INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-2-7

Interpretation of shear strength data for construction on mine tailings deposits

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ABSTRACT: The safety of an upstream embankment raise or final capping for a conventional surface slurried tailings storage requires that the existing tailings be desiccated and a geotechnical investigation to demonstrate adequate bearing capacity. Typical geotechnical investigation methods include in situ shear vane testing and cone penetration testing. Heavily desiccated tailings may allow direct access using a conventional rig. Otherwise, a rig with wide tracks may be required, or access roadways may have to be constructed over the tailings. The data from these tests are then interpreted to determine the shear strength profile for the desiccated tailings, to enable bearing capacity, geotechnical slope stability and settlement analyses of a proposed upstream embankment raise or capping. The paper describes two case studies of such geotechnical investigations, test data interpretation, and geotechnical analyses; one for an upstream embankment raise on heavily desiccated tailings and the other for the capping of variably desiccated tailings.

1 INTRODUCTION

For mine tailings conventionally deposited as a slurry in a surface tailings storage facility (TSF), in situ vane shear testing and cone penetration testing including pore water pressure measurement (CPTu) are typically employed to determine the shear strength profile with depth of the tailings. The shear strength profile is used to assess the feasibility and safety of upstream raising of the containment embankment on tailings or final capping of the tailings for rehabilitation purposes.

Two case studies of such geotechnical investigation, test data interpretation and geotechnical analyses are described. The first involves the proposed upstream embankment raise on heavily desiccated tailings at South23's Cannington Underground Mine in north-west Queensland, Australia. The second involves the capping of variably desiccated tailings at New Hope Group's New Acland Coal Mine in south-east Queensland. The focus of the paper is on test data interpretation, which is an area that is often deficient.

2 DESCRIPTION OF CANNINGTON SITE

South32's Cannington Underground Mine is located 250 km south-east of Mount Isa in north-west Queensland, Australia, and has produced silver, lead and zinc since 1997. The ore is ground to -180 micron, and processed to produce Sandy SILT to Silty SAND-sized tailings. The tailings are thickened in a high rate thickener and discharged at 65% solids by mass. Of the tailings produced by the processing of the ore, 60% is returned underground as cement paste backfill, and 40% reports to a surface tailings storage facility (TSF) comprising three cells. Tailings deposition into Cell 1 ceased about 4 years ago, and the embankment is proposed to be raised by the upstream method using borrow material located partially on heavily desiccated tailings to accommodate tailings from late 2017. The proposed 3 m high upstream raise of Cell 1 is the optimal solution to cost-effectively and safely provide additional tailings storage capacity beyond the filling of Cell 3.

2.1 *Tailings storage facility to be raised*

The surface TSF comprises three cells. Cell 1, with an area of 44 ha, and Cell 2, with an area of 44 ha, were constructed in the late 1990's, and have each been raised a number of times to reach their current embankment heights. Tailings deposition into Cell 1 ceased about four years ago and deposition into Cell 2 ceased about one year ago. Cell 3, with an area of 58 ha, was completed in May 2014 and is currently the active cell. Cell 3 is expected to be filled by August to October 2017. A 20 September 2013 aerial view of the Cannington surface TSF, with Cell 2 still operational and Cell 3 under construction, is shown in Figure 1, and a view of the heavily desiccated surface of Cell 1 is shown in Figure 2.

Figure 1. Aerial view of Cannington's surface TSF (Google Earth, 20 September 2013).

Figure 2. View of heavily desiccated surface of Cannington's surface TSF Cell 1.

2.2 *Geotechnical investigation and testing*

The geotechnical investigations reported by SRK Consulting (2015) included Dynamic Cone Penetration Tests carried out in the desiccated Cell 1 and 2 tailings, which highlighted the far greater desiccation of the Cell 1 tailings that had been left to desiccate about four times as long as the Cell 2 tailings since the last deposition of tailings. Twelve Cone Penetration Tests with pore water pressure measurement (CPTu) and *in situ* vane shear testing were carried out in the heavily desiccated Cell 1 tailings. Laboratory characterisation and geotechnical parameter testing was carried out on tailings and borrow samples.

The Cannington tailings particle size distribution is Silty SAND to Sandy SILT-sized, with 40 to 70% sand-size (0.06 to 1.5 mm), 37 to 63% silt-size (0.002 to 0.06 mm), and 3 to 7% clay-size (<0.002 mm). The tailings are generally non-plastic, with a Liquid Limit of 14 to 16%. The specific gravity of the tailings is about 3.15, and the near surface settled and desiccated dry density is about 1.76 t/m^3 (SRK Consulting 2015).

2.3 *Interpretation of CPTu and vane shear data*

The consolidation state of a soil may simply be interpreted using the method of Schmertmann (1978), which was applied to all 12 CPTu cone resistance profiles with depth in the heavily desiccated Cell 1 tailings. The Schmertmann (1978) method involves extrapolating lines through the lower bounds of the cone resistance profiles to the surface. The lower bound line intersecting the surface to the right of the origin indicates under-consolidated tailings, passing through the origin indicates normally-consolidated tailings, and intersecting the surface to the right of the origin indicates over-consolidated (usually desiccated) tailings. In addition, the depth to the (presumed) perched water table within the tailings was estimated based on the measured pore water pressures. A typical interpretation is shown in Figure 3.

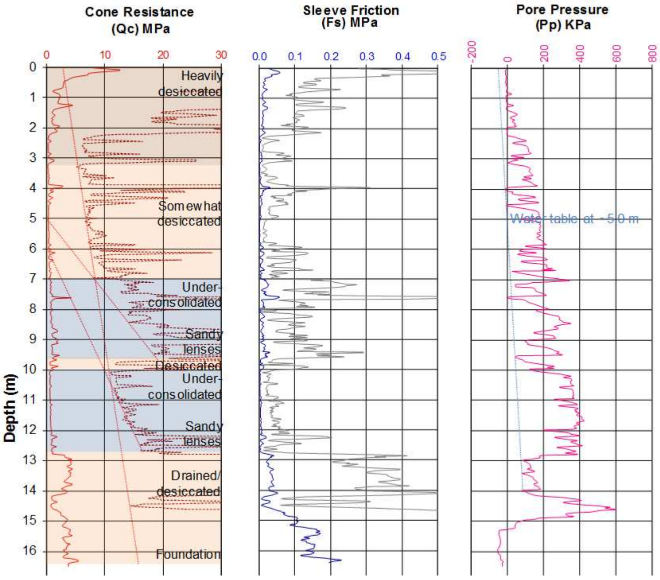

Figure 3. Typical interpreted consolidation state and depth to water table for a CPTu in heavily desiccated Cell 1 tailings.

The upper layer of the tailings in Cell 1 is seen in Figure 3 to have become heavily over-consolidated due to four years of desiccation since tailings deposition ceased. The layer below that is generally somewhat desiccated (over-consolidated) due to intermittent surface desiccation followed by re-wetting by fresh tailings, or normally-consolidated (maintained under water), and occasionally under-consolidated (unable to drain the self-weight-induced excess pore water pressures). The layer of tailings above the foundation is drained or desiccated. The spikes in cone resistance profile indicate sandy lenses. The range and average interpreted consolidation states and estimated perched water table depths estimated from all 12 CPTu profiles in Cell 1 tailings are summarised in Figure 6.

Vane shear strength testing carried out in the Cell 1 tailings gave the data shown in Figure 4 (SRK Consulting 2015). There is a lack of vane shear strength data in the upper 4 m constituting the desiccated crust since the crust was too stiff to test. Correlating the vane shear strengths S_u with the corresponding CPTu cone resistance values Q_c gives the bearing capacity factor N_c :

$$N_c = \frac{Q_c}{S_u} \qquad (1)$$

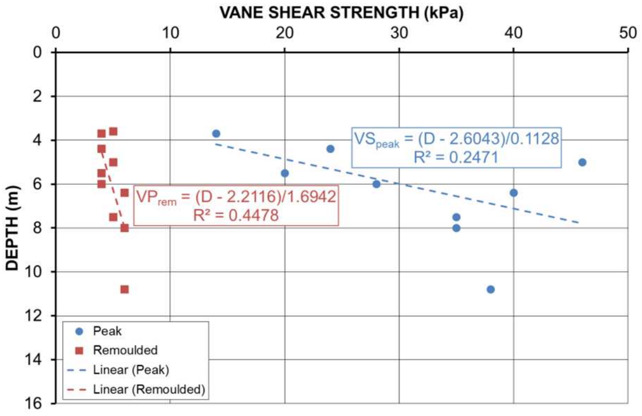

Figure 4. Peak and remoulded vane shear strengths with depth in Cell 1 tailings.

Values for the peak and remoulded bearing capacity factors are plotted in Figure 5. The reported vane shear strength data and the calculated bearing capacity factors are very scattered. The range of peak bearing capacity factors is 7.8 to 24.0, with an average value of 14.4, while the range of remoulded bearing capacity factors is 53 to 160, with an average value of 88.6.

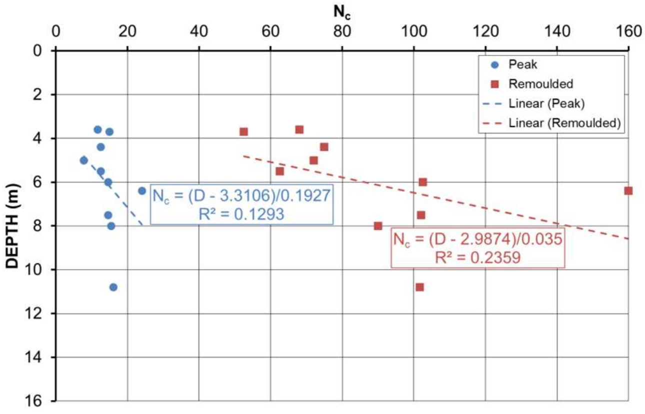

Figure 5. Calculated peak and remoulded bearing capacity factors with depth in Cell 1 tailings.

Conservative (lower bound) values of the peak vane shear strength are equivalent to 0.25 times the vertical effective stress, and conservative values of the remoulded vane shear strength are equivalent to 0.04 times the vertical effective stress. The average ratio of the remoulded to the peak vane shear strengths of 0.16 is low compared with ratios expected for tailings of about 0.5 below the water table and about 0.33 above the water table (Williams 2005). The remoulded vane shear strength is representative literally of the shear strength that applies on remoulding, such as that caused by loading the tailings so much and so rapidly as to cause "bow-wave" failure.

Skempton and Henkel (1953) were the first to suggest an empirical relationship between undrained shear strength S_u and vertical effective stress σ_v'. For normally-consolidated (nc) soils (in the context of tailings, those always stored below water):

$$\left(\frac{S_u}{\sigma_v'}\right)_{nc} = 0.11 + 0.37\left(\frac{I_P}{100}\right) \qquad (2)$$

where I_P = Plasticity Index. For over-consolidated (oc) soils (in the context of tailings, those subjected to desiccation drying followed by re-wetting):

$$\left(\frac{S_u}{\sigma_v'}\right)_{oc} = \left(\frac{S_u}{\sigma_v'}\right)_{nc} OCR^m \qquad (3)$$

where OCR = over-consolidation ratio, and m = an empirical exponent, generally taken as 0.8. Inputting the values of the parameters for Cannington Cell 1 tailings, Equation (2) gives $(s_u / \sigma_v')_{nc}$ = 0.17, which is low compared with the value typical for normal soils of 0.25. It will subsequently be shown that a value for $(s_u / \sigma_v')_{nc}$ of 0.25 is consistent with the CPTu and vane shear data, and can be adopted. The upper Cannington Cell 1 tailings are clearly over-consolidated due to their heavy desiccation, leading to a higher value for $(s_u / \sigma_v')_{oc}$.

All 12 CPTu cone resistance profiles are plotted in Figure 6, together with the average profile. In Figure 7, the CPTu cone resistance data have been divided by the average peak bearing capacity factor of 14.4 to provide the estimated profiles of peak shear strength with depth, again including the average profile, plus the "smoothed" lower bound of the average profile, ignoring the peaks caused by the sandy lenses.

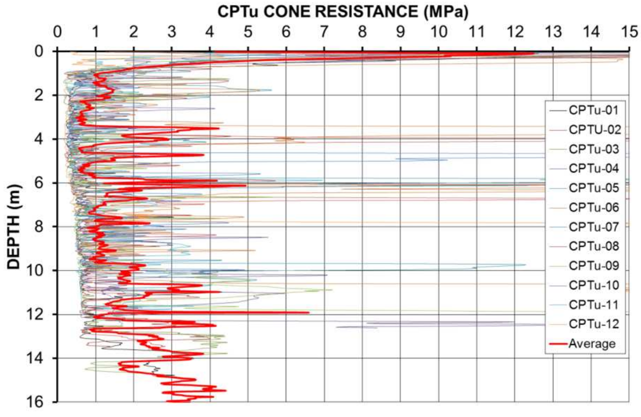

Figure 6. CPTu cone resistance versus depth profiles.

Also shown in Figure 7 are the approximate normally-consolidated, self-weight profile and the approximate over-consolidated profile, the latter made to match the smoothed average profile below the water table (from about 4.6 m depth). The average OCR is approximately 3.15 and, using Equation (3), $(s_u / \sigma_v')_{oc}$ is approximately 0.63, 2.5 times the adopted normally-consolidated value of 0.25. The remoulded values are approximately 0.4 times these values, but will only be realised if remoulding is initiated.

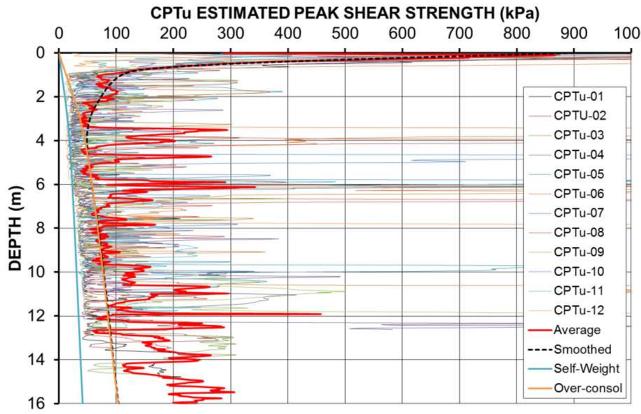

Figure 7. Estimated peak shear strength versus depth profiles.

3 DESCRIPTION OF NEW ACLAND SITE

New Acland Coal Mine in the Clarence Moreton Basin within the lower Walloon Coal Measures, is located north-west of Oakey in South East Queensland, Australia. Initially, New Acland discharged slurried tailings generated by their coal processing plant to a surface tailings storage facility (TSF1 and TSF1 Extension), before establishing in-pit TSFs (see Figure 8).

Figure 8. New Acland surface and in-pit TSFs (aerial photograph taken on 12 March 2013).

Sometime after the cessation of tailings deposition into TSF1, following surface crusting, spoil was dumped from haul trucks onto the surface of the tailings from the northern and eastern upper tailings beach. However, this resulted in 'bow-waving' of the crusted tailings. Spoil placement was stopped when a 1 to 1.5 m high bow-wave overtopped the bund dividing TSF1 from TSF1 Extension, and approached the southern external wall of TSF1. Subsequently, New Acland committed to more effectively capping the surface TSF.

3.1 *Method of capping of surface TSF*

The bow-waving that occurred on the placement of spoil on the upper northern tailings beach of TSF1 highlighted the need to select a less impacting capping method. Coarse reject from the coal preparation plant was proposed as the initial capping material due to its availability as a waste material that had to be disposed of, and it being better-draining than spoil, which degrades rapidly. The overall cover was to comprise and initial approximately 1 m thick capping layer of coarse reject, followed by a second 2 to 3 m thick layer of coarse reject, and finally a topsoil layer that was to be seeded with pasture grasses and fertilised.

Pushing coarse reject by D6 Swamp Dozer was adopted as the initial capping method. The D6 Swamp Dozer, with an operating mass of 21.7 t exerts an average track bearing pressure of 35 kPa, equivalent in bearing pressure to about 1 m height of fill. This needs to be taken into account in addition to the height of fill placed, to ensure safe operation on the crusted tailings.

3.2 *Assessing bearing capacity of tailings*

The bearing capacity of tailings is a function of their shear strength profile with depth. Given the difficulty of sampling and generally low shear strength of fine-grained coal tailings, in situ vane shear testing is the most appropriate and direct means of obtaining an estimate of the shear strength profile of the tailings with depth. Both the peak and remoulded vane shear strengths should be measured. The peak vane shear strength is the value obtained on initial shearing, while the remoulded vane shear strength is the value obtained on re-shearing after remoulding by rotating the vane a nominal three revolutions. The vane shear strength of the tailings S_v is estimated using:

$$S_v = T\,10^6 / \left[\pi\left(\frac{D^2 H}{2} + \frac{D^3}{6}\right)\right] \qquad (4)$$

where T = measured (peak or remoulded) torque in N.m, D = vane diameter in mm, and H = vane height in mm (typically twice the diameter, to limit the shear resistance on the ends of the vane to about 10% of the total shear resistance on the vane).

The fill height H in m that may safely be placed by pushing using a D6 Swamp Dozer over crusted tailings, without causing remoulding and bow-waving, is given by (adapted from Williams 2005):

$$H = \left(\frac{N_c S_v}{F \gamma}\right) - H_e \qquad (5)$$

where N_c = bearing capacity factor = 5.14 assuming that a strip of fill is pushed over a broad front, F =

adopted factor of safety with a minimum value of say 1.5, γ = unit weight of the fill of about 18 kN/m³, and H_e = equivalent height of fill corresponding to the average bearing capacity of the D6 Swamp Dozer, which is about 1 m. Hence:

$$H \approx 0.190\, S_v - 1 \tag{6}$$

The peak shear strength of loaded tailings will increase as they drain, according to (Williams 2005):

$$\Delta\tau = \Delta\sigma_v' \tan\phi' \tag{7}$$

where $\Delta\tau$ = increase in the peak shear strength, $\Delta\sigma'$ = increase in the effective stress following loading by a height of fill H and drainage of the excess pore water pressures generated, and ϕ' = effective (drained) friction angle of the tailings of about 30°. Hence:

$$\Delta\tau \approx 10\, H \tag{8}$$

on full drainage (after about one to four weeks, depending on the hydraulic conductivity of the tailings).

Note that the peak vane shear strength is a measure of how much additional fill can be placed, since any fill previously placed and left for a sufficient time to dissipate all excess pore water pressures, is already supported.

3.3 *Vane shear strength testing of crusted tailings*

Ahead of the capping of TSF1, the peak and remoulded vane shear strengths, and hence bearing capacities, of the tailings were assessed. The vane shear testing was carried out using a hand-operated, 65 mm diameter by 130 mm high vane shear and torque wrench. The vane shear testing was carried out at depth intervals of 0.2 m, starting at 0.1 m depth and extending to between 0.9 m and 1.9 m depth. The test hole was advanced by hand augering between vane tests, which also enabled tailings samples to be collected for subsequent laboratory testing (not reported herein). The vane was connected to a central rod within an outer sleeve, so that the shear resistance on the vane alone was recorded by the torque wrench.

Note that self-weight consolidation of submerged coal tailings results in a linear increase in shear strength of only about 0.8 kPa/m depth. If desiccation crusting occurs, but the depth and shear strength of the surface crust are limited, and/or there has been no desiccation of previously deposited tailings layers, there will be increased risk of bearing capacity failure through the crust into the underlying soft tailings. This will result in remoulding and loss of shear strength, followed rapidly by the generation of a bow-wave failure. The excess pore water pressures generated by fill placement will dissipate relatively rapidly (over one to four weeks, depending on the hydraulic conductivity of the tailings, affected by their particle size distribution and clay mineral content), accompanied by an increase in shear strength given by Equation (8), after which fill placement can recommence.

Selected peak and remoulded vane shear strength profiles with depth for TSF1 tailings are shown in Figure 9. Included in Figure 9 is the shear strength profile expected for coal tailings maintained 'underwater', due to its self-weight alone. The tailings at the bow-wave induced by the previous placement of spoil is capable of safely supporting a fill height of up to 6 m, while the surface of the tailings towards the reeds can only support a maximum of 2 to 3 m of fill, from Equation (6). The average ratio of the remoulded:peak vane shear strength for TSF1 tailings is about 0.4, implying a corresponding drop in the fill height that can safely be supported on remoulding.

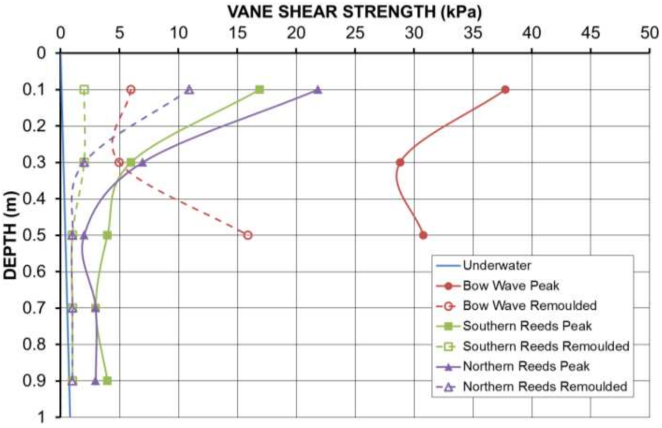

Figure 9. Selected peak and remoulded vane shear strength profiles with depth.

3.4 *Capping experience at TSF1*

Photographs of the early pushing of the initial capping of coarse reject over the raised crest of the old bow wave of TSF1 are shown in Figure 9. Fill placement caused the tailings to drain, often raising the water table to the surface of the tailings, as seen in Figure 10(a). The first sign of imminent bow-waving was the appearance of hydraulic fractures radiating out from the toe of the fill, as seen in Figure 10(b), with continued dozing leading to the formation of a bow-wave, as seen in Figure 10(c).

Figure 9. Early pushing of a capping of coarse reject over old bow-wave of surface TSF.

(a) (b) (c)

Figure 10. Fill placement causing: (a) water table rise to tailings surface, (b) hydraulic fractures radiating out from toe of fill, and (c) formation of a bow-wave on continued dozing.

On the placement of the initial capping layer (typically about 1 m high in an effort to avoid bow wave failure), excess pore water pressures are induced in the tailings, raising the water table (often to the surface). These excess pore water pressures dissipate through drainage to the surface, resulting in a general increase and greater uniformity of the peak vane shear strength profile with depth, as shown in Figure 11. The increased peak shear strength, averaging 15.3 kPa in Figure 11, corresponding to Equation (8), would allow an additional fill height of almost 2 m to be safely placed using the D6 Swamp Dozer.

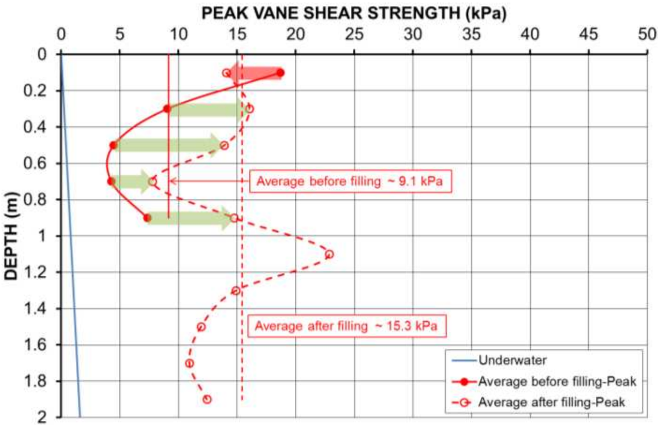

Figure 11. Increase in peak vane shear strength due to dissipation of excess pore water pressures.

Figure 12 shows the progress of capping TSF1 as at June 2015, with the initial 1 m thick layer and the follow-up 2 to 3 m thick layer of coarse reject.

4 CONCLUSIONS

The paper presents two case studies involving the interpretation of shear strength data for construction on mine tailings deposits. In the Cannington case study, heavily desiccated tailings are shown to provide adequate bearing capacity to cost-effectively and safely support a proposed 3 m high upstream embankment raise on a conventional surface slurried tailings storage facility. Data from cone penetration and vane shear testing of the tailings were interpreted to determine their shear strength profile, with an average peak cone factor of 14.4 being obtained.

The New Acland case study involves the successful capping of a conventional, surface slurried coal TSF, to facilitate rehabilitation of the crusted tailings surface for grazing purposes. The capping involved placing by D6 Swamp Dozer an initial 1 m thick layer of coarse reject, followed by a second 2 to 3 m thick layer of coarse reject placed by a D6 and D9 dozers. The shear strength and bearing capacity of the crusted coal tailings were first assessed using vane shear strength testing, backed-up by observations of the placement of the initial capping. As capping progressed, further vane shear testing was carried out to assess the shear strength of the tailings beyond the capping layer, and the strength gain over time in the already covered tailings, which enabled further capping material to be safely placed.

Figure 12. Progress of capping of TSF1 as at 25 June 2015, showing the initial 1 m thick layer and the follow-up 2 to 3 m thick layer of coarse reject.

5 ACKNOWLEDGEMENTS

The managements of South32's Cannington Mine and New Hope Group's New Acland Coal Mine are acknowledged for providing access and granting approval to publish the site and tailings data contained in this paper.

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