Evaluation of the Settlement Behavior of Flyash for Ash Basin Closure Projects

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ABSTRACT

New regulations for wet ash handling operations may lead to the majority of the wet ash impoundments being closed within the next 10 years. These facilities will require surface stabilization of the flyash, and the installation of a low permeability liner or cover system. The geotechnical design of these systems requires predictions of the primary and secondary consolidation of the flyash in the impoundments. With the depths of the flyash in many ash basins ranging from 20 to 100 feet below the surface, there is a need for accurate information to estimate the amount of settlement and mitigate its impact on the performance of the closed facility. Conventional methods for estimating the amount of settlement involve developing compression coefficients and an understanding of the consolidation characteristics of the materials present through a combination of undisturbed Shelby tube sampling and laboratory testing. These tests rely heavily on the drilling crews and laboratories to obtain and test high-quality undisturbed samples of saturated, moisture sensitive and non-cohesive flyash in a consistent manner. Due to the difficulties associated with sampling and handling of wet ash, the results may be inconsistent and/or may represent only a discrete portion of the deposition relative to the total thickness of the compressible fly ash materials. Recent developments with various in-situ testing methods indicate that the cone penetrometer (CPT) or the flat blade dilatometer (DMT) may provide a cost effective method to obtain frequent measurements of the behavior of saturated flyash impoundments. These in-place measurements may allow representative estimates of actual settlement that may occur in a saturated flyash impoundment as a result the proposed closure. This paper and presentation will contain a summary of design information obtained from current flyash impoundment closure projects. In addition, a comparison of settlement predictions based on results from both laboratory and insitu test methods will be presented to illustrate settlement computation methodologies for impounded flyash materials.

INTRODUCTION

The geotechnical design of ash basin closure projects requires that representative estimates of the amount of settlement be obtained. The current “state of the practice” involves obtaining undisturbed Shelby tube samples of wet ash samples and conducting laboratory consolidation testing. These methods rely heavily on the skills of the drilling crews and laboratories to obtain, transport and test a limited number of samples of the ash basin profile. These limited number of samples are used to represent a discrete portion of the wet fly ash profile relative to the total thickness of the compressible fly ash materials. It is not uncommon for the flyash samples to become disturbed in the sampling, transport and preparation process in a manner that yields a non-representative estimate of the amount of settlement.

As more fly ash basins are closed at coal combustion plants the importance of developing accurate estimates of the final cover settlement will increase. Some of the final cover components that can be influenced by total settlement and/or differential settlement of the saturated fly ash materials include:

- The slope of the stormwater management channels and the drainage system piping;
- The slope and positive drainage of the final cover as it pertains to the grading design;
- Connection to existing stormwater management structures including sumps, stormwater outfalls, and perimeter dam embankments;
- Minimum regulatory requirements for the final cover slopes that are necessary to reduce infiltration and provide positive drainage of the stormwater.

In addition to an innovative approach for estimating the settlement of fly ash, this paper offers useful information about the immediate settlement and near surface stabilization of soft/wet fly ash under a surcharge load. This information, when properly understood and applied, can be important for the design and construction of the final cover system. When a surcharge load is applied to the surface of saturated fly ash material the pore water initially supports the load and no compression or settlement takes place. This is consistent with the principles of effective stress of fine particle soils and “soil like” materials such as fly ash. Over time this excess pore water pressure is able to dissipate and the consolidation process or settlement of the fly ash material takes place as the water content decreases. The rate at which the porewater is removed and the volume of the fly ash decreases is dependent on the stress that is applied by the surcharge load, the permeability of the fly ash and the drainage conditions beneath and in the near vicinity of the surcharge load. As the excess porewater pressure dissipates and the saturated fly ash densifies, there is a noticeable increase in the stability of the near surface fly ash, and the ability of the saturated ash basin to support the final cover soils.

Until recently it was not possible to obtain readings of the rate at which the excess porewater pressure dissipates in a surcharge loading condition over very soft, and saturated fly ash. This was due to variety of circumstances including a concern for safety, the need for special equipment and geosynthetics, and/or the potential of losing heavy equipment in unstable areas as the surcharge load was placed over the soft/saturated fly ash materials. The following sections provide some practical examples of how soft/saturated fly ash materials can be safely loaded, access roads constructed, and the rate of stabilization can be measured using in-situ porewater pressure reading devices. Of course it should be noted that the site specific drainage conditions, and near surface flyash materials are expected to vary from site to site. The potential for variable site conditions require interpretation by skilled contractors and experienced geotechnical engineers. At the same time the information included in this paper can provide useful principles and some general guidelines, for determining ***how and when saturated/soft fly ash stabilizes*** under the initial surcharge loading conditions.

ESTIMATING THE SETTLEMENT OF SATURATED FLY ASH

A critical part of the design of any final cover system is determining the amount of primary and secondary settlement that occurs during and after the installation of the final cover materials. The depth of the fly ash in most ash basin ranges from 20 to 100 feet below the surface, with the greatest thickness of the compressible materials typically being located in the center of the basin.

This section describes the different methods available for predicting the amount of settlement in a typical, wet processing fly ash basin.

Conventional Methods for Predicting Settlement of Fly Ash

A review of the available literature indicates that there are very few studies on the settlement behavior of saturated, impounded fly ash materials. (3) The conventional method for estimating settlement of fly ash materials typically involves the following step-by-step process:

1. Conduct standard penetration test (SPT) borings to identify the compressible fly ash layers and obtain samples.

2. Attempt to obtain undisturbed Shelby tube samples of the compressible fly ash layers.

3. Transport the undisturbed samples to the laboratory and extract specimens of the compressible fly ash layers.

4. Test the fly ash specimens in a conventional oedometer consolidation test device according to ASTM D2435.

5. Determine the results of Compression index, Cc, Recompression Index, Cr, and the Consolidation Coefficient, Cv for the fly ash specimen that was tested.

6. Determine the initial void ratio and other input parameters using a combination of field measure and laboratory derived methods.

7. Develop a representative soil/fly ash profile for the ash basin, and calculate the amount of settlement for each layer using the lab results and the following relationship:

$$\triangle \mathrm{H} = \frac{C_r}{1+e_0} H \log\left(\frac{\sigma'_{zc}}{\sigma'_{z0}}\right) + \frac{C_c}{1+e_0} H \log\left(\frac{\sigma'_{zf}}{\sigma'_{zc}}\right)$$

Difficulties with the Field Sampling of Fly Ash

One of the main difficulties that is encountered by geotechnical engineers and drillers is obtaining a representative sample of fly ash material that is saturated, non-cohesive and has relatively low strength. Even if a sample is obtained it is often difficult to get the sample to the surface and transported to the laboratory for testing. Figures 1 and 2 are examples of typical disturbance that can occur during the field sampling of saturated fly ash samples.

Figure 1: “Undisturbed” Fly Ash Sample
Evidence of Vertical Mixing

Figure 2: “Undisturbed” Fly Ash Sample
Evidence of Compression During Sampling

Difficulties with Sample Preparation and Testing

As many geotechnical engineers and soils laboratory technicians have experienced, it is often very difficult to get a sample of low strength, non-cohesive soils or fly ash materials into the consolidation test device. The typical sample for consolidation testing is less than 1 to 2 inches in height, and information developed from the lab testing is often used to represent several feet of a compressible fly ash layer. Some of the potential sources of error that may occur during the sample preparation and consolidation testing process for fly ash include:

- Selecting a representative sample for testing from a variable and/or heterogeneous undisturbed field sample;
- Inserting a sample with an irregular cross section into a test mold can cause additional disturbance;
- Laboratory loading conditions that do not accurately model the conditions that will be experienced during construction;
- Computing the initial void ratio, e_o for a fly ash sample with a lower specific gravity than what is typical for most fine-grained soils. (3)

Typical Ash Basin Profiles, Discrete Samples and Settlement

A typical ash basin profile includes a wide range of density and in-place moisture content of the fly ash. In general, fly ash slurry from the coal combustion process is placed using wet disposal methods where the ash is deposited in the ash basins and allowed to settle over time. The heavier bottom ash particles tend to settle near the slurry discharge pipe, and the lighter fly ash settles in thin layers across the ash basin. The fly ash in the lower portions of most ash basins consolidates under its weight, and overburden stress applied by subsequent fly ash layers. As the ash basin fills portions of the fly ash will break the water surface, and the surface will dry and create a surface “crust layer”. These “crust layers” range in thickness from several inches to greater than 10 feet. The long term result is an ash basin with three distinct layers of differing degrees of compressibility, in-place density, moisture content, and potential for settlement:

> **Surface Layer or Crust Layer:** Tends to be 1 foot in thickness to greater than 10 feet in thickness with relative low compressibility and settlement potential compared to the underlying layers.

Middle Layer – High Moisture Content and Compressible: Can range in thickness from several feet to up to 70 feet in the center of the deeper ash basins. The middle layer tends to have the high moisture content, and relative high compressibility as compared to the Surface and Lower layers.

Lower Layer – Lower Moisture Content and Less Compressible: Located at the bottom of the ash basin, these layers can range in thickness from several feet up to 20 feet depending on the overburden stress created by the over lying fly ash layers.

One difficulty that is encountered when estimating the settlement in a ponded ash basin is obtaining sufficient samples of the different types of fly ash at a representative moisture content and in-place density. The most compressible layers are often in the middle of the ash basin under the decant and process water. This requires access roads and/or shallow draft barges to access the test locations. The less compressible layers can be located in different parts of the ash basin and are often comprised of coarser particle bottom ash, fly ash or a mixture of both materials. Using discrete samples and laboratory tests from a limited number of test borings can result in the unintended consequence of predicting settlements that are much higher than those that would experienced during an actual closure construction. The inherent heterogeneity of most ash basins, and the difficulties associated with using conventional drilling and laboratory tests suggest that other methods would be useful for obtaining more represent estimates of amount of settlement. It is the main author's experience that more representative settlement estimates for fly ash can be obtained using a combination of both conventional and in-situ test methods.

IN-SITU TEST METHODS FOR ESTIMATING CONSOLIDATION

As indicated above, recent developments with the various in-situ test methods suggest that the using the cone penetrometer (CPT) or the flat blade dilatometer (DMT) may provide a cost effective method for obtaining more frequent measurement of the layers in saturated fly ash impoundments. Measurements of the variable layers of compressible fly ash at more frequent intervals result in more representative predictions of the amount of settlement that would be experienced by a final cover system and/or embankment constructed over a saturated ash basin. The following sections describe how the CPT and DMT were used to estimate settlement on a confidential ash basin closure design project. The subject ash basin had the following design requirements and fly ash characteristics:

Area of Ash Basin:	Approximately 35 acres
Minimum Thickness of Ash:	5 feet
Maximum Thickness of Ash:	80 feet
In-place Wet Density:	70 to 125 pcf
In-place Moisture Content:	20 to 50 percent
Final Cover Material:	Combination of soil cover and geomembrane – 3 to 10 feet thick
Types of Ash Material:	Predominately fine grained fly ash, some bottom ash near discharge pipes, and a mixture of sections with a dry crust and soft/saturated fly ash at the surface.

Drilling Access Roads and Initial Pore Water Pressure Measurements

To be able to access the test locations with the greatest thickness of soft and saturated fly ash required the construction of access roads. These access roads were constructed over wet sections of the fly ash basin using a geogrid stabilization layer and bottom ash to model the conditions that would be encountered during construction. The soft and highly compressible fly ash materials at the surface of the ash basin were instrumented with vibrating wire (VW) pore water pressure transducers. The transducers were placed after the geogrid stabilization layer, and prior to placement of the bottom ash for the access roads to provide safe access for personnel and construction equipment. This innovative approach to access road construction provided the design team the following:

- Practical guidelines and the demonstration of methods on how the final cover could be constructed over soft and saturated ash materials;
- Information about shear strength of the near surface fly ash materials prior to loading and after stabilization with a surcharge load;
- Information and "real time" measurements of the time rate of settlement and dissipation of excess pore water pressure in a large scale construction demonstration project over saturated fly ash;
- Demonstration of construction methods and health and safety protocols for placement of the final cover materials over the soft and saturated fly ash subgrade.

The figures and photos demonstrate the approach that was used to obtain valuable geotechnical design parameters during the drilling access road construction.

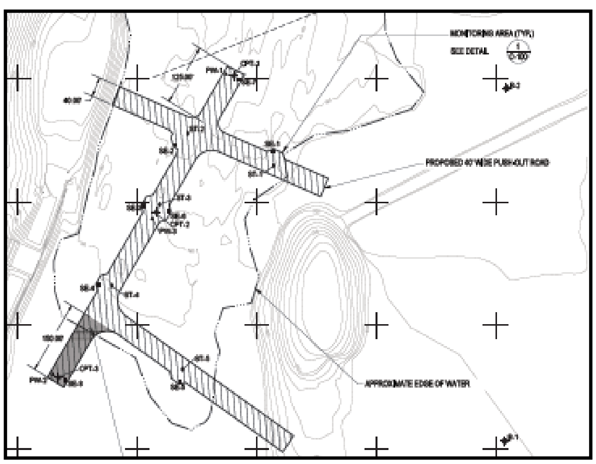

Figure 2A: Access Road Diagram

Figure 2B: Porewater Pressure Device Calibration

Figure 2C: Porewater Pressure Transducer in Protective Sleeve

Figure 2D: Remote Transducer Readout Continuous Data Collection

Figure 2E: Porewater Pressure Device Installation

Figure 2F: Access Road Construction

The porewater pressure readings were obtained after placement of the surcharge loads, at 1 to 10 minute intervals, for a period of several days to several weeks. The porewater pressure readings and observations of the surcharge load placement indicated the following:

- Bottom ash and flyash can be used for construction over saturated ash basins if geogrid stabilization layers are used and/or lift thickness is carefully controlled.
- Triaxial Geogrid by Tensar provides an effective stabilization layer that allows placement of material in 3 to 6 foot lifts.
- Most of the initial ***porewater pressure dissipated in less than 12 hours*** after placement of a surcharge load and subsequent lifts of material.
- Contractor skills and experience when working over soft and saturated ash materials are essential for a successful ash basin closure project.

The following figure shows how the porewater pressure readings we correlated to a photo log of the surcharge loading process. The record of the sequence of construction of the access road construction and surcharge load placement provided the design team valuable information about: 1) the placement and application of the geogrid stabilization layer; 2) how quickly the final cover soil could be placed; and 3) the minimum lift thickness that is required.

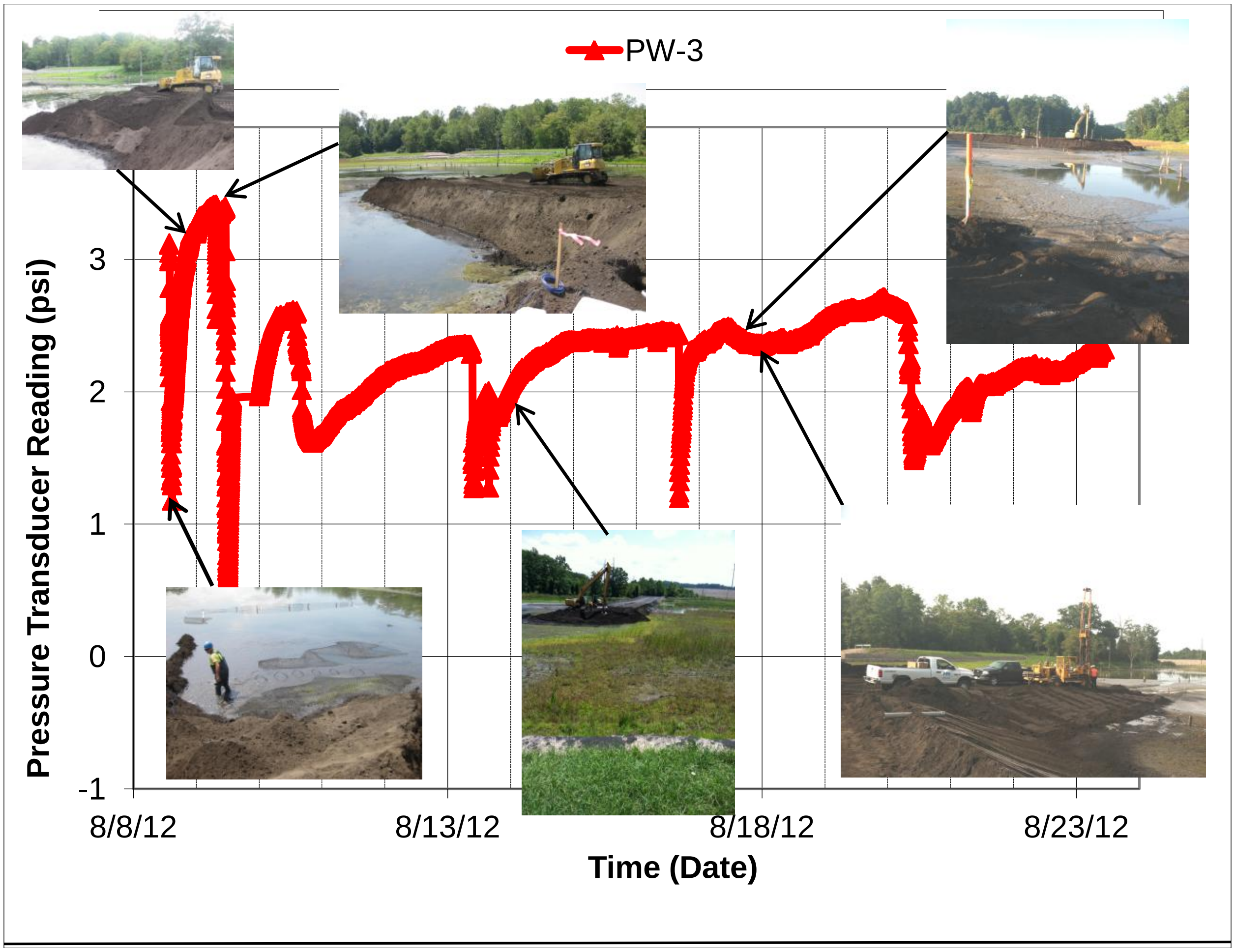

Figure 3: Typical Porewater Pressure Readings
Load Sequence and Photo Log

Cone Penetrometer Method

The cone penetrometer (CPT) was used at the subject site to provide information about the fly ash material properties including: undrained shear strength, drained friction angle, total density, probable soil classification, constrained modulus, and fines content. In addition to the static material properties, the CPT was also used to provide a measurement of the in-place shear wave velocity for the seismic stability analysis. The CPT results at the subject site indicated the following:

- The predominant soil behavior or type in the upper 10 feet of the coal ash in the basin was characterized as a sandy SILT or silty SAND material that is moisture sensitive;
- From 10 to approximately 70 feet below the surface of the ash basin the predominant soil behavior type of the coal ash was as a silty CLAY or clayey SILT material.
- The shear wave velocity data obtained from the CPT probes indicated a shear wave velocity ranging from 20 m/s to 110 m/s.

Flat Blade Dilatometer Method

The flat blade dilatometer (DMT) is recognized by many practitioners of geotechnical engineering as providing accurate estimates of total settlement for problem fine grained soils -- most notably for moisture-sensitive silt sized particles (J. Schmertmann, 1985 and S. Marchetti, P. Monaco, M. Calabrese & G. Totani, 2004). Since coal ash is primarily a silt-sized particle the DMT was used to predict total settlement and provide an indication of the in-place strength of the saturated fly ash materials.

The basic DMT equipment consists of a stainless steel blade 96 mm wide and 15 mm thick with a sharp edge and a 60 mm diameter stainless steel membrane centered on and flush with one side of the blade. A syringe activated pressure-vacuum system permits the routine field calibration of each membrane and horizontal activation and loading of the in-place soils. A combination of nitrogen gas and electrical line extends through the rods and down to the blade from a surface control and pressure readout box. The horizontal pressure readings of the activated DMT blade were obtained at three different locations at the subject site to determine the following:

- The measurement of the elastic modulus of the fly ash in an undisturbed condition allowed correlation of the settlement characteristics of saturated fly ash to those of similar silt-sized materials;
- Relative effective stress of the materials based on the depth below the water table, the in-place strength characteristics, and the proposed loading conditions;
- An indication of the soil behavior and strength properties based on correlation to the DMT data tables;
- Small incremental estimates of the probable settlement that in turn provides a more accurate estimate of the total settlement in the highly compressible, saturated and softer fly ash layers.

Advantages of the Insitu Methods for Saturated Fly Ash Testing

One of the difficulties associated with the use of the Standard Penetration Test (SPT) for the testing of saturated fly ash samples is that the silt-sized particles are subject to disturbance by the dynamic penetration of the sampling method. SPT sampling of saturated fly ash material will frequently result in N-values that are lower than the actual in-situ subsurface conditions. In-situ test methods such as the CPT or the DMT provide the following advantages for fly ash material testing:

- The impact of the disturbance on the saturated fly ash is minimized;
- These methods provide an excellent correlation to the in-situ horizontal stress of materials without the disturbance dynamic sampling methods;
- The elastic modulus provides an effective method for computing the settlement of silt-sized, saturated materials;
- In general the estimated settlement computed using the DMT correlates well to field measurements of the actual settlement.

COMPARISON OF RESULTS FOR ESTIMATING SETTLEMENT

The purpose of this section is to provide a comparison of the results for estimated settlement that were developed for the subject site and projects with similar material and subsurface conditions.

Comparison of Conventional to Dilatometer Settlement Estimates

The settlement for the subject site was computed using a combination of conventional consolidation test results, and the DMT results using the elastic modulus. The results from the settlement evaluation at the subject site indicated the following:

- That the Standard Penetration Test (SPT) can be useful for locating the soft, compressible strata for obtaining undisturbed samples for conventional laboratory testing;
- That in-situ tests such as the flat blade dilatometer (DMT) or the cone penetrometer (CPT) provide more consistent results for highly saturated fly ash materials. This mainly due to the lack of sample disturbance.
- That the SPT provides non-represent, and low N-values for highly saturated fly ash materials.
- That the DMT and CPT are useful for obtaining in-place measurements of the very low strength fly ash materials that typically cannot be sampled or tested using conventional geotechnical test methods.

Summary of Settlement Evaluation – Confidential Site No. 1					
Boring Location	**Evaluation Method**	**Thickness of Compressible Layer (feet)**	**Constrained Deformation Modulus - M (TSF)**	**Range of SPT N-Values**	**Total Estimated Settlement (inches)**
B-1	Conventional Methods	50	NA	1 to 23	7.2
B-2	Conventional Methods	80	NA	1 to 12	8.1
DMT-1	Dilatometer Schmertmann's Ordinary Method	75.4	9 to 698	NA	3.4
DMT-2	Dilatometer Schmertmann's Ordinary Method	77.8	2 to 368	NA	7.0
DMT -3	Dilatometer Schmertmann's Ordinary Method	38.7	1 to 877	NA	4.9

Notes: 1) The SPT borings, B-1 and B-2, were located in an area with a 10 foot dry crust underlain by a saturated compressible layer of fly ash. Several of the saturated, soft layers of fly ash in B-1 and B-2 could not be sampled due to the low strength, and high moisture content of the in-place materials.
2) The DMT probes were located in an area with no dry crust, and a surface layer of saturated fly ash.

Comparison of the Settlement Estimates to Field Measurements

In addition to developing estimates of the amount of settlement using computational methods, the design team also installed settlement plates at locations near the DMT and CPT test locations. **As of the writing of this paper the long term settlement measurements are still in the process of being compiled and evaluated.** The pictures below demonstrate how the settlement plates were installed over the saturated flyash materials.

Figure 4A: Settlement Plate Installation

Figure 4B: Completed Settlement Plate Long term Monitoring

Observations in the field at the time the drilling access roads were installed, indicated that the most of the settlement in the near surface fly ash materials occurred in the first 24 hours after the surcharge loads were placed. This initial settlement was difficult to measure with the standard settlement plates, but the field observations indicated that 3 to 12 inches of settlement occurred in the soft saturated fly ash materials as the initial surcharge loads were placed. These field observations are consistent with the porewater pressure measurements shown in previous figures. The first three months of settlement measurements indicated the following:

- The settlement after 3 months, for a surcharge load of 10 feet or less, was less than a 1/10 of a foot or approximately 1 inch at all the locations tested;
- Additional surcharge load placed above the initial 10 foot surcharge load will allow settlement to start again if placed in an area without a thick dry crust of fly ash;
- Vibrations from construction equipment, the placement and compaction of new lifts of soil cover material can cause surface instability and settlement in the underlying soft ash layers.

In addition, a review of the DMT settlement computation spreadsheet for the project indicated that almost 70 percent of the settlement will occur in layers where the constrained deformation modulus as measured by the DMT or the CPT test is less than 100 tons/SF. These highly compressible and soft/saturated layers are virtually impossible to sample with a conventional Shelby tube equipment and test in the lab, but they are able to be measured in the field using in-situ test methods. The large amount of settlement that is experienced in these soft/saturated layers confirms the importance of obtaining in-situ constrained modulus information using the DMT and/or CPT test devices.

Summary and Conclusions:

Based on the results of the estimated settlement computations at the subject site the flat blade dilatometer (DMT) and cone penetrometer (CPT) appear to offer a cost effective alternative to conventional methods for obtaining accurate and representative results for estimated settlements. In addition, a comparison of the settlement estimates from a site with similar subsurface and loading conditions indicates that the elastic modulus provides an excellent method for predicting the long term settlement of the saturated and more compressible layers present in most fly ash basins. Additional testing and field verification is still required, but this study indicates that in-situ testing methods, when correlated to lab tests, offer an effective method for predicting the amount of long term settlement of saturated fly ash materials.

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