Determination of Undrained Strength for Contractive Coal Combustion Residuals

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KEYWORDS: Undrained Shear Strength, Cone Penetration Test, Slope Stability, Direct Simple Shear Test

INTRODUCTION

Slope stability for impoundments of Coal Combustion Residuals (CCR) has become more important as failures involving undrained behavior of granular materials has occurred over the past few years. Common practice for the evaluation of the stability of completed CCR impoundments considered only long-term stability assessments. The logic has been that an impoundment is in place for some time, not being added to, and is under steady state pore pressures where the controlling stability is drained. Undrained stability has generally not been considered a potential failure mode unless the impoundment is still under construction, or some significant alteration has been done to its condition. However, this common approach for stability assessments overlooks the potential for an undrained failure to be triggered by something that causes a rapid increase in mobilized shear stress or a rapid decrease effective stress. In these instances, if contractive saturated materials are present, an undrained failure can be triggered, requiring to perform a stability analysis under undrained load case. Undrained strength parameters for CCR materials can be highly variable. Cone penetration tests (CPTs) can provide lots of data quickly and inexpensively, but the measurement is an index test which must be converted to strength through semi-analytical-empirical correlations. Such correlations are reasonably well understood for natural clays and sands but there exists only limited correlation data for CCR materials. As part of the work presented, a program was developed to collect CPTu data from CCR impoundments and companion “undisturbed” tube samples for laboratory strength testing. This testing program was performed at five different CCR impoundments for the Tennessee Valley Authority. The mud-rotary borings using Osterberg tube sampling were located approximately 5 feet away of the CPTu soundings. Laboratory testing to measure undrained strength was done in direct simple shear devices on specimens reconsolidated to in situ effective stresses. The data presented in this paper are all from laboratory tests on ash materials that showed contractive behavior. In addition, CPTu data were used to estimate the undrained strength using available correlations. Generally, reasonable agreement was obtained by the two independent approaches but with significant scatter. This paper describes the methods used and the results obtained for undrained strength of CCR materials. It summarizes the approaches used to apply best applicable practices to make a reliable determination of undrained shear strength. It also makes some recommendations for how to improve the methods to determine undrained shear strength of contractive materials. The results are applicable to CCR impoundments and other liquefiable materials such as mine tailings and loose alluvial deposits.

WHY WE EVALUATE CCR STACKS AND IMPOUNDMENTS?

We evaluate CCR stacks and impoundments with the purpose of assessing the overall stability and identifying and mitigating potential failures. Failure can be defined as an unacceptable difference between expected and observed performance[8]. Examples of these unacceptable differences can include a range of performances including the generation of tension cracks to rupturing and flow of CCR materials. A couple of examples of CCR failures are described to show their impact.

In February 1972, a failure of impounded CCR materials occurred along Buffalo Creek in West Virginia, US[4]. This failure was sudden and had no warning. The dam released millions of cubic yards of material. The wave of spilled materials destroyed over 500 homes, left over 4,000 homeless, thousands injured, and killed about 125 people. The failure results in about $50 million in damages to property. The likely contributors to the failure of these dams are internal erosion and seepage.

In December 2008, a failure of impounded CCR materials occurred at the Kingston Fossil Plant in Tennessee, US. This failure was sudden and had no warning. The embankment spilled about 4.1 million cubic meters of CCR[15]. Over 180 properties have been damaged and over $1.2 billion have been spent to clean up the CCR materials[3]. AECOM determined that the main cause of the spill was the result of a slippage of a fine wet coal ash layer at the bottom of the impoundment[1].

Between these two examples, and from many more, a common feature is found to be the driving these failures. Both failures involved the triggering of a contractive, undrained strength of the CCR materials. Determination of undrained strengths of contractive CCR materials is necessary acknowledging the complications.

BEST APPLICABLE PRACTICES

Geocomp employs, “Best Applicable Practices” (BAP) which can be defined as the application of best available, yet practical technologies and methods to determine realistic soil parameters with minimum use of assumptions. These technologies and methods, as far as CCR stacks and impoundments are concerned, combine field testing and laboratory testing to determine contractive, undrained strengths.

FIELD TESTING

The field testing component of BAP consists of performing a number of field tests and collecting samples of CCR in the field.

One of the most common field tests includes performing the cone penetration test (CPT). The CPT provides a continuous profile of data in the form of tip and sleeve resistances. Additional capabilities can be added to the cone to measure dynamic or dissipated pore pressure (CPTu), as well as shear wave or compression wave velocities (SCPT). An example of seismic CPTu data can be seen in Figure 1. An important aspect of the CPT data is that it provides an index to strength, that is CPT data does not provide a direct measurement of strength. The CPT data needs to be correlated to get a measurement of strength along the profile. However, the input parameters of these correlations need to be calibrated for site-specific conditions.

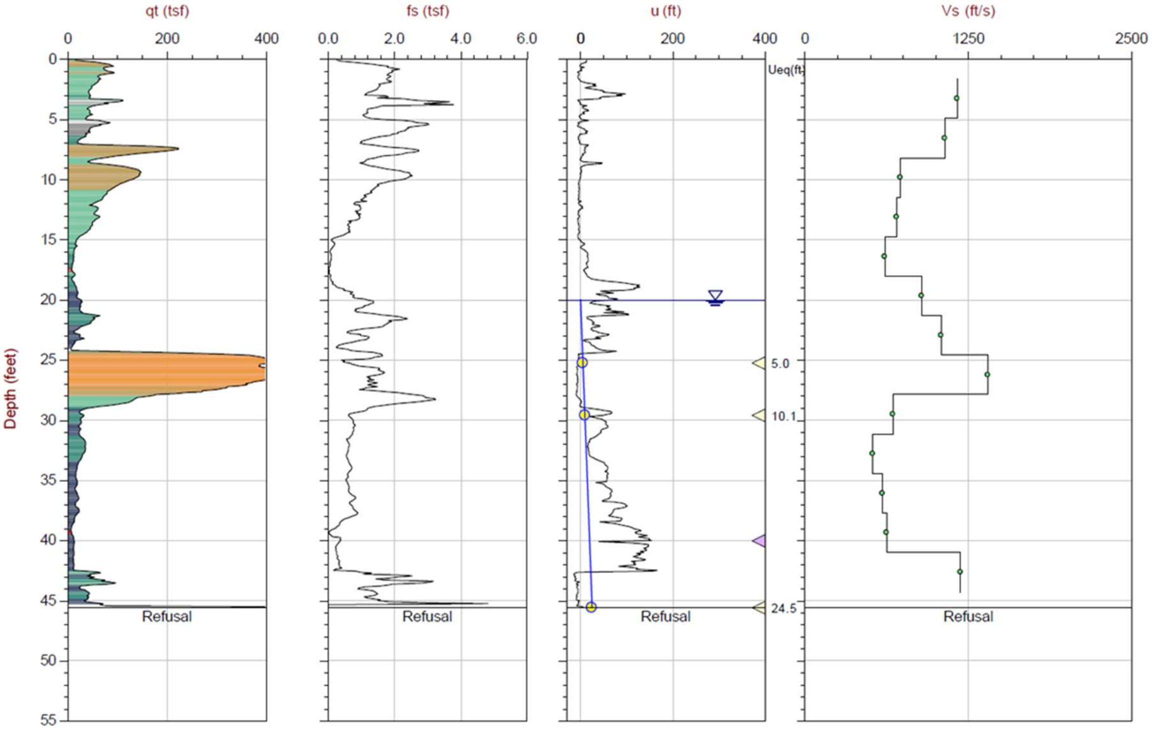


Figure 1 - Example of Typical Seismic CPTu Results

Another common field test is to collect samples by drilling. The preferred drilling method for collecting samples is mud rotary drilling as part of BAP. Mud rotary drilling helps minimize sample disturbance[14]. The drilling fluid used in mud rotary drilling needs to be maintained at the top of the borehole to maintain a consistent drilling fluid pressure at the bottom of the borehole. Drilling provides the opportunity to collect disturbed samples, undisturbed samples, and instrumentation. Disturbed samples come in the form of split spoon sampling. Split spoon sampling also provides an index of the material's behavior and strength in the form of a SPT-N value. The SPT-N value can also be correlated to get a measurement of strength. Undisturbed samples come in the form of thin-walled tube samples. The preferred sampler for collecting undisturbed samples is the Osterberg sampler, which takes advantage of piston sampling and a larger diameter sample. An Osterberg sample is shown in Figure 2. These undisturbed samples are sealed, stored, and transported to the laboratory for further advanced testing. Companion CPT sounding can be used to guide where to sample with Osterberg sampler versus where to collect split spoon samples. Once the borehole is done being sampled, geotechnical instrumentation can be installed. This instrumentation includes installing multiple strings of piezometers in the same borehole at different depths. These multiple strings of piezometers in the same borehole provides a means of understanding the groundwater flow along the profile, which give a more realistic interpretation of the in-situ pore pressures.

Figure 2 - Osterberg Tube Sampler

While the CPT and drilling methods are considered common, there are several additional field tests that can provide useful information. These additional field tests include the geophysical testing, vane shear testing (VST), dilatometer testing (DMT), and pressuremeter testing (PMT). Geophysical testing can include both surficial testing and borehole testing. Surficial testing covers tests performed on the ground surface, such as multichannel analysis of surface waves (MASW), providing a site-wide screening of the CCR unit. Borehole testing covers geophysical tests performed in a cased borehole, such as cross hole seismic testing, providing depth specific seismic tests. While this can be useful, seismic CPT's can provide a similar level geophysical testing in conjunction with CPT data. VST data are direct measurements of strength at a specific depth. However, when testing in CCR, a couple of assumptions are made. DMT data are similar to CPT data with respect that DMT data provides an index to strength. However, DMT testing is not often utilized for CCR materials so the reliability of DMT correlations applied to CCR are not strong. PMT testing is rarely utilized for CCR materials. The likely reason for this is because PMT testing requires above average specialized training and equipment, on top of the limited tests performed on CCR.

LABORATORY TESTING

After collecting disturbed and undisturbed samples from the field, they should be transferred into the laboratory with caution to control the vibrations. A number of tests are performed on CCR samples. These tests broadly include index and strength tests, where specific tests can be categorized into one of these two tests. An important aspect of laboratory testing of CCR materials is that the results are unique to the byproducts produced and storage processes utilized by the specific power plant. The following paragraph describes results from ash materials encountered at various fossil plants, as well as the logic for strength parameter selection.

Typical index tests performed on CCR samples include specific gravity, water content, grain size, and Atterberg Limits. These tests can be performed on disturbed or undisturbed samples. Specific gravity values of CCR can go as low as 2.0 and may go up to about 2.6. This range is a result of the byproducts produced by the fossil plant. Water content values may range from about 20% to 80%, which can result from dewatering operations of CCR to dry stacked CCR to wet, sluiced CCR. CCR is composed of materials generally classified as sand to silty sand to silt. This range is intended to cover the more coarse-grained materials, such as bottom ash, to the fine-grained byproducts, such as fly ash, and the intermixing of these two products. CCR is typically classified as non-plastic based on Atterberg Limits, however it can show up as plastic depending on how the CCR was placed.

Prior to performing strength tests on CCR materials from tube samples, each tube is x-rayed. X-ray testing of the tubes is used to examine and screen the contents of the tube without extruding the sample out of the tube. The first observation the x-ray reveals is a sense of sample disturbance. Sample disturbance can be observed along the interior sides of the CCR to tube interface. A disturbed sample would show the sides of the CCR concaving downward. An undisturbed sample would show planes of CCR, either horizontal or at a slight angle depending on how it was deposited. A typical example of sample disturbance in tube samples is shown in Figure 3[11]. The second observation the x-ray reveals is a sense of the heterogeneity of the CCR with its layered deposition. Darker lines in the tube represent coarser CCR that settled out during sluicing operations. An example of undisturbed CCR samples showing various heterogeneity is shown in Figure 4.

After performing x-rays on tube samples, strength tests are performed on selected samples typically starting from the bottom of the tube. The strength test performed on CCR materials is Direct Simple Shear (DSS) tests. The DSS test is an undrained shear test conducted under constant volume. The sample size for DSS tests is 1-inch tall, making it 1/6 that of a typical triaxial test and allowing for many more tests to be run on the same tube. In addition, the test duration is relatively shorter for DSS tests than that compared to triaxial because of the smaller sample size.

DSS tests are selected to be more representative for determination of shear strength for stability assessments. Along a particular slip surface, the CCR is expected to undergo a combination of triaxial compression, direct simple shear, and triaxial extension[2]. Based on laboratory comparison of these three types of tests, DSS testing is representative of the average strength of these three shear modes. In addition, if undrained shear strengths are selected, the slip surface tends to be horizontal through this layer. Horizontal slip surfaces are best represented through the DSS failure mode.

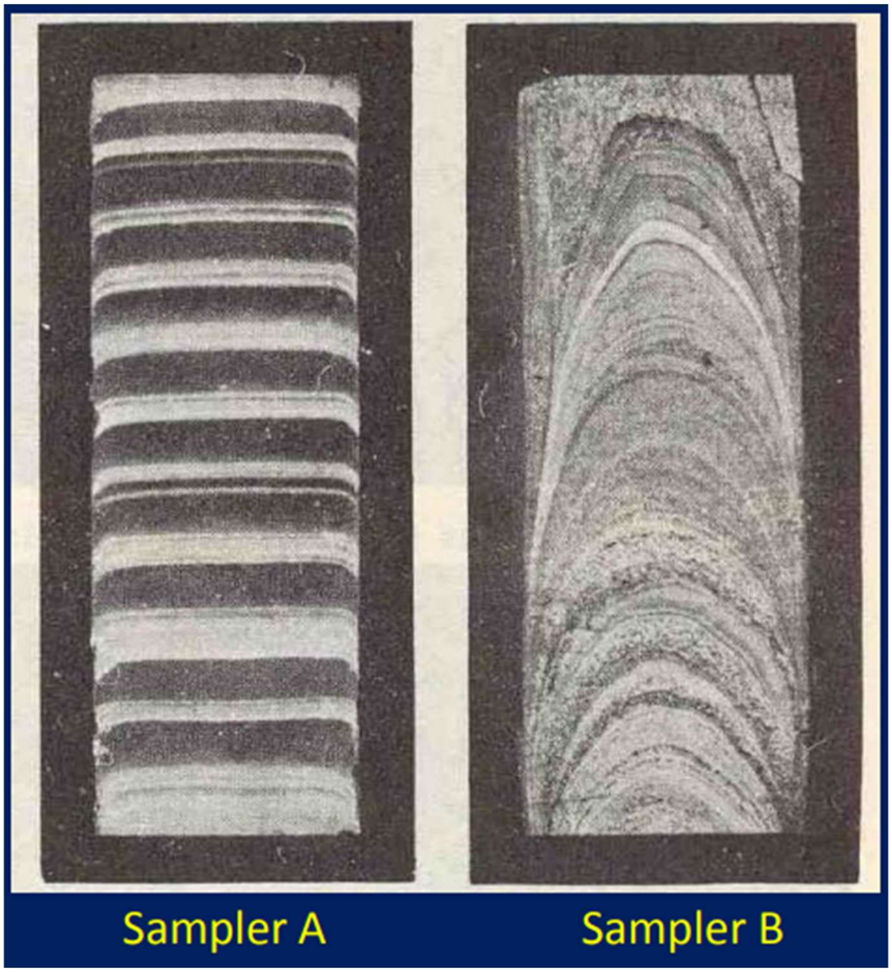


Figure 3 - Example of Undisturbed (left) and Disturbed (right) Tube Samples

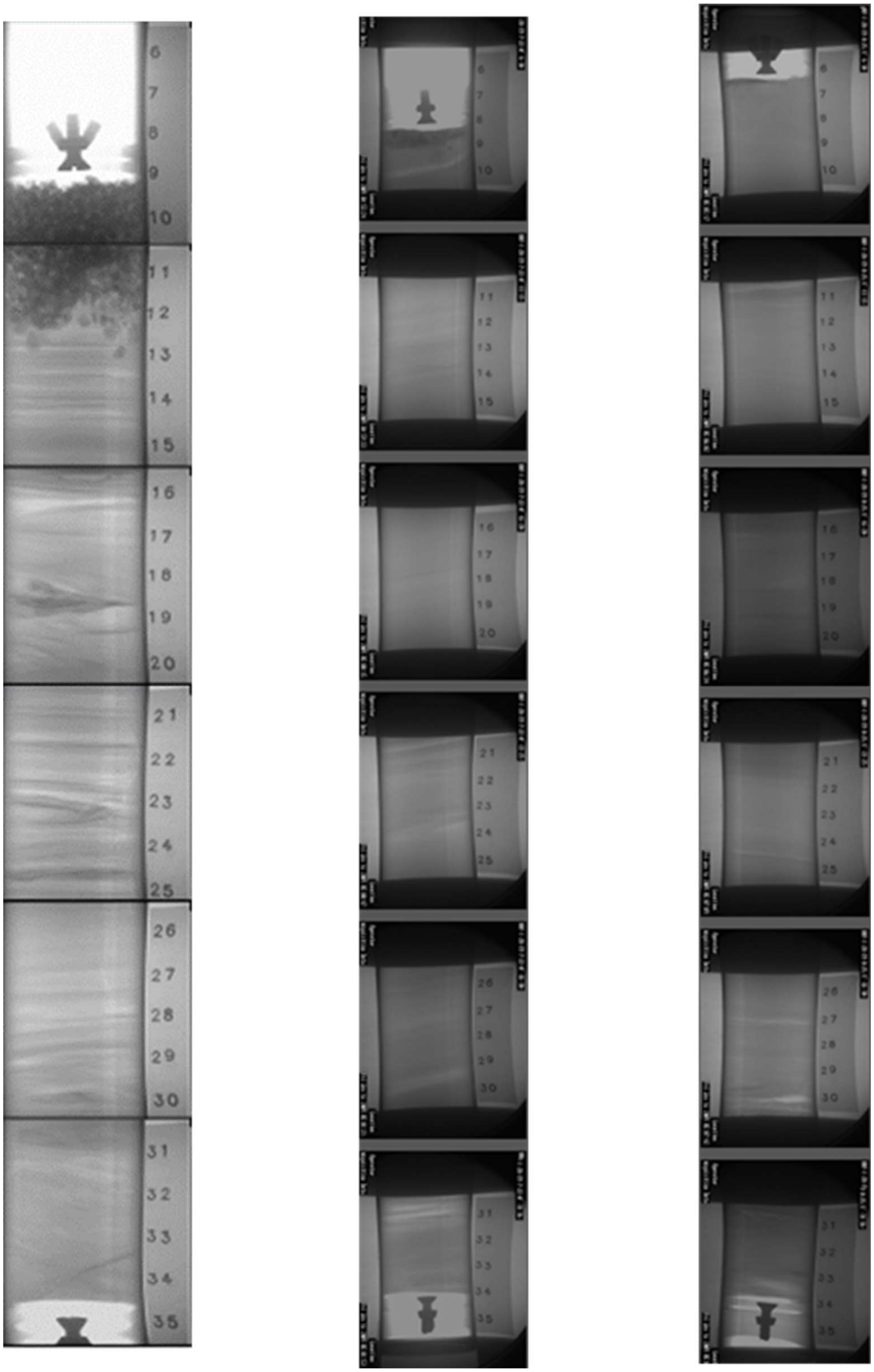


Figure 4 - Example of Osterberg Tube Samples of CCR Materials

PARAMETER DEVELOPMENT

Having collected and processed both field and laboratory data, the data is combined to determine appropriate strengths for slope stability analyses.

Before determining the appropriate strengths, it is best to examine the behavior that is expected from the CCR under applied shear stress. Different responses to shear loading are simply represented in Figure 5 which are the contractive response, drained response, and dilative response[5]. In Figure 5, stress path going to the left represents a contractive response. A contractive response may be triggered by rapid loading or an increase in pore pressures when sheared. Contractive responses produce lower strengths than the drained and dilative responses. The strengths produced by contractive responses result in strengths based on undrained strength, such as the undrained strength ratio. Figure 5 also shows a vertical stress path that represents drained behavior. In drained response, there is no change in pore pressure, and effective stress strengths, such as the friction angle and cohesion intercept are typically used to model drained response. This strength is commonly used in long-term slope stability assessments. Finally, the stress path going to the right in Figure 5 represents a dilative response. Dilative responses are triggered mostly by rapid loading or a decrease in pore pressures when sheared. Dilative responses produce strengths higher than the friction angle and cohesion intercept because of the negative pore pressures. Materials that give dilative responses should be modeled with drained strengths because the negative pore pressures generated during shear cannot be relied on.

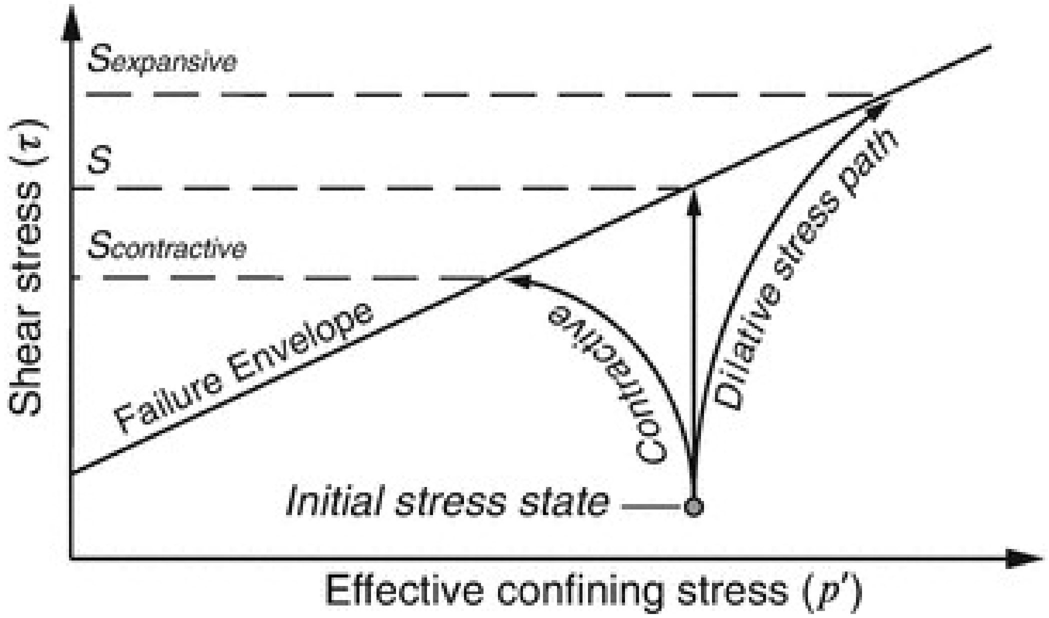


Figure 5 - Typical Stress Paths for Contractive, Drained, and Dilative Behavior

To determine where contractive and dilative behaviors are expected along a soil profile, state parameter can be used as an index. State parameter is the difference between the initial void ratio and the void ratio at the critical state[6]. The state parameter can be developed from CPT data using correlations. When the state parameter is positive, the CCR is estimated to be contractive. Theoretically, when the state parameter is negative, the CCR is estimated to be dilative. In literature of CPT correlations, contractive behavior has been observed between state parameters of 0 and -0.05[13], despite being negative. This region is referred to as transitional and may require some caution as to whether or not the material is truly dilative. Further strength testing for transitional materials is warranted if they are encountered. An example of the CPT state parameter, and its subdivisions of contractive, transitional, and dilative, can be seen in Figure 6.

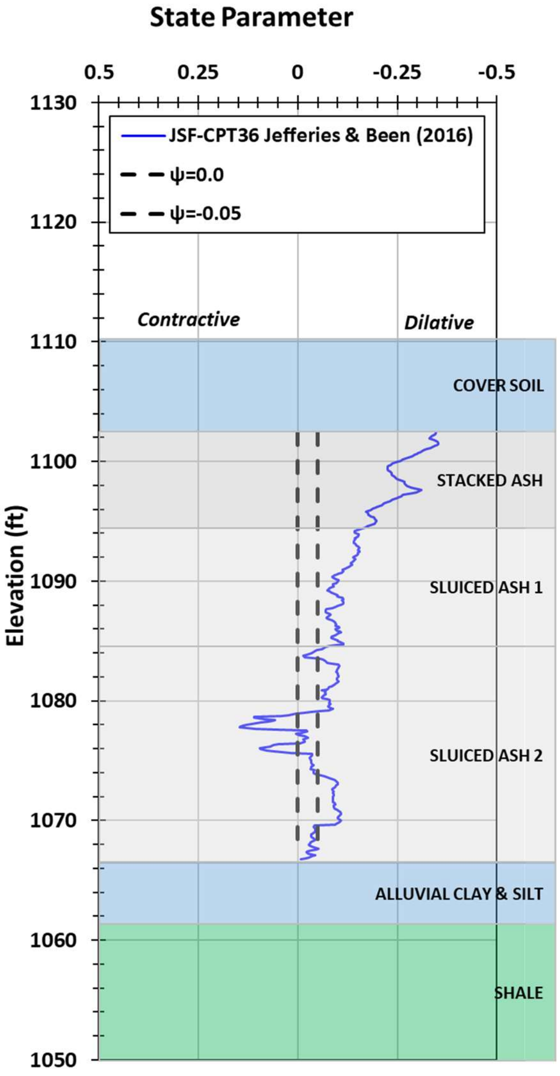


Figure 6 - Example Profile of State Parameter from CPTu Data

After the CCR layer is subdivided into contractive, transitional, and dilative zones using the state parameter, the next step is to determine the applicable shear strengths to these zones from DSS test results. Figure 7 provides an example results from three DSS tests on contractive, transitional, and dilative zones. Dilative samples, as shown by the blue line, will generate negative excess pore pressures while shearing. The figure also shows that dilative samples generate the highest undrained strengths. Contractive samples, as shown by the red line, will generate only positive excess pore pressures while shearing. The figure also demonstrates that the contractive samples generate the lowest undrained strengths. Transitional samples, as shown by the black line, generate low to zero excess pore pressures while shearing. The strength of transitional samples is between contractive and dilative strengths. Due to the potential of positive pore pressure generation, transitional and contractive materials should be modeled with undrained strengths.

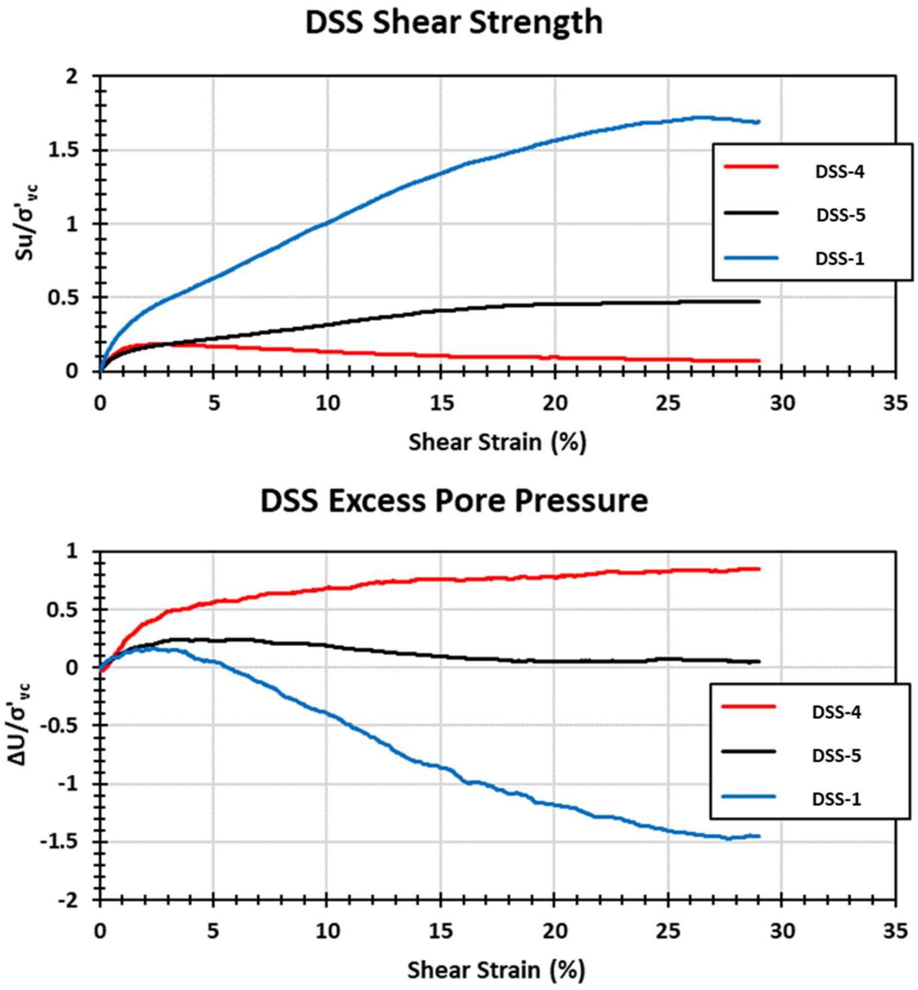
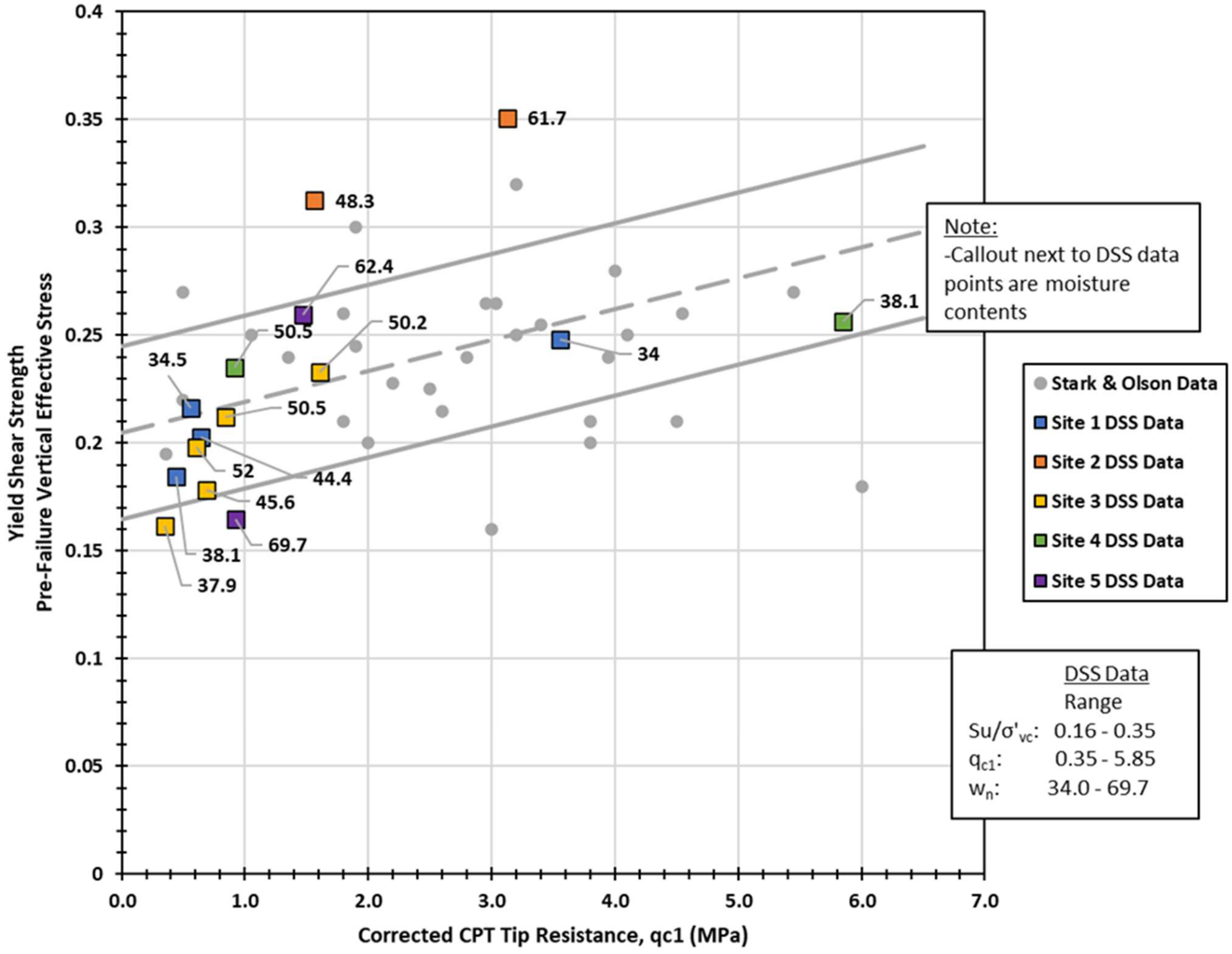


Figure 7 - Typical DSS Results of Contractive (Red Line), Transitional (Black Line), and Dilative (Blue Line) Tests

DSS tests on contractive CCR materials from five different sites are compared to published correlations[12] as shown in Figure 8. The CCR data shown in Figure 8 has significant variability between sites, but follows a similar trend as the published values. In addition to the scatter in undrained shear strength, the water contents vary from 34% to about 70%, suggesting that the samples are initially wet when prior to shear. Finally, the undrained strength ratios are in the range from 0.16 to 0.35, which are significantly lower than effective stress friction angles on CCR materials. These observations agree with the importance of understanding how the CCR is placed and its heterogeneity and how wet the CCR remains. All of these contribute to how contractive the CCR is, as well as its resulting undrained strength.



Note:
-Callout next to DSS data points are moisture contents

DSS Data
Range
Su/σ'_{vc}: 0.16 - 0.35
q_{c1}: 0.35 - 5.85
w_n: 34.0 - 69.7

Figure 8 - DSS Results of Undrained Strength on CCR compared to Olson & Stark (2003)

Other methods may be used to examine the undrained strength of CCR, but these methods are more empirical and requires calibration to a reference. One of the common methods is to use bearing capacity theory involving the CPT. Bearing capacity theory involves methods that use the N_{ke}, $N_{\Delta u}$, and N_{kt} factors. The first two methods, N_{ke} and $N_{\Delta u}$, require positive u_2 pore pressure generation for the CPT, which may not occur given the CCR's heterogeneity and permeability. Even if positive u_2 measurements are collected, the only values that these can be compared to are for clays, to which CCR material is sand to silt. The third method, N_{kt}, is a published parameter compared to the first two, but still has problems, in addition to the fact that the comparison can only be made to clay factors. These problems are that N_{kt} is neither constant along a profile[10], nor is N_{kt} constant for a deposit[7] even in homogenous deposits. Given the expected variable condition of CCR deposits, using all of the CCR data from Figure 8, N_{kt} was found to range from 13 to 292, with an average of 51. These values are beyond the recommended values of 10 to 20[9] for clays, which raises questions for suitability of the use of N_{kt}.

SUMMARY

This paper demonstrates the importance of screening for contractive CCR materials and recommends Best Applicable Practices to determine the undrained strength of contractive CCR materials. The undrained strengths can control the stability of CCR stacks and impoundments when contractive sublayers of CCR are encountered. CCR has much uncertainty and variability even within the same unit where different responses are expected within the same layer. This variability is the result of how the CCR is deposited and is observed both in laboratory test results and published values. Therefore, a site-specific assessment following recommended Best Applicable Practices is warranted when evaluating and analyzing CCR stacks and impoundments.

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