# Stability Evaluation and Monitoring During Staged Construction of Fly Ash Closure Projects

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ABSTRACT

The Final Rule of US EPA regulation for the Disposal of Coal Combustion Residuals (CCRs) requires that CCR surface impoundments “be closed in the shortest amount of time consistent with recognized and generally accepted good engineering practices”. One of the difficulties being encountered by many CCR impoundment owners, design engineers and contractors is how to assess the stability of ash slopes and fill embankments during the completion of a closure project. As a typical CCR impoundment is drained and prepared for either excavation or close-in-place closure, the subsurface drainage conditions, effective stresses and undrained shear strength of the fly ash materials frequently change. To address these challenges, experienced geotechnical engineers and contractors have developed innovative and practical methods for in-situ testing, verification testing and construction monitoring acros the range of saturated and partially saturated fly ash materials. This paper and presentation will provide several case studies and explanation of the following:

- Utilizing the cone penetrometer (CPT), the Van Den Berg vane shear device, and hand held vane shear devices for obtaining strength measurements of the fly ash during the design and construction phase.
- Developing guidelines for staged construction by completing pre-construction engineering evaluations and adjusting those guidelines as necessary during ash impoundment closure by assessing the behavior using the Observational Method as explained by Terzaghi and Peck, 1969.
- Field measurement and assessment of changing conditions, and changes in porewater pressure by using “real time” porewater pressure transducers.
- Promoting open working relationships between engineers and contractors as they develop the means and methods for closure construction, and construction safety monitoring programs.
- Potential advantages of using an undrained shear strength analysis (USA) method during staged construction to assess strength gain of the fly ash as the impoundment closure project is completed.

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## INTRODUCTION

Since the Final Rule of US EPA regulation for the Disposal of Coal Combustion Residuals (Final CCR Rule) became effective on April 17, 2016 electric power utilities with ash basins, design engineer and contractors have been considering methods for CCR surface impoundments to "be closed in the shortest amount of time consistent with recognized and generally accepted good engineering practices". In general, the experience gained from the initial testing and work activities over wet ash basin closure project indicates that inconsistent subsurface conditions and changing water levels present unique challenges for ash basin closure construction. Recent experience indicates that these challenging site conditions can be overcome. This technical paper and presentation provides a summary of practical guidelines, lessons learned and safety considerations for ash basin closure projects.

One of the most important topics outlined in this technical paper and presentation is a summary of items that need to be considered for excavation and fill placement over wet ash basin subgrade materials. Another important topic that is considered, is how much geotechnical testing and in-situ monitoring is "enough". This includes providing enough geotechnical information for contractors to safely and effectively "do the job" of wet ash excavation, placement and construction for ash basin closure projects. The final topic is to maintain flexibility in the design and construction of ash basin closures. This includes developing and implementing contracting mechanisms and confirmation monitoring and testing opportunities during construction that encourage cooperation and a "team approach" that fosters joint responsibility for completing challenging ash basin closure projects safely.

It is important to note that this technical paper and presentation ***do not attempt to "solve" the problems*** associated with the stability evaluation or monitoring of staged ash basin construction projects. Rather the principles and suggested practices offered in this paper and presentation are provided to ***"start the conversation"*** that will help bridge the gaps between owner's safety concerns, design engineer's needs and contractor's concerns for wet ash basin closure.

## INFORMATION FROM GEOTECHNICAL PRACTITIONERS AND PROJECTS

The Observational Method was developed by Terzaghi and Peck (1969), and has been used successfully on numerous geotechnical construction projects to effectively address challenging soils and/or potentially unexpected changes in subsurface conditions. A summary explanation in Wikipedia that was prepared by several experienced geotechnical engineers is offered to provide perspective and context:

> "The observational method was proposed by Karl Terzaghi and discussed in a paper by Ralph B. Peck (1969) in an effort to reduce the costs during construction incurred by designing earth structures based on the most-unfavorable assumptions (in other words, geological conditions, soil engineering properties and so on). Instead, the design is based on the most-probable conditions rather than the most-unfavorable. Gaps in the available information are filled by observations: geotechnical-instrumentation measurements (for example, inclinometers and piezometers) and geotechnical site investigation (for example, borehole drilling and

> CPT). These observations aid in assessing the behavior of the structure during construction, which can then be modified in accordance with the findings.[2] *Reference: From Wikipedia based on information from several experts in the Observational Method.*

The practical approach and guidelines offered to geotechnical engineers and contractors working over wet ash basins by the Observational Method are especially helpful when dealing with an industrial byproduct material like coal fly ash. Fine-grained soils and industrial byproduct materials like coal fly ash and mine tailings have geotechnical properties and characteristics that can be complex leading to behaviors that can be inconsistent with traditional predictions and analyses. Characterization of coal ash and other manufactured materials like mine tailings is a difficult and underestimated problem in geotechnical engineering (even neglecting the geochemical aspects). Much of the difficulty arises because these materials are waste products from complex industrial processes and generally consist of sand and silt size particles, without clay minerals although cohesion may be present. These materials often fall into a “transitional material” category, somewhere between idealized sand-like or clay-like behavior (idealizations controlled by void ratio or over-consolidation respectively). The pressure to minimize costs of investigation without a coherent approach to evaluate transitional materials means that empirical methods derived from research work on sands or clays is often applied inappropriately (or at least with significant uncertainty).

The Observational Method applied to ash basin closure should always be used as a supplement to, and not replacement for sufficient pre-construction testing and stability evaluations of each stage of construction. Additionally, application of the Observational Method is only truly valid when the design and construction process are flexible enough to handle any necessary adaptations to design deemed necessary by the observations. A quote from Ralph Peck’s explanation of the Observational Method, (Peck, 1969) is applicable to most ash basin closure projects:

> “The observational method is suitable for construction which has already begun when an unexpected development occurs, or when a failure or accident threatens or has already occurred. (Peck, 1969) The method is not suitable for projects whose design cannot be altered during construction.”

**A Cautionary Note on the Observational Method:** A feature of staged construction of earthworks is that it is done slowly to allow consolidation during fill placement. This aspect is often formalized with piezometric measurement to confirm drained or consolidated conditions. Yet, as we’ve seen recently with the 2015 Fundao failure in Brazil and centuries earlier in many hydraulic fill dams, dams and stacks can fail suddenly and in a brittle fashion under rapid loading events (which could be a quickly placed berm raise, an earthquake, or even simply an increase in phreatic level). In such cases, if the applied rapid loading stresses are less than the peak undrained shear strength (instability limit, see e.g. Been, K., 2015), the soil has sufficient strength reserve to withstand the perturbation and the expected consolidation can develop. But, if the perturbation stresses exceed the peak undrained strength then monitoring construction and/or onset of failure with piezometers in conjunction with drained shear strengths is an unsafe engineering approach, as there will be no warning of the liquefaction failure (static or dynamic depending on the loading mechanism). The idea of triggering undrained instability during drained loading is difficult to appreciate as it involves the balance between drainage time and strain rates, with internal load transfers also affecting the mechanics. As such, it is typically simpler to think in the same manner as stage loading on soft clays and always maintain stability using undrained strengths in analyses.

At this time in human history and for the development of ash basin closure designs, it may be important to return to some of the core “principles and practice” that helped develop the principles and practice of modern soil mechanics. A few principles and guidelines that may need to be considered:

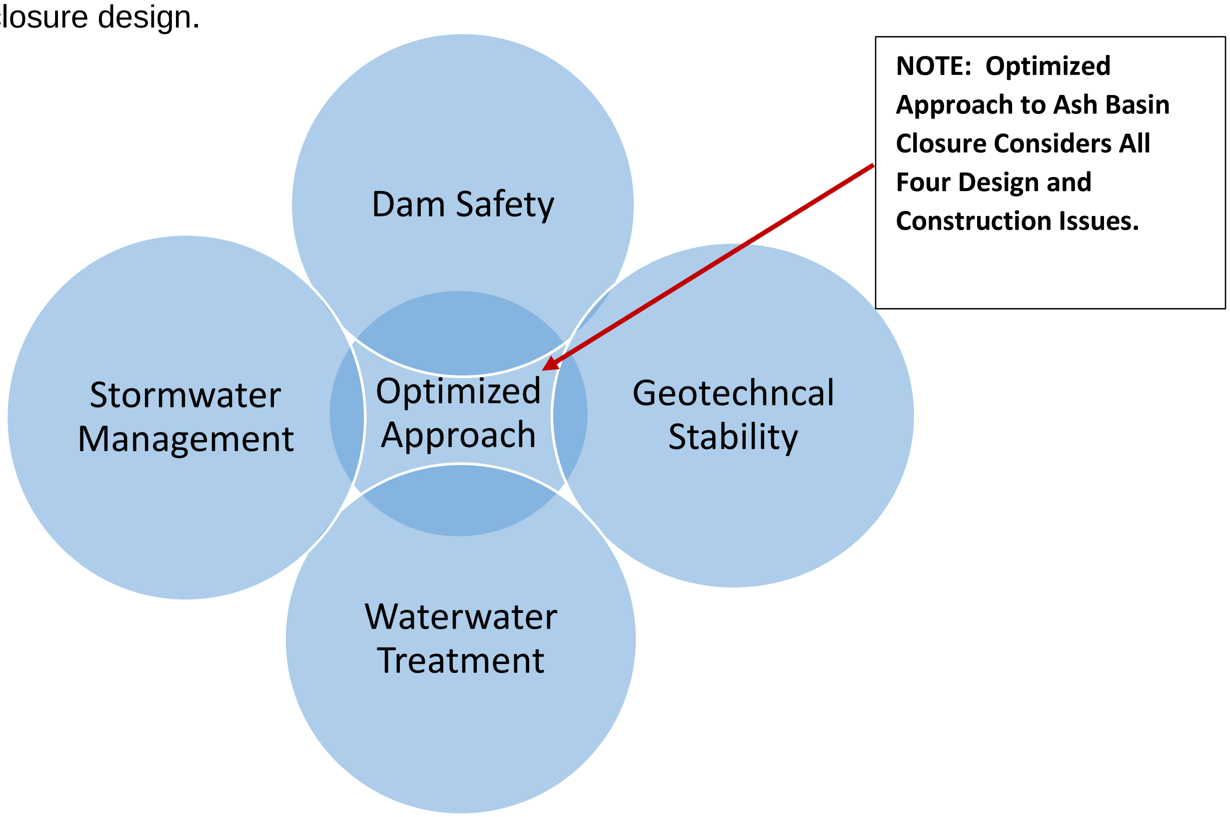
- **Practical Applied Research:** Some of the best academic researchers and university professors tend to work closely with construction professionals and industry leaders so that their research is practical and applied to the “real world” construction conditions. This often makes them better researchers and professors of geotechnical engineering.
- **Avoid Problems by Some In-Depth Analysis:** Industry leaders and construction engineers who work with practical researchers and university professors are often able to avoid hidden, unseen problems that can only be discovered by in-depth evaluation conducted in the lab or as part of a field demonstration project. This interaction creates a healthy interdependence between construction professionals and applied research engineers. It also helps educate young engineers by having them involved with solving “real world” problems.
- **Healthy Tension Between Research and Construction:** It is recognized that this interaction is at times difficult and causes geotechnical engineers to feel “stretched” beyond what they consider to be their ”comfort zone”. At the same time this interaction and healthy tension is essential because it develops new ideas that keeps construction workers safe and protects the general public.
- **Working Together as Team to Address Challenging Site Conditions:** During the completion of a challenging ash basin closure project working together as a collaborative team environment is essential. Different and/or opposing viewpoints from the geotechnical engineer, general contractor, and/or power utility professional can be confusing at times, but the professional with the opposite viewpoint is never the “enemy”. One the best ways to avoid the difficulties is to work as a team with patience, dedication and a science-based approach that remains focused on solving problems.

**Practical and Visionary Concepts:** Defining the principles and practice and the “art and science” of geotechnical engineering was the challenge of previous generations. Based on recent catastrophic failures and/or costly “blunders” (i.e. blunders is a Karl Terzaghi, and Ralph Peck term for massive, screw-up or failure that could have been avoided with good engineering input and practice) at TVA Kingston, Mount Polley British Columbia, and Fundao Brazil there are indications that we can do better. The challenge of geotechnical engineers, contractors, and electric power industry leaders in our generation may be developing a practical application of the “principles and practice” and “art and science” of modern soil mechanics to industrial materials like fly ash and mine tailings. By working closely together as industry leaders and geotechnical engineers there is a high probability that as an industry we can avoid similar problems, reduce risk, and create a more sustainable and positive future.

## TYPICAL ASH BASIN CLOSURE PROJECT – DESIGN AND CONSTRUCTION GEOTECHNICAL ISSUES

A typical ash basin closure project includes a carefully balanced consideration of stormwater, geotechnical stability, dam safety, regulatory compliance and wastewater treatment issues. These items are often considered in the context of a closure design that addresses the following:

- **Stormwater Management:** Control of off-site and on-site stormwater runoff typically is one of the most important items that influences the grading design and closure cover system selection.
- **Geotechnical and Stability Concerns:** A basic geotechnical investigation of the soft/wet ash materials at critical locations provides valuable information about the material characteristics for dewatering and closure.
- **Grading Design:** A grading design that minimizes moving of ash material and cover soils, and the placement of deep fills over soft/wet ash materials is an essential component of most ash basin closure projects.
- **Drainage, Drying and Dewatering:** There are a wide variety of methods for dewatering and drying of ash materials. An understanding of the grain size, plasticity and layering in an ash basin closure project is important for developing the closure design.



**Interim Condition Designs and Minimizing Instability:** Recent project experience and laboratory testing indicates that coal ash is a moisture sensitive, silt-sized material that can become unstable when saturated and subjected to extended periods of precipitation or stormwater run-off. To account for challenges presented by highly erodible, potentially unstable fly ash material many design engineers and owner's engineers are separating ash basin closure project site into smaller 5 to 15 acre sub-areas for design and construction purposes. The advantages of incremental approach to design and constructionare as follows:

- **Reduced Risk for Erosion and Instability Due Saturation:** Separating a typical ash basin project into smaller 5 to 15-acre sub-areas reduces the risk caused by erosion from a large site, and creates more manageable areas to control of stormwater runoff and on-site wastewater treatment. If previously graded areas of the ash basins are stabilized with erosion control products then the potential of instability due to infiltration of rainwater during the closure process is reduced.
- **Reduced Volume of Contaminants and Cost of Wastewater Treatment:** Minimizing the volume of stormwater that impacts previously stabilized ash basin surfaces has an added benefit of reducing the amount particulates and contaminant levels that need to be treated or removed from ash basin wastewater. Reducing runoff and contaminant levels by proactive site management can greatly reduce the cost of wastewater treatment from a typical ash basin closure project.
- **Interim Stormwater Collection Ponds Can Reduce Instability and Decrease the Cost of Wastewater Treatment:** Controlling the amount of stormwater runoff from a typical ash basin closure project has been identified as and effective means and method that reduces instability of the ash basin, and decreases the cost of wastewater treatment. Examples of how this approach has been applied for different types of ash and a variety of site conditions are available from the CALM Office and Golder Associates upon request.

**Undrained Shear Strength Analysis (USA) for Ash Basin Closures:**

The technical paper entitled: Stability Evaluation During Staged Construction, was presented as the Twenty-Second Karl Terzaghi Lecture in 1991 by Dr. Charles Ladd. It provides important information and guidelines that link principles developed by the "fathers" of modern soil mechanics to the current day. Throughout this precedent setting paper several practical recommendations for evaluating the stability of staged construction of embankments are described. The overall theme of this paper is increasing safety and avoiding failure or near failure conditions during construction over soft and saturated fine grained materials. A few key concepts in the technical lecture by C. Ladd, 1991 that apply to excavation and embankment construction over wet and partially saturated ash basin subgrades are provided below:

- The Total Stress Analysis (TSA) described in the classic papers by C. Ladd, 22$^{nd}$ Terzhaghi Lecture, 1991 and Bishop and Bjerrum (1960) recommended unconsolidated-undrained (UU) be used, and a ***minimum factor of safety based on measured field conditions.*** One problem encountered in saturated coal fly ash in ash basins is the difficulty of obtaining representative laboratory samples or field measurement of the undrained properties of saturated ash. Coal ash is difficult to sample and test using conventional geotechnical sampling and laboratory test methods. This suggests that factor of safety and monitoring for staged embankments over wet/soft fly ash should take into consideration the potential inconsistency of testing results.

- It is interesting to note that in the technical paper by C. Ladd, 1991 he mentions that several respected geotechnical engineers did not consider differences between lab and field conditions to be a serious practical limitation. In this same paper, Dr. Ladd indicated that others thought that not taking into consideration the difference between lab and field conditions to be dangerous. In this technical paper Dr. Ladd mentioned that Birinch—Hansen 1962: and Barron, 1964 believed that staged construction should be treated as a consolidated-undrained (CU) case with appropriate porewater pressure measurement to connect lab conditions to field conditions.
- For staged construction over saturated, fine practical materials C. Ladd and other industry leading geotechnical engineering professionals indicated that the "greatest uncertainty, lied in estimating the rate of pore pressure dissipation via consolidation theory and hence field observations of porewater pressure are advisable for important works."
- "Since the undrained shear strength ($c_u$) of normally consolidated soils is substantially less than the drained strength under normal loading conditions, the undrained shear strength analysis (USA) will give both safer and more reliable estimates of the actual factor of safety". C. Ladd, 1991

Recognizing that saturated coal fly ash provides unique challenges for sampling and testing using conventional geotechnical laboratory procedures, senior geotechnical engineers are relying more on a combination of in-situ field tests (CPT and field vane shear tests) for characterization of the strength characteristics of wet/partially saturated ash basin materials. (Hardin, Falmezger, Amaya, Heisey, Zand, 2011, and Hebeler, 2016). An example of a typical correlation to the undrained shear strength properties for fly ash materials and other industrial byproducts that can be obtained using the cone penetrometer (CPT), the Van den Berg vane shear device, and conventional laboratory testing is provided below:

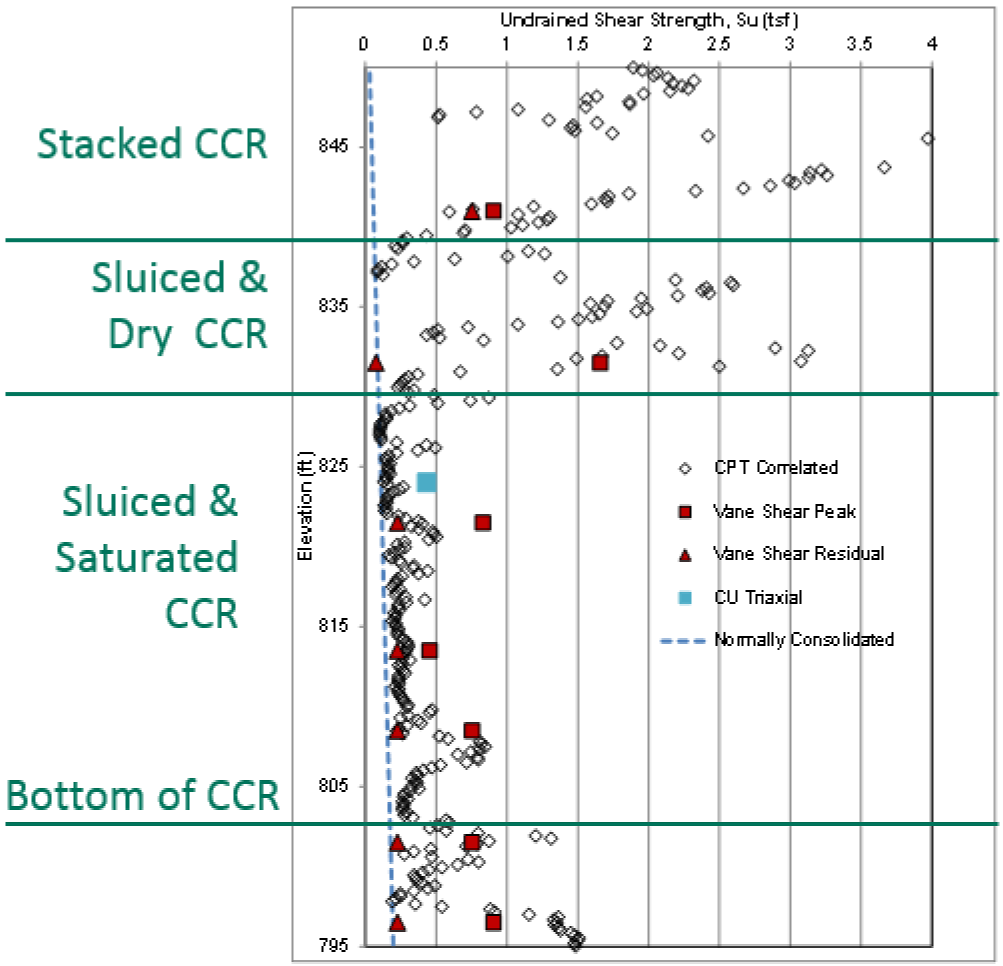



**Figure 1** – Example undrained strength data at a CCR impoundment using a combination of CPT, VST, and laboratory testing.

Previous experience from construction over soft subgrade materials, and information information from "classic" geotechnical technical papers by C. Ladd, 1991 and others indicate that a USA may be the most applicable for assessing the interim stability of partially saturated ash basins. For areas of ash basins requiring deeper excavation and/or the placement of large amounts of fill material the following test methods are often used:

- **Pre-Construction CPT and Vane Shear Tests:** Prior to the start of construction and dewatering of the ash basin it is imperitive to obtain undrained strength parameters using a combination of CPT and vane shear tests. These in-situ tests are often correlated to laboratory triaxial shear tests and index property testing to provide the shear strength properties of ash materials that can be used in a global slope stability analysis.
- **Global Slope Stability Analysis and Development of Target Factor of Safety:** Since the pre-construction, undrained shear strength is typically the "worst case" condition the USA can provide useful information about the

minimum factor of safety that needs to be developed by dewatering and soil improvement methods.

- **Construction Guidelines and Assessing Strength Gain During Construction:** The USA can be used as a tool to develop a range of dewatering and construction scenarios to safely excavate and place partially saturated fly ash materials. The results of incremental testing via CPT or VST, and porewater pressure monitoring measurements provide useful tools that can be used to predict that amount of strength that is gained by the dewatering and/or construction process. Figures 2a and 2b below show example sets of CPT test data pairing pre-construction and during construction post partial dewatering showing the strength gain from dewatering.

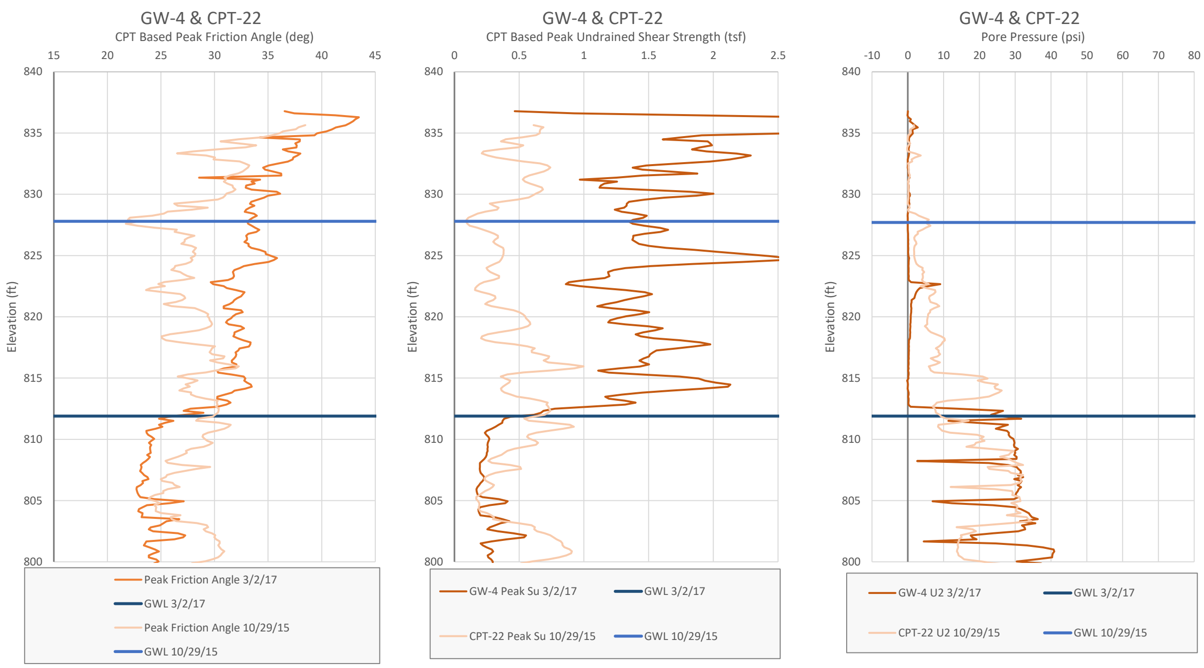



**Figure 2a –** Example CPT measurment and correlation comparison of pre-construction (lighter lines) and during construction with ~ 15 feet of dewatering.

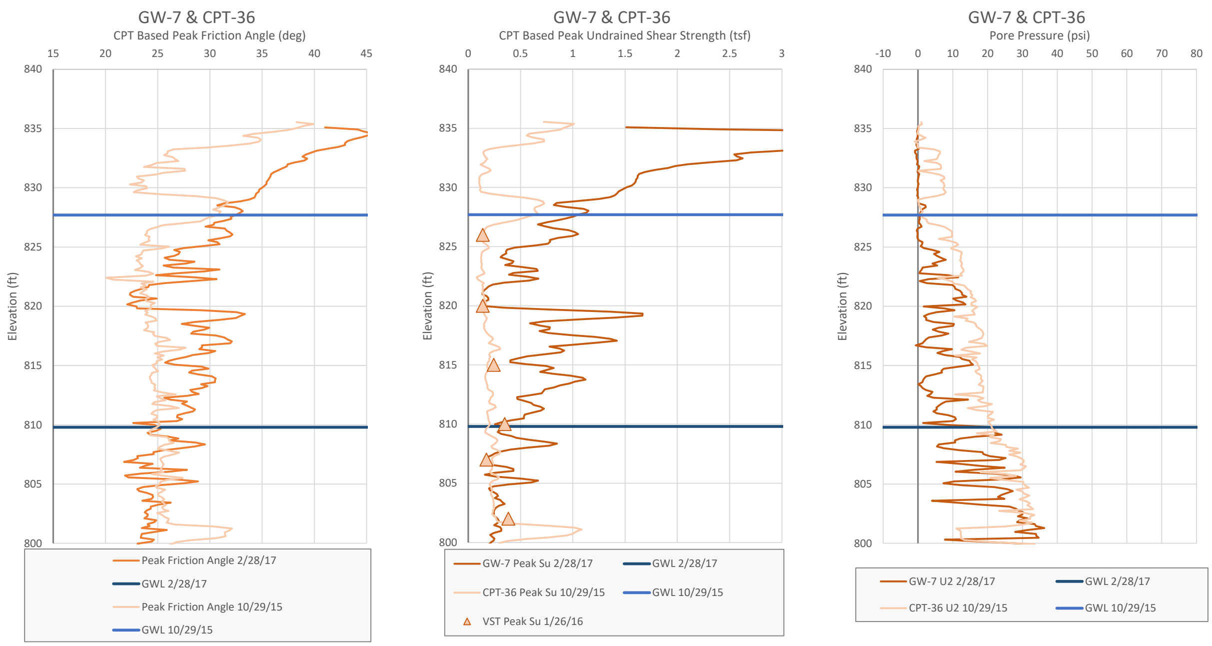



**Figure 2b** – Example CPT measurment and correlation comparison of pre-construction (lighter lines) and during construction with ~ 15 feet of dewatering (darker lines).

Both Figures 2a and 2b show an influence on the CPT response and correlated friction angle and undrained shear strength within the zones between the pre-construction water level and the lower water levels following dewatering during ash basin closure. Of particular note in the comparison between Figures 2a and 2b is the magnitude of the increase in undrained strength being directly correlated to magnitude of the drainage and saturation level within the ash as seen in the CPTu pore pressure responses during penetration. As seen in Figure 2a the ash above the water line has achieved a low enough saturation level that it no longer exhibits significant pore pressure response during CPT penetration, a trend along the zero line above the water table. Whereas, the test location in Figure 2b still shows remnant CPT penetration induced pore pressures for a large portion of the dewatered zone and in kind shows a much lower change in undrained shear strength. The importance of this observation is that the dewatering in the upper Figure 2a plots indicate ash materials dried sufficiently to not likely be sensitive to small changes in water levels and able to maintain the strength increases shown. Whereas the ash zones in Figure 2b are likely much closer to fully saturated (as seen by the remnant pore pressure generation during CPT penetration) and as such zones are likely potentially susceptible to variations in moisture within the ash that could lead to rapid phreatic level and strength changes.

Incremental testing during construction can serve to not only check and confirm pre-design assumptions, but to allow adaptations to closure phasing operations, and controls based on the observed changes from the pre-construction test results. Incorporation of such incremental testing into closure specifications and procedures not only provides confidence and information to engineers and owner's but also serves to allow for engagement between engineers and contractors using direct feedback from ongoing closure efforts promoting a sense of team.

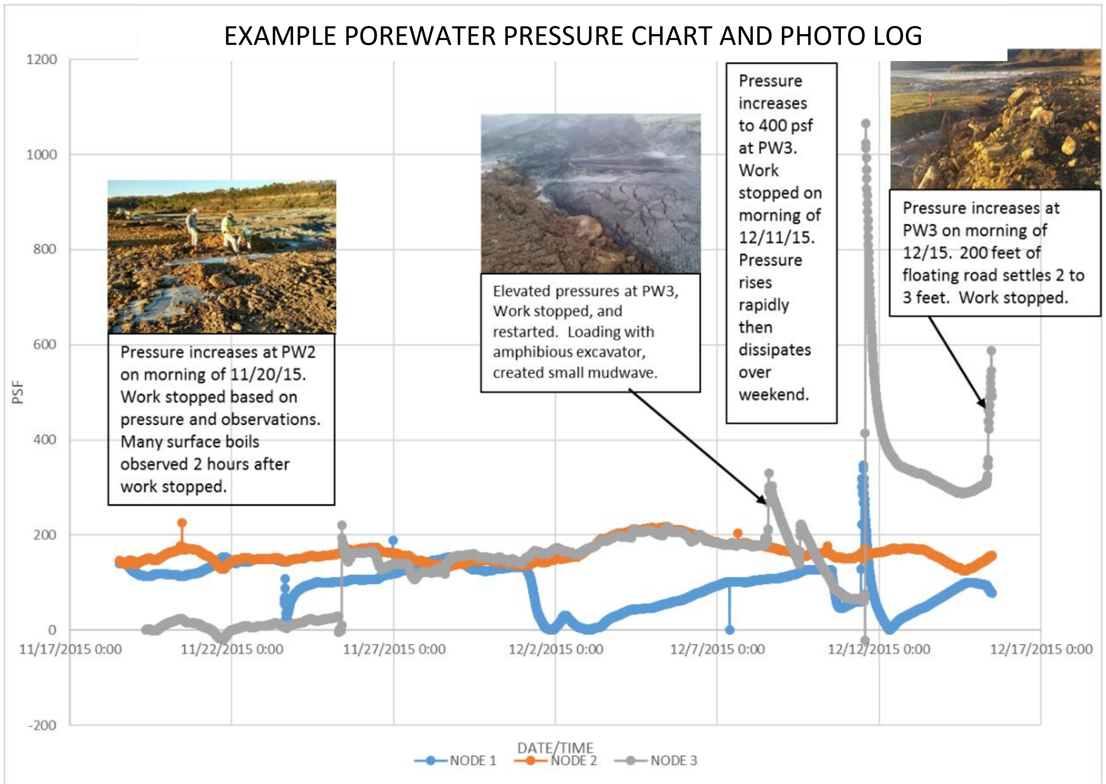
## RECENT PROJECT EXPERIENCE – PRACTICAL TOOLS THAT WORK

Project experience on several ash basin closure projects has provided useful information on how field measurement and an interim evaluation of strength gain can be used for a typical ash basin closure construction. This project experience included development of the following tools for assessing strength gain and predicting instability caused by excess porewater pressure:

- **Vane Shear Readings, CPT Reading and Slope Stability Analysis:** Vane shear readings and CPTs provide a measurement of the undrained shear strength that can be used for slope stability analysis. This analysis provides the probable factor of safety that would be present at the beginning of construction and at regular time intervals during the dewatering process. This information can provide the contractor and field engineer useful information about constructability and the recommended rate of fill placement.
- **"Real-time" or Frequent Measurement of Porewater Pressure:** Modern technology allows "real-time" porewater pressure readings to provide field engineers and contractors direct and rapid feedback during the excavation and/or fill placement process. When used as part of a project placement and safety monitoring plan these porewater pressure readings allow the contractor to assess when potentially unsafe conditions are present, and to modify construction activities as needed.
- **Use of Dewatering and Soil Improvement Methods to Increase Soil Strength:** Removing porewater from a wet or partially saturated ash basins, is known to increase strength and improve constructability. Periodic measurement of the undrained shear strength with vane shear devices and porewater pressure reading with vibrating wire porewater pressure transducers or CPT dissipations are effective ways to evaluate the increase in soil strength. See Figures 2a and 2b.

### Case Study: Vane Shear Testing and "Real-time" Porewater Pressure Readings

The contractor and quality control engineer on this project utilized a hand held vane shear device to pre-test the upper 10-ft of the crusted, but partially saturated ash subgrade to identify areas with soft or unstable areas. Test locations were located on a grid approximately 150 to 200 feet apart, and areas were retested if changing conditions and/or after heavy rainfall event. A detailed Work Plan that initiated Go/No Go procedures depending on the measured undrained shear strength, and observations made by an experienced heavy equipment operators or the Project Superintendent provided additional safety measures. For areas where soft ash layers were located beneath the surface, and where construction equipment and surcharge loads could create instability several Geokon, "real-time" porewater pressure transducers were installed.




SUMMARY AND CONCLUSIONS

Several of the methods described in this paper can be useful tools for contractors and field engineers dealing with challenging ash basins that required work over soft and partially saturated ash materials. The methods described above were developed to increase safety, while reducing the overall cost of ash basin closure projects This is accomplished by providing valuable information about subsurface conditions and strength gain. For those who are interested, additional information and site specific applications of the practical tools for ash basin stability evaluation and monitoring are available upon request.

As mentioned previously, the purpose of this paper is ***not to "solve" the problems*** associated with stability evaluation and monitoring of staged construction of ash basin closure process. This is an area of geotechnical engineering and construction that is continuing to develop. Advancements in engineering design, innovative technology and means and methods for ash basin closures are expected to continue over the next 5 to 10 years. It is anticipated that the principles and practice described in this paper will help advance the body of knowledge, and ***continue the conversation*** about what is needed for safely monitoring and evaluating ash basin construction. By offering the ideas and concepts in this paper, the authors are also soliciting input on how best to address the challenges of working over and around soft and saturated ash basins.

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