Investigation of Dynamic Liquefaction Potential of Impounded Class F Fly Ash

THESIS

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By

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Abstract

The susceptibility of class F fly ash in coal burning power plant retention ponds to earthquake induced liquefaction is a concern of both regulators and facility owners. Due to planned closures of selected ponded fly ash storage reservoirs, the liquefaction potential of the site materials must be investigated. Cyclic loads can develop excess pore pressures within saturated soils, leading to liquefaction. This phenomenon can be characterized as the conversion of a stable soil structure to an unstable liquid form. According to ASTM D 5311-04, Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil, initial liquefaction is defined as when the peak excess pore-water pressure equals the initial effective confining pressure. The objective of this study was to determine the susceptibility to earthquake induced liquefaction of impounded fly ash at coal burning utility plants located in the Midwest United States. In order to accomplish this objective, four parameters were studied to determine their effect on liquefaction resistance. These four parameters were 1) cyclic stress ratio, 2) effective confining stress, 3) relative density, and 4) pH levels.

Due to the difficulty of obtaining in-situ samples, reconstituted specimens were created by wet pluviation. Specimens from seven different power plant locations were consolidated at a range of effective confining stress ($\sigma_3'$) from 10 to 40 psi and allowed to saturate. Once saturation was achieved, a cyclic triaxial test was performed with a
programmed cyclic stress ratio (CSR) for each specimen. CSR values for the tests ranged from 0.1 to 0.4. Results of each test were plotted as the number of cycles required to induce liquefaction ($N_{\text{liq}}$) versus the stress, strain and excess pore water pressure in the specimen. Cyclic strength curves displaying CSR and $N_{\text{liq}}$ were created for each sample. Plots of $N_{\text{liq}}$ against $\sigma_3'$ were developed to determine the correlation between liquefaction resistance of ponded fly ash and effective confining stress. Minimum and maximum realizable densities were determined for one fly ash sample. Specimens were created with a range of relative densities. Plots of relative density versus $N_{\text{liq}}$ were created. The pH of each sample was measured. The correlation between the pH of the specimens and $N_{\text{liq}}$ was determined.

Upon completion of this research effort, it was concluded that as CSR increased, the number of cycles to liquefaction decreased for all seven fly ash samples. No definitive conclusion was reached of the correlation between $N_{\text{liq}}$ and $\sigma_3'$ of the fly ash specimens. It was observed that as the relative density of the fly ash specimens tested increased, liquefaction resistance increased. The effect of pH was determined on the liquefaction potential. It was concluded that at a high CSR (CSR = 0.4) pH has a significant effect on the resistance to liquefaction of fly ash. Specimens with a pH value of 8 or greater liquefied sooner than specimens with a pH value of less than 8. For specimens tested between CSRs of 0.2 and 0.3, pH also affected the liquefaction resistance, but not as profoundly as when the CSR was higher. The trend of increasing pH values causing a decrease in $N_{\text{liq}}$ was seen in specimens tested at CSRs between 0.2
and 0.3. For specimens tested at a low CSR (CSR = 0.1) it appears that liquefaction resistance is independent of pH.
Dedication

This document is dedicated to my family, especially for my Nana. She raised me into the goal-oriented man I am today. She always said the path was more rewarding than the destination. I also dedicate this document to my friends and my loving girlfriend Stephanie for all of their support. Their ability to ease my mind from work helped me greatly. I could not have persevered through my studies without them.
Acknowledgments

I express my deepest gratitude to my academic and research advisors and mentors, Dr. Tarunjit Butalia and Dr. William Wolfe. Their support and guidance assisted me greatly in this research effort. I would like to thank Mr. Pedro Amaya for serving on my advisory committee, and providing his time and commitment in this study. I would also like to thank American Electric Power for providing the fly ash materials and support for this research study.
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Chapter 1: Introduction

1.1 Background

Coal burning power plants produce a number of byproducts during the electricity generation process. These byproducts or coal combustion residuals (CCRs) include fly ash, bottom ash, and flue gas desulfurization (FGD) material. Historically, the most common method to store these CCRs is to place them in water filled retention ponds\(^1\). During this research only the liquefaction potential of ponded fly ash was studied because fly ash is the main component in most CCR wet disposal facilities.

Little research has been performed regarding the liquefaction potential of ponded fly ash due to cyclic loading events, such as earthquakes. This thesis examines the susceptibility to dynamic liquefaction of ponded fly ash from coal burning power plants located in the Midwest United States.

The resistance of a soil to dynamic liquefaction can be measured by its cyclic resistance ratio (CRR). The CRR of natural soils such as sands and silty sands can be predicted based on previous research\(^8,9\). However, the same relationships used to determine CRR of natural soils may not correlate well to CCRs such as ponded class F fly ash. Therefore specific laboratory experiments are needed on ash samples to determine the CRR of ponded fly ash.
This thesis presents an extensive research regarding the liquefaction resistance of class F fly ash from power plants in the Midwest United States. These power plants are located in Winfield, WV; Louisa, KY; Madison, IN; Cheshire, OH; Beverly, OH; New Haven, WV; and Lawrenceburg, IN. Fly ash was collected from the fly ash reservoirs at each power plant. These fly ash reservoirs contain only fly ash as no bottom ash was placed in these reservoirs. Table 1-1 provides the sample name that correlates with the fly ash location.

Table 1-1 Fly Ash Sample Designation with Location

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Sample Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Winfield, WV</td>
</tr>
<tr>
<td>BS</td>
<td>Louisa, KY</td>
</tr>
<tr>
<td>CC</td>
<td>Madison, IN</td>
</tr>
<tr>
<td>G</td>
<td>Cheshire, OH</td>
</tr>
<tr>
<td>MR</td>
<td>Beverly, OH</td>
</tr>
<tr>
<td>S</td>
<td>New Haven, WV</td>
</tr>
<tr>
<td>TC</td>
<td>Lawrenceburg, IN</td>
</tr>
</tbody>
</table>

1.2 Purpose

Due to planned closure of several fly ash reservoirs, and the repurposing of the reservoir sites, the engineering properties of ponded fly ash need to be investigated. One of the properties that must be determined is liquefaction susceptibility. This thesis investigates the effects of cyclic loadings on ponded fly ash from coal burning power plants located in the Midwest United States. Past research has focused on the liquefaction resistance of sands and silty sands, but the study of liquefaction resistance on CCRs is still in its infancy.
Pending CCR regulations may lead to the closure of existing wet fly ash storage reservoirs. Once a pond is closed, no additional fly ash will be added to the reservoir. Liquefaction susceptibility due to dynamic events, such as seismic occurrences, need to be determined upon closure and before alternate development can be performed at the site of the existing reservoir.

1.3 Research Objectives and Approach

The primary objective of this research was to determine the dynamic liquefaction resistance of class F ponded fly ash. In order to accomplish this objective, four parameters were examined to determine their effect on liquefaction resistance; 1) cyclic stress ratio (CSR), 2) effective confining stress ($\sigma_3'$), 3) relative density (Dr), and 4) pH levels.

Samples were obtained from seven fly ash reservoirs in the Midwest United States and sent to The Ohio State University’s (OSU) Soil Mechanics Laboratory. Specimens were created from the gathered samples using a wet depositional process to simulate the method employed at the power plants for placing fly ash into the reservoirs. In order to study the effect of CSR, $\sigma_3'$, and pH levels on liquefaction resistance, specimens underwent cyclic triaxial laboratory tests at different CSRs and $\sigma_3'$ selected to represent possible site specific cyclic stresses and effective confining stresses experienced by material in the ash pond. During specimen construction and testing the following parameters were measured and recorded; moisture content, dry density, pH level, B-value, pore water pressure build-up, cyclic stress, and axial strain. The number of cycles
to liquefaction ($N_{\text{liq}}$) is used to determine the resistance of liquefaction of the fly ash due to cyclic loads. This term provides the total number of cycles the applied loading as completed before the material liquefies. In order to determine the effect relative density has on liquefaction resistance, minimum and maximum realizable densities ($D_{\text{r min}}$ and $D_{\text{r max}}$) of one fly ash sample were measured. Specimens from this sample were created with a range of relative densities. Cyclic triaxial tests were performed with a constant CSR and $\sigma_3'$ to study the parameter of relative density.

Plots of the following correlations were created to understand their effect on dynamic liquefaction resistance of ponded fly ash; 1) $N_{\text{liq}}$ versus CSR (with respect to sample location), 2) $N_{\text{liq}}$ versus CSR (with respect to $\sigma_3'$), 3) $N_{\text{liq}}$ versus Dr, and 4) $N_{\text{liq}}$ versus pH.

1.4 Thesis Outline

This thesis is comprised of five chapters which include important background information, motivation, and the objectives of the research in Chapter 1. Chapter 2 provides a comprehensive review of related previous research. Emphasis is on results and conclusions of past studies regarding dynamic liquefaction. The design of the laboratory experiments are discussed in Chapter 3. Explanation of the experimental set up and testing is also presented in that chapter.

Chapter 4 presents the results of the experimental program. Plots of the test results are presented in Chapter 4 as well. Chapter 5 provides conclusions and summary of the research and its objectives. Problems that arose during testing and
recommendations for future research interest are also detailed in Chapter 5. Appendix A provides data and plots relating to cyclic triaxial tests of specimens created at in-situ densities, and Appendix B provides data and plots relating to cyclic triaxial tests of specimens created with range of relative densities.
Chapter 2: Literature Review

Numerous researchers and studies have focused on the phenomenon of liquefaction\textsuperscript{8, 9, 11, 15}. Seismic behavior addressing saturated soils, from sand to clay, has been evaluated extensively. A fundamental understanding of how these soils behave during seismic events has already been developed. However, it is uncertain that the understanding of the liquefaction potential of these soils is similar to the behavior of ponded fly ash during seismic events. Further studies are needed to develop the appreciation of seismic behavior of CCRs such as fly ash. Five relatively recent studies that are closely related to the current thesis topic are addressed in this chapter. A brief discussion of these studies along with figures and conclusions are provided.

- Bray and Sancio (2006)\textsuperscript{11}: During the 1999 Kocaeli earthquake in Adapazari, Turkey, fine-grained soil apparently liquefied, even though these soils were deemed not susceptible to liquefaction according to the Chinese criteria\textsuperscript{12}. Tests performed by Bray and Sancio showed that rather than basing liquefaction potential on particle size, susceptibility should be based on the amount of fines and results of Atterberg limits. Bray and Sancio concluded that silty soils are vulnerable to liquefaction if the water content ($w_c$) to liquid limit (LL) ratio is equal to or greater than 0.85 ($w_c/LL \geq 0.85$), and the soil has a plasticity index...
(PI) of 12 or less (PI ≤ 12). Any soil with a plasticity index greater than 12 and less than or equal to 20 (12 < PI ≤ 20) with a liquid limit ratio equal to or greater than 0.8 (w_c/LL ≥ 0.8) has the potential to liquefy and should be tested in the laboratory. Soils with PI > 20 were considered too clay-like to be prone to liquefaction. Figure 2-1 displays the above information along with the tests that Bray and Sancio performed.

![Seismic Liquefaction Potential for Fine-Grained Soils](image)

**Figure 2-1** Seismic Liquefaction Potential for Fine-Grained Soils

- Jakka, Datta, and Ramana (2010): In this study, fly ash from the ash ponds of two different thermal power plants in India was investigated for seismic liquefaction potential. The behavior of fine and coarse grained specimens under loose and dense conditions was studied. Dr values for loose specimens were in the range of 27 to 35%, while Dr values for dense specimens were between 70 to
Cyclic triaxial tests were conducted on the fly ash specimens with varying CSR and \( \sigma_3' \) values. The study concluded that: (i) an increase in relative density will lead to an increase in liquefaction resistance; (ii) resistance to liquefaction decreases as the confining pressure increases; and (iii) specimens with a large amount of fines experienced low resistance to liquefaction. The comparison of cyclic strength curves for coarse and fine ash samples in loose and dense conditions can be seen in Figures 2-2 and 2-3, respectively. The designation of the specimen names are as followed; BP: fly ash from Badarpur, IP: fly ash from Indraprastha, YS: sands from Yamuna River, F: fine ash, C: coarse ash, LS: loose state, DS: dense state. According to Jakka et al., it is essential to determine the liquefaction susceptibility of all fly ash samples before engineering projects are performed with the fly ash.

**Figure 2-2** Seismic Liquefaction Potential of Coarse Fly Ash Samples in Loose and Dense States

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18. Amaya, et al. (2013): Regulations in the utility industry may lead to closure of several existing wet fly ash storage reservoirs in the Midwest United States. Upon closure, dynamic and static liquefaction susceptibility of the ponded fly ash must be evaluated. Four American Electric Power (AEP) facilities were investigated for liquefaction potential of their fly ash storage reservoirs. Since the closed fly ash reservoirs will be graded and fill placed on top of the ponds, the susceptibility of the ponded fly ash under dynamic liquefaction was evaluated. The CRR of the fly ash was determined from cyclic triaxial tests on reconstituted water pluviated specimens. For the reservoirs studied it was determined that dynamic liquefaction is unlikely. However, it was seen that the characteristics of each fly ash reservoir are different, and the authors suggested that site specific...
sampling and testing be done to evaluate the resistance to liquefaction of fly ash reservoirs.

- Santamarina (2012): This report presents an extensive collection of tests and results detailing the engineering properties of ponded fly ash, static liquefaction behavior, and guidance for the characterization of ponded fly ash and fly ash storage facilities. Samples were collected from several power plant sites in the United States; most were recovered from ponded fly ash storage reservoirs. Tests that were done on the fly ash samples included scanning electron micrographs (SEM), grain size distribution analysis, specific gravity, pH, Atterberg limits, credible minimum and maximum densities, consolidation, and other geotechnical experiments. Santamarina discovered that occluded and internally connected voids, and voids between particles in fly ash can dramatically affect the consistency in obtaining the specific gravity. These voids can be seen in the SEM images in Figure 2-4. This directly affects calculations on void ratio, porosity, and degree of saturation. These in turn affect any conclusions made on the properties and behavior of the tested fly ash. It was suggested that results that do not rely on void ratio be used to more accurately classify ponded fly ash.
Permeability, pore water pressure dissipation, and strength have been shown to be affected by the segregation of fines within the fly ash, producing anisotropic properties. Santamarina also concluded that samples with a relatively high pH, values greater than 9.5, can undergo early diagenetic cementation. This can increase the contractive tendency of the ponded fly ash. Minimum and maximum realizable densities were constructed to provide a more robust parameter of the susceptibility of static liquefaction of ponded fly ash. It was determined that low in-situ relative densities are a strong indicator of possible material failure under normal or shear loadings. Samples created using wet pluviation, similar to how fly ash is deposited in reservoirs, exhibited relative densities greater than 60% which can lead to dilative properties. Relative density values and behavior of the tested fly ash are found in Figure 2-5. Similar to the other studies referred to, Santamarina suggested that pond-specific characterization be evaluated to ensure correct fly ash properties and estimation of liquefaction potential. Even though
this report only provided data relating to static liquefaction, many insightful results and conclusions were implemented in this thesis.

![Relative Density Diagram](image)

**Figure 2-5** Behavior of Fly Ash Specimens Tested with Varying Relative Densities

- Boulanger and Idriss (2004): This report developed guidelines and analytical procedures for the evaluation of the potential for liquefaction of low-plasticity silts and clays during seismic events. Boulanger and Idriss determined that an improvement in the understanding of liquefaction susceptibility is needed for low-plasticity silts and clays that are near the transition between “sand-like” and “clay-like”. In their review, they define “liquefaction” in “sand-like” silts as being characterized by the onset of high excess pore water pressures and large shear strains during undrained cyclic loadings, while the term “cyclic failure” also is characterized by the onset of high excess pore water pressures, but in “clay-like” fine-grained soils. Standard Penetration Tests (SPT) or Cone Penetration Tests (CPT) are recommended to evaluate the liquefaction potential of “sand-like” fine-grained soils. SPT-CPT/CRR correlations can be found in the Seed-Idriss simplified procedure for evaluating earthquake-induced stresses. To evaluate the cyclic failure potential for “clay-like” fine-grained soils, Boulanger and Idriss
suggested three different approaches. The cyclic strength of these soils may be determined by: 1) the direct measurement of CRR in laboratory testing; 2) measurement of the in-situ or laboratory shear strength, $s_u$, then combined with an empirical factor to predict the CRR, or 3) estimate the CRR based on the stress history profile. Case histories of ground failure in fine-grained soils during seismic events were studied to evaluate the effectiveness of the recommended procedures for liquefaction and cyclic failure potential. Boulanger and Idress concluded that in the case histories studied, the proposed procedures were able to adequately predict the observed ground deformations.

By reviewing these five studies, it can be observed that while fly ash physical characteristics, texture, and fabric are unique, it can exhibit liquefaction behavior that is common in natural silty soils and loose sands with fines.
Chapter 3: Experimental Design

3.1 Samples

Bulk samples were collected from seven fly ash ponds of Midwestern coal burning power plants. The fly ash samples were placed in five-gallon buckets and shipped to The Ohio State University’s Soil Mechanics Laboratory. Upon arrival, the fly ash was dried in an oven at a temperature of 40\(^\circ\) C. This temperature was chosen because earlier studies have shown that a low temperature was required to prevent modifying the physical properties of the fly ash.

3.2 Experimental Tests

Cyclic triaxial tests were performed on reconstituted ponded fly ash specimens. In order to determine the effect CSR and \(\sigma_3'\) has on liquefaction resistance of ponded fly ash, specimens were created by a wet pluviation method simulating in-situ densities. CSR values between 0.1 and 0.4 and \(\sigma_3'\) values between 10 psi and 40 psi used during testing.

To determine the effect relative density has on liquefaction resistance of ponded fly ash, specimens with a range of relative densities were created. Minimum and maximum realizable densities were measured for Sample A. Refer to Chapter 3.5 for explanation of minimum and maximum realizable density procedures. Specimens
were created from this sample with desired relative densities of 25%, 50%, 75%, and 100%. To calculate the desirable dry density \( (\rho_{d_{\text{desired}}}) \) based on relative densities, the following equation was used.

\[
\rho_{d_{\text{desired}}} = D_r \times (\rho_{d_{\text{max}}} - \rho_{d_{\text{min}}}) + \rho_{d_{\text{min}}}
\]  \hspace{1cm} (3.1)

In order to concentrate on the effect of dynamic liquefaction due to relative density only, CSR and effective confining stress remained constant at 0.2 and 20 psi, respectively.

Santamarina observed fly ash samples undergo early diagenetic cementation with pH values of 9.5. The pH of each fly ash sample was measured in accordance with ASTM D5239-12 Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization\(^4\) and ASTM D1293-12 Standard Test Methods for pH of Water\(^3\). Three measurements were taken for each sample. Specimens that were created with in-situ densities and tested at \( \sigma_3' = 20 \) psi were plotted against their pH values and \( N_{\text{liq}} \) to negate any effects from relative density and \( \sigma_3' \).

3.3 Specimen Preparation

Specimen preparation and testing were performed according to ASTM D5311-04 Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil\(^5\). Reconstituted fly ash specimens were created in a laboratory through wet pluviation to recreate in-situ conditions. A lift was created by mixing 500 grams of oven-dried fly ash with de-aired and distilled water to create a slurry. Six to eight lifts were poured in a
large cylinder with an inner diameter of 5.5 in. and a length of 12 in. A lift of fly ash before water was added, and a lift of fly ash after water was added to create a slurry can be seen in Figure 3.1. The bulk sample was allowed to settle for a minimum of 24 hours.

![Figure 3-1 (a) One Lift of Fly Ash Before Added Water, (b) One Lift of Fly Ash After Added Water to Create Slurry.](image)

Five thin walled copper tubes with an inner diameter of 1.51 inches, outer diameter of 1.62 inches, and a length of 3.52 inches were pushed into the bulk sample by hand. Five specimens were extruded from the tubes and one specimen was used to determine moisture content and dry density of the bulk sample. Specimen weight, height, and diameter were recorded.

The specimens were placed on the pedestal of a triaxial cell chamber. Figure 3-2 displays the extruded specimen on the pedestal.
Porous stones were placed below and above the specimen. A latex membrane was placed around the specimen, with O-rings sealing the membrane to the pedestal and top cap. Top drainage lines were connected to the loading cap with O-rings to prevent leakage. Figure 3-3 displays the extruded specimen with the membrane and O-rings attached. The triaxial cell was filled with water and then assembled. Figure 3-4 shows an assembled triaxial cell chamber with a specimen inside.
Preparation for specimens that were created with a range of relative densities was slightly different than described above. Specimens with design relative densities greater than 75% were created using the method described previously. Formation of specimens using wet pluviation created relative densities between 70% and 90%. To achieve higher relative densities, a bulk sample was created and a confining load was applied until the desired density was reached. Specimens were then extruded and placed in a triaxial cell in the same manner as previously explained.

For specimens with a design relative density less than 75%, specimens were created using wet pluviation. However, instead of preparing a bulk sample and extruding specimens, specimens were created individually. A specific amount of fly ash based on the desired density was placed in a 1000 mL volumetric flask. The flask was half-filled with water and boiled for approximately 30 minutes. The flask was then filled completely with de-aired water and allowed to cool overnight. A split 1.4 inch mold was placed around the pedestal in a triaxial cell. A membrane was placed in the mold and an
applied vacuum allowed the membrane to open. The mold was filled with de-aired water. The flask with fly ash and water was capped and mixed thoroughly. The flask was then inverted and lowered below the water level in the mold. The cap was removed to allow the fly ash to deposit directly into the mold. The total weight of the soil transported into the mold was used to calculate the dry density. The chamber was filled with water and assembled.

Once the triaxial cell chamber was assembled, a cell pressure of 50.0 psi with a back pressure of 49.0 psi and a top pressure of 48.5 psi were placed on the specimen. This differential pressure allowed water to flow throughout the specimen during saturation. The effective pressure during saturation was 1.0 psi. A pressure transducer was attached to the top drainage line to record specimen pressure. Measurement of the pore pressure parameter $B^{5.26}$ was performed for each specimen. Saturation was deemed complete if the B-value reached a value of 0.95 or greater, or if the specimen has been saturating for longer than two weeks. Refer to Chapter 4.1 for further discussion regarding B-value.

3.4 Cyclic Triaxial Testing

Once the saturation criterion had been achieved, each specimen was consolidated under the desired effective confining stress. A CSR for the test was determined and using equation 3.2 the applied axial load was calculated. The major principal stress is labeled as $\sigma_1$ and the minor effective principal stress is labeled as $\sigma_3'$. 
Cyclic triaxial tests were performed using an MTS 55 kip hydraulic load frame. The load frame with a specimen mounted inside along with labels of other pertinent equipment can be seen in Figure 3-5.

For each test, a 1 Hz sine wave load was applied. During cyclic tests, cell pressure was held constant under undrained conditions. Pore water pressure was measured via an external 100 psi pressure transducer. Axial load applied was recorded by an external 100 lb. load cell. A linear variable differential transformer (LVDT) recorded axial displacement throughout the test. All recorded values were obtained at a

\[
CSR = \frac{\sigma_1}{2\sigma_3} \quad (3.2)
\]
sampling rate of 100 Hz. The number of completed cycles was recorded for each specimen. Using the recorded axial load and displacement, and measured specimen dimensions, stress and strain were calculated.

Specimens were tested until 1) excess pore water pressure reached the initial effective confining pressure, 2) the axial load deviated from the programmed load by more than 5%, or 3) 500 cycles were applied. Liquefaction was defined as the point during loading when the pore pressure equaled the confining stress ($\sigma_3' = 0$), or the axial load deviated by more than 5% from the programmed axial load.

3.5 Realizable Densities

According to the results of the experiments performed by Santamarina\textsuperscript{24}, void ratio and porosity are not necessarily the most suitable parameters for the characterization of fly ash due to the three types of voids within the fly ash particles; internal occluded voids, internally connected voids, and voids between the fly ash grains. These voids produce misleading values of specific gravity. As a result of the inability to accurately determine the volume of solids in the fly ash specimens, Santamarina developed methods to produce minimum and maximum realizable densities. These densities provide endpoints to compare the in-situ density of ponded fly ash in storage facilities. Relative densities of specimens created in the laboratory can be referenced to the minimum and maximum densities as well. Table 3-1 displays the six methods Santamarina used to produce realizable densities, along with the calculated nominal energy related with each method.
Based on density results, the methods named “formation under shear” and “standard compaction test” were determined to create the lowest and highest realizable densities, respectively, that can be consistently reproduced. The following procedures were used to obtain minimum and maximum realizable densities of Sample A fly ash.

- Procedure for Minimum Realizable Density – Formation Under Shear: 150 grams of oven-dried fly ash was placed in a transparent cylinder with the top open. For this study, a 1000 mL graduated cylinder was used with an inner diameter (IDc) of 2.4 in. and a length (L) of 16.0 in. While the cylinder was positioned horizontally, it was rotated on a flat surface at a rate of one rotation every 10
seconds, for at least 6 rotations. Once 6 rotations have been completed, the cylinder was slowly tilted up while maintaining rotation until the container was completely vertical. The height (h) of the fly ash in the container was measured. The lowest realizable dry density ($\rho_{d_{\text{min}}}$) was determined. Figure 3-6 provides a graphical display of the method to determine minimum realizable density.

![Graphical display of the method to determine minimum realizable density.](image)

**Figure 3-6** Method to Determine Minimum Realizable Density

- Procedure for Maximum Realizable Density – Standard Proctor Compaction (ASTM D698-07): Following the procedure described in ASTM D698-07 Standard Proctor Compaction, the highest realizable dry density ($\rho_{d_{\text{max}}}$) was determined.
Chapter 4: Results and Discussions

The objective of this thesis was to determine the liquefaction susceptibility of ponded class F fly ash. In order to accomplish this four parameters were examined; cyclic stress ratio, effective confining stress, relative density, and pH. Results from this program will assist engineers in the closure design of ponded fly ash reservoirs. These results will add further understanding to the liquefaction behavior of ponded fly ash.

4.1 Experimental Test Results Examining the Parameters of CSR and $\sigma_3'$

The effect CSR and $\sigma_3'$ on liquefaction resistance of ponded fly ash was examined by testing 84 fly ash specimens. For each sample, CSR and $\sigma_3'$ values were varied to produce an array of data points. CSR values varied within 0.1 and 0.4, while $\sigma_3'$ ranged from 10 psi to 40 psi. These specimens were created by wet pluviation simulating in-situ densities.

The results of the cyclic triaxial tests focusing on the parameters of CSR and $\sigma_3'$ are summarized in Table 4-1 through Table 4-7. The tables display the sample name, specimen name, dry density, moisture content, B-value, CSR, cyclic stress amplitude, effective confining stress, and cycles to liquefaction for all seven fly ash samples.
Table 4-1 Sample A Liquefaction Data

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dry Density (pcf)</th>
<th>Moisture Content (%)</th>
<th>B-value (%)</th>
<th>CSR</th>
<th>Cyclic Stress Amplitude (psi)</th>
<th>Effective Confining Stress (psi)</th>
<th>Cycles to Liquefaction</th>
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<td>23.65</td>
<td>87.30</td>
<td>0.100</td>
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<td>A2</td>
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<td>23.54</td>
<td>98.20</td>
<td>0.200</td>
<td>8.00</td>
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Table 4-2 Sample BS Liquefaction Data

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<th>Moisture Content (%)</th>
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<th>CSR</th>
<th>Cyclic Stress Amplitude (psi)</th>
<th>Effective Confining Stress (psi)</th>
<th>Cycles to Liquefaction</th>
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Table 4-3 Sample CC Liquefaction Data

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Table 4-4 Sample G Liquefaction Data

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<th>B-value (%)</th>
<th>CSR</th>
<th>Cyclic Stress Amplitude (psi)</th>
<th>Effective Confining Stress (psi)</th>
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### Table 4-5 Sample MR Liquefaction Data

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<th>Dry Density (pcf)</th>
<th>Moisture Content (%)</th>
<th>B-value (%)</th>
<th>CSR</th>
<th>Cyclic Stress Amplitude (psi)</th>
<th>Effective Confining Stress (psi)</th>
<th>Cycles to Liquefaction</th>
</tr>
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<td>0.150</td>
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<td>500</td>
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### Table 4-6 Sample S Liquefaction Data

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<th>Moisture Content (%)</th>
<th>B-value (%)</th>
<th>CSR</th>
<th>Cyclic Stress Amplitude (psi)</th>
<th>Effective Confining Stress (psi)</th>
<th>Cycles to Liquefaction</th>
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<td>7</td>
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<td>500</td>
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<td>S86</td>
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<td>85.10</td>
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<td>0.159</td>
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<td>96.50</td>
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<td>S123</td>
<td>70.60</td>
<td>40.60</td>
<td>97.60</td>
<td>0.194</td>
<td>15.52</td>
<td>40.00</td>
<td>8</td>
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</tbody>
</table>
As can be seen in the tables, dry density varied from site to site, but stayed consistent for each location. The saturated moisture content also stays consistent within each location, but varies between samples. According to ASTM D5311-04, saturation is deemed complete when the B-value reaches a value of 0.95 or greater, or if the B-value versus back pressure plot indicates no further increase in B-value with increasing back pressure. As can be seen in the tables, the B-value did not always reach 0.95. Specimens were allowed to saturate for two weeks. If a B-value of 0.95 was not reached by 2 weeks, the specimen underwent consolidation, then cyclic triaxial testing. Due to the three types of voids determined by Santamarina, the B-value of a fly ash specimen may never reach a value of 0.95. The surface tension of water will not allow the occluded and internally connected voids within fly ash particles to saturate. This will lead to a lower B-value. The fly ash specimens were deemed to be as saturated as the fly ash in the ponded reservoirs.
Examples of the results from cyclic triaxial tests can be seen in Figures 4-1 and 4-2. Figure 4-1 displays the $N_{\text{liq}}$ versus recorded axial stress, $\sigma_a$. The red vertical line indicates the point where liquefaction occurred, according to the prescribed criterion in Chapter 3.5. Figure 4-2 displays the $N_{\text{liq}}$ versus ratio of excess pore water pressure to effective pressure, $\text{r}_{\text{u}}$, and axial strain, $\varepsilon_a$. Plots similar to the displayed figures were created for each specimen and can be seen in Appendix A.

**Figure 4-1** Identification of Liquefaction on Number of Cycles Tested vs. Axial Stress Plot

**Figure 4-2** Identification of Liquefaction on Number of Cycles Tested vs. Ratio of Excess Pore Water Pressure to Effective Stress and Axial Strain Plot
Figure 4-3 displays the number of cycles to liquefaction based on the applied CSR for all fly ash samples examined with in-situ densities. The vertical red line in Figure 4-3 identifies the test limit of 500 cycles. Specimens that were tested and did not reach the liquefaction criterion by 500 cycles were deemed to not liquefy.

**Figure 4-3 Liquefaction Data of Ponded Fly Ash Reservoir Samples**

From the liquefaction data shown in Figure 4-3, as the applied CSR increases, the number of cycles to liquefy the specimen decreases. The susceptibility of liquefaction of the tested ponded fly ash samples increases as the CSR escalates. This trend is common for every site tested. These results are also consistent with studies of liquefaction potential using sands, silts, and clays\(^8, 9, 11, 18, 37\).

Figure 4-4 represents the liquefaction data in Figure 4-3, referencing the effect of \(\sigma_3\) on sample specimens.
Figure 4.4 Liquefaction Data of AEP Ponded Fly Ash Reservoirs Based on Effective Confining Stress (a) Sample A, (b) Sample BS, (c) Sample CC, (d) Sample G, (e) Sample MR, (f) Sample S, (g) Sample TC

continued
Since each site’s fly ash varies in prepared dry density, moisture content, and liquefaction results (Figure 4-3), analysis of effective confining stress on liquefaction susceptibility of ponded fly ash will be examined on a site basis. All fly ash samples experienced cyclic triaxial testing at $\sigma_3'$ of 20 psi. Samples A, BS, G, MR, and TC had additional specimens tested at 10 psi $\sigma_3'$. Sample BS was the only sample to have additional specimens tested at $\sigma_3'$ of 30 psi. Samples A, CC, S, and TC had additional specimens tested at $\sigma_3'$ of 40 psi. By examining the results displayed in Figure 4-4, a definitive conclusion cannot be made relating $N_{\text{liq}}$ to $\sigma_3'$. In past studies of ponded fly ash$^{18,17}$ and sands$^{17}$, the behavior of increasing $\sigma_3'$ causes liquefaction resistance to decrease has been observed. However, in this research program the data is too scattered to provide any definitive correlation.
4.2 Experimental Test Results Examining the Parameter of Dr

The effect relative density has on resistance of ponded fly ash to dynamic liquefaction was studied. Ponded fly ash from Sample A was used to create specimens of various relative densities.

Minimum and maximum realizable densities were determined based on the procedures outlined in Chapter 3.5. Table 4-8 displays the minimum and maximum realizable density of Sample A.

**Table 4-8 Minimum and Maximum Realizable Density of Sample A**

<table>
<thead>
<tr>
<th></th>
<th>Minimum Relative Density (pcf)</th>
<th>Maximum Relative Density (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Amos</em></td>
<td>74.04</td>
<td>93.58</td>
</tr>
</tbody>
</table>

Standard Proctor curve for fly ash Sample A is shown in Figure 4-5. A peak value of 93.58 pcf was used as the maximum realizable density for Sample A.
Using both the minimum and maximum realizable densities, specimens were created to produce a range of relative densities. Relative densities of 25%, 50%, 75%, and 100% were desired. Upon construction of the specimens, relative densities between 34.65% and 91.61% were achieved. Table 4-9 and display the specimen liquefaction data for Sample A.

Table 4-9 Sample A Liquefaction Data Based on Relative Density

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dry Density (pcf)</th>
<th>Relative Density (%)</th>
<th>Moisture Content (%)</th>
<th>B-value (%)</th>
<th>CSR</th>
<th>Cyclic Stress Amplitude (psi)</th>
<th>Effective Confining Stress (psi)</th>
<th>Cycles to Liquefaction</th>
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</thead>
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<td>A22</td>
<td>89.51</td>
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<td>26.45</td>
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<td>91.61</td>
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<td>23.73</td>
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<td>20.00</td>
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</table>

Figure 4-5 Standard Proctor Compaction Curve of Sample A
As can be seen in Table 4-9, the applied CSR value remained constant at 0.2 and the effective confining stress applied remained constant at 20.0 psi.

Plots of $\sigma_a$, $\varepsilon_a$, and $r_u$ for these cyclic triaxial tests, similar to Figures 4-1 and 4-2, are found in Appendix B. Figure 4-6 displays the number of cycles to liquefaction with respect to the relative density of Sample A.

![Liquefaction Curve of Sample A based on Relative Density](image)

**Figure 4-6** Liquefaction Data of Sample A Ponded Fly Ash Based on Relative Density

As can be seen in the figure, as relative density increases, the liquefaction resistance of the tested fly ash samples also increases. This conclusion is consistent with past fly ash and sand research.\textsuperscript{18, 37}
4.3 Experimental Test Results Examining the Parameter pH

The pH values of all seven fly ash samples were measured. Three measurements were made for each site. Figure 4-7 displays pH values according to each facility.

![pH Values of Fly Ash Samples](image)

**Figure 4-7** pH Values of Fly Ash Samples Tested

Figures 4-8(a) through 4.8(d) displays $N_{\text{liq}}$ based on pH values. Liquefaction data of specimens that were created at in-situ densities was used. Specimens with an effective confining stress of 20.0 psi were used and CSR values were constant for each figure.
Figure 4-8 Liquefaction Data Based on pH with $\sigma_3' = 20$ psi and (a) CSR = 0.1, (b) CSR = 0.2, (c) CSR = 0.3, (d) CSR = 0.4

continued
At the highest CSR value tested, 0.4, Figure 4-8d shows an apparent effect of the pH on the resistance to liquefaction. The data exhibited fly ash specimens with a pH value of 8 or greater liquefied at a lower $N_{\text{liq}}$ than fly ash specimens with pH values less than 8. At CSR values greater than 0.1 but less than 0.4, Figures 4.8b and 4.8c, the resistance to liquefaction seems to be less dependent on the pH value. However, there is a slight trend where the resistance to liquefaction seems to increase with decreasing pH. At the lowest CSR values tested, 0.1, Figure 4.8a shows that resistance to liquefaction to be independent of the pH value.
Chapter 5: Summary and Conclusions

5.1 Summary

The dynamic liquefaction resistance of impounded class F fly ash from seven different coal burning utility plants’ ponded reservoirs in Midwest United States was investigated. Four parameters were examined to study their effect on liquefaction resistance of ponded fly ash. These four factors include CSR, $\sigma_3^\prime$, Dr and pH.

The effects of CSR and $\sigma_3^\prime$ on the fly ash specimens were examined. The cyclic shear strength of the impounded fly ash was presented graphically in terms of cyclic strength curves displaying a relationship between cyclic stress amplitude and number of cycles to liquefaction for each fly ash sample studied. Graphical plots of CSR and $N_{\text{liq}}$ were created showing the effect of effective confining stress.

The effect of relative density on liquefaction resistance was also determined. Minimum and maximum realizable densities were determined for one fly ash sample. From these values, specimens were created with various relative densities and cyclic triaxial tests were performed. Plots of relative density and $N_{\text{liq}}$ were developed to determine the effect relative density has on liquefaction resistance of ponded fly ash.

In order to determine the effect pH levels have on liquefaction resistance, pH measurements of all fly ash samples were taken. These values were graphed against $N_{\text{liq}}$ for specimens that were created to simulate in-situ densities and tested at $\sigma_3^\prime = 20$ psi.
5.2 Conclusion

The following conclusions were formulated during this research are as follows:

1. As the applied cyclic stress ratio increases, the cyclic stress resistance of fly ash decreases. This was found to be common for each fly ash reservoir studied.

2. No definitive correlation could be justified between effective confining stress and liquefaction resistance. The data was too scattered for a trend to be concluded.

3. As the relative density of a specimen increased, the liquefaction resistance of that specimen increased as well.

4. A correlation between pH levels and liquefaction resistance was observed. At relatively high CSR values (CSR = 0.4), it was seen that as pH levels increased, the liquefaction resistance decreased. As CSR values decreased, the effect of pH on liquefaction resistance also decreased. For CSR values between 0.2 and 0.3, a similar but weaker correlation was seen as compared to CSR = 0.4. At relatively low CSR values (CSR = 0.1), it appeared that liquefaction resistance was independent of pH levels.
5. Due to the differences in moisture content, in-situ dry densities, cyclic strength curves, and pH values observed, it is suggested that liquefaction susceptibility be based on a site specific analysis. This conclusion is consistent with other studies of liquefaction potential of ponded fly ash.\textsuperscript{16}

5.3 Recommendations for Future Work

In order to provide conclusive evidence relating to the effect of effective confining stress on the fly ash specimens tested, further cyclic triaxial tests would be required. Specifically, additional tests at effective confining stresses of 30 psi and 40 psi are required. Additional tests at a broader range of pH values should be done to provide further evidence of the correlation between pH levels and dynamic liquefaction resistance in ponded fly ash.
References


Appendix A: Cyclic Triaxial Test Results for Specimens with In-situ Densities
Figure A-1 Specimen A1 Deviator Stress

Figure A-2 Specimen A1 Pore Water Pressure Build-up and Axial Strain
Figure A-3 Specimen A2 Deviator Stress

Figure A-4 Specimen A2 Pore Water Pressure Build-up and Axial Strain
**Figure A-5** Specimen A3 Deviator Stress

**Figure A-6** Specimen A3 Pore Water Pressure Build-up and Axial Strain
Figure A-7 Specimen A4 Deviator Stress

Figure A-8 Specimen A4 Pore Water Pressure Build-up and Axial Strain
Figure A-9 Specimen A5 Deviator Stress

Figure A-10 Specimen A5 Pore Water Pressure Build-up and Axial Strain
Figure A-11 Specimen A6 Deviator Stress

Figure A-12 Specimen A6 Pore Water Pressure Build-up and Axial Strain
Figure A-13 Specimen A7 Deviator Stress

Figure A-14 Specimen A7 Pore Water Pressure Build-up and Axial Strain
Figure A-15 Specimen A9 Deviator Stress

Figure A-16 Specimen A9 Pore Water Pressure Build-up and Axial Strain
Figure A-17 Specimen A10 Deviator Stress

Figure A-18 Specimen A10 Pore Water Pressure Build-up and Axial Strain
**Figure A-19** Specimen A11 Deviator Stress

**Figure A-20** Specimen A11 Pore Water Pressure Build-up and Axial Strain
Figure A-21 Specimen A13 Deviator Stress

Figure A-22 Specimen A13 Pore Water Pressure Build-up and Axial Strain
Figure A-23 Specimen BS1 Deviator Stress

Figure A-24 Specimen BS1 Pore Water Pressure Build-up and Axial Strain
Figure A-25 Specimen BS2 Deviator Stress

Figure A-26 Specimen BS2 Pore Water Pressure Build-up and Axial Strain
Figure A-27 Specimen BS3 Deviator Stress

Figure A-28 Specimen BS3 Pore Water Pressure Build-up and Axial Strain
**Figure A-29** Specimen BS4 Deviator Stress

**Figure A-30** Specimen BS4 Pore Water Pressure Build-up and Axial Strain
Figure A-31 Specimen BS5 Deviator Stress

Figure A-32 Specimen BS5 Pore Water Pressure Build-up and Axial Strain
Figure A-33 Specimen BS6 Deviator Stress

Figure A-34 Specimen BS6 Pore Water Pressure Build-up and Axial Strain
Figure A-35 Specimen BS7 Deviator Stress

Figure A-36 Specimen BS7 Pore Water Pressure Build-up and Axial Strain
Figure A-37 Specimen BS9 Deviator Stress

Figure A-38 Specimen BS9 Pore Water Pressure Build-up and Axial Strain
**Figure A-39** Specimen CC3 Deviator Stress

**Figure A-40** Specimen CC3 Pore Water Pressure Build-up and Axial Strain
Figure A-41 Specimen CC5 Deviator Stress

Figure A-42 Specimen CC5 Pore Water Pressure Build-up and Axial Strain
Figure A-43 Specimen CC7 Deviator Stress

Figure A-44 Specimen CC7 Pore Water Pressure Build-up and Axial Strain
Figure A-45 Specimen CC10 Deviator Stress

Figure A-46 Specimen CC10 Pore Water Pressure Build-up and Axial Strain
Figure A-47 Specimen CC11 Deviator Stress

Figure A-48 Specimen C11 Pore Water Pressure Build-up and Axial Strain
**Figure A-49** Specimen CC12 Deviator Stress

**Figure A-50** Specimen CC12 Pore Water Pressure Build-up and Axial Strain
Figure A-51 Specimen CC13 Deviator Stress

Figure A-52 Specimen CC13 Pore Water Pressure Build-up and Axial Strain
Figure A-53 Specimen CC16 Deviator Stress

Figure A-54 Specimen CC16 Pore Water Pressure Build-up and Axial Strain
Figure A-55 Specimen CC18 Deviator Stress

Figure A-56 Specimen CC18 Pore Water Pressure Build-up and Axial Strain
Figure A-57 Specimen CC19 Deviator Stress

Figure A-58 Specimen CC19 Pore Water Pressure Build-up and Axial Strain
Figure A-59 Specimen G88 Deviator Stress

Figure A-60 Specimen G88 Pore Water Pressure Build-up and Axial Strain
Figure A-61 Specimen G90 Deviator Stress

Figure A-62 Specimen G90 Pore Water Pressure Build-up and Axial Strain
Figure A-63 Specimen G92 Deviator Stress

Figure A-64 Specimen G92 Pore Water Pressure Build-up and Axial Strain
Figure A-65 Specimen G93 Deviator Stress

Figure A-66 Specimen G93 Pore Water Pressure Build-up and Axial Strain
Figure A-67 Specimen G95 Deviator Stress

Figure A-68 Specimen G95 Pore Water Pressure Build-up and Axial Strain
Figure A-69 Specimen G100 Deviator Stress

Figure A-70 Specimen G100 Pore Water Pressure Build-up and Axial Strain
Figure A-71 Specimen G132 Deviator Stress

Figure A-72 Specimen G132 Pore Water Pressure Build-up and Axial Strain
Figure A-73 Specimen G134 Deviator Stress

Figure A-74 Specimen G134 Pore Water Pressure Build-up and Axial Strain
Figure A-75 Specimen G135 Deviator Stress

Figure A-76 Specimen G135 Pore Water Pressure Build-up and Axial Strain
Figure A-77 Specimen MR1 Deviator Stress

Figure A-78 Specimen MR1 Pore Water Pressure Build-up and Axial Strain
Figure A-79 Specimen MR2 Deviator Stress

Figure A-80 Specimen MR2 Pore Water Pressure Build-up and Axial Strain
**Figure A-81** Specimen MR3 Deviator Stress

**Figure A-82** Specimen MR3 Pore Water Pressure Build-up and Axial Strain
Figure A-83 Specimen MR4 Deviator Stress

Figure A-84 Specimen MR4 Pore Water Pressure Build-up and Axial Strain
Figure A-85 Specimen MR1 Deviator Stress

Figure A-86 Specimen MR1 Pore Water Pressure Build-up and Axial Strain
Figure A-87 Specimen MR3 Deviator Stress

Figure A-88 Specimen MR3 Pore Water Pressure Build-up and Axial Strain
Figure A-89 Specimen MR4 Deviator Stress

Figure A-90 Specimen MR4 Pore Water Pressure Build-up and Axial Strain
Figure A-91 Specimen MR5 Deviator Stress

Figure A-92 Specimen MR5 Pore Water Pressure Build-up and Axial Strain
Figure A-93 Specimen MR7 Deviator Stress

Figure A-94 Specimen MR7 Pore Water Pressure Build-up and Axial Strain
Figure A-95 Specimen MR8 Deviator Stress

Figure A-96 Specimen MR8 Pore Water Pressure Build-up and Axial Strain
Figure A-97 Specimen MR9 Deviator Stress

Figure A-98 Specimen MR9 Pore Water Pressure Build-up and Axial Strain
Figure A-99 Specimen S2R Deviator Stress

Figure A-100 Specimen S2R Pore Water Pressure Build-up and Axial Strain
Figure A-101 Specimen S3 Deviator Stress

Figure A-102 Specimen S3 Pore Water Pressure Build-up and Axial Strain
Figure A-103 Specimen S6 Deviator Stress

Figure A-104 Specimen S6 Pore Water Pressure Build-up and Axial Strain
**Figure A-105** Specimen S7 Deviator Stress

**Figure A-106** Specimen S7 Pore Water Pressure Build-up and Axial Strain
Figure A-107 Specimen S8 Deviator Stress

Figure A-108 Specimen S8 Pore Water Pressure Build-up and Axial Strain
Figure A-109 Specimen S10 Deviator Stress

Figure A-110 Specimen S10 Pore Water Pressure Build-up and Axial Strain
**Figure A-111** Specimen S11 Deviator Stress

**Figure A-112** Specimen S11 Pore Water Pressure Build-up and Axial Strain
Figure A-113 Specimen S18 Deviator Stress

Figure A-114 Specimen S18 Pore Water Pressure Build-up and Axial Strain
Figure A-115 Specimen S21 Deviator Stress

Figure A-116 Specimen S21 Pore Water Pressure Build-up and Axial Strain
Figure A-117 Specimen S81 Deviator Stress

Figure A-118 Specimen S81 Pore Water Pressure Build-up and Axial Strain
Figure A-119 Specimen S84 Deviator Stress

Figure A-120 Specimen S84 Pore Water Pressure Build-up and Axial Strain
Figure A-121 Specimen S85 Deviator Stress

Figure A-122 Specimen S85 Pore Water Pressure Build-up and Axial Strain
Figure A-123 Specimen S86 Deviator Stress

Figure A-124 Specimen S86 Pore Water Pressure Build-up and Axial Strain
**Figure A-125** Specimen S87 Deviator Stress

**Figure A-126** Specimen S87 Pore Water Pressure Build-up and Axial Strain
Figure A-127 Specimen S109 Deviator Stress

Figure A-128 Specimen S109 Pore Water Pressure Build-up and Axial Strain
Figure A-129 Specimen S111 Deviator Stress

Figure A-130 Specimen S111 Pore Water Pressure Build-up and Axial Strain
**Figure A-131** Specimen S114 Deviator Stress

**Figure A-132** Specimen S114 Pore Water Pressure Build-up and Axial Strain
Figure A-133 Specimen S117 Deviator Stress

Figure A-134 Specimen S117 Pore Water Pressure Build-up and Axial Strain
Figure A-135 Specimen S119 Deviator Stress

Figure A-136 Specimen S119 Pore Water Pressure Build-up and Axial Strain
Figure A-137 Specimen S120 Deviator Stress

Figure A-138 Specimen S120 Pore Water Pressure Build-up and Axial Strain
Figure A-139 Specimen S122 Deviator Stress

Figure A-140 Specimen S122 Pore Water Pressure Build-up and Axial Strain
Figure A-141 Specimen S123 Deviator Stress

Figure A-142 Specimen S123 Pore Water Pressure Build-up and Axial Strain
**Figure A-143** Specimen TC1 Deviator Stress

**Figure A-144** Specimen TC1 Pore Water Pressure Build-up and Axial Strain
**Figure A-145** Specimen TC2 Deviator Stress

**Figure A-146** Specimen TC2 Pore Water Pressure Build-up and Axial Strain
Figure A-147 Specimen TC3 Deviator Stress

Figure A-148 Specimen TC3 Pore Water Pressure Build-up and Axial Strain
Figure A-149 Specimen TC8 Deviator Stress

Figure A-150 Specimen TC8 Pore Water Pressure Build-up and Axial Strain
Figure A-151 Specimen TC9 Deviator Stress

Figure A-152 Specimen TC9 Pore Water Pressure Build-up and Axial Strain
Figure A-153 Specimen TC10 Deviator Stress

Figure A-154 Specimen TC10 Pore Water Pressure Build-up and Axial Strain
Figure A-155 Specimen TC11 Deviator Stress

Figure A-156 Specimen TC11 Pore Water Pressure Build-up and Axial Strain
Figure A-157 Specimen TC12 Deviator Stress

Figure A-158 Specimen TC12 Pore Water Pressure Build-up and Axial Strain
Figure A-159 Specimen TC13 Deviator Stress

Figure A-160 Specimen TC13 Pore Water Pressure Build-up and Axial Strain
Figure A-161 Specimen TC16 Deviator Stress

Figure A-162 Specimen TC16 Pore Water Pressure Build-up and Axial Strain
Figure A-163 Specimen TC17 Deviator Stress

Figure A-164 Specimen TC17 Pore Water Pressure Build-up and Axial Strain
Figure A-165 Specimen TC18 Deviator Stress

Figure A-166 Specimen TC18 Pore Water Pressure Build-up and Axial Strain
Figure A-167 Specimen TC19 Deviator Stress

Figure A-168 Specimen TC19 Pore Water Pressure Build-up and Axial Strain
Appendix B: Cyclic Triaxial Test Results for Specimens with Range of Relative Densities
**Figure B-1** Specimen A22 Deviator Stress

**Figure B-2** Specimen A22 Pore Water Pressure Build-up and Axial Strain
Figure B-3 Specimen A33 Deviator Stress

Figure B-4 Specimen A33 Pore Water Pressure Build-up and Axial Strain
Figure B-5 Specimen A44 Deviator Stress

Figure B-6 Specimen A44 Pore Water Pressure Build-up and Axial Strain
**Figure B-7** Specimen A55 Deviator Stress

**Figure B-8** Specimen A55 Pore Water Pressure Build-up and Axial Strain
Figure B-9 Specimen A2 Deviator Stress

Figure B-10 Specimen A2 Pore Water Pressure Build-up and Axial Strain
**Figure B-11** Specimen A6 Deviator Stress

**Figure B-12** Specimen A6 Pore Water Pressure Build-up and Axial Strain