# Ash Behavior in the Capillary Fringe

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ABSTRACT

It is well known that saturated fly ash has engineering properties that make it difficult to work in; it has a low undrained shear strength, and it is highly susceptible to liquefaction. Those unfavorable characteristics are expected below the phreatic surface or "water level" where the ash is saturated. When working well above the phreatic surface in "dry" fly ash, the material exhibits more favorable conditions for tracking equipment, excavating, and hauling.

There is a transition zone, however, between the saturated ash and the overlying well drained ash. The consistent experience from working on dozens of ponds is that instability in the ash is often encountered several feet above the phreatic surface. This is often attributed to capillary action or in some cases delayed drainage. The characteristics of the ash in this changeable transition zone are not well understood.

The focus of this paper is to discuss recent pilot testing on an ash pond in the southeastern United States performed to provide additional insight into the ash transition zone. The pilot testing utilized several instruments to correlate ash apparent cohesion, shear strength and behavior to the degree of saturation. Findings will be presented.

INTRODUCTION

The TVA Allen Closure by Removal project in Memphis, Tennessee contains 3 million cubic yards of Coal Combustion Residual (CCR) that must be removed from site. Figure 1 shows the two ash ponds on site, the East Ash Pond (EAP) and the West Ash Pond (WAP). The CCR was sluiced into ponds up to 28 feet deep.

The CCR was sluiced from west to east in the EAP. Therefore, coarse CCR settled in the west and fine CCR settled in the east portions of the pond.

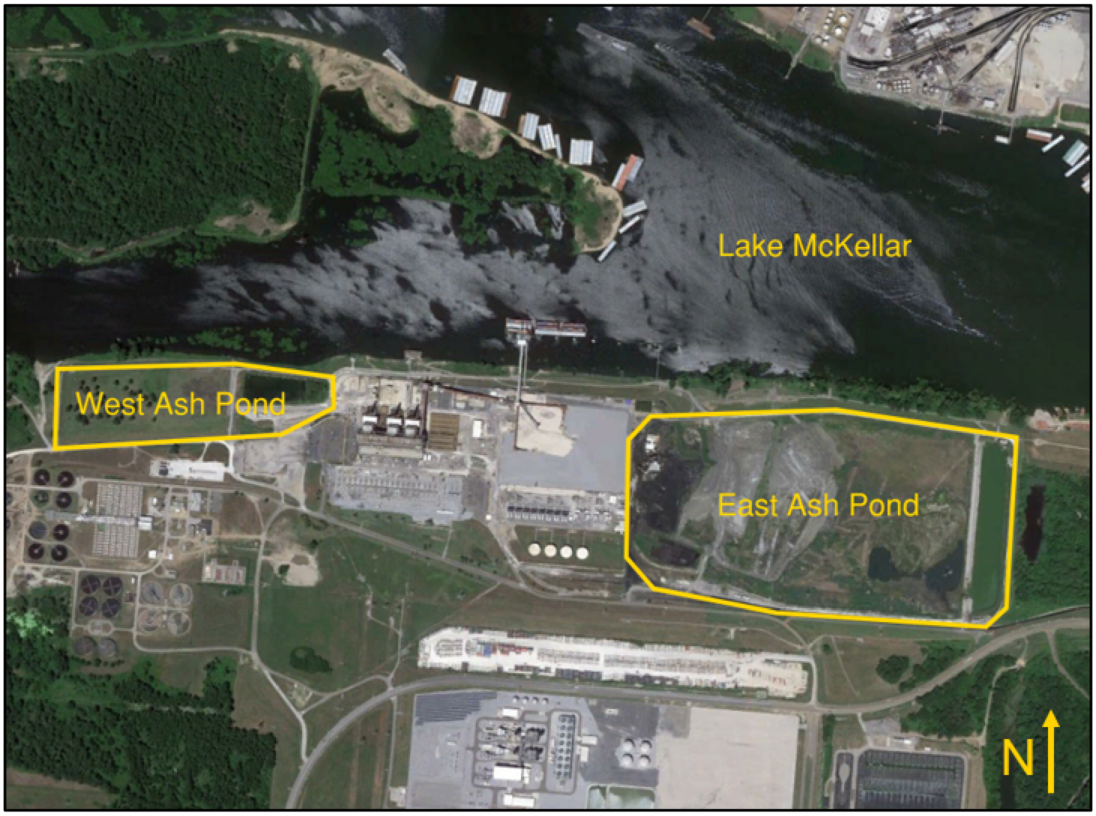


Figure 1. TVA Allen Planview

The challenges faced by the construction team are highly variable site conditions and engineering properties of CCR deposited in the impoundments; high phreatic surfaces; low shear strength of saturated CCR materials; need for stable stockpiles; and equipment access over sluiced CCR. To gain a better understanding of the materials within the ash ponds, as well as the conditions to be expected, a Demonstration Program was performed.

## THE DEMONSTRATION PROGRAM

The original purpose of the Demonstration Program was as follows:

- Characterize CCR materials, CCR strength, and phreatic surface conditions before wellpoint dewatering
- Evaluate dewatering drawdown and wellpoint yield performance
- Observe dewatered CCR in test pits
- Repeat CCR strength measurements with field Vane Shear Test (VST) and Cone Penetration Test (CPT) in dewatered CCR
- Develop initial cut slope and access design based on dewatered CCR strength and phreatic surface levels
- Set initial Vibrating Wire Piezometer (VWP) instrumentation notifications for threshold and action triggers

The demonstration program was focused in three distinct phases: pre-dewatering field testing, dewatering, and post-dewatering field testing. The field testing and dewatering was sequenced as follows:

- Installation of Open Standpipe Piezometers (OSPs) and VWPs
- Installation of dewatering wells (this occurred simultaneously as pre-dewatering field testing)
- Pre-dewatering VSTs
- Pre-dewatering CPTs
- Pre-dewatering test pits
- Wells operated for approximately two months
- Post-dewatering CPTs
- Post-dewatering test pits
- Post-dewatering VSTs

The capillary fringe is the zone above the phreatic surface where capillary rise occurs. The height of the capillary fringe is dependent on grain size. Within the capillary fringe, pore pressure is negative. Shear strength increases with negative pore pressure (-u). The shear strength increase caused by negative capillary pore pressure is referred to as apparent cohesion. A schematic of this concept is shown in Figure 2.

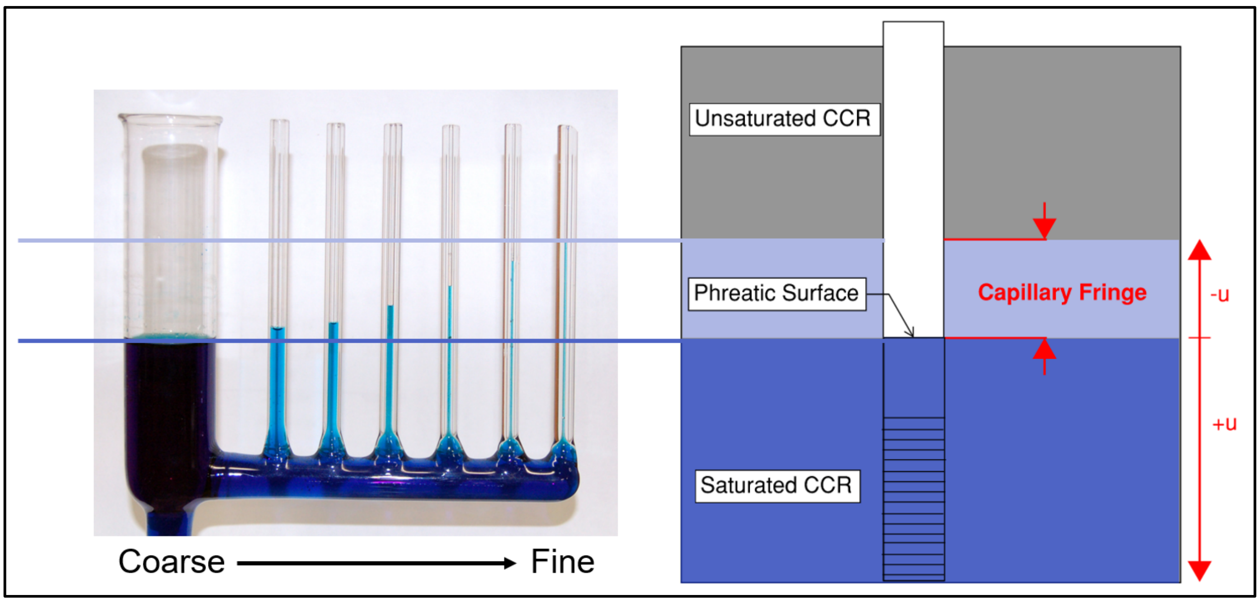


Figure 2. Capillary Fringe

Before the Demonstration Program began, the following assumptions were made:

- Post-dewatering field VST undrained shear strength would increase in the capillary fringe
- Post-dewatering CPT resistance would increase in the capillary fringe

- Improved conditions would be observed in test pits (standup, seepage, drainage, moisture condition, and excavation stability)
- Wellpoint yield on the order of 1 gpm per wellpoint could be obtained
- Drawdown radius of influence of wellpoint lines would be measured

The demonstration area was initially prepared by knocking down vegetation with an amphibious excavator. Geogrid and plywood platforms were placed in the locations shown in Figure 3. After VSTs were performed, it was determined that geogrid and plywood working surfaces were not required for human access and access for skid-steer mounted CPT equipment.

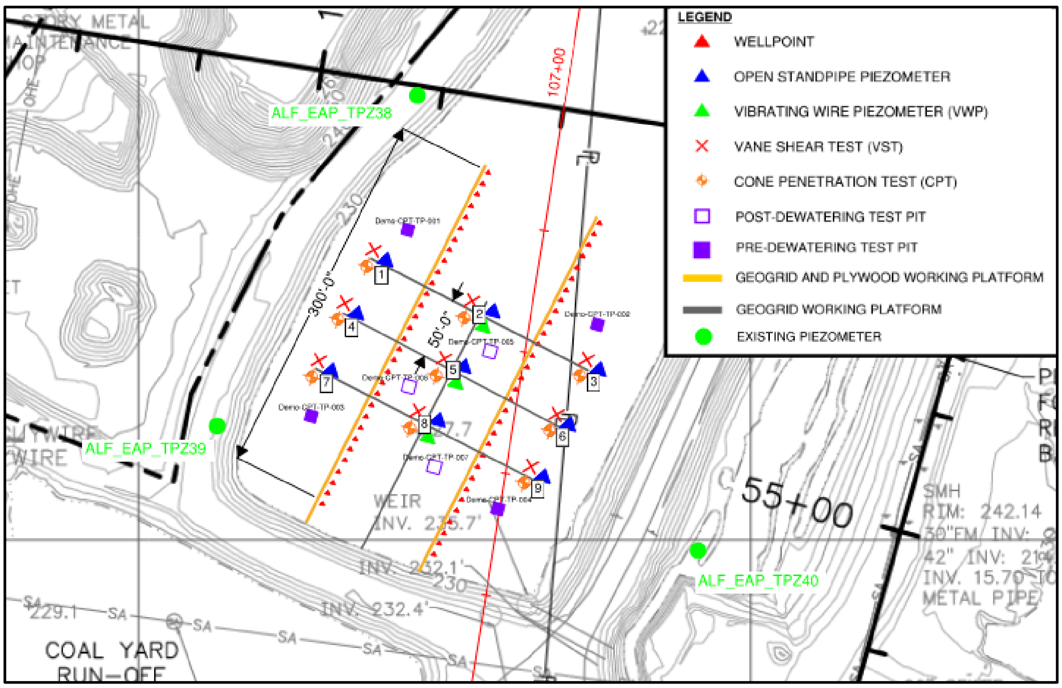


Figure 3. Demonstration Program Layout

## CONDITIONS ENCOUNTERED AND MEASURED

Four distinct layers of CCR were identified in the demonstration program area. These layers can be seen in the cross-section shown in Figure 5. From top to bottom, the layers are as follows:

- Cemented Bottom Ash/Fly Ash
- Fine Fly Ash – Liquifiable, poorly drained, weak shear strength. The initial phreatic surface was in this layer.
- Red Clay – Low permeability, fissured/blocky structure, soft to stiff. Phreatic surface lowed to this layer at the time of post-dewatering field work.
- Bottom Ash – Coarse, confined, permeable, poorly graded. Over time, the phreatic surface was lowered into the Bottom Ash.


Figure 4. Cross-Section Location

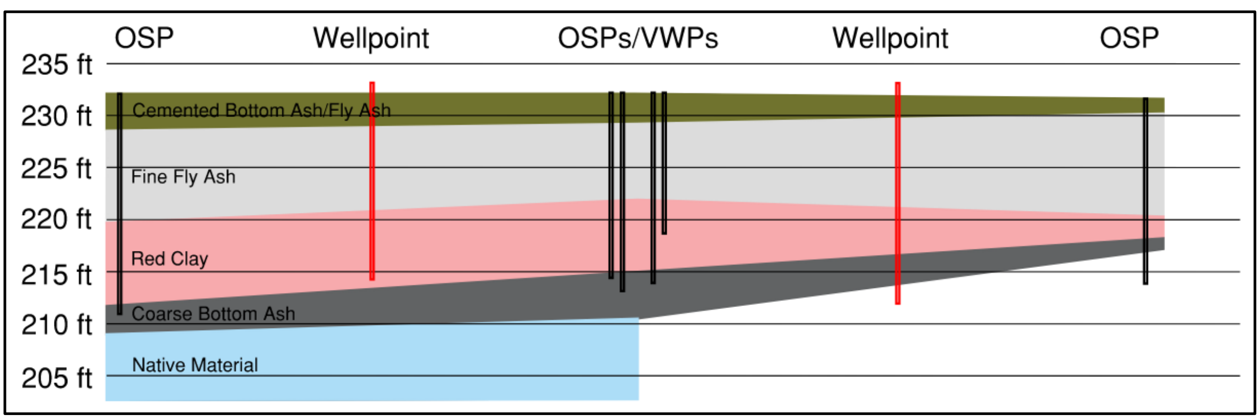


Figure 5. Cross-Section

The dewatering system was turned on May 25th, 2021 and ran for 64 days before the post-dewatering field testing began on July 29th, 2021. The wells were shut down a total of 28 days during this period. Figure 6 shows the phreatic surface drawdown at each of the OSP locations over time.

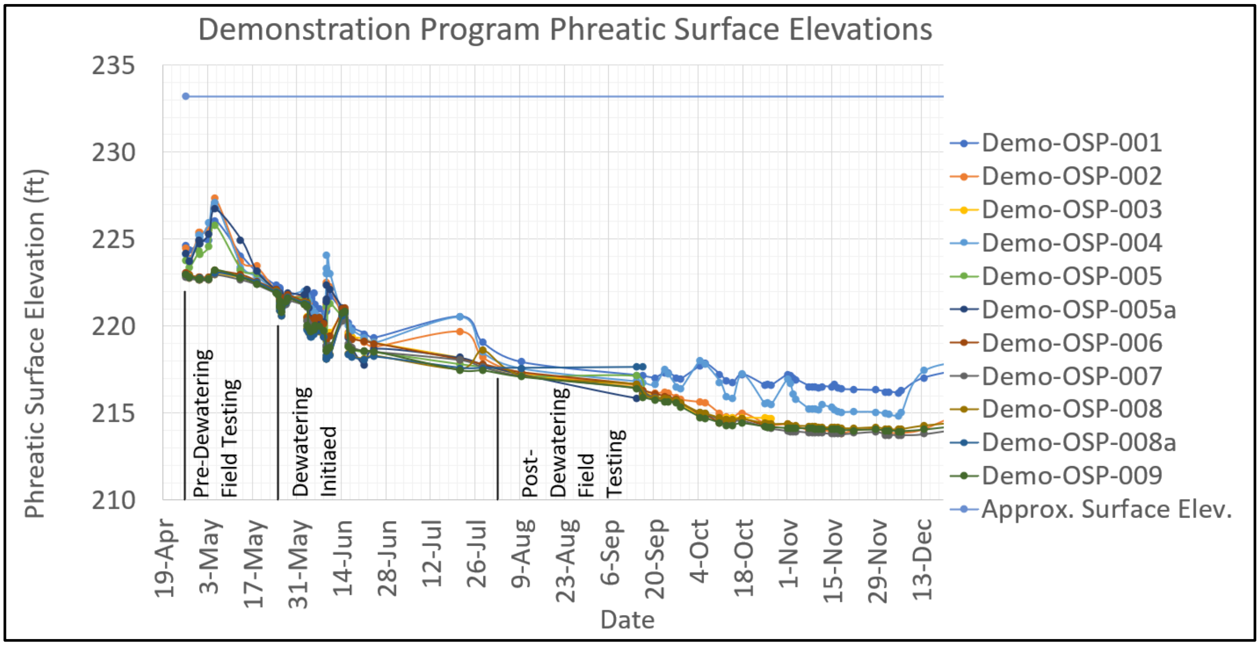


Figure 6. Phreatic Surface Drawdown Over Time

Around 8 million gallons of water was pumped from the system in the first six months. The gallons pumped over time can be seen in Figure 7. During the dewatering period, the max flowrate was over 180 gpm, equating to an average of 3 to 4 gpm per wellpoint. The gallons per minute (GPM) pumped over time can be seen in Figure 8.

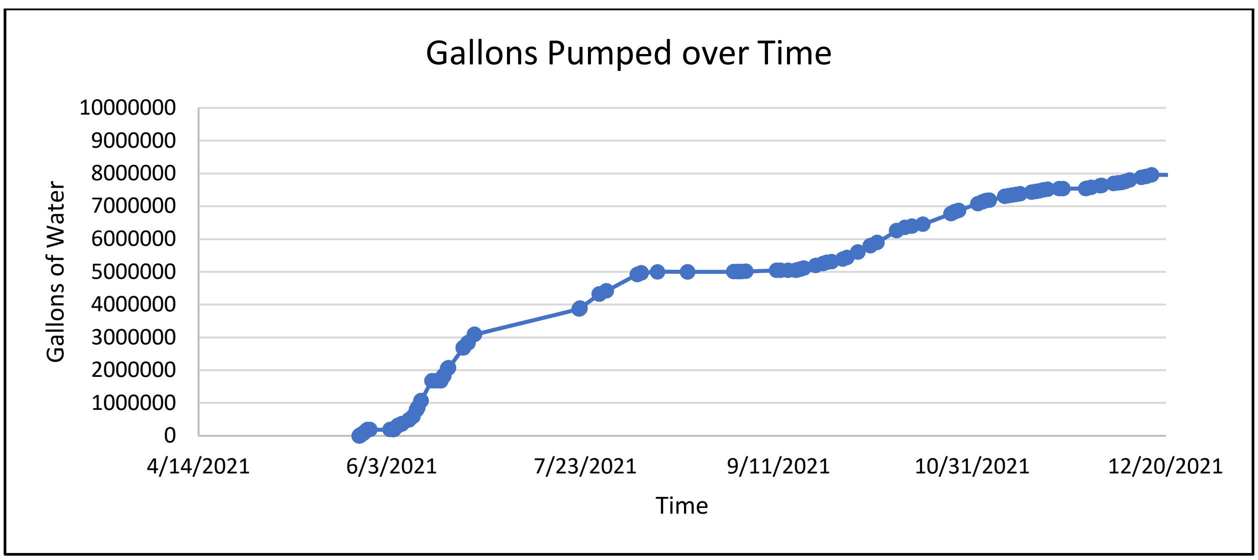


Figure 7. Gallons Pumped from the Demonstration Program

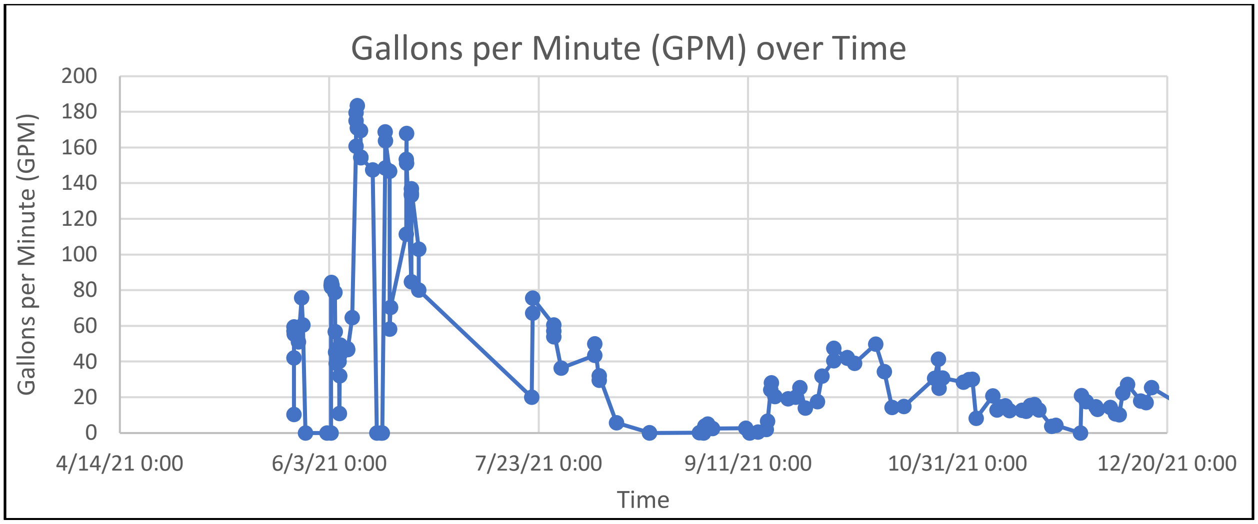


Figure 8. Gallons per Minute (GPM) from the Demonstration Program

OSPs were installed at nine different locations, as shown in Figure 3. OSPs consisted of a 2-inch diameter Polyvinyl Chloride (PVC) pipe with 5-foot of screen and a cap at the bottom of the PVC. The annulus surrounding the outside of the PVC was a coarse sand.

VWPs were installed at three different locations, as shown in Figure 3. At each of these locations, two different VWPs were installed. One VWP was installed just above the Red Clay layer, and one VWP was installed just above the bottom of the pond.

The upper piezometers reflected unconfined conditions above the Red Clay. Lower piezometers reflected confined conditions in the Bottom Ash. The distance drawdown extending to the Coal Yard Runoff Pond (CYRP) was representative of a confined aquifer response.

On average, there was an 8.2-foot drawdown measured in the OSPs from April 26$^{th}$ – November 29$^{th}$. The average drawdown was 19 feet below the wellpoint header, the effective limit of a typical wellpoint system. The drawdown recorded in each OSP can be seen in Table 1.

| | Demo-OSP-001 | Demo-OSP-002 | Demo-OSP-002a* | Demo-OSP-003 | Demo-OSP-004 | Demo-OSP-005 | Demo-OSP-005a | Demo-OSP-006 | Demo-OSP-007 | Demo-OSP-008 | Demo-OSP-008a | Demo-OSP-009 | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial Water Elev. (ft) (4-26-21) | 224.6 | 224.5 | 223.8 | 222.9 | 224.2 | 223.8 | 224.2 | 223.1 | 222.9 | 223.0 | 222.9 | 223.0 | |
| Water Elev. after 6-months of dewatering (ft) (11-29-21) | 216.3 | 214.1 | 223.3 | 214.7 | 215.1 | 215.8 | 215.2 | 214.2 | 213.9 | 214.2 | 213.2 | 214.0 | |
| Drawdown (ft) | 8.3 | 10.4 | 0.5 | 8.2 | 9.1 | 8.0 | 9.0 | 8.9 | 9.0 | 8.8 | 9.8 | 9.0 | 8.2 |

Table 1. Drawdown in Open Standpipe Piezometers

The three VWPs installed at the bottom of the pond averaged 6.9 feet of drawdown over the first 6 months of dewatering (May 25th – November 29th). The drawdown results can be seen in Table 2.

| | Demo-VWP-002a | Demo-VWP-005a | Demo-VWP-008a | Avg. |
|---|---|---|---|---|
| Initial Water Elev. at Start of Dewatering (ft) (5-25-21) | 221.4 | 221.3 | 221.1 | |
| Water Elev. after 6-months of dewatering (ft) (11-29-21) | 215.6 | 213.8 | 213.6 | |
| Drawdown (ft) | 5.8 | 7.5 | 7.5 | 6.9 |

Table 2. Drawdown in Each Vibrating Wire Piezometer

Before dewatering began, VSTs were performed at nine different testing locations, as shown in Figure 3. The VSTs were performed at 1.5-foot intervals beginning at 0.5 to 1 foot deep, with the deepest test between 9.5 to 10 foot deep. Most initial VSTs were performed above the phreatic surface of elevation 223 feet. The CCR was augured in between testing intervals with a 4-inch diameter hand auger. The pre-dewatering VST results can be seen in Table 3. The post-dewatering VST results can be seen in Table 4.

| Demonstration Program - Pre-Dewatering VSTs | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (ft) | Demo-VST-001 | Demo-VST-001a | Demo-VST-002 | Demo-VST-003 | Demo-VST-004 | Demo-VST-005 | Demo-VST-006 | Demo-VST-007 | Demo-VST-008 | Demo-VST-009 |
| | 4/26/21 | 4/26/21 | 4/26/21 | 4/26/21 | 4/27/21 | 4/27/21 | 4/26/21 | 4/27/21 | 4/26/21 | 4/26/21 |
| | Undrained Shear Strength (psf) | | | | | | | | | |
| 0.5 | 4553 | - | 1921 | 1128 | 1295 | 470 | 668 | 982 | 689 | 752 |
| 2 | 3885 | - | 1671 | 815 | 679 | 689 | 418 | 397 | 480 | 533 |
| 3.5 | 2715 | - | 397 | 292 | 272 | 376 | 313 | 355 | 397 | 355 |
| 5 | 2715 | - | 230 | 783 | 324 | 251 | 355 | 407 | 188 | 574 |
| 6.5 | - | 710 | 261 | 376 | 178 | 167 | 240 | 345 | 209 | 355 |
| 8 | - | 501 | 251 | 282 | 272 | 230 | 334 | 167 | 146 | 261 |
| 9.5 | - | 397 | 132 | 313 | 365 | 261 | 637 | 470 | 1358 | 794 |

Table 3. Pre-Dewatering Vane Shear Test Results

| Demonstration Program - Post Dewatering Test Results | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Depth (ft) | Demo-VST-Post-001 | Demo-VST-Post-002 | Demo-VST-Post-003 | Demo-VST-Post-004 | Demo-VST-Post-005 | Demo-VST-Post-006 | Demo-VST-Post-007 | Demo-VST-Post-008 | Demo-VST-Post-009 |
| | 8/6/21 | 8/9/21 | 8/9/21 | 8/6/21 | 8/9/21 | 8/9/21 | 8/6/21 | 8/9/21 | 8/9/21 |
| | Undrained Shear Strength (psf) | | | | | | | | |
| 0.5 | TH | 2715 | 877 | 2548 | 1483 | 1002 | 2715 | 971 | 856 |
| 2 | 5430 | 2715 | 679 | 1504 | 815 | 606 | 731 | 533 | 668 |
| 3.5 | 2715 | 2715 | 282 | 627 | 627 | 522 | 710 | 428 | 543 |
| 5 | 1107 | 439 | 418 | 459 | 365 | 992 | 689 | 407 | 449 |
| 6.5 | 1545 | 564 | 480 | 251 | 386 | 397 | 470 | 407 | 470 |
| 8 | 898 | 512 | 480 | 376 | 282 | 261 | 386 | 376 | 627 |
| 9.5 | 627 | 386 | 428 | 428 | 658 | 731 | 731 | 1358 | 480 |

Table 4. Post-Dewatering Vane Shear Test Results

| | |
|---|---|
| 0-300 | psf |
| 300-500 | psf |
| 500-1000 | psf |
| 1000-2000 | psf |
| >2000 | psf |

The pre and post-dewatering VST results were compared with each other at each location to see if the undrained shear strength improved. Table 5 shows this comparison. It was noted that CCR removed from the VST boring with the hand auger was significantly drier after dewatering occurred.

| Demonstration Program - Pre to Post Dewatering Comparison | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Depth (ft) | Demo-VST-001 | Demo-VST-002 | Demo-VST-003 | Demo-VST-004 | Demo-VST-005 | Demo-VST-006 | Demo-VST-007 | Demo-VST-008 | Demo-VST-009 |
| | Undrained Shear Strength (psf) | | | | | | | | |
| 0.5 | TH | 794 | -251 | 1253 | 1013 | 334 | 1733 | 282 | 104 |
| 2 | 1545 | 1044 | -136 | 825 | 125 | 188 | 334 | 52 | 136 |
| 3.5 | 0 | 2318 | -10 | 355 | 251 | 209 | 355 | 31 | 188 |
| 5 | -1608 | 209 | -365 | 136 | 115 | 637 | 282 | 219 | -125 |
| 6.5 | 835 | 303 | 104 | 73 | 219 | 157 | 125 | 198 | 115 |
| 8 | 397 | 261 | 198 | 104 | 52 | -73 | 219 | 230 | 365 |
| 9.5 | 230 | 255 | 115 | 63 | 397 | 94 | 261 | 0 | -313 |

Table 5. Undrained Shear Strength Improvements in Vane Shear Test Results

| |
|---|
| Increased shear strength 0 to 100 psf |
| Increased shear strength 100 to 300 psf |
| Increased shear strength 300 to 1000 psf |
| Increased shear strength > 1000 psf |
| Decreased shear strength |

The VST results showed an average improvement of 125 psf when the top three tests were not considered due to desiccation. The analysis also considered strength gain as compared to the % of material passing through the 200 sieve, the layer classification, and the height above the initial phreatic surface. The strength gain in the VSTs was less than expected, and there were no discernable strength gains.

CPTs were performed at the same nine locations as the VSTs. CPTs were pushed 20 feet or more or until refusal at an ASTM rate of 2 cm/s.

The pre and post-dewatering CPT results were compared, as seen in Figure 9. The comparison also includes the pre and post-dewatering phreatic surface elevations, the pre and post-dewatering VST results in the shear strength column, as well as the interpreted soil layers.

Similar tip and sleeve resistances were in pre and post-dewatering CPTs. The post-dewatering CPT results generally showed a decrease in pore pressure throughout all CPTs. Overall, the CPT results showed no discernable strength gains.

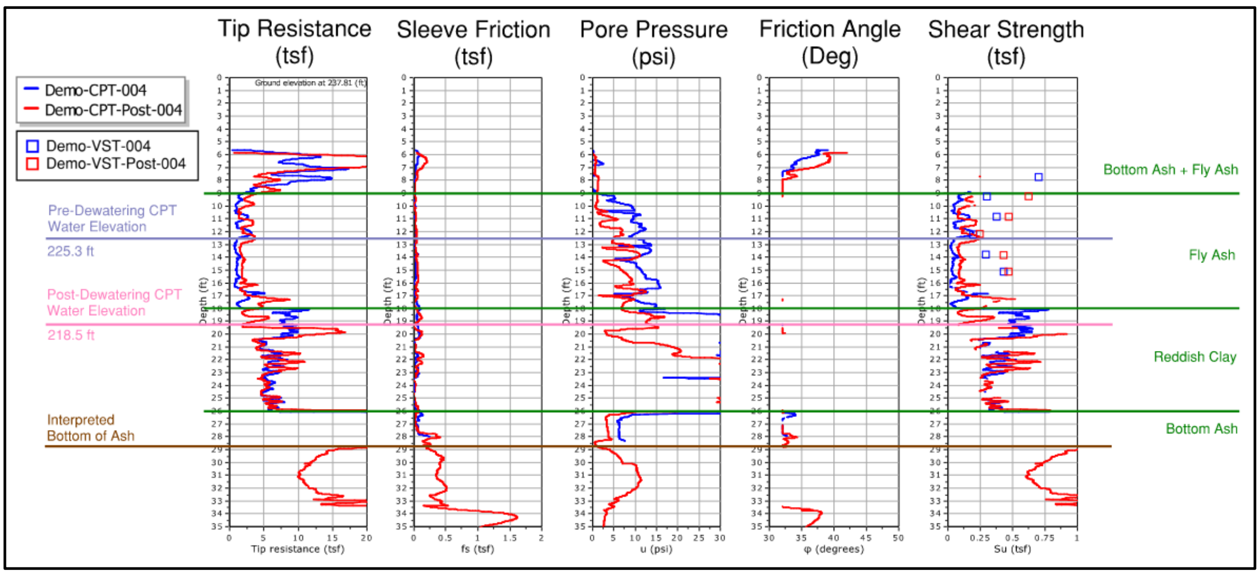


Figure 9. Cone Penetration Test Comparison

Test pits were excavated up to 20 feet deep using an amphibious excavator in the seven locations indicated in Figure 3. The post-dewatering test pits were observed to have a lower phreatic surface elevation, were drier, and had a higher angle of repose in the Fly Ash. The material removed from the post-dewatering test pits was still liquifiable. Test Pits did not cave in both cases.

## SUMMARY OF FINDINGS AND INTERPRETATION

Four distinct layers of CCR were observed in the following order: Bottom Ash/Fly Ash Cap, fine Fly Ash, Red Clay, and Coarse Bottom Ash. The VST results showed some strength gain in the upper 10 feet but less than anticipated. The CPT comparisons showed no change in penetration resistance but there was a decrease in pore pressures.

Drawdown of the phreatic surface into the Red Clay may have prevented development of a capillary fringe. It is also likely that the Red Clay prevented drainage and a capillary fridge developed above the perched groundwater.

Observation wells and VWPs indicate an upper and lower aquifer condition due to the Red Clay confining layer. The upper fly ash was dewatered successfully as observed by drawdown measurements and test pit observations. Confined conditions in the Coarse Bottom Ash resulted in a significant radius of influence of drawdown and drainage of a large area. This was observed in the dewatering of the Coal Yard Runoff Pond a few hundred feet away by the system. Overall, the wellpoint dewatering system was effective with respect to drawdown and improved stability in CCR.

Variable conditions have been encountered and are expected across the site. A dedicated CPT Rig is being used to characterize discrete areas for purpose of excavation and access design. CPT Data is being used to identify drainable CCR for wellpoint dewatering design. Additional test programs will be conducted, and lessons learned will be employed.

Additional conclusions are expected to be drawn as excavation progresses. Strength improvements were not clearly measures; however, dewatering has proven beneficial towards the goal of excavating, site access, and reducing moisture content for hauling the CCR off-site.