yallourn Open Cut in 2007 (Mining Warden Report 2008). The failure raised questions about current understanding of the long term behaviour of the coal and the risks to electricity production and infrastructure in the Latrobe Valley from further collapses. A program of reanalysis of the coal and interseam geotechnical properties is presently being implemented by the new Department of Primary Industries-funded Geotechnical and Hydrogeological Research Group at Monash University Churchill Campus that seeks to improve the understanding of the long term rock and groundwater movements controlling geotechnical risk. The current paper reports on the design of a bespoke ring shear test apparatus to look at large strain stress path behaviour in the brown coal and the interseam silts/clays.

2 BROWN COAL MINING IN THE LATROBE VALLEY

2.1 Geological Setting

The brown coals of the Latrobe Valley were deposited within the Gippsland Basin of Victoria, Australia, during the Eocene to Late Miocene. Within the valley the major coal deposits extend over an area of approximately 900 sq. km. The important geological sequence, the Latrobe Valley Group, is comprised of essentially non-marine sands, clays and coals. This is further divided into three main coal seam stratigraphic units; namely the Yallourn Morwell and Traralgon Formations. The seams accumulated in place within distinct coal depocentres largely south of the present-day Latrobe River and west of a marine interface with the Gippsland Limestone. The depocentres have shifted with time, probably due to differential compaction. Clay sequences effectively surrounded the coal forming peat swamps and protected them from the more destructive fluvial inputs coming from higher ground beyond the Latrobe Valley edges. As a result, the peat swamps became stabilised for long periods of time to produce the thick brown coal seams (Barton et al. 1993). Coal thickness is typically greater than 50m at the mine sites. The seams are separated by aquifer units of the Morwell Formation and underlain by the aquifer units of the Traralgon Formation. These seams were compacted by significant depths of fluvial material in the late Tertiary and were subsequently folded, eroded and covered by a "sheet" of Pliocene-Pleistocene aged fluvial gravels, sands and clays. The upper coal seams were eroded out in many areas during this period (Figure 1). The interseam materials are low strength and highly variable in thickness. Current overburden thicknesses at the mine sites are typically less than 20m. The rank of the coals increases with depth of burial; increased carbon and reduced oxygen content reflects historical burial depths.

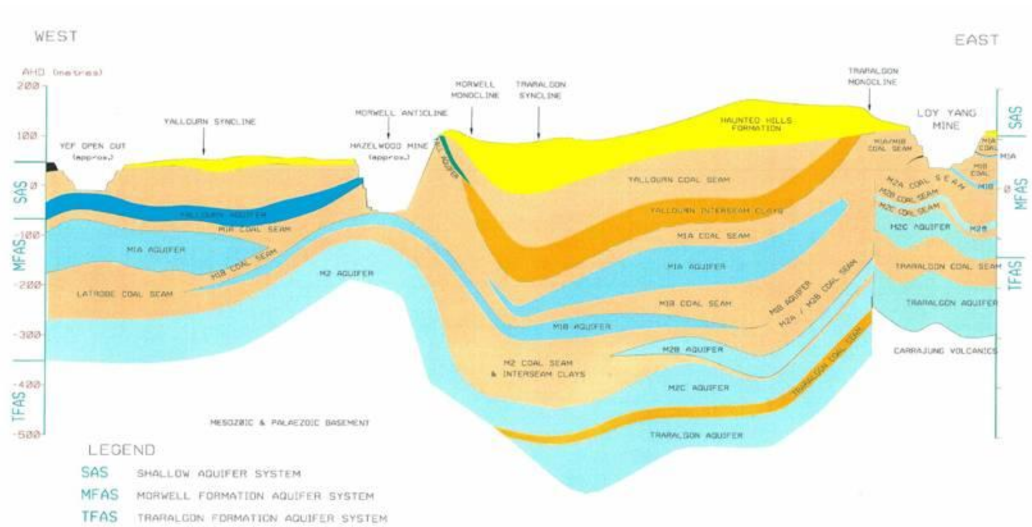

Figure *1 E-W Section through mining area (reproduced from Schaeffer 2008)*

2.2 Brown Coal Properties

The brown coal is predominantly organic with little mineral content: typically less than 2% dry weight. It is laterally and vertically variable within the formations, with increasing sizes of 'woody' material in the upper sections trending to amorphous short fibrous material at depth. Under the microscope the material has a largely granular appearance (Figure 2). The coal becomes a fine powder on drying and sieving, presenting little observable structure with grain sizes ranging over the fine to coarse sand range (Yallourn) and fine to coarse silt range (Loy Yang), characteristic of the different burial depths and ages. The chain lengths of the fibres can be assumed to be short due to the loss of cellulose, so that the material is much less fibrous than its precursor, peat. The coal is wet, with average moisture contents observed in the ranges 150 to 220% (Wt/Wt). Consequently, the coal has a very low bulk density, ranging between 1.1 and 1.2 g/cm^3 across the three coal formations. The permeability of the intact coal is also very low, around 1e-5 m/d, with most water bound to the coal grains within the fine pores and relatively few large pores for fluid flow. Permeability is related to moisture content. Sub vertical jointing is evident in the coal mass with a mean spacing that varies depending on the formation. The permeability of the joints can be high depending on aperture. Joint orientations are consistent with the tectonic history of the coal.

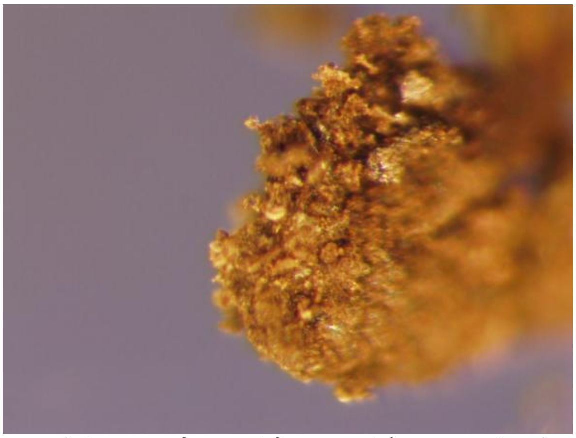

Figure 2 Image of a coal fragment (approx size 2mm)

Oedometer tests (Trollope et al. 1965) show consolidation responses similar to undisturbed clay with clearly defined pre-consolidation stresses and relatively low elasticity. All tested samples exhibit time dependent strain at high loads. No references have been found for any evaluation of time-dependent strain in the brown coal at low effective stresses. Drained and undrained triaxial tests were also carried out by Trollope et al. (1965). The key points from these tests were that the failure was brittle in character with the appearance of definite shear planes; failure was unaffected by woody fragments for compressive failure but was affected by such fragments during tensile failure; the drained tests showed significant volumetric strain, often comparable to the axial strain of the test. This makes it difficult to minimise end effects of the triaxial test at the point of failure. Mohr Coulomb failure envelopes for the undrained compression tests on samples from Yallourn yielded apparent angles of friction of 45^{o} for drained conditions and 17^{o} for undrained conditions. While peak stresses at failure have been reported, there is little information on the residual strength of the brown coal and, more importantly, there is little information identifying the shear strength of pre-existing joints. Key slope stability questions are concerned with whether the ratios of lateral to vertical effective stresses in the coal can lead to the creation of shear surfaces and what are the shear characteristics of these shear surfaces.

2.3 Batter Failure Mode

The following extract is taken from the executive summary of the Mining Warden's report of the Yallourn batter failure in 2007:

"The failure occurred by a mechanism called block sliding, where a large block of coal slid horizontally across the mine floor. The failure extended as far back as the Latrobe River, which was completely diverted into the mine by the failure.

There were two main causes for the failure. The principal cause was water pressure in a joint along the rear of the failure. The joint, which is a naturally occurring crack in the coal, connected with the Latrobe River. The water in the joint exerted a horizontal pressure on the coal block. The other main cause of the failure was water pressures in the interseam clays underlying the block of coal. These water pressures caused a buoyancy effect on the block of coal reducing the resistance to sliding along its base."

This summary provides a simple image of the final failure but the processes occurring over an extended period prior to failure and the conclusions from back analysis of the failure also require elaboration. Data on movements prior to failure showed considerable horizontal and vertical strains, exceeding 1m and 0.5m respectively. These occurred over the preceding eight years, during which period the rates of movement were accelerating. Equally, the back analysis showed that the apparent shear strength at the time of failure was required to be 16^{o} for the interseam clays, a significantly lower figure than that identified from testing or adopted for slope stability assessments. These observations suggest either the driving forces for horizontal movement were much greater than estimated (and they were increasing over the previous two years), or that the peak shear strength of the failure surface had been exceeded and that the shear strength of the failure surface was reducing over time. One mechanism that may explain part of the problem is an increase of fluid pressures at the failure surface arising from a progressively increased recharge behind the batters. The other mechanism could be a reduction of shear strength due to the large strains along the shear plane prior to failure. A combination of these two changes is perhaps the most likely, but it is the latter process that is of interest for this paper. The magnitude of the change in shear strength arising from large strain needs to be addressed. The relationship between the shear strength and effective stress at different phases of deformation must also be quantified. In order to explore these relationships a ring shear apparatus has been designed for the conditions and materials encountered in the open cuts.

3 RING SHEAR TESTING

3.1 Historical Development

There have been numerous designs for ring shear apparatus developed since the beginning of the 20th Century. Bishop et al. (1971) provides a useful overview of the work completed by various researchers leading up to their proposed new design. Sample shapes adopted included circular, cylindrical and annular configurations of varied thickness from 1mm to 60mm depth and alternative lateral confinement and loading. The cylinder method was found to be the least successful of the configurations due to the complexity of mounting the sample in the apparatus. Circular samples were adopted in early developments but were largely superseded by annular designs after 1940. The mean diameter of the annular samples has been varied considerably in the different apparatus from 6cm to 20cm with the annular width varying from 2cm to 5cm. The relative sizing of the annular widths and diameters has clear implications for the magnitudes of the loads that can be applied and for the required torque needed to rotate the sample to induce shear. All early designs including Bishop’s apparatus assumed drained conditions for testing. The thickness of the sample reflected the materials to be tested including the granularity of the sample and the anticipated thickness of the shear zone. Successful testing of clays appeared to be possible even at thicknesses as low as 3mm as long as shear could be induced within the body of the sample and not at one of the surfaces of the confining platens. Bishop’s design was adopted recently by Toyota et al. (2009) for remoulded soil samples.

In Japan a ring shear apparatus (DPRI versions 1 - 6) for the investigation of liquefaction flows in landslides and seismic response of landslip materials has been progressively developed (Okada et al. 2004, Trandafir and Sassa 2004, Jurko et al. 2008). The apparatus is designed for relatively coarse materials and for testing undrained as well as drained samples to understand fluid pressure responses during liquefaction. The annular section has 3cm width and a thickness of 6cm with mean diameter of 15cm. The modification of this ring shear apparatus to maintain high fluid pressures clearly presented a significant technical challenge and novel challenges for the initialisation of the test procedure. Nevertheless, the DPRI suite of testing rigs represents the current state-of-the-art in terms of ring shear apparatus for coarse to fine geomaterials. The large thickness of a sample has implications for shear test response of cohesive samples arising from the potential for vertical as well as lateral shearing. Hong et al. (2011) report the use of the DPRI-version 3 test apparatus for remoulded over consolidated silty clay samples with encouraging results.

Commercial ring shear testers have been developed (Schulze 2011) but these are mostly designed for the investigation of powders in manufacturing. As such their design has less to do with investigation of failure surfaces but more to do with the internal shearing resistance of powders under different, typically low, confining loads to explore aspects of flowability. Small diameter ring shear testers are commercially available for evaluating the residual strength of clay soils but it is unclear how far these can be used to evaluate stress paths at low shear velocities.

3.2 Design Criteria

The fine grained nature of the brown coal and the silty clay interseam materials suggests that it is not necessary to adopt thick samples. Thick samples require much greater lateral confinement to prevent sample loss from the annular space as well as greater drainage time to achieve undrained conditions during loading. Nevertheless, the potential for use of either disturbed or undisturbed samples is required and this will limit the minimum thickness permissible. Methods for shaping brown coal are clearly explained in Trollope *et al.* (1965) and it is possible to cut and turn thin (<1cm) sections of brown coal for testing from core samples. These methods have been trialled by the authors and found to be satisfactory for thicknesses on the order of 0.5cm under carefully controlled environmental conditions. Field methods will need to be designed for non-disturbed sampling of the interseam clays at exposures in the mine floor and walls to achieve similar thicknesses. Methods similar to those used for oedometer sample preparation are suggested. The previous triaxial testing of the brown coal when considered in conjunction with the rate of movement of the batters prior to failure indicates that drained testing will be sufficient for gaining the required understanding of the shear strength of the coal at large strains. A similar argument can be applied to the testing of the interseam materials. Evidence from previous studies with ring shear testers (Bishop et al.1971, Schmitt and Feise 2004) suggests shear speed is not an important variable, but in all reported cases the test speeds are substantially higher than those that may be observed in the field at the base of a batter prior to the onset of final collapse. Therefore, some care is required to confirm the independence from shear velocity of the shear results at low deformation rates of the brown coal and the interseam clays.

The key design criteria are, therefore:

1. The maximum normal stress to be applied to the sample;
2. The maximum expected shear stress to be applied to the sample;
3. The ratio of the maximum to minimum shear displacement rates across the sample;
4. The mean minimum and maximum shear rotational displacement rates;

3.3 The Final Design

3.3.1 Maximum normal and stress

The maximum normal effective stress (σ'_N) adopted assumes negligible groundwater pressures at the base of the batter and a maximum batter height of 90 m comprised of 10 m overburden and 80m of brown coal with specific gravities of approximately 2.0 and 1.2, respectively. This yields a value for σ'_N of 1140 kN/m^2.

Assuming a maximum shear stress equal to the peak shear stress at failure from the triaxial testing carried out by Trollope *et al.* (1965) and the failure angle to be 45^o, the maximum design shear stress (τ_s) will be 570 kN/m^2.

3.3.2 Shear Ring Sizing

Sizing of the ring shear is a trade-off between the shear differential across the ring and the maximum torque permissible for the required shear stress, subject to component maximum load constraints for the motor and gear reduction units and the drives connecting the gearbox to the rotating plate. A chain drive has been adopted to provide a smooth uptake of the motor speed onto the sample. A maximum outer ring diameter of 200mm with an annular width of 4cm is feasible for the required magnitude of the torque and the proposal to operate the shear box at displacement rates less than 0.05mm/sec maximum displacement velocity at the outer limit of the ring,. This configuration means that the ratio of the outer to inner velocities is 1.7:1, which is consistent with other ring shear test designs. The relatively large diameter compared to commercial testers should minimise the impact of side wall friction on the development of the shear surface. Moreover using a nominal sample thickness of 5mm will reduce edge effects and minimise times for pressure equilibration.

3.3.3 Exploded view

The final design for the shear tester is illustrated in Figure 3. Roughened surfaces on the fixed and rotating plates minimise the risk of shear occurring at the sample's upper or lower boundaries. The adoption of an inner confining ring made from Silicone rope facilitates sample installation. The upper outer confining ring is free to rotate. The adoption of a sintered brass porous plate allows rapid equilibration of pore pressures across the sample.

4 DISCUSSION AND CONCLUSIONS

A new ring shear test apparatus has been designed specifically for testing the relationship between brown coal and interseam clay shear strength and the magnitude of shear displacement on a sliding surface. The design takes account of previous experience of ring shear testing, the properties of the materials being tested and the anticipated conditions for the slopes of interest.

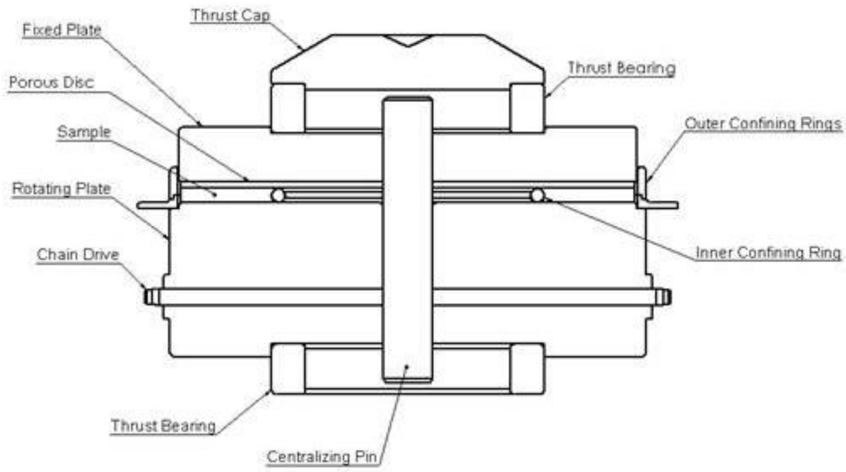

Figure 3: Section through main shear ring assembly (excluding drives, motors and housing)

Three key reasons for building a new ring shear device were (1) to reduce the minimum shear velocity to allow early stage development of a shear surface to be monitored, (2) to achieve the loads expected for the conditions in the open cuts without the requirement to compensate for equipment-based stresses and (3) to provide a large surface area to ensure the consistency of the results. Certain elements of the design have been constrained by the mechanical demands of delivering the required normal and shear loads. A particular constraint is the maximum output torque of the motor gearbox, which governs the upper limit of the sample size. Following completion of detailed equipment testing and calibration, a program of brown coal testing will be undertaken to quantify the stress-strain behaviour of the different brown coal lithotypes observed in the Latrobe Valley open cuts. Of key importance for testing is the ability to impose low rate displacements smoothly at high normal and shear forces and this has necessitated the adoption of a highly geared electric motor with chain drive.

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