Is critical state soil mechanics framework applicable to pond ash?

Jiajun Zhang, Sik-Cheung Robert Lo, Jun Yan and Md Mizanur Rahman

i) Ph.D., School of Engineering and IT, UNSW Canberra, Canberra, ACT 2600, Australia
ii) Associate Professor, School of Engineering and IT, UNSW Canberra, Canberra, ACT 2600, Australia
iii) Ph.D. candidate, School of Engineering and IT, UNSW Canberra, Canberra, ACT 2600, Australia
iv) Senior Lecturer, School of Natural and Built Environments & Barbara Hardy Institute, UniSA, Adelaide, SA 5001, Australia

ABSTRACT

Pond ash, being a form of coal ash, consists mainly of silt-size glassy particles with a significant percentage containing internal occluded voids. By analysing the evolution of particle size distribution before and after triaxial testing at normal stress range using a Laser Particle Size Analyser, specific gravity and SEM photography, it was found that these hollow particles may breakup as a result of shearing. This type of particle disintegration is different from localised grain crushing or shearing off of asperities at high contact stress points. The stress-strain responses measured in an extensive programme of triaxial testing were synthesised. It was established that a unique and consistent critical state line was achieved, irrespective of initial state, drainage conditions and stress histories. Furthermore, the overall pattern of stress-strain responses was related to the location of initial state relative to the critical state line. This supports the use of critical state soil mechanics framework in synthesising and modelling the stress-strain behaviour of pond ash.

Keywords: pond ash, particle breakage, critical state soil mechanics, critical state line, SEM, triaxial testing

1 INTRODUCTION

Coal ash generated from coal-fired power stations can be broadly classified into two types: bottom coal ash and fine coal ash. Bottom coal ash, which is precipitated at the bottom of a furnace, is generally sandy in size and can be used as engineered fill (e.g., Rogbeck and Knutz 1996; Consoli et al. 2007). Fine coal ash, which is carried away from a furnace by flue gas (exhaust), is generally silty in size. In modern coal-fired power stations, fine coal ash is collected by electrostatic precipitators before the flue gas is discharged through chimneys. It can be used as fly ash in structural concrete if the fineness requirement is satisfied (ASTM Standard C618-12a 2012). However, despite efforts to utilize coal ash, a large amount, e.g., approximately 7.4 million tons in 2012 in Australia (ADAA 2012), cannot be effectively utilized and needs to be disposed of.

A common method is wet disposal which involves mixing the coal ash residue (dominantly fine coal ash but may contain some bottom coal ash) with water to form a material of a ‘wet paste’ consistency that can be pumped and placed in ash ponds. In this study, the coal ash residue in these ash ponds is referred to as pond ash. A recent case of slope stability failure of an ash pond at the Tennessee Valley Authority Kingston Fossil Plant in 2008 (AECOM 2009), which resulted in a major spill of pond ash, aroused public concern about the safety of ash ponds.

Early investigations suggested that pond ash has a number of non-plastic soil attributes (e.g., Li and Dutton 1991; Li 1993), but its particles are mostly glassy and hollow spheres (Fisher et al. 1976; Fisher et al. 1978) containing internal occluded voids, which are isolated from the exterior, and thus the specific gravity ($G_s$) of pond ash was found to be lower than those of most natural soils (e.g., Trivedi and Singh 2004; Tu et al. 2007; Prakash and Sridharan 2009). It could be considered as a light weight non-plastic granular geomaterial provided that the content of calcium oxide (CaO) is low (e.g., Kim et al. 2005; Prakash and Sridharan 2009). Also, it manifests a similar behaviour to that of sandy soil (e.g., Kim and Prezzi 2008; Jakka et al. 2010) and may undergo liquefaction under cyclic loading (e.g., Jakka et al. 2010; Baki et al. 2012). Two attempts at evaluating the behaviour of pond ash under critical state soil mechanics (CSSM) framework were reported, but the findings were either not conclusive (AECOM 2009;) or preliminary (Baki 2011). Furthermore, these studies were not based on specimens formed in a manner that simulate wet disposition in ash ponds.

Therefore, the objectives of this study are:

1. To study particle breakage of pond ash during triaxial testing.

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2. To experimentally investigate the monotonic stress-strain behaviour of pond ash using an extensive triaxial testing programme with specimens reconstituted with a technique that simulate the wet disposal of pond ash in ash ponds.

3. To examine whether the CSSM framework is applicable to pond ash.

2 TESTED MATERIAL

The tested pond ash was sourced from an ash pond in Queensland, Australia, and it was a non-plastic sandy silt-sized material and contained a small amount of coarse sand particles (particle size >1.18mm) in the range of 0.9% to 3.6% among batches. The specific gravity, $G_s$, of the as-delivered material was 2.04 which is significantly lower than those of most natural soils. X-ray fluorescence analysis indicated that its CaO content was only 0.07%, implying the lack of any self-cementing property (ASTM Standard C618-12a 2012). The absence of self-cementing properties was also independently verified.

3 TRIAXIAL TESTING ARRANGEMENT

A triaxial testing system with automatic data logging and control capabilities was used in this study. Free ends with enlarged platens, as described by Lo et al. (1989), were used to minimize end restraint to an insignificant level. Triaxial specimens were 100mm in height and 100mm in diameter. After a specimen was formed, it was saturated by vacuum flushing and back pressure to ensure a $B$-value=0.98.

Pond ash specimens were reconstituted by a paste deposition (PD) technique developed in this study to simulate the wet disposal of pond ash in ash ponds. This technique could give specimens that were highly uniform, free of particle segregation and achieving initial states over a wide range (Zhang 2014).

The testing programme for this study comprised a large number of conventional consolidated drained, denoted as D, and undrained, denoted as U, triaxial compression tests. A wide range of initial density and stress states is covered by the testing programme. In addition to these conventional tests, special tests with pre-compression and pre-shearing histories were conducted to examine the uniqueness of critical state line (CSL). The stress-strain responses of these special tests are not discussed in details in this paper.

4 PARTICLE BREAKAGE

Only the pond ash specimens that been sheared to an axial strain ($\varepsilon_a$) beyond 25% in triaxial testing are discussed in this section. Thus $q_{\text{max}}$ is used to indicate the extent of shearing, where deviator stress $q=\sigma_1-\sigma_3$ ($\sigma_1$ and $\sigma_3$ are major and minor principle stresses) and subscript “max” denotes maximum value attained in test.

4.1 Particle Size Distribution

The influence of shearing on the grading of pond ash particles is illustrated by comparing the particle size distributions (PSD, plotted in conventional format) and histograms for size range (plotted as step-curves) of pre-test and post-test specimens. A Laser Particle Size Analyser was used to obtain these curves. Three sets of curves corresponding to post-drained test (post-D), post-undrained test (post-U) and pre-test specimens are compared in Fig. 1.

The PSDs of the post-test specimens evolved leftward with increase in $q_{\text{max}}$. This shift in PSD, though small, is consistent. The histograms indicated that the percentage around the peak size range showed obvious reduction with increase in $q_{\text{max}}$, and this reduction came with a small increase in particles in the range of ~2$\mu$m to ~20$\mu$m. It is important to note that the $q_{\text{max}}$ of these two pond ash samples were not particularly high (<3MPa), implying that the particles of pond ash are much weaker than other granular geomaterials.

The above pattern of the change in particle grading is not consistent with particle crushing or shearing off of asperities at high contact stress points, i.e. localised disintegration. Nonetheless, this pattern is consistent with the hypothesis that particle breakage, as hypothesized by Baki et al. (2012), is a major component of the disintegration of pond ash.

4.2 Specific Gravity

Pond ash particles are mostly glassy, hollow spheres. Thus, if particle breakage occurred, internal occluded voids could be released, resulting in an increase in the measured $G_s$. On the other hand, localised crushing could not produce the same consequence. To address this issue, the measured $G_s$ of pond ash particles are plotted against $q_{\text{max}}$ in Fig. 2, noting that the pre-test $G_s$ were plotted at $q_{\text{max}}=0$.

It can be seen that the measured $G_s$ exhibited a clear correlation with $q_{\text{max}}$ with $G_s$ increasing with increase in $q_{\text{max}}$, thus indicative of particle breakage which “release” the internal occluded voids with shearing.
4.3 SEM Observation

Fig. 3 is a scanning electron microscope (SEM) photo of a post-test sample. It illustrates the breakage of a hollow pond ash particle (60~70μm in size) being broken up into several smaller pieces.

5 TRIAXIAL TEST RESULTS

Due to the large number of triaxial tests carried out, only typical test results are presented and discussed in this section.

As discussed in 4.3, the measured $G_s$ of pond ash particle increased as $q_{\text{max}}$. However, the calculation of void ratio ($\varepsilon$) in this study was based on the assumption that the $G_s$ was a constant throughout the test.

Moreover, to take into account the varying, though small, amount of coarse sand particles among batches, the $\varepsilon$ presented in subsequent analysis were corrected to interfines void ratio as proposed by Thevanayagam and Mohan (2000).

5.1 Drained Tests Results

Four typical D test results are presented in the form of stress ratio responses ($\eta$-$\varepsilon$) in Fig. 4 (a) and volumetric responses ($\varepsilon$-$\varepsilon$) in Fig. 4 (b), where $\eta=q/p'$, $p'=$ effective mean stress $=(\sigma_1'+2\sigma_3')/3$ and $\varepsilon$ = volumetric strain. The subscript “0” denotes “initial” i.e., after consolidation/before shearing.

D-3 and D-4, of which the $\eta$-$\varepsilon$ curves were mostly overlapping, exhibited strain hardening ($d\eta/d\varepsilon_1>0$) with a contractive volumetric response ($d\varepsilon_1/d\varepsilon>0$) throughout shearing, and this type of behaviour pattern is denoted as SH+C. For D-1 and D-2, the response at the early stage of shearing was strain hardening and contraction, but eventually, strain softening ($d\eta/d\varepsilon<0$) and dilation ($d\varepsilon_1/d\varepsilon_1<0$) were manifested. This type of behaviour pattern is denoted as SS+D.

Both $\eta$ (and thus $q$, as $d\sigma_3'=0$) and $\varepsilon_1$ of D-3 and D-4 attained stationary values with continuous shearing at the end of test, and thus critical state (CS) was unambiguously attained. For other tests, which could not completely attain but end up close to CS (not shown in Fig. 4), a simple linear extrapolation technique described by Zhang et al. (2014) was employed to obtain CS data. For D-1 and D-2, which were terminated early due to the development of visible shear band and this is reflected as kinks and
sharp bends on the $\eta-\varepsilon_l$ and $\varepsilon_c-\varepsilon_l$ curves, this extrapolation technique is not suitable. Such tests were not used to obtain CS data points.

### 5.2 Undrained Test Results

Five typical U test results are presented as deviator stress-strain curves ($q-\varepsilon_l$) in Fig. 5 (a) and pore water pressure responses ($\Delta u-\varepsilon_l$) in Fig. 5 (b), where $\Delta u$ is the change of pore water pressure. The effective stress paths (ESP) are presented in Fig. 5 (c), with both $q$ and $p'$ normalized by $p'_0$ so that they can be compared in the same figure.

![Fig. 5. Typical U test results: (a) $q-\varepsilon_l$ and (b) $\Delta u-\varepsilon_l$](image)

It can be seen that, irrespective of $\varepsilon_l$ and $p'_0$, all these five tests exhibited non-flow (NF) behaviour ($dg/d\varepsilon_l > 0$), and NF was the only undrained behaviour pattern observed for the PD pond ash in this study.

For tests U-3, U-4 and U-5, both $q$ and $\Delta u$ attained stationary values with continuous shearing at end of test. Thus steady state (SS), which is mathematically equivalent to CS, was unambiguously attained. However, due to the limited capacity of the load cell, U-1 and U-2 were terminated when both $q$ and $\Delta u$ were still changing considerably with shearing. Thus such tests could not be used to obtain any SS or CS data points.

The effective stress paths (ESPs) of all five tests tracked leftward (ie with $dp'<0$) at the beginning and then manifested an elbow and tracked rightward (ie with $dp'>0$). This revealed an initial contractive trend followed by a subsequent dilative trend. For U-5, the subsequent dilative trend was not sufficiently high to overwhelm the initial contractive trend, and thus it terminated at a CS with a corresponding effective mean stress, $p'_{cs}$, lower than the $p'_0$ i.e., $p'_{cs}/p'_0<1$, where subscript “cs” denote at CS. This implies an overall behaviour dominated by plastic contractancy. On the other hand, for the other four tests, although CS may not be attained, $p'_{cs}$ was higher than/equal to the $p'$ at the end of test which in turn was higher than $p'_0$. Thus, $p'_{cs}/p'_0>1$, implying an overall behaviour dominated by plastic dilatancy.

### 6 CSSM FRAMEWORK

#### 6.1 Critical State Line

All the CS data points achieved in this study, irrespective of whether it was obtained from drained or undrained tests, are plotted in the $q-p'$ and $e-logp'$ planes in Fig. 6. It is pertinent to emphasize that the data points in Fig. 6, in addition to covering a wide range of initial states, also include tests on specimens with pre-compression and pre-shearing stress histories. This enables a detailed examination of the uniqueness of CSL for pond ash.

The CS data points in the $q-p'$ plane followed a straight line passing through the origin, as indicated in Fig. 6 (a), and it gave a critical state stress ratio ($M$) of 1.357.

The CS data points in the $e-logp'$ plane also followed a single trend curve irrespective of drainage conditions and stress histories. Although these data points in Fig. 6 (b) may be approximated by a straight line, a slight curvature was evident. The power function introduced by Wang et al. (2002) was used to fit the CSL by Eqn. (1) below

$$e_{cs}=1.265-0.323\times(p'_{cs}/p_a)^{0.16}, \quad \cdots\cdots\cdots\cdots (1)$$

where $p_a=100kPa$. The root mean square deviation (RMSD) of the scatter of data points around Eqn. (1) is $\sim 0.005$. 

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D-C: Drained test on pre-compressed specimen  
U-C: Undrained test on pre-compressed specimen  
U-S: Undrained test on pre-sheared specimen

Fig. 6. CS data points of PD pond ash: (a) e-logp' and (b) q-p'

### 6.2 Prediction of Overall Behaviour Patterns

The initial states of the pond ash specimens are plotted in the e-logp' plane as Fig. 7 (a) for D tests and Fig. 7 (b) for U tests. The best-fit CSL i.e., Eqn. (1), is plotted as a solid curve, and the error band is indicated by a pair of dotted curves plotted at ±RMSD from the best-fit CSL.

As evident in Fig. 7 (a), the initial states of the D tests that exhibited SH+C behaviour were located above the CSL while the SS+D ones were located below it. Thus under drained shearing, the CSL acts as a dividing curve between the SH+C and SS+D behaviours.

Only NF behaviour was observed in the U tests, even when the initial state was slightly but clearly above the CSL. Therefore, the location of initial state relative to the CSL cannot be used to establish NF behaviour. However, as evident in Fig. 7 (b), tests with initial states located above the CSL corresponded to p'_c/p'_o<1 i.e., behaviour dominantly plastic contractancy, while those located below the CSL corresponded to p'_c/p'_o>1 i.e., behaviour dominantly plastic dilatancy. Thus, in undrained shearing, the CSL can be considered as a curve that divides dominantly plastic contractancy from dominantly plastic dilatancy.

The above discussions clearly showed that the overall pattern of stress-strain responses is related to the location of initial state relative to the CSL. This supports the use of the CSSM framework in synthesising and modelling the stress-strain behaviour of pond ash.

### 7 CONCLUSIONS

By analysing the evolution in particle size distribution before and after triaxial testing at normal stress range using Laser Particle Size Analyser, specific gravity and SEM photography, it was found that the hollow particles of pond ash may breakup as a result of shearing. This type of particle disintegration is different from localised grain crushing or shearing off of asperities at high contact stress points.

Nonetheless, triaxial test results showed that:
1. Both SH+C and SS+D behaviour could be observed from the D tests. However, in the U tests, only NF behaviour was observed.
2. A unique and consistent CSL was achieved for the tested pond ash, despite different drainage conditions and stress histories.
3. The overall pattern of stress-strain responses is related to the location of initial state relative to the CSL.

Therefore, pond ash exhibits similar behaviour to sand and other granular geo-materials, and the CSSM framework is applicable for predicting its behaviour.
despite the fact that pond ash undergoes particle breakage during triaxial testing.

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REFERENCES

1) ADAA (2012). "Annual Membership Survey Results." Ash Development Association of Australia.
2) AECOM (2009). "Root Cause Analysis of TVA Kingston Dredge Pond Failure on December 22, 2008." AECOM.
3) ASTM Standard C618-12a (2012). "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." ASTM International, West Conshohocken, PA.
4) Baki, M. A. L. (2011). "Cyclic Liquefaction Behaviour of Granular Materials with Fines." Ph. D., University of New South Wales at Australian Defence Force Academy.
5) Baki, M. A. L., Rahman, M. M., and Lo, S. R. "Cyclic Instability Behaviour of Coal Ash." Proc., Geo-Congress 2012, ASCE, 849-858.
6) Consoli, N. C., Heineck, K. S., Coop, M. R., Fonseca, A. V. D., and Ferreira, C. (2007). "Coal Bottom Ash as a Geomaterial: Influence of Particle Morphology on the Behavior of Granular Materials." Soils and Foundations, 47(2), 361-373.
7) Fisher, G. L., Chang, D. P. Y., and Brummer, M. (1976). "Fly Ash Collected from Electrostatic Precipitators: Microcrystalline Structures and the Mystery of the Spheres." Science, 192(4239), 553-555.
8) Fisher, G. L., Prentice, B. A., Silberman, D., Ondov, J. M., Biermann, A. H., Ragaini, R. C., and McFarland, A. R. (1978). "Physical and Morphological Studies of Size-Classified Coal Fly Ash." Environmental Science and Technology, 12(4), 447-451.
9) Jakka, R. S., Datta, M., and Ramana, G. V. (2010). "Liquefaction Behaviour of Loose and Compacted Pond Ash." Soil Dynamics and Earthquake Engineering, 30(7), 580-590.
10) Kim, B., and Prezzi, M. (2008). "Evaluation of the Mechanical Properties of Class-F Fly Ash." Waste Management, 28(3), 649-659.
11) Kim, B., Prezzi, M., and Salgado, R. (2005). "Geotechnical Properties of Fly and Bottom Ash Mixtures for Use in Highway Embankments." Journal of Geotechnical and Geoenvironmental Engineering, 131(7), 914–924.
12) Li, K. S. (1993). "Flyash as a Structural Fill." Proc., 11th Southeast Asian Geotechnical Conference, 375-380.
13) Li, K. S., and Dutton, C. (1991). "Geotechnical Properties of Pulverized Fuel Ash as a Reclamation Fill." Proc., 9th Asian Regional Conference, 405-408.
14) Lo, S. R., Chu, J., and Lee, I. K. (1989). "A Technique for Reducing Membrane Penetration and Bedding Errors." Geotechnical Testing Journal, 12(4), 311-316.
15) Prakash, K., and Sridharan, A. (2009). "Beneficial Properties of Coal Ashes and Effective Solid Waste Management." Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, 13(4), 239-248.
16) Rogbeck, J., and Knutz, A. (1996). "Coal Bottom Ash as Light Fill Material in Construction." Waste Management, 16(1), 125-128.
17) Thevanayagam, S., and Mohan, S. (2000). "Intergranular State Variables and Stress-Strain Behaviour of Silty Sands." Geotechnique, 50(1), 1-23.
18) Trivedi, A., and Singh, S. (2004). "Cone Resistance of Compacted Ash Fill." Journal of Testing and Evaluation, 32(6), 1-9.
19) Tu, W., Zand, B., Ajlouni, M. A., Butalia, T. S., and Wolfe, W. E. (2007). "The Consolidation Characteristics of Impounded Class-F Fly Ash - A Case History." World of Coal Ash Conference, ACAA, Covington, KY.
20) Wang, Z.-L., Dafalias, Y. F., Li, X.-S., and Makdisi, F. I. (2002). "State Pressure Index for Modelling Sand Behaviour." Journal of Geotechnical and Geoenvironmental Engineering, 128(6), 511-519.
21) Zhang, J. (2014). "Monotonic Behaviour of Pond Ash." Ph.D., University of New South Wales at Canberra, Canberra, Australia.
22) Zhang, J., Lo, S. R., Rahman, M. M., and Yan, J. (2014). "Monotonic Behaviour of Pond Ash under Critical State Soil Mechanics Framework." Geo-Congress 2014, ASCE, Atlanta GA.