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Cyclic Loading of Soils: A Study of Resilient Modulus and Cyclic Liquefaction

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CYCLIC LOADING OF SOILS: A STUDY OF RESILIENT MODULUS AND
CYCLIC LIQUEFACTION

BY

JEFFREY MICHAEL COSTA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

IN

CIVIL AND ENVIRONMENTAL ENGINEERING

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2013

MASTER OF SCIENCE THESIS
OF
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UNIVERSITY OF RHODE ISLAND

2013

Abstract

This thesis presents the results of two studies. The first is a study performed to characterize the resilient modulus properties of unbound subbase material containing Reclaimed Asphalt Pavement (RAP) that has been previously reclaimed. The Rhode Island Department of Transportation (RIDOT) is moving toward the use of the Mechanistic-Empirical Pavement Design Guide (MEPDG) for pavement design. The guidelines require the resilient modulus of the pavement structure as an input including both the bound (i.e. asphalt) and unbound layers (i.e. subbase/subgrade). This study characterizes the resilient moduli of RAP/aggregate blends sampled from an existing roadway subbase layer in Rhode Island. The RAP content of the samples tested ranged from approximately 15% to 40%. The test results showed that the average resilient modulus ranged from approximately 120 MPa to 520 MPa, with increasing values occurring with higher confining stress and cyclic stress levels. Neither the percentage of RAP nor the relative compaction had an effect on the resilient modulus value.

The second portion of this thesis presents the results of a study of cyclic triaxial tests performed on Monterey sand to investigate the influence of initial effective confining stress on the dissipated energy at initial liquefaction. Energy-based liquefaction procedures have been proposed as a more fundamental alternative to the more commonly used cyclic stress-based procedures. It is well known that in the shear stress-based simplified procedures, for example, that initial confining pressure has an influence on the cyclic resistance. These effects are accounted for by multiplying the Cyclic Resistance Ratio (CRR) by an overburden stress correction factor (K_{σ}).

However, it is uncertain at this point if a similar overburden correction factor is required for energy-based simplified procedures (K-sigma-energy). Therefore, this thesis performs cyclic triaxial tests on Monterey sand at various relative densities and initial effective confining stresses to investigate this effect. The results suggest that no overburden stress correction factor is needed for use with energy-based liquefaction procedures.

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Preface

Manuscript format is in use throughout this thesis. This thesis is comprised of two manuscripts with the intent of future publication in the American Society of Civil Engineers Geo-Congress. Both manuscripts relate to the cyclic loading of soils. The first is in relation to traffic loading and soil resilient modulus characterization for a previously reclaimed subbase material in Rhode Island. The second is comprised of a study performed on Monterey sand to assess soil liquefaction as it relates to the overburden correction factor for the energy-based liquefaction procedure. The abstracts to both manuscripts have been accepted for the 2014 ASCE Geo-Congress.

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**1. The Resilient Modulus of a Previously Reclaimed Asphalt Pavement and
Aggregate Blend**

by

Jeffrey Michael Costa

This manuscript has been prepared for future publication in the American Society of
Civil Engineers Geo-Congress.

Abstract

This manuscript presents the results of a study performed to characterize the resilient modulus properties of unbound subbase material containing Reclaimed Asphalt Pavement (RAP) that has been previously reclaimed. The Rhode Island Department of Transportation (RIDOT) is moving toward the use of the Mechanistic-Empirical Pavement Design Guide (MEPDG) for pavement design. The guidelines require the resilient modulus of the pavement structure as an input including both the bound (i.e. asphalt) and unbound layers (i.e. subbase/subgrade). There is a scarcity of published data on the resilient properties of RAP/aggregate mixtures, particularly mixtures containing previously reclaimed aggregates. This study characterizes the resilient moduli of a RAP/aggregate blend sampled from the existing roadway subbase layer along a segment of Route 165 in Rhode Island. The RAP was produced during a previous resurfacing project performed in the 1980s and therefore has been naturally aged for roughly 30 years. The material is a well-graded mixture of sand and gravel-sized particles ($D_{50} = 1.5\text{mm}$ to 3mm). Consistent with the original project specifications, test specimens were compacted at their optimum water content and to a relative compaction of at least 95%. The RAP content of the samples tested ranged from approximately 15% to 40%. The test results showed that the average resilient modulus ranged from approximately 120 MPa to 520 MPa, with increasing values occurring with higher confining stress and cyclic stress levels. Neither the percentage of RAP nor the relative compaction had an effect on the resilient modulus.

Introduction

Current pavement design utilizes the Mechanistic-Empirical Pavement Design Guide (MEPDG) that provides a framework for efficient and reliable pavement design. The design guide requires the characterization of the resilient modulus that describes the recoverable stiffness of all pavement and supporting layers under cyclic (i.e. traffic) loading. Currently, site-specific resilient modulus properties for reclaimed, unbound, subbase materials commonly used on roadway projects in the state of Rhode Island, are unknown.

A typical pavement cross section used in the state of Rhode Island is shown in Figure 1.1a. The top layers consist of bound aggregates that are adhered together with asphalt binder or bitumen. Historically, the subbase layer has consisted of unbound virgin or recycled aggregates that are imported and compacted in place. In the late 1970's, much of the resilient modulus research was on virgin aggregates. Advances in pavement design, along with the rising cost of virgin aggregates have made the use of RAP in pavement resurfacing projects an economic alternative. This has caused resurgence in RAP research and a shift in resilient modulus research from virgin aggregates to RAP. The RAP materials can be produced in the field by grinding the existing pavement layers, along with the addition of stabilizers and admixtures to produce a new subbase material. For example if the first three layers in Figure 1.1a are ground away and mixed with the granular subbase layer, this new product with the addition of admixtures, would be classified as a RAP/aggregate blend. This can be seen in Figure 1.1b. Extra reclaimed material is taken off site and used elsewhere.

The MEPDG was developed to move the practice toward a more mechanistic approach to pavement design as opposed to a purely empirical approach. The software used in the MEPDG models the pavement structure and subbase as elastic materials. Therefore, the modulus of each layer must be determined.

The resilient modulus (M_r) represents the secant modulus of a stress-strain curve of the material after many repetitions of cyclic loads. It is defined as the ratio of cyclic deviator stress (S_{cyclic}) to the recoverable axial strain (ϵ). This is shown by Figure 1.2.

There has been some previous research performed on the resilient modulus of RAP. For example, Potturi (2006) and Puppala et al. (2011) looked into the effect of cement concentration on the resilient modulus of RAP. According to Potturi, the resilient modulus of RAP samples containing low cement to aggregate ratios increased with an increase in confining pressure. However, in samples with higher cement to aggregate ratios, this effect is not seen. Potturi suggests that this is due to the increase in aggregate strength from cementation. Puppala also found similar results. In their study it was found that a 2% increase in cement content increased the resilient modulus by 32% and a cement content of 4% increased the resilient modulus by 50%.

Other researchers have looked into different ratios of RAP and virgin aggregates. Kim et al. (2007) showed that an increase in RAP content (0% RAP to 75% RAP) increased the resilient modulus by 200%. This study also showed that the samples with higher RAP to aggregate ratios had a larger amount of permanent deformation, sometimes as much as a 200% increase in permanent deformation. Permanent deformation is related to the rutting and cracking performance of pavements.

Multiple experiments have also been performed to determine the influence of temperature on the resilient modulus. A report by Janoo et al. (1999) found that the resilient modulus of soils was greatly affected by temperature especially near the freeze-thaw line. In their testing the greatest rate of change in the resilient modulus occurred between temperatures of -2°C and 0°C . Between the temperature range of -5°C and 5°C , the resilient modulus decreased by approximately 2 orders of magnitude.

Hamzah et al. (2006) investigated the effects of temperature and age on the resilient modulus of different asphalt mixtures. Two mixtures were tested: one pavement mixture consisting of 100% steel slag as aggregates, and the second containing 50% steel slag aggregates and 50% granite aggregates. In this study, a temperature change from 25°C to 40°C reduced the resilient modulus of the sample by 85%. Prior to testing, the specimens were aged in an oven. This process was called short-term oven aging. It was found that the short-term oven aging increased the resilient modulus. In the mixture containing 100% steel slag, the resilient modulus was found to increase by 30%. The mixture consisting of 50% steel slag and 50% granite aggregates witnessed an increase in the resilient modulus by 114% because of short-term oven ageing.

Attia et al. (2010) researched the sensitivity of untreated RAP to the effects of moisture content, density and freeze thaw conditions. The objective of the research was to assess the structural capacity of RAP as a base layer and to investigate the effect of RAP content, moisture content, freeze-thaw conditioning, and dry density on the resilient modulus of untreated RAP as a base layer. Their research studied RAP/aggregate blends of 0%, 50%, 75%, and 100% RAP. The research concluded that

RAP and RAP/aggregate blends had a higher resilient modulus and lower permanent deformation when compared to the base (0% RAP) material. The effect of moisture content at testing and dry density on the resilient behavior of RAP was identical to the typical base material. Typically, as the moisture content increased, the resilient modulus value decreased. As the dry density increased, the resilient modulus increased, except at moisture contents greater than 2% of optimum. RAP is expected to have a higher resilient modulus than the typical granular material if it is properly compacted.

From the literature it is clear that the resilient modulus is influenced by the percentage of RAP, temperature, moisture content, dry density, and age of the pavement. It has been shown that an increase in percentage of RAP, dry density, or age, all contribute to a higher resilient modulus value. However, an increase in moisture or temperature was found to reduce the resilient modulus. The resilient modulus is also influenced by the mineralogy and grain size of the virgin aggregates used in that region. The percentage of RAP used in a mix design is project specific but a mixture containing 50% RAP and 50% virgin aggregates is common.

The resilient modulus is anticipated to be site or region specific. Therefore, the objective of this thesis is to characterize the resilient modulus of local subbase material containing previously reclaimed RAP/aggregate mix. The remaining contents of this thesis will include the test material, testing procedures, and a discussion of the results and conclusions.

Test Material

The reclaimed testing material was gathered from Rhode Island Route 165 by RIDOT. The RIDOT construction crew cut an area of approximately 1 meter square out of the existing pavement and roughly 15 cm to 20 cm deep. Approximately 13 kilograms of previously reclaimed subbase material were placed in sealed buckets from each test location.

The standards by the American Association of State and Highway Transportation Officials (AASHTO) were used throughout this study. A grain size distribution curve was produced in general accordance to AASHTO T 27 for the material collected from each test location which can be seen in Figure 1.3. The AASHTO classification of this soil is A-1-a, which is a well graded, granular material, with less than 15% fines. As witnessed in this grain size distribution figure all the samples are relatively similar. A summary of all the physical property results can be seen in Table 1.1. Also shown are the dry density, moisture content, and relative compaction (RC) of each sample during testing.

In addition to the grain size curve, modified proctor tests were performed in general accordance to AASHTO T 180. The values of dry density from the modified proctor tests were corrected for oversized particles in general accordance to AASHTO T 224. The maximum dry density values range from approximately 1938 kg/m^3 (121 pcf) to 2098 kg/m^3 (131 pcf).

Specific gravity tests were performed in general accordance to AASHTO T 209 on grain size particles larger than 1.9 cm ($\frac{3}{4}$ in). Specific gravity values ranged from approximately 2.43 to 2.58.

The original RAP/aggregate blend specification was not known for the Rt. 165 site. Therefore it had to be estimated. RIDOT performed multiple asphalt burn off tests in general accordance to AASHTO T 308 to back calculate the amount of RAP in each sample. One test was performed on larger, hand-picked conglomerates of RAP from the samples to determine the original asphalt/bitumen content of the bound asphalt layers from the 1960s. This was determined to be 6.5%. Upon reclamation in the 1980s, this asphalt layer was broken apart and mixed with the virgin aggregates that were the original subbase from the 1960s to the 1980s. Another burn off test was performed on the RAP/aggregate blend subbase and resulted in the amount of bitumen to range from 1%-3%. The ratio of the amount of bitumen burned off, to the original amount, yields the estimated amount of RAP in the sample. The RAP content ranged from approximately 15% to 40%.

Resilient Modulus Testing

Sample Preparation

The specimens were prepared in general accordance to AASHTO T 307: Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials. Test samples were prepared by compacting 6 lifts of approximately equal mass to a total compacted height of 304 mm (12 in.). This produced a soil sample approximately 152 mm (6 in.) in diameter and 304 mm (12 in.) in height. The soil

samples were prepared at optimum moisture content (OMC) and to a relative compaction of at least 95% of the maximum field dry density, consistent with the specification.

Equipment

Resilient modulus testing was performed using an Instron Fast Track 8800 hydraulic loading frame, a triaxial cell that can accommodate 152 mm (6 in.) diameter specimens, an Instron control and data acquisition system, and a computer with Instron WaveMatrix control software. The load frame is located in an environmental chamber that allows for testing at temperatures between 4° C and 60° C. However, all tests were performed at ambient temperature.

Procedures

The resilient modulus test was performed in general accordance to the AASHTO T 307 standard mentioned above. The testing procedure for a base/subbase material consists of two phases. The first phase is a condition phase which is approximately 500 to 1000 cycles. The second phase consists of 15 cyclic compression load sequences with varying confining pressures. Maximum axial stresses during this phase range from approximately 20 kPa to 275 kPa, and confining pressure ranges from approximately 20 kPa to 138 kPa.

Each of the 15 load sequences applies a different axial and confining stress combination, and consists of 100 cycles. Each cycle consists of a haversine waveform that has a load duration of 0.1 seconds and a rest period of 0.9 seconds. The resilient modulus is determined from the slope of the stress-strain curve for the last five cycles

of each load sequence. By the completion of the test, 75 resilient moduli are calculated for each sample.

A Matlab code was developed for post-processing. A typical stress-strain plot is shown in Figure 1.4. The Matlab code determines the resilient modulus for the last 5 cycles in each load sequence. The different load sequences are shown as different stress-strain loop groups. The resilient modulus values along with other pertinent testing information were outputted to a Microsoft Excel Spreadsheet template. An example of this spreadsheet is shown in Table 1.2., and is referred to as Report Form C.4 in the AASHTO T 307 standard. The table shown is only a portion of the actual results table which is 15 sequences long for a base/subbase material.

Resilient Modulus Results and Discussion

The resilient modulus test applies 15 different combinations of cyclic stress and confining stress. A typical stress-strain plot of all 1500 cycles is shown in Figure 1.4 for one sample. In the figure the cyclic stresses increase with each sequence. In addition, the resilient modulus increases as the test progresses. This trend is observed because as the test progresses the sample is becoming permanently deformed. The deformation and particle rearrangement make the sample stiffer, thus causing an increase in the resilient modulus.

It is also noticed in Figure 1.4 that the group of stress-strain loops in sequence 9 appear to be the widest. This signifies that the most permanent deformation occurs during this load sequence. This is because this sequence has the highest maximum principal stress ratio ($\sigma_{1max}/\sigma_{3max}$) of 4. This permanent deformation can also be

explained through contractive and dilative behavior. The samples prepared for testing are dense and most likely dilative. The shearing caused by load sequences 1 through 8 causes the void ratio of the sample to increase. When load sequence 9 is applied to the sample, it is the combination of a looser sample and higher confining stress that produces a more contractive sample, yielding a lower modulus.

The average slope of the last 5 cycles in each load sequence was recorded for every sample tested. Figure 1.5 is a stress-strain plot of only the last 5 cycles in each load sequence for one sample. A summary of this data for all samples is shown in Table 1.3. This information is also represented in a graphical form in Figure 1.6. In this figure the vertical axis represents the resilient modulus in MPa, while the horizontal axis represents the load sequence. The data points represent the average resilient modulus value for that load sequence. The error bars represent plus and minus one standard deviation.

Figure 1.6 also shows that as the test progresses the standard deviation increases. However, based on the coefficient of variability (COV) shown in Table 1.3, which is a normalized standard deviation, and defined as the standard deviation divided by the average resilient modulus value, the opposite is the case. The COV is approximately 0.1 for all sequences indicating low variation amongst the data. This also shows that the majority of the data is within one standard deviations of the mean (Harr 1987).

Additional analysis of the data was performed to assess the impact of relative compaction for samples within 2% of their optimum moisture content (OMC). Figure 1.7 plots the resilient modulus against confining pressure for samples with relative

compactions ranging from 91% to 97%. Five different confining pressures are applied during the test, thus explaining the grouping of the data. For each sample tested, three different load sequences are performed at the same confining pressure. For example load sequences 1, 2, and 3 are performed at a confining pressure of 20.7 kPa. Trend lines were created for samples with relative compactions greater than 95% and relative compactions of 94% and less at each confining pressure. It is these data points that are represented by the lower trend lines in this figure.

The difference between the trend lines is minimal. Note that the data series for relative compaction of 95% or higher consists of 7 samples, while the data series for the relative compaction of 94% or lower consists of 2 samples. Results from sample 8-3 are not included in this figure because of the high moisture content of the sample during testing.

The results of this study are similar to those found in Attia et al. (2010) who tested a 50/50 RAP to aggregate blend at relative compactions of 90% and 100%. The trend lines from the results of Attia et al. are also shown on the figure. Two observations can be made from this. The first is that the results compare reasonably well to Attia et al. (2010), especially at low confining pressures. The second observation is there is minimal influence of relative compaction on the resilient modulus value. This is possibly due to differences in soil fabric that may result from compacting at different dry densities.

The results from the literature are slightly higher than what was obtained in this study. This difference can be explained in three ways. This first is that Attia et al. (2010)

performed resilient modulus testing using the National Cooperative Highway Research Program (NCHRP) 1-28A Protocol, Procedure 1A, which is a competing protocol to AASHTO T 307. The NCHRP includes higher stress levels and additional load sequences. The second difference can be explained because of the difference in the soil being tested. Attia et al. (2010) performed testing on 50/50 RAP/aggregate blends; where this study performed testing on blends with significantly less than 50% RAP. As previously stated, a higher RAP content generally leads to higher resilient modulus value. Also, the soil tested in this thesis consisted of previously reclaimed RAP/aggregate blends from Rhode Island, where the samples used in Attia et al. (2010), consisted of 50% RAP base material for reclaiming projects in Minnesota. Third, in the research performed in Attia et al. (2010), the specimens were also prepared using a gyratory compactor which kneads the sample as it is being compacted. In this thesis the samples were prepared using a vibratory hammer which does not include any kneading action. Sample preparation may have an effect on the cyclic behavior due to its effect on the soil fabric.

The RAP/aggregate blends tested in this thesis had an approximate RAP content that ranged from 15% to 40%. A plot of resilient modulus vs. load sequence number at different RAP contents was developed and can be seen in Figure 1.8. When comparing the RAP content to the measured resilient modulus values, the data is wide spread with no visible trend as seen in this figure.

The wide range of RAP content and possible reason for the lack of trend can be explained by the process during reclamation and also the sampling techniques. The original thickness of the pavement placed on Rt. 165 during the 1960s is unknown. If

the pavement was placed unevenly at this time, the reclamation performed in the 1980s may have reclaimed thicker amounts of pavement in some sections and less in others. In the areas with thicker pavement, the reclaiming crew would create a reclaimed subbase containing a higher percentage of RAP. The opposite would be the case if the original pavement was placed thin.

The sampling techniques used by RIDOT may also contribute to the error in calculating the amount of RAP. The road crew was not aware of the thickness of the subbase material. Therefore, if the road crew penetrated the subbase while gathering samples, some of the gathered samples may have contained virgin aggregate subgrade material. This would dilute the RAP content and cause a lower estimated RAP/aggregate blend.

Conclusions

This study characterized the resilient moduli of a RAP/aggregate blend sampled from the existing roadway subbase layer along a segment of Route 165 in Rhode Island. Resilient modulus testing was performed in accordance to AASHTO T 307 on 6 RAP/aggregate subbase blends from the Rhode Island Route 165 subbase. A total of 10 tests were performed and the results show a resilient modulus value that ranges from 120 MPa to 520 MPa, with increasing values occurring with higher confining stress and cyclic stress levels. The results also indicated that all the soils tested have very similar resilient modulus properties. This is reasonable considering the soil samples are from the same project, in the same geographical region, subjected to the same traffic loading, and have the same role in the pavement structure (subbase). It was also determined that relative compaction had little effect on the resilient modulus

when prepared at optimum moisture content and for relative compaction ranging from 90% to 100%. No trend was determined between the RAP content and the measured resilient modulus values. This is possibly due to uncertainty in calculating the amount of RAP within the testing sample, and also the unfamiliarity with construction practices and pavement methods available during 1960s. It is not known at this point how the effect of the natural ageing process would affect the resilient modulus value because the resilient modulus value of the “young” material is unknown. However, this testing provides the baseline data needed for future research on RAP/aggregate blends.

Recommendations for Future Research

Based on the results of this study, a few future recommendations for resilient modulus testing can be suggested. The first is the effect of the loading sequence. The AASHTO standard applies the lowest cyclic stress first, and increases the stress throughout the test. However, cyclic loading from traffic is random, and it would be interesting to investigate the effect of 1500 cycles of random amplitude loading.

It would also be of interest to investigate why load sequence 9 causes the most permanent deformation of the sample. It is the author’s hypothesis that the sample may be behaving in a contractive, dilative, or combination of both; fashion throughout the test. To investigate this hypothesis, the equipment at URI can be modified to perform the resilient modulus test procedure under saturated conditions. This would provide the capability of tracking the volume change during testing, and would provide insight to the contractive or dilative behavior of the sample.

Future resilient modulus testing will also consist of testing the subgrade soil from the Rhode Island Route 165 site. This will allow RIDOT to effectively model the entire pavement structure in the MEPDG program. Along with the subgrade testing, RIDOT will also be investigating the effect of admixtures and stabilizers such as: bitumen, cement, calcium chloride, and geogrid, to the RAP/aggregate blend.

This gathered data can be used to fit or calibrate the results of the local RAP/aggregate blend to a resilient modulus constitutive model.

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**Table 1.1 Physical properties testing results performed sample gathered by
RIDOT. Note that all values have been corrected for oversized particles and
represent a field condition.**

Sample Number	Estimated Amount of RAP %	Max Dry Density (pcf)	Specimen Dry Density (pcf)	Specific Gravity of 3/4" +	Water Content of Sample Tested %	Specimen Relative Compaction (%)
4-2	24.6	133.5	121.2	2.52	3.5	90.8
4-3	24.6	133.5	127.1	2.52	3.4	95.2
6	15.4	133.7	129.9	2.48	3.5	97.2
8-1	24.6	136.9	127.9	2.58	2.5	93.4
8-2	24.6	136.9	131.1	2.58	3.3	95.7
8-3	24.6	136.9	124.5	2.58	8.5	90.9
8-4	24.6	136.9	130.3	2.58	3.4	95.2
9	26.2	133.2	127.4	2.46	5.0	95.6
11	20.0	135.6	131.3	2.52	3.3	96.8
12	40.0	133.6	126.6	2.43	4.6	94.8

Table 1.2 Example of Report Form C.4 as an output from the data processing software.

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Parameter	Chamber Confining Pressure	Nominal Max. Axial Stress	Cycle No.	Actual Applied Max. Axial Load	Actual Applied Cycle Load	Actual Applied Contact Load	Actual Applied Max Axial	Actual Applied Cycle Stress	Actual Applied Contact Stress	Recov Def. LVDT #1 Reading	Recov Def. LVDT #2	Average Recov Def. LVDT 1 and	Resilient Strain	Resilient Modulus
Designation	S ₃	S _{max}	C ₁	P _{max}	P _{cyclic}	P _{contact}	S _{max}	S _{cyclic}	S _{contact}	H ₁	H ₂	H _{avg}	ε _r	M _r
Unit	kPa	kPa		kN	kN	kN	kPa	kPa	kPa	meter	meter	meter	m/m	MPa
Precision														
Sequence 1	20.7	20.7	96.00	0.35	0.31	0.03	18.94	17.06	1.88	4.21E-05		4.21E-05	1.38E-04	123.45
	20.7	20.7	97.00	0.35	0.31	0.03	18.93	17.05	1.88	4.19E-05		4.19E-05	1.38E-04	123.87
	20.7	20.7	98.00	0.35	0.31	0.03	18.95	17.08	1.88	4.24E-05		4.24E-05	1.39E-04	122.82
	20.7	20.7	99.00	0.35	0.31	0.03	18.94	17.06	1.88	4.19E-05		4.19E-05	1.38E-04	124.01
	20.7	20.7	100.00	0.35	0.31	0.03	18.95	17.06	1.89	4.19E-05		4.19E-05	1.38E-04	124.03
Sequence 2	20.7	41.4	96.00	0.73	0.65	0.07	39.71	35.74	3.97	7.74E-05		7.74E-05	2.54E-04	140.66
	20.7	41.4	97.00	0.73	0.65	0.07	39.72	35.75	3.97	7.75E-05		7.75E-05	2.54E-04	140.65
	20.7	41.4	98.00	0.73	0.65	0.07	39.73	35.76	3.96	7.72E-05		7.72E-05	2.53E-04	141.10
	20.7	41.4	99.00	0.73	0.65	0.07	39.70	35.74	3.97	7.75E-05		7.75E-05	2.54E-04	140.62
	20.7	41.4	100.00	0.73	0.65	0.07	39.74	35.77	3.97	7.74E-05		7.74E-05	2.54E-04	140.82

Table 1.3 Resilient modulus summary of results with statistical data.

Sample Number	Average Resilient Modulus (MPa)														
	Sequence Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4-2	123.6	140.8	154.2	170.0	190.7	200.7	251.3	272.5	267.9	269.9	285.5	317.0	323.6	337.8	368.7
4-3	122.5	140.8	160.9	177.9	206.8	225.3	266.4	305.1	315.9	290.5	318.2	368.1	355.5	379.4	423.9
6	119.6	131.7	144.8	163.4	181.7	192.8	244.5	268.5	274.9	280.8	293.4	324.9	330.5	343.5	372.7
8-1	121.1	136.9	152.9	176.1	197.6	211.5	269.9	301.3	312.6	317.3	336.0	381.5	386.6	407.1	451.6
8-2	138.6	154.0	168.4	187.9	209.3	220.5	271.6	298.5	303.1	295.1	316.3	352.1	349.7	368.1	403.5
8-3	147.8	167.7	188.5	214.3	242.7	265.1	342.4	388.0	404.8	362.0	392.9	458.0	414.4	443.1	513.4
8-4	158.1	175.1	193.8	225.9	252.1	267.4	335.2	368.0	373.5	373.1	391.8	440.2	432.8	453.5	501.8
9	123.3	135.3	148.7	166.5	184.4	196.0	241.8	262.9	268.8	272.2	284.1	312.1	317.5	328.7	354.4
11	148.4	163.8	180.9	157.5	228.9	248.0	296.2	328.1	343.1	325.7	347.3	390.4	380.6	402.4	440.5
12	147.4	161.8	177.4	196.0	220.3	236.0	299.9	328.8	336.7	340.5	359.7	396.0	406.5	424.0	455.2
Average	135.0	150.8	167.0	183.6	211.4	226.3	281.9	312.2	320.1	312.7	332.5	374.0	369.8	388.8	428.6
STDEV	14.5	15.5	17.4	22.5	24.2	27.3	35.7	41.7	45.4	37.0	40.4	49.7	40.4	44.3	54.6
Plus 1 STDEV	149.6	166.3	184.4	206.1	235.7	253.6	317.6	353.9	365.6	349.7	372.9	423.8	410.2	433.1	483.1
Minus 1 STDEV	120.5	135.2	149.7	161.0	187.2	199.0	246.2	270.5	274.7	275.7	292.1	324.3	329.3	344.4	374.0
COV	0.11	0.10	0.10	0.12	0.11	0.12	0.13	0.13	0.14	0.12	0.12	0.13	0.11	0.11	0.13

Figure 1.1 Typical cross section of pavement structure used in the state of Rhode Island (adapted from Lee et al. 2001). Prior to reclamation (a) 1960s, after reclamation (b) 1980s.

Figure 1.2 Cyclic stress-strain curve illustrating how the resilient modulus is defined.

Figure 1.3 Grain size distribution for all samples tested.

Figure 1.4 Typical stress-strain plot for all loading cycles during the resilient modulus test (sample 8-1).

Figure 1.5 Typical stress-strain plot for the last 5 cycles of each load sequence during the resilient modulus test (sample 8-1).

Figure 1.6 Data points represent the average resilient modulus of all tested RAP/aggregate subbase samples at ambient temperature. Error bars represent one standard deviation.

Figure 1.7 Resilient modulus plotted with relative compaction (RC) for all samples tested that were within optimum moisture content (OMC) $\pm 2\%$. Also, including trend lines from research performed by Attia et al. (2010) on 50% RAP/aggregate blends at OMC ± 2

Figure 1.8 Resilient modulus plotted with RAP content for all samples tested meeting relative compaction of 95% and OMC $\pm 2\%$.

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**2. The Effect of the Initial Effective Confining Stress on the Dissipated Energy
at Initial Liquefaction of Monterey Sand**

by

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Civil Engineers Geo-Congress.

Abstract

This thesis presents the results of a study where cyclic triaxial tests were performed on Monterey sand to investigate the influence of initial effective confining stress on the dissipated energy at initial liquefaction. Energy-based liquefaction procedures have been proposed as a more fundamental alternative to the more commonly used cyclic stress-based procedures. For example, it is well known that in the shear stress-based simplified procedures, initial confining pressure has an influence on the cyclic resistance. These effects are accounted for by multiplying the Cyclic Resistance Ratio (CRR) by an overburden stress correction factor ($K\text{-}\sigma$). However, it is uncertain at this point if a similar overburden correction factor is required for energy-based simplified procedures ($K\text{-}\sigma\text{-energy}$). Therefore, this thesis performs cyclic triaxial tests on Monterey sand at various initial effective confining stresses to investigate this effect. The results of this study suggest that, no overburden stress correction factor is needed for use with energy-based liquefaction procedures.

Introduction

Researchers for the last half century have been developing different techniques to evaluate the liquefaction potential of soils. There are three main procedures for determining this liquefaction potential: the stress-based procedure, proposed by Seed and Idriss (1971), the strain based procedure proposed by Dobry et al. (1982), and the energy-based procedure that began with early seismologists such as Gutenberg and Richter (Green 2001). The focus of this study is on the energy-based procedure.

Energy-based procedures were first proposed in 1956 when Gutenberg and Richter published their paper on the *Magnitude and Energy of Earthquakes*. Since then

researchers have used their approach to quantify the amount of energy produced by an earthquake. Nemat-Nasser and Shokooh (1979) developed a link between the amount of energy produced by an earthquake and the response in pore water pressure.

This research was a breakthrough in showing that the change in pore water pressure is related to the change in dissipated energy. Berrill and Davis (1985) were guided by the information from Nemat-Nasser and Shokooh (1979), as well as tests performed by Simcock et al. (1983), and determined that a representative model of the pore pressure increase is given by the equation

$$\frac{\Delta u}{\sigma_o'} = \alpha \left[\frac{\Sigma \Delta W}{\sigma_o'} \right]^\beta \quad (2.1)$$

where Δu =change in pore water pressure, $\Sigma \Delta W$ =cumulative dissipated energy, σ_o' =initial effective stress, and α and β are curve fitting parameters.

As shown in this power equation, the excess pore water pressure and the dissipated energy are normalized by the initial effective stress. Dissipated energy is defined as the area enclosed by the stress-strain plot under a cycle of loading, and can be illustrated by Figure 2.1.

Researchers used this information to develop energy-based liquefaction procedures such as the procedures presented in Berrill and Davis (1982), Berrill and Davis (1985), Trifunac (1995), Kayen et al. (1997), and Green (2001). Most are similar in that they relate the pore water pressure ratio to the normalized cumulative dissipated energy. The only procedure that does not normalize energy by the initial effective stress is

Kayen et al. (1997) whose method is based on arias intensity which does not account for stress.

There is concern that normalizing the cumulative energy dissipated by the initial effective stress is an over simplification of the behavior. This is analogous to the stress-based liquefaction assessment procedure. When the stress-based liquefaction procedure was originally developed, it was assumed that resistance to cyclic stress increased linearly with confining pressure. After further analysis and testing this relationship was shown to not be a perfect fit. To resolve this issue, a correction factor for non-linear effects of overburden stress was attached to the stress-based procedure. This correction factor was given the name K-sigma. Because of this it is unsure if normalizing the dissipated energy in the energy-based liquefaction procedure, by the initial effective stress is an over simplification. It is important that this effect be known so that accurate analysis of energy-based liquefaction procedures can be performed. The objective of this study is to investigate the effect of the initial effective confining pressure on the normalized energy capacity of the soil, and if necessary propose a correction factor comparable to K-sigma in the stress-based procedure.

Triaxial Testing

The soil tested for this study was loose Monterey sand purchased from Kleenblast in Hayward, CA. Another name for this material is CEMEX Lapis Lustre Sand #0/30. Physical properties testing was performed at the University of Rhode Island for minimum and maximum density (ASTM D 4254-00, ASTM D 4253-00) and grain size distribution (ASTM D422-63 (98)). The minimum and maximum void ratios were found to be 0.808 and 0.589 respectively. A grain size distribution can be seen in

Figure 2.2, which indicates $D_{50}=0.55$ mm. The soil samples were prepared by wet pluviation to an initial relative density of approximately 50%. The relative density changed slightly from preparation to testing because of the confining stress. Cyclic triaxial tests were performed on samples 71 mm (2.8 inches) in diameter and 165 mm (6.5 inches) in height.

Slurry pluviation was used to obtain a homogenous and saturated sample. This method yields an extremely loose sample fabric that is anticipated to be representative of a fluvial soil deposit. Denser samples are created through vibratory methods. As found in Mulilis et al. (1977), the type of vibration affects the soil fabric and cyclic resistance. Soil samples created with high frequency vibrations yielded a stronger soil fabric with higher cycle resistance than those samples prepared with a low frequency. The samples in this study were prepared by low frequency vertical vibration to yield the lowest cyclic strengths.

This study used a split mold, and PVC pipe filled with a known mass of soil. The PVC pipe was lifted slowly allowing the soil to pluviate into a water filled membrane similar to Carraro et al. (2003). A metal plate was placed on the split mold, and a standard proctor hammer was dropped from a height of 3 inches onto the plate. The number of drops by the standard proctor hammer can be changed to achieve different relative densities. Details of the sample preparation are presented in Appendix C.

The triaxial cell was assembled and samples were placed under back pressure saturation of approximately 413.6 kPa (60 psi). A B-parameter check was performed which is defined as the change in pore water pressure over the change in total stress.

Samples were held under back pressure until a B-parameter of at least 0.95 was achieved. The samples were isotropically consolidated to three different confining pressures of 50 kPa, 100 kPa, and 200 kPa. After 5 minutes of consolidation, the sample was then cyclically sheared at a specified Cyclic Stress Ratio (CSR) that ranged from 0.18 to 0.25.

As shown in Table 2.1, a total of 12 tests were completed. Samples achieved B-values greater than 0.95. This study was able to achieve repeatable sample preparation as shown in the relative densities among the same initial effective confining pressure. Relative densities increased for higher initial effective confining pressures, and ranged from 46% to 54%. Sample failure was defined when the pore pressure parameter r_u , which is the ratio of excess pore water pressure to initial effective confining stress, reached a value of 1. The number of cycles until failure ranged from approximately 4 to 313 depending on CSR and initial effective confining pressure.

Figures 2.3 and 2.4 illustrate typical stress-strain curves for the samples tested. The plots contain deviator stress in kPa on the vertical axis and raw axial strain on the horizontal. Positive values indicate compression. As shown in figures, none of the samples have perfect elliptical shaped hysteresis loops. In some of the plots in the figures, the banana shaped hysteresis loops appear more definitively than in others. This may suggest that though the sample preparation method is consistent with the amount of energy applied to the sample, the sample may not be homogenous. Further testing would need to be performed to solidify the hypothesis that mild banana shaped hysteresis loops during loading indicate a heterogeneous soil sample, or if this variability is a result of the cyclic testing itself.

It is also shown in Figures 2.3 and 2.4 that as the test progresses the values of axial strain become more negative. This indicates that the sample is becoming extended throughout the test. The loops are larger below the x-axis, showing that more energy is being dissipated during the extension portion of the cycle. According to results shown in Simcock et al. (1983), this is typical behavior.

It is common to present cyclic test results on a plot of CSR vs. number of cycles at failure such as Figure 2.5. This figure presents the achieved CSR on the vertical axis and the number of cycles at failure on the horizontal. A power function is fit through each set of data points of the same initial effective confining pressure. The data points for the initial effective confining stresses of 50 kPa and 200 kPa fit the power function well, as indicated by the high R^2 values of the trend line. Testing performed at an initial effective confining stress of 100 kPa had more scatter, and thus a lower R^2 value of the trend line.

The results of this study are compared to the results of Mulilis et al. (1977). Trend lines are also shown in the figure for the two soil preparation methods of Mulilis et al. (1977) closest to the sample preparation method used in this thesis. The methods were low frequency vertical vibrations, and pluviation through water. The results from the authors testing at an initial confining pressure of 50 kPa, plot within or very close to the trend lines from Mulilis for the number of cycles until failure greater than 20. This indicates reliable testing practices were used.

Analysis of Dissipated Energy

Using the results from the triaxial tests, the cumulative energy dissipated was calculated by integrating the stress-strain plot, such as Figure 2.3, according to the equation

$$\Sigma \Delta W = \Sigma (\sigma_{d,i+1} + \sigma_{d,i}) (\epsilon_{a,i+1} - \epsilon_{a,i}) \quad (2.2 \text{ adapted from Green 2001})$$

where $\Sigma \Delta W$ = the cumulative dissipated energy for all stress-strain loops, $\sigma_{d,i}$ = the i^{th} increment in deviator stress, $\epsilon_{a,i}$ = the i^{th} increment in axial strain.

Figure 2.6 presents the cumulative dissipated energy on the vertical axis and the number of cycles on the horizontal axis. The data points were created by calculating the cumulative sum of the area enclosed by the stress-strain loops. This area was calculated at every half cycle, or in other words at each half of the hysteresis loop; for the number of loops until the soil reached initial liquefaction. This is $\Sigma \Delta W_L$. Each data point represents the cumulative dissipated energy of the sample up to that point.

$\Sigma \Delta W$ includes the effect of pore pressure and needs to be corrected for the softening of the soil due to the development of excess pore water pressure. This correction needs to be performed to remain consistent with previous liquefaction studies performed by the stress-based procedure. In the stress-based procedure a SHAKE analysis (Idriss and Sun 1992) software is used which performs a total stress analysis and does not account for excess pore water pressure generation. To correct for soil softening in the energy-based procedure, a trend line is drawn through the initial linear points in Figure 2.6 and continued until it crosses the number of cycles at failure. The linear trend line drawn through the data points corresponds to a pore pressure ratio of 0.4 and lower.

The data points fitting this criterion are represented by an “x” in Figure 2.6. The value of 0.4 was reached empirically and was found to encompass a representative amount of linear data points. The intersection represented in Figure 2.6 by the trend line and the vertical line at failure is called $\Sigma\Delta W_L^*$. This point on the plot represents the amount of dissipated energy from the soil specimen adjusted for the development of excess pore water pressure generation. This value can be normalized by the initial effective confining pressure. The normalized term is represented as $\Sigma\Delta W_L^*/\sigma'_o$, and is often called the normalized energy capacity.

Results and Discussion of Dissipated Energy

Table 2.2 presents the dissipated energy results used for analysis in this study. The area under the stress-strain hysteresis loops for all samples tested is also numerically shown in the last three columns in Table 2.2.

The cumulative dissipated energy at liquefaction for each sample tested is shown in Figure 2.7 as $\Sigma\Delta W_L$. Where the vertical axis is $\Sigma\Delta W_L$, and the horizontal axis is initial effective confining pressure. Also shown are the error bars which represent the standard deviation associated with the different initial effective confining pressure tests. The standard deviation indicates that there is a wide spread in the data. The average at each initial effective confining pressure is also shown. A linear trend line was fit through the average data and through the origin. This trend line provides a reasonable fit to the average of the data as represented by the R-squared value 0.95, illustrating that the total dissipated energy increases linearly with effective confining pressure. A similar effect can be seen with $\Sigma\Delta W_L^*$ in Figure 2.8, where the results have been corrected for softening due to an increase in excess pore pressure.

Figure 2.9 represents the dissipated energy corrected for soil softening, normalized by the initial effective confining pressure (i.e. $\Sigma\Delta W_L^*/\sigma'_o$). The flat trend line indicates that the amount of dissipated energy increases linearly with effective confining stress. Since this is a flat trend line, no additional corrections need to be made to the dissipated energy. This suggests that no K-sigma-energy is necessary. However, this study was limited to Monterey sand prepared at one density, because of this there is scatter in the data. It is believed that the scatter is caused by the sensitivity of the loose soil fabric produced by the slurry deposition method. To reduce the scatter, future testing should be performed at a higher relative density.

Table 2.3 represents the statistical information of the normalized data points ($\Sigma\Delta W_L^*/\sigma'_o$). The coefficient of variation (COV), which is defined as the average value divided by the standard deviation, quantifies the variation of the results. The COV of the values is high for the test data. A COV value greater than 1 indicates that some of the data is not within one standard deviations of the mean (Harr 1987). This suggests that though great care was taken during sample preparation and testing, the nature of this cyclic liquefaction testing has variation.

Conclusions

Cyclic triaxial tests were performed on 12 samples of Monterey sand. The samples were tested at different initial effective confining pressures that ranged from 50 kPa to 200 kPa. All samples were produced using the slurry pluviation method to an approximate relative density of 50%. The cumulative area under the stress-strain curve, also known as the cumulative dissipated energy, was calculated until the point of liquefaction for all tests ($\Sigma\Delta W_L$). The total cumulative dissipated energy was

corrected for soil softening due to excess pore water pressure development ($\Sigma\Delta W_L^*$). The corrected value was then normalized by the initial effective confining stress ($\Sigma\Delta W_L^*/\sigma'_o$). The results suggest that normalization of the cumulative dissipated energy by the initial effective confining pressure captures the behavior and thus no additional modification or correction factor is needed. However, the study was limited to samples with a relative density of approximately 50%. Further testing should be performed on samples with other relative densities to determine the applicability of the trends presented in this thesis to other relative densities.

Recommendations for Future Research

Due to the sensitivity of testing very loose soil samples with weak fabric, future energy-based liquefaction testing should consist of testing higher relative density samples. The results of this testing also only apply to a specific type of soil and therefore, other soil types should be tested. It would also be interesting to investigate the hypothesis that mild banana shaped hysteresis loops during loading indicate a heterogeneous soil sample, or if this variability is a result of the cyclic testing itself. A possible method to investigate this is through a different soil preparation method such as moist tamping. This may improve upon the knowledge of the energy-based liquefaction procedure as well as, possibly, lower the variability amongst the results.

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Table 2.1 Parameters for all samples tested.

Test Number	Initial Effective Confining Stress (kPa)	Relative Density %	B-value Range		CSR	Number of Cycles at $r_u=1$
cyc-13-21	50	51	0.97	0.98	0.226	36.0
cyc-13-22	50	51	0.98	0.99	0.216	29.6
cyc-13-23	50	51	0.98	0.98	0.194	313.0
cyc-13-24	50	50	0.95	0.96	0.238	13.2
cyc-13-25	50	51	0.96	0.96	0.246	10.2
cyc-13-27	100	53	0.99	1.00	0.210	81.1
cyc-13-28	100	52	0.96	0.97	0.215	147.1
cyc-13-29	100	53	0.97	0.97	0.218	4.0
cyc-13-30	100	46	0.98	0.98	0.213	20.2
cyc-13-32	200	54	1.00	1.00	0.197	63.1
cyc-13-33	200	54	0.97	0.98	0.197	36.1
cyc-13-34	200	54	0.97	0.98	0.217	6.1

Table 2.2 Dissipated energy for tests at approximately Dr=50%.

Test Number	Initial Effective Confining Pressure (kPa)	Relative Density %	Number of Cycles at $r_u=1$	$\Sigma \Delta W_{Liq}$	$\Sigma \Delta W_{Liq}^*$	$\Sigma \Delta W_{Liq}^*/\sigma'_o$
cyc-13-21	50	51	36.0	0.717	0.494	0.010
cyc-13-22	50	51	29.6	0.519	0.289	0.006
cyc-13-23	50	51	313.0	2.963	2.180	0.044
cyc-13-24	50	50	13.2	0.347	0.210	0.004
cyc-13-25	50	51	10.2	0.511	0.300	0.006
cyc-13-27	100	53	81.1	3.195	2.557	0.026
cyc-13-28	100	52	147.1	4.360	2.522	0.025
cyc-13-29	100	53	4.0	0.673	0.466	0.005
cyc-13-30	100	46	20.2	0.994	0.724	0.007
cyc-13-32	200	54	63.1	9.287	4.488	0.022
cyc-13-33	200	54	36.1	6.817	2.444	0.012
cyc-13-34	200	54	6.1	2.917	0.873	0.004

Table 2.3 Statistical data on the normalized dissipated energy corrected for softening ($\Sigma\Delta W_L^*/\sigma'_o$) of samples with Dr=50%.

Initial Effective Confining Pressure (kPa)	Standard Deviation	Average	COV
50	0.017	0.014	0.830
100	0.011	0.016	1.390
200	0.009	0.013	1.435

Figure 2.1 Illustrates the area bound by the hysteresis loop (Green 2001).

Figure 2.2 Grain size distribution of Monterey sand.

cyc-13-21

cyc-13-22

cyc-13-23

cyc-13-24

cyc-13-25

cyc-13-27

Figure 2.3. Stress-strain curves for the first six samples tested, $D_r \sim 50\%$.

cyc-13-28

cyc-13-29

cyc-13-30

cyc-13-32

cyc-13-33

cyc-13-34

Figure 2.4. Stress-strain curves for the last six samples tested, $D_r \sim 50\%$.

Figure 2.5 Achieved cyclic stress ratio vs. number of cycle until failure for all tests, also including trend lines from Mulilis et al. (1977) for similar soil preparation methods.

Figure 2.6 Typical results of cumulated energy dissipated from sample cyc-13-22.

Figure 2.7 Sum of cumulative dissipated energy at initial liquefaction. Error bars assume a log-normal distribution.

Figure 2.8 Sum of cumulative dissipated energy at initial liquefaction corrected for soil softening for all tests. Error bars assume a log-normal distribution.

Figure 2.9 Sum of the dissipated energy at initial liquefaction normalized by the initial effective confining pressure for all tests. Error bars assume a log-normal distribution.

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3. Appendix A: Equipment Operation

The equipment and use of the equipment are given in this appendix. This includes the types of equipment, computer software, and maintenance plan of the equipment.

Equipment

The figures below show both pieces of equipment. The first is the resilient modulus testing equipment shown in Figure 3.1. This is often referred to as the Instron 8800. Another system, Instron 8872, was purchased and retrofitted to suit the cyclic liquefaction needs of the author and is shown in Figure 3.2. Both systems operate in a similar fashion; below is an outline to the operation of the equipment.

(a)

(b)

Figure 3.1 Resilient modulus testing equipment at URI including (a) computer and control system, and (b) 6 inch diameter triaxial cell.

Figure 3.2 Cyclic liquefaction testing equipment at URI.

Operation of Equipment

1. Turn water to pump on
 - a. Resilient modulus equipment has a quarter turn ball valve above the hydraulic pump
 - b. Cyclic liquefaction equipment has (2) quarter turn ball valves behind the hydraulic pump. These should always remain open.
2. Turn computer on
 - a. Instron 8800 (resilient modulus) password: frankterra
 - b. Instron 8872 (cyclic liquefaction) password: instron

3. Open Instron Console – this is the software controlling the system in the background
 - a. Click the blue arrow on the left side of the screen (known as the setpoint)
 - b. Select “position” from the control mode drop down menu
 - c. Make sure the piston on the machine is free to move up or down and press start
 - d. The system is now in position control mode and the buttons on the remote should now be lit
 - e. The buttons move the machine piston up and down (coarse control), the roller on the remote moves the piston as a fine control
 - f. From the same blue arrow, load control mode can also be selected
 - g. Position the sample in the load frame
 - h. Select the button below the “STOP” button, this will open the system controls
 - i. At the top there are menus for position, load, LVDTs, or pressure transducers
 - j. Select the one of choice (example load cell)
 - i. If you click the load cell icon this brings up a screen that displays “load cell shortcuts”. From this screen the user has three hyperlink options:
 1. **Primary limits-** this sets the upper and lower limits. If a limit is tripped the user can change the limit action in the

drop down menu. When a limit is tripped the user will have to return to this menu and turn the limit off. The limit menu can also be accessed next to the load cell icon by selecting the arrows. If the arrows are green the limits are set. If they are white the limits are not set. When an arrow is red, that is the limit that has been tripped.

2. **Control-** by selecting the control hyperlink, the user is able to change the PID settings. This is responsible for specimen stiffness. **WARNING: NEVER CHANGE THE PID SETTINGS OF THE PISTON. INSTRON WILL HAVE TO BE CALLED IN ORDER TO FIX!**
To change the PID settings the user can select the:

- a. **Auto Tuning Wizard** - Once selected this displays the auto tuning parameters. When adjusting the PID settings a setting load should be applied to the sample. For example, the author used 50 lbs. for the resilient modulus tests. The tuning disturbance amplitude parameter can be modified based on the required test. If the test being perform is always in compression than the tuning amplitude should be less than the seating load. If the test being performed requires

compression and tension, the tuning disturbance amplitude should represent this.

- b. **Loop Tuning Wizard** – This option can be used if the user wants to control the tuning process manually. See Figure 3.3 below. The user can adjust the PID settings in the upper left corner of the screen. The red line depicts the output from the computer, and the green line represents the load cells response. The goal is to make the green line have the same shape as the red line. It is the author's experience that the auto tuning wizard does an excellent job in the tuning process, and therefore, the loop tuning procedure was rarely used.

Figure 3.3 PID loop tuning (manual) settings window.

3. **Calibration-** The units of the machine can be changed here. When this hyperlink is selected the user has two options: WARNING: NEVER PERFORM A BALANCE OR CALIBRATION ON THE PISTON. INSTRON WILL NEED TO BE CALLED TO RESET.
 - a. Balance- this is where the load cell, LVDT, or user defined can be tarred.
 - b. Calibration Wizard - this option can be used to reset the calibration of the equipment.

4. Open Instron Wavematrix – this is the software where the user can design the testing needed
 - a. The user has 5 options on the home screen
 - i. Test- by selecting this option the user can create a project to store all the testing results, or continue with a project that is already created. Once a project is selected or created, select next. The next screen displays the testing methods the user wishes to perform. Once chosen select next. The testing graphs will be displayed. To begin the test select start. The computer will then display an icon asking if the user is positive the test is ready. By selecting “OK” the test will begin.
 - ii. Method - by selecting this option, the user is allowed to make a testing sequence
 1. Select Create new method or open method
 - a. Creating a new method – the home screen opens to the testing sequence. This is the area of the test method where the user can piece together the sequence of events they want the machine to perform (steps). This can be seen in the picture below.

Figure 3.4 Instron test method development and sequence editing screen.

The solid square located at the top of the page near the arrow indicates what the step will do. The line in the middle of the square will turn green if the control mode is position, and red if the control mode is load. The lower arrow points to the possible waveform that can be used. The options starting from the top are: hold, absolute ramp, relative ramp, trapezoidal, cyclic, tri-modal, sampled data waveform, and user defined.

Hold- holds the specimen in either position or load for a set amount of time

Absolute ramp- moves the piston in an absolute fashion, uses the location of the internal piston LVDT. For example if the internal piston LVDT reads 1.5", and the absolute ramp is set to 2", the piston will move 0.5".

Relative ramp – moves the piston in a relative fashion, uses the location of the internal piston LVDT. For example if the internal piston reads 1.5", and the relative ramp is set to -2.0", the piston will move until the internal LVDT reads -0.5", thus displacing 2".

Trapezoidal – a cyclic function where there is a hold function build into the peak and trough.

Cyclic – a cyclic function where the shape of the wave can be defined

Trimodal - see Instron manual for detail

Sampled Data – the user can use this function to import a set of data, for example and earthquake time history

User defined – the user can make their own waveform, this often allows for faster response when asking the machine to perform very fast calculations such as the resilient modulus. By selecting the data acquisition block, represented by the blue square just above the upper arrow in the figure below, the user can turn the data acquisition system on.

Figure 3.5 Instron data acquisition development and editing window, which is located within the test method window.

The user can specify which information the data acquisition system saves by moving through the tabs shown enclosed by the rectangle. For example in this figure the machine will save every point between cycles 1 and 10. From cycles 10 to 20, the machine will save only the 10th cycle, this pattern can continue. The user can change and edit these settings by selecting them.

On the method home screen, the user will also notice different options as shown in the figure below. The first tab is labeled “General” the settings in this tab should not need to be changed. The second tab is labeled “Channels”. This tab displays two columns. The column on the left displays the channels that are available on the Instron machine, and the column on the right displays the channels you want to use in the testing method. Be sure to always have position, and load. The other channels displayed depend on what accessories are plugged into the machine. External LVDTs are referred to as “extension”. The arrow buttons between the two columns can be used to add or remove channels from the testing method.

Also on the method home screen are tabs for the graphical display throughout the test. These can be opened and edited according to the users preferences. Graphs are not directly saved from Instron Wavematrix, they are only a tool that can be used to ensure the machine is doing what the user wants it to do.

Figure 3.6 Channel selecting window located within the test method window.

- iii. Admin- by selecting this option the user can view the software versions and preferences in the system
- iv. Help – opens the manual for Instron Wavematrix
- v. Exit – closes the system

5. Results

- a. At the time of this writing the results from testing are stored in the following folder path: Documents/Instron/wavematrix/projects/(project that was created)/test number
- b. This file path can be changed in the Admin tab

6. Development of pore water pressure transducer

- a. Instron uses a 25 way D-type connector, and the connection on the pore-water pressure transducer is a 4 way microphone plug.
- b. Wires should be connected and soldered as shown in the table below.

Table 3.1 Pore pressure transducer to Instron wiring diagram (1).

Pore Water Pressure Transducer		Instron		Wire Color
Pin Number	Description	Pin number	Description	
1	Signal Output +	15	Lo A	Green
2	Signal Output -	14	Lo B-	White
3	Excitation +/- Power Supply	1	Excitation A+	Red
4	Excitation -/ Ground	2	Excitation B-	Black
		4	Jumped	
		5	Together

Figure 3.7 Pore pressure transducer to Instron wiring diagram.

c. Once the connections are made, plug the transducer into the Instron.

The operator will need to communicate to the Instron what this new device is. The Instron will read it as “user-defined”.

i. Enter the calibration wizard window and follow the prompts.

ii. An example of the calibration window is:

Figure 3.8 Instron Wavematrix calibration wizard.

For further detail on any of the above mentioned information, use the Help function in either Instron Console or Instron Wavematrix.

Maintenance of Equipment:

The author along with staff from the department of Civil and Environmental Engineering performed routine maintenance on the resilient modulus existing equipment. The same steps can be used for the cyclic liquefaction equipment. The hydraulic oil in the Instron hydraulic pump was changed along with the filter. The resilient modulus pump requires approximately 13 gallons of Mobil DTE-25 hydraulic oil. The filter which can be purchase from Pall Trincor, part number HC7400SKP4H, is approximately \$113. The same filter can also be purchased from Instron for approximately \$215. During this process the system should also be flushed to circulate

the new hydraulic oil and rid the system of air pockets. The process for changing the hydraulic oil and filter is as follows:

1. Lift Hydraulic pump approximately 1 ft above the ground.
2. Remove oil drain plug on lower left side of pump.
3. Drain the existing oil from the pump.
4. Reinstall the oil drain plug.
5. Lower pump to ground.
6. Replace oil filter. Be sure to fill the new oil filter partially before installing.
7. Fill the pump reservoir located in the back right portion of the pump.

The process for flushing the system is as follows:

1. Turn the water to the pump on, and turn the pump on.
2. On the front right portion of the pump is a pressure gauge, press the silver button and record the existing pressure.
3. Turn the knob next to the silver button to reduce the pressure to a minimum, the lower the pressure the better. The pressure should be just high enough to circulate the hydraulic oil.
4. Turn the pump off.
5. Remove the servo valve (see note below) from the back of the Instron load frame.
6. Install the flushing valve (see figure below)
 - a. The resilient flushing valve is located in the cabinet of the graduate office in the basement of Bliss Hall. The flushing valve for the cyclic liquefaction equipment is located on the back of the equipment. Be sure

to install the valve so the ports on the back side of the flushing valve line up with the ports of the machine. Failure to do so could cause hydraulic damage or leak.

Figure 3.9 Hydraulic flushing valve for both systems.

7. Turn the pump on and monitor the flushing valve to ensure there are no leaks.
8. Leave the pump running for approximately 10 minutes.
9. Shut the pump off and reinstall the servo valve.
10. Restore the hydraulic pressure on the pump.

Note: ***servo valve may need to be replaced or rebuilt if making a high pitch whining sound. Ensure that sound is not caused by the oscillation of the servo valve if the PID settings are not at optimum. If rebuild or replacement is needed, contact Perfection Servo.

Carol Biela

Perfection Servo | Inside Sales Manager

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Cost: (July 2012)

Clean & Calibrate-\$480.00

Minor motor-\$595.00

Major motor-\$940.00

Re-spool-\$1,115.00

Max-\$1,290.00

Resilient modulus system (Instron 8800)

Model: Moog 760-964A

Serial Number: 103

Cyclic Liquefaction system (Instron 8872)

Model: Moog G761-3054B

Serial Number: 5100

This process should be performed every two years, or every 2000 motor hours. The author performed this maintenance in August 2012, and at this time the motor had 2100 hours on it. The motor bearings on the hydraulic pump should also be greased every 6 months with use. The author also did this at the same time.

4. Appendix B: Resilient Modulus Test Procedure

The testing procedure used for the resilient modulus is given in this appendix. This includes the determination of input loads, piston friction, pre-specimen sample preparation and correction factors, sample preparation, and the Matlab code used to perform the post processing of the data.

Determination of Loads

Loads were developed to input into the Instron testing method. The base line base/sub-base loads used came from AASHTO T 307: Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials. The loads entered into the testing method were corrected for external weight including: the piston, LVDT, LVDT bracket, and the sample top cap. The loads were also corrected for the confining pressure and piston friction. Details on the piston friction correction are explained below. The author created a spreadsheet to determine these loads, and the new input loads if any changes were made to the equipment.

Table 4.1 Load inputs and load corrections for base/subbase.

Sequence number	Confining Pressure (kPa) S3	Load added to load cell from Confining Pressure (kN)		Load added to sample due to piston weight (kN)	Load added to sample due to LVDT (kN)	Load added to sample due to LVDT bracket (kN)		Load added to sample due to top cap (kN)	Piston Friction (kN)	Max Axial Smax		Amplitude in Instron (kN)	Amount of load reset (setpoint) (kN)
										Stress (kPa)	Load (kN)		
0	103.4	0.118		0.032	0.001	0.004	0.015	0.01	103.4	1.958	1.762	0.196	
1	20.7	0.024		0.032	0.001	0.004	0.015	0.01	20.7	0.359	0.323	0.036	
2	20.7	0.024		0.032	0.001	0.004	0.015	0.01	41.4	0.735	0.662	0.074	
3	20.7	0.024		0.032	0.001	0.004	0.015	0.01	62.1	1.112	1.001	0.111	
4	34.5	0.039		0.032	0.001	0.004	0.015	0.01	34.5	0.626	0.563	0.063	
5	34.5	0.039		0.032	0.001	0.004	0.015	0.01	68.9	1.252	1.127	0.125	
6	34.5	0.039		0.032	0.001	0.004	0.015	0.01	103.4	1.880	1.692	0.188	
7	68.9	0.079		0.032	0.001	0.004	0.015	0.01	68.9	1.291	1.162	0.129	
8	68.9	0.079		0.032	0.001	0.004	0.015	0.01	137.9	2.547	2.292	0.255	
9	68.9	0.079		0.032	0.001	0.004	0.015	0.01	206.8	3.801	3.421	0.380	
10	103.4	0.118		0.032	0.001	0.004	0.015	0.01	68.9	1.330	1.197	0.133	
11	103.4	0.118		0.032	0.001	0.004	0.015	0.01	103.4	1.958	1.762	0.196	
12	103.4	0.118		0.032	0.001	0.004	0.015	0.01	206.8	3.840	3.456	0.384	
13	137.9	0.157		0.032	0.001	0.004	0.015	0.01	103.4	1.998	1.798	0.200	
14	137.9	0.157		0.032	0.001	0.004	0.015	0.01	137.9	2.625	2.363	0.263	
15	137.9	0.157		0.032	0.001	0.004	0.015	0.01	275.8	5.135	4.622	0.514	

Piston Friction

The piston friction was determined for a range of confining pressures to determine if the magnitude of the confining pressure had a role in the piston friction. The piston friction was calculated by removing the piston from the triaxial cell and attaching it to the load cell as shown in the picture below.

Figure 4.1 Resilient modulus triaxial cell piston hanging from load cell.

The load cell was then balanced (tarred) to show a load of zero. The triaxial cell was then reassembled around the piston. The confining pressure was increased to pressures

of: 0 kPa, 20.7 kPa, 34.5 kPa, 68.9 kPa, 103.4 kPa, and 137.9 kPa. The piston friction was calculated using the equation below.

$$0 = LC - \sigma_3 A - P_f \quad (4.1)$$

Where LC is the readout of the load cell corresponding to a confining pressure (σ_3), A is the cross sectional area of the piston, and P_f is the piston friction in kN. A plot showing the calculated values is shown below.

Figure 4.2 Piston friction vs. confining pressure.

As the plot indicates, the piston friction is approximately 0.01 kN for the majority of the confining pressures. The author believes that the piston friction corresponding to a confining pressure of 137.9 kPa is different than the rest because at this higher confining pressure, the force generated is enough to mobilize the friction in the

opposite direction. In other words, the o-ring inside the piston had turned the opposite way as it was with the lower confining pressures.

Static and dynamic piston friction was also measured to verify the accuracy of using 0.01 kN. The static friction was measured by balancing the load cell as mentioned above. Next, the triaxial cell was assembled and a confining pressure applied. The author performed a displacement controlled test at a rate of 1 mm/min and measured the load. This was performed for all confining pressures and the results are displayed below. From this figure, the approximate average value of piston friction for all tests was chosen to be 0.01 kN.

Figure 4.3 Load vs. time for static piston friction test at a displacement rate of 1 mm/min.

A similar test was also performed for a dynamic position controlled pulse load with a displacement of 0.5 mm. The position controlled pulse load is the same type of wave

seen during the resilient modulus test only position controlled instead of load controlled. This displacement of 0.5 mm was chosen based on the authors experience in performing the resilient modulus test, and witnessing the amount of permanent deformation that is typically seen. The results of the dynamic test are also shown below.

Figure 4.4 Load vs. time for dynamic piston friction test with a pulse displacement of 0.5mm.

Based on the various piston friction tests, the author chose to use a constant piston friction of 0.01 kN.

Resilient Modulus Load Sequence

A user defined Instron Wavematrix was developed according to the load input table mentioned above. The user defined data imported to the Instron loading sequence test method is shown below.

Time (s)	% Amplitude
0.005	0
0.05	-1
0.1	0
0.2	0
0.3	0
0.4	0
0.5	0
0.6	0
0.7	0
0.8	0
0.9	0
1	0

Figure 4.5 Instron Wavematrix user defined import data

This load sequence is imported into the Instron Wavematrix software along with the loads from the column entitled “Amplitude in Instron” from the load Table 4.1. The Instron Wavematrix is also designed with rest periods which provide the operator a set amount of time to change the confining pressure where appropriate.

Pre-Sample Preparation

The soil in this thesis generally consisted of a moist, black to brown, fine to coarse SAND, little Gravel, little RAP, trace Silt. The AASHTO standard for the resilient modulus states to prepare the soil samples to their in place dry density and moisture content. Multiple steps and other geotechnical laboratory testing had to be performed to meet this requirement. These tests are referred to as the physical properties testing. The physical properties testing were performed at the University of Rhode Island, and repeated at the Rhode Island Department of Transportation. The steps taken and the testing performed at the University of Rhode Island are explained below.

After receiving the soil samples from RIDOT, the samples were cone and quartered in order to make a representative sample. From this process two representative samples from the same location were created (e.g. 4-1 and 4-2 would mean location 4 sample 1 and 2). Both samples were separated into $\frac{3}{4}''+$ (19 mm) material and $\frac{3}{4}''-$ (19 mm) material. The moist weight of this material was recorded and the samples were allowed to air dry. Once the samples appeared to be dry (after a few days to a week) they were then weighed again. The natural water content of the $\frac{3}{4}''+$ (19 mm) and the $\frac{3}{4}''-$ (19 mm) was calculated and recorded. The percent finer and percent coarser than $\frac{3}{4}''$ (19 mm) were calculated and recorded according to the equations below from AASHTO T224.

$$P_F = \frac{100M_{DF}}{(M_{DF} + M_{DC})} \quad (4.2)$$

$$P_C = \frac{100M_{DC}}{(M_{DF} + M_{DC})} \quad (4.3)$$

Where P_f and P_c are the percent finer and percent coarser respectively, M_{df} is the dry mass of the $\frac{3}{4}''-$ (19 mm) material, and M_{cd} is the dry mass of the $\frac{3}{4}''+$ (19 mm) material.

The cone and quartered sample (e.g. 4-1) was saved for resilient modulus testing. Geotechnical laboratory testing was performed on the other cone and quartered sample (e.g. 4-2). A Modified Proctor test was performed on the $\frac{3}{4}''-$ (19 mm) material in general accordance with AASHTO T 180, and a grain size distribution was also performed which included sieves (mm): 37.5, 10, 4.75, 2.38, 0.599, and 0.075. From

this grain size distribution the percent finer than 1.5" (38 mm) and the percent coarser than 1.5" (38 mm) was calculated. A specific gravity test of the 3/4"+ (19 mm) material was also performed in general accordance to AASHTO T 209-04.

AASHTO T 224: Standard Test Method for Correction for Coarse Particles in the Soil Compaction Test was used to correct for the 3/4"- (19 mm) maximum dry density obtained in the proctor test to the maximum dry density in the field of the entire sample. To perform this correction the following equation was used.

$$D_d = \frac{100D_f k}{(D_f P_c + kP_f)} \quad (4.4)$$

Where D_d is the corrected maximum dry density of the entire sample, k is 62.4 pcf or 1000 kg/m^3 * the bulk specific gravity of the 3/4"+ (19 mm) material, and D_f is the maximum dry density of the 3/4"- (19 mm) material obtained by the Modified Proctor test. A computer programming code was developed to assist with this calculation, and can be seen below.

```

Moisture and Density Correction for Resilient Modulus made by Jeff Costa
%%AASHTO T-224-01
%%Laboratory Proctor Test to Field Conditions
pf34=86.7758;%percentage of fine material by weight (in percent) 3/4-
pc34=13.224;%percentage of coarse material by weight (in percent) 3/4+
mcf=0.024;%moisture content of fine material in decimal
mcc=0.007;%moisture content of the coarse material in decimal
%%corrected moisture content in the field
moisture_content_field=((mcf*pf34)+(mcc*pc34))/100;%corrected moisture content in field of the combined oversize and finer
particles expressed as a decimal
df=130.5;%pcf maximum dry density from proctor from 3/4- particles
gs=2.519;%specific gravity of coarse material obtained from specific gravity test 3/4+ particles
k=62.4*gs;%use 1000 if you are in metric units or 62.4 if you are in english
%%corrected dry density in the field
max_dry_density_field=(100*df*k)/((df*pc34)+(k*pf34));%corrected dry density combined oversize and fine (pcf) in the field
% % % %field condition to resilient modulus
pf15=92.74;%percent finer than 1.5" from grain size analysis
pc15=1.26;%percent coarser than 1.5" from grain size analysis

```

Figure 4.6 Computer code used to perform the necessary density corrections.

In order for 95% of the maximum field density to be easily obtained, the samples were compacted into the split mold at optimum moisture content. The optimum moisture content was calculated based on the equation below. This equation was derived based on the assumption that the ratio of water content to percentage of weight holds constant for a specific soil.

$$W_{ct} = W_f * P_f + W_c * P_c \quad (4.5)$$

Where W_{ct} is the corrected optimum water content of the entire sample, W_f is the optimum water content of the finer fraction from the Modified Proctor test, W_c is the optimum water content of the coarser fraction determined by the equation below, and P_f and P_c are the percent finer $\frac{3}{4}$ "- (19 mm) and percent coarser $\frac{3}{4}$ " + (19 mm) by weight.

$$W_c = \frac{W_{f2} * W_{c1}}{W_{f1}} \quad (4.6)$$

Where W_{f2} is the optimum water content of the $\frac{3}{4}$ "- material from the Modified Proctor test, W_{c1} is the natural water content of the coarse material, and W_{f1} is the natural water content of the fine material.

Resilient Modulus Sample Preparation

The resilient modulus samples prepared for this thesis were prepared using the corrected dry density (D_d) and corrected optimum moisture content (W_{ct}). The untouched half of the cone and quarter sample (e.g. sample 4-1) was used for the resilient modulus test. The dry weight of the sample to be used was measured and recorded. Water was added to the dry sample to increase the moisture content to optimum conditions. The 1.5"+ (38 mm) material were scalped. The total density necessary to achieve 95% of the corrected dry density was calculated. From this, the total weight of the resilient modulus sample was determined. The amount of soil per lift was calculated. Each lift of soil was then compacted to a height of 2" (50.8 mm) into the steel split mold using an electric impact hammer as shown in the picture below.

(a)

(b)

Figure 4.7 Electric impact hammer (a) and attachment (b) used to compact resilient modulus samples.

Figure 4.8 Steel resilient modulus split mold.

During soil preparation a soil preparation sheet was completed to keep track of the details. All soil samples were prepared in this manner.

Test Date	1-29-13	Sample No.	4
-----------	---------	------------	---

Soil Material	RIDOT RAP
---------------	-----------

Goal Unit Weight (pcf)			
Total	131.16	Dry	126.58

Goal Moisture Content %	3.62
-------------------------	------

Pounds per lift atleast	4.292
-------------------------	-------

Length from bottom of sample to top of mold (inches)	14.5
--	------

Lift Number	Weight (lbs)	Length from top of sample to top of mold (inches)	Thickness of lift (inches)
1	4.31	12.5	2
2	4.30	10.5	2
3	4.30	8.5	2
4	4.30	6.5	2
5	4.31	4.5	2
6	4.30	2.5	2
Total Weight	25.81		12

Height of Sample (inches)	12
---------------------------	----

Achieved Unit Weight (pcf)	Total Dry	131.11 129.79	Achieved Moisture Content %	3.4
----------------------------	-----------	------------------	-----------------------------	-----

Figure 4.9 Example of resilient modulus sample preparation sheet.

Once the soil preparation is complete, the sample to be tested should look similar to the picture below. A vacuum was applied to the sample to ensure there were no holes in the membrane.

Figure 4.10 Resilient modulus soil specimen after compaction.

The triaxial cell was then assembled and the sample was tested in accordance to AASHTO T 307.

Post-Processing

The large amount of data recorded by the Instron data acquisition system was processed by a Matlab code created by the author and colleagues, Amanda Persichetti, and Jennifer Giard. The code used to process the data can be seen below. An example of the results created by this processing program is shown below and is referred to as

Report Form C.4 in the AASHTO Standard. The table shown below is only a portion of the actual results table which is 15 sequences long.

Report Form C4.1														
Sample #	4-2		Specimen Area (m*2)		0.0183									
Material Type	RIDOT RAP													
Test Date	1/27/2013		Specimen Height (m)		0.3048									
Resilient Modulus														
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Parameter	Chamber Confining Pressure	Nominal Max. Axial Stress	Cycle No.	Actual Applied Max. Axial Load	Actual Applied Cycle Load	Actual Applied Contact Load	Actual Applied Max Axial Stress	Actual Applied Cycle Stress	Actual Applied Contact Stress	Recov Def. LVDT #1 Reading	Recov Def. LVDT #2 Reading	Average Recov Def LVDT 1 and 2	Resilient Strain	Resilient Modulus
Designation	S ₁	S _{max}	C ₁	P _{max}	P _{cyclic}	P _{contact}	S _{max}	S _{cyclic}	S _{contact}	H ₁	H ₂	H _{avg}	ε _r	M _r
Unit	kPa	kPa		kN	kN	kN	kPa	kPa	kPa	meter	meter	meter	m/m	MPa
Precision														
Sequence 1	20.7	20.7	96.00	0.35	0.31	0.03	18.94	17.06	1.88	4.21E-05		4.21E-05	1.38E-04	123.45
	20.7	20.7	97.00	0.35	0.31	0.03	18.93	17.05	1.88	4.19E-05		4.19E-05	1.38E-04	123.87
	20.7	20.7	98.00	0.35	0.31	0.03	18.95	17.08	1.88	4.24E-05		4.24E-05	1.39E-04	122.82
	20.7	20.7	99.00	0.35	0.31	0.03	18.94	17.06	1.88	4.19E-05		4.19E-05	1.38E-04	124.01
	20.7	20.7	100.00	0.35	0.31	0.03	18.95	17.06	1.89	4.19E-05		4.19E-05	1.38E-04	124.03
Sequence 2	20.7	41.4	96.00	0.73	0.65	0.07	39.71	35.74	3.97	7.74E-05		7.74E-05	2.54E-04	140.66
	20.7	41.4	97.00	0.73	0.65	0.07	39.72	35.75	3.97	7.75E-05		7.75E-05	2.54E-04	140.65
	20.7	41.4	98.00	0.73	0.65	0.07	39.73	35.76	3.96	7.72E-05		7.72E-05	2.53E-04	141.10
	20.7	41.4	99.00	0.73	0.65	0.07	39.70	35.74	3.97	7.75E-05		7.75E-05	2.54E-04	140.62
	20.7	41.4	100.00	0.73	0.65	0.07	39.74	35.77	3.97	7.74E-05		7.74E-05	2.54E-04	140.82

Figure 4.11 Example of Report Form C.4

Resilient Modulus Matlab Code

3/7/13 9:33 AM F:\Thesis\Resilie...\resilientmodulusSI.m 1 of 11

```
% RESILIENT MODULUS---made by Jeff Costa, Amanda Persichetti, and Jenn
% Giard

%% variables
heightenglish=12.0;% inches
height= heightenglish*.0254; %meters
membrane_thickness=.0173;%inches
diameterenglish =6.025-membrane_thickness; %inches
diameter=diameterenglish*.0254; %meters
area=((diameter^2)*pi)/4; %meters squared
volumeenglish=((((diameterenglish^2)*pi)/4)*heightenglish)/12^3;%volume in cubic feet
pistonarea=.001140; % m^2
friction=.01; %friction force between the piston and the bearings (kN)
pistonweight=0.031528;%piston weight in kN
%weight of lifts in lbs
weightlayer1=4.085;
weightlayer2=4.090;
weightlayer3=4.170;
weightlayer4=4.050;
weightlayer5=4.155;
weightlayer6=4.075;
totalweight=weightlayer1+weightlayer2+weightlayer3+weightlayer4+weightlayer5+weightlayer6✓
;%total weight in pounds
totalunitweightpcf=(totalweight/volumeenglish);
unitweightsi=totalunitweightpcf*16.0185;%unit weight in kg/meter cubed. 16.0185 is the✓
conversion factor from pcf to kg/m3

%% cell pressure loads
confiningpressure20_7=20.7*pistonarea; %this is the amount of load in (kn) that is✓
applied to the load cell from confining pressure and piston area
confiningpressure34_5=34.5*pistonarea;
confiningpressure68_9=68.9*pistonarea;
confiningpressure103_4=103.4*pistonarea;
confiningpressure137_9=137.9*pistonarea;

%% steps tracking data

tracking=importdata('Test2.steps.tracking.csv');

a= (tracking.data(1:length(tracking.data),1)); %total time in seconds
b= (tracking.data(1:length(tracking.data),2)); %cycle elapsed time in seconds
c= (tracking.data(1:length(tracking.data),3)); %total cycles
d= (tracking.data(1:length(tracking.data),4)); %elapsed cycle
e= (tracking.data(1:length(tracking.data),5)); %step number
f= (tracking.data(1:length(tracking.data),6)); %total cycle count
g= (tracking.data(1:length(tracking.data),7)); %position in mm from instron LVDT
h= (tracking.data(1:length(tracking.data),8))*-1; %load in kn

%% True or Corrected Load Calculation

ww=ones(length(h),1); %ww is the raw load minus the different loads from confining✓
```

```

pressure (kN)
for i=1:length(h)
    if e(i,1)==1
        ww(i,1)=h(i,1)-confiningpressure20_7;%sequence number 1
    elseif e(i,1)==3
        ww(i,1)=h(i,1)-confiningpressure20_7;%sequence number 2
    elseif e(i,1)==5
        ww(i,1)=h(i,1)-confiningpressure20_7;%sequence number 3
    elseif e(i,1)==8
        ww(i,1)=h(i,1)-confiningpressure34_5;%sequence number 4
    elseif e(i,1)==10
        ww(i,1)=h(i,1)-confiningpressure34_5;%sequence number 5
    elseif e(i,1)==12
        ww(i,1)=h(i,1)-confiningpressure34_5;%sequence number 6
    elseif e(i,1)==15
        ww(i,1)=h(i,1)-confiningpressure68_9;%sequence number 7
    elseif e(i,1)==17
        ww(i,1)=h(i,1)-confiningpressure68_9;%sequence number 8
    elseif e(i,1)==19
        ww(i,1)=h(i,1)-confiningpressure68_9;%sequence number 9
    elseif e(i,1)==22
        ww(i,1)=h(i,1)-confiningpressure103_4;%sequence number 10
    elseif e(i,1)==24
        ww(i,1)=h(i,1)-confiningpressure103_4;%sequence number 11
    elseif e(i,1)==26
        ww(i,1)=h(i,1)-confiningpressure103_4;%sequence number 12
    elseif e(i,1)==29
        ww(i,1)=h(i,1)-confiningpressure137_9;%sequence number 13
    elseif e(i,1)==31
        ww(i,1)=h(i,1)-confiningpressure137_9;%sequence number 14
    elseif e(i,1)==33
        ww(i,1)=h(i,1)-confiningpressure137_9;%sequence number 15
    else
        ww(i,1)=h(i,1);
    end
end

forcesample=ww-friction+pistonweight;% (kN) this calculates the actual load on the sample
and should be close to what the standard calls for
%% Strain Calculations

stress=forcesample/area;%stress in kpa
k=ones(length(tracking.data),1);
for j=1:length(tracking.data)
    k(j,1)=g(1,1)-g(j,1); %k column is displacement in mm from piston lvdt
end
l=(k/1000)/height;%raw strain from piston lvdt in m/m
lvdt1=((tracking.data(1:length(tracking.data),9)))/1000;%displacement in meters from
lvdt1
lvdt2=((tracking.data(1:length(tracking.data),9)))/1000;%displacement in meters from
lvdt2

```

```

strain1=(lvdt1)/height); % raw strain from lvdt1
strain2=(lvdt2)/height); % raw strain from lvdt2
averagedisplacement=(lvdt1+lvdt2)/2; %calculates the average displacement of the two✓
lvdt5 meters
averagestrain=averagedisplacement/height; %calculates the average strain from the LVDTs

%permeanant strain
permeanantstrain1=lvdt1(end)/height;
permeanantstrain2=lvdt2(end)/height;
average_permeanant_strain=(permeanantstrain1+permeanantstrain2)/2;%calculates the average✓
permeanant strain
%% Recoverable Strain Calculation
%
% %%%LVDT1
recovd1=ones(5,15);% the second number is the number of total steps 15 for subbase 13 for✓
subgrade
recovd2=ones(5,15);% the second number is the number of total steps
maxd1=ones(5,15);
mind1=ones(5,15);
mind1L=ones(5,15);
permd1=ones(5,15);

maxd2=ones(5,15);
mind2=ones(5,15);
mind2L=ones(5,15);
permd2=ones(5,15);

maxforcesample1=ones(5,15);
minforcesample1=ones(5,15);
pp=1;
for ii=[1 3 5 8 10 12 15 17 19 22 24 26 29 31 33]
stepi=find(e==ii);
for j=96:100;%last 5 cycles
cyclei=find(d(stepi(1):stepi(length(stepi)),1)==j);
cyclei=cyclei+(stepi(1)-1);
maxd1(j-95,pp)=max(lvdt1(cyclei(1):cyclei(length(cyclei)),1));
cyclestart=find(lvdt1(cyclei(1):cyclei(length(cyclei)),1)==maxd1(j-95,pp));
mind1(j-95,pp)=min(lvdt1(cyclei(cyclestart):cyclei(length(cyclei)),1)); % finds min✓
after peak
mind1L(j-95,pp)=min(lvdt1(cyclei(1):cyclei(cyclestart),1)); % finds min before peak
recovd1(j-95,pp)=maxd1(j-95,pp)-mind1(j-95,pp); % max-min after peak
permd1(j-95,pp)=mind1(j-95,pp)-mind1L(j-95,pp); % min right side of peak-min left✓
side of peak for cycle 96-100
maxforcesample1(j-95,pp)=max(forcesample(cyclei(1):cyclei(length(cyclei)),1));%max✓
and min load of the last 5 cycles
minforcesample1(j-95,pp)=min(forcesample(cyclei(1):cyclei(length(cyclei)),1)); %✓
minimum of the cycle

forcerange=forcesample(cyclei(1):cyclei(length(cyclei)),1);
avgmaxforceIndex=find(forcerange==maxforcesample1(j-95,pp)); % find index of maximum

```

```

    % takes average starting ten numbers after the maximum to the end of the
    % cycle (constant load)
    avgmaxforce(j-95,pp)= mean(forcerange(avgmaxforceIndex+10:length(forcerange)-
    avgmaxforceIndex)); % calculating the average of the constant load

    maxd2(j-95,pp)=max(lvdt2(cyclei(1):cyclei(length(cyclei)),1));
    cyclestart=find(lvdt2(cyclei(1):cyclei(length(cyclei)),1)==maxd2(j-95,pp));
    mind2(j-95,pp)=min(lvdt2(cyclei(cyclestart):cyclei(length(cyclei)),1)); % finds min
after peak
    mind2L(j-95,pp)=min(lvdt2(cyclei(1):cyclei(cyclestart),1)); % finds min before peak
    recovd2(j-95,pp)=maxd2(j-95,pp)-mind2(j-95,pp); % max - min after peak
    permd2(j-95,pp)=mind2(j-95,pp)-mind2L(j-95,pp); % min right side of peak-min left
side of peak for cycle 96-100

end
pp=pp+1;
end

% reshape matrices into columns
start=1;
ending=5;
for ii=1:15;
    maxforcesample1a(start:ending,1)=maxforcesample1(:,ii);
    minforcesample1a(start:ending,1)=avgmaxforce(:,ii);
    recoverabledeflection1(start:ending,1)=recovd1(:,ii);
    recoverabledeflection2(start:ending,1)=recovd2(:,ii);
    permanentdeformation1(start:ending,1)=permd1(:,ii);
    permanentdeformation2(start:ending,1)=permd2(:,ii);

    start=ending+1;
    ending=start+4;
end

%% permanent deformation for all cycles

cummaxd1=ones(100,15);
cummind1=ones(100,15);
cummind1L=ones(100,15);
cumpermd1=ones(100,15);

cummaxd2=ones(100,15);
cummind2=ones(100,15);
cummind2L=ones(100,15);
cumpermd2=ones(100,15);
pp=1;
for ii=[1 3 5 8 10 12 15 17 19 22 24 26 29 31 33]
    stepi=find(e==ii);
    for j=1:100;%all cycles cycles
        cumcyclei=find(d(stepi(1):stepi(length(stepi)),1)==j);
        cumcyclei=cumcyclei+(stepi(1)-1);
    end
end

```

```

        cummaxd1(j,pp)=max(lvdt1(cumcyclei(1):cumcyclei(length(cumcyclei)),1));
        cumcyclestart=find(lvdt1(cumcyclei(1):cumcyclei(length(cumcyclei)),1)==cummaxd1(j,
pp));
        cummind1(j,pp)=min(lvdt1(cumcyclei(cumcyclestart):cumcyclei(length(cumcyclei)),1)); %
finds min after peak
        cummind1L(j,pp)=min(lvdt1(cumcyclei(1):cumcyclei(cumcyclestart),1)); % finds min
before peak
        %recovd1(j,pp)=maxd1(j,pp)-mind1(j,pp); % max-min after peak
        cumpermd1(j,pp)=cummind1(j,pp)-cummind1L(j,pp); % min right side of peak-min left
side of peak
        %maxforcesample1(j, (pp))=max(forcesample(cumcyclei(1):cumcyclei(length(cumcyclei)),
1)); %max and min load of the last 5 cycles
        %minforcesample1(j, (pp))=min(forcesample(cumcyclei(1):cumcyclei(length(cumcyclei)),
1));

        cummaxd2(j,pp)=max(lvdt2(cumcyclei(1):cumcyclei(length(cumcyclei)),1));
        cumcyclestart=find(lvdt2(cumcyclei(1):cumcyclei(length(cumcyclei)),1)==cummaxd2(j,
pp));
        cummind2(j,pp)=min(lvdt2(cumcyclei(cumcyclestart):cumcyclei(length(cumcyclei)),1)); %
finds min after peak
        cummind2L(j,pp)=min(lvdt2(cumcyclei(1):cumcyclei(cumcyclestart),1)); % finds min
before peak
        %recovd2(j,pp)=maxd2(j,pp)-mind2(j,pp); % max - min after peak
        cumpermd2(j,pp)=cummind2(j,pp)-cummind2L(j,pp); % min right side of peak-min left
side of peak for every cycle

    end
    pp=pp+1;
end

% reshape cumulative deformation matrices into columns
allcycles_permanent_deformation1=reshape(cumpermd1,1500,1);%%creates a column 1500 rows
long of permeant deformations in each cycle
allcycles_permanent_deformation2=reshape(cumpermd2,1500,1);

%%
averagerecoverabledeflection=((recoverabledeflection1+recoverabledeflection2)/2); %column
12
recoverablestrain1=recoverabledeflection1/height; %%column of recoverable strain from
lvdt 1
recoverablestrain2=recoverabledeflection2/height; %%column of recoverable strain from
lvdt 2
averagerecoverablestrain=(recoverablestrain1+recoverablestrain2)/2; %%column 13 average
recoverable strain
averagepermanentdeformation=(permanentdeformation1+permanentdeformation2)/2;%%this
calculates theaverage permanent deformation (m) per cycle
averagepermanentstrain=averagepermanentdeformation/height; % calculates permeant strain
per cycle

start=1;
ending=0;

```

```

col=1;
for ii=[1 3 5 8 10 12 15 17 19 22 24 26 29 31 33]; % loop through step numbers
    stepi=find(e==ii);
    for j=96:100;
        goodcycle=d(stepi(1):stepi(end));
        cyclei=find(goodcycle==j); % find where cycle = 96:100

        % stress/strain relating to odd step numbers
        goodstress=stress(stepi(1):stepi(end));
        goodstrain=averagestrain(stepi(1):stepi(end));

        % stress/strain relating to cycle numbers 96:100
        goodstress1=goodstress(cyclei(1):cyclei(end));
        goodstrain1=goodstrain(cyclei(1):cyclei(end));

        % all step numbers in one colum for cycle numbers 96:100
        l5stress1col(start:length(cyclei)+ending,1)=goodstress1(:,1);
        l5strain1col(start:length(cyclei)+ending,1)=goodstrain1(:,1);

        l5stress1(start:length(cyclei)+ending,1)=goodstress1(:,1);
        l5strain1(start:length(cyclei)+ending,1)=goodstrain1(:,1);

        start=length(cyclei)+start;
        ending=ending+length(cyclei);
    end
    % each step number has own column
    % in each column is stress and strain relating to cycle numbers 96:100
    stressnew(1:length(l5stress1),col)=l5stress1(1:length(l5stress1),1);
    strainnew(1:length(l5strain1),col)=l5strain1(1:length(l5stress1),1);
    col=col+1;
    clear stepi
    clear cyclei
    clear l5stress1
    clear l5strain1
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Steps Tracking Plots
%% %
set(0,'DefaultAxesFontName', 'Times New Roman') %changes the default axis font and size
set(0,'DefaultAxesFontSize', 24)

% figure (1)
% plot(a,forcesample,'black')
% title('Time Vs. True Load')
% xlabel('Time in Seconds')
% ylabel('Load in kN')
% %axis([xmin xmax ymin ymax])
% %axis([1540 1600 .37 .5])
% %

```

```

% % %
% figure (2)
% plot(a,stress,'black')
% title('Time Vs. Stress')
% xlabel('Time in Seconds')
% ylabel('Stress in kPa')
% %axis([xmin xmax ymin ymax])
% %axis([0 1500 0 45])
% %
% % figure (3)
% % plot(a,k,'black')
% % title('Time Vs. Displacement from Piston LVDT')
% % xlabel('Time in Seconds')
% % ylabel('Displacement in meters')
% % %axis([xmin xmax ymin ymax])
% % %axis([0 1500 0 .08])
% %
% figure (4)
% plot(a,l,'black')
% title('Time Vs. Strain from Piston LVDT')
% xlabel('Time in Seconds')
% ylabel('Raw Strain')
% %axis([xmin xmax ymin ymax])
% %axis([0 1500 0 .006])
% %
% figure (5)
% %adata=a(1:1000,1);
% %straindata=strain1(1:1000,1);
% %plot(adata,straindata,'black')
% plot(a,lvdt1,'black')
% title('Time Vs. Displacement from LVDT1')
% xlabel('Time in Seconds')
% ylabel('Displacement')
% %axis([xmin xmax ymin ymax])
% %axis([0 1500 0 .006])

% figure (6)
% plot(a,strain1,'black')
% %plot(a,strain1,'black')
% title('Time Vs. Strain from LVDT1')
% xlabel('Time in Seconds')
% ylabel('Raw Strain')
% %axis([xmin xmax ymin ymax])
% %axis([0 1500 0 .006])

% %
% figure (7)
% plot(averagedisplacement,forcesample,'black')%averaged displacement vs. true load
% title('Load Vs. Average Displacement')
% xlabel('Displacement in meters')

```

93


```

column9=(column6/area); %column number 9 actual applied contact stress in report form C4.✓
1
column10=recoverabledeflection1; %column number 10 in report form C4.1
column11=recoverabledeflection2; %column number 11 in report form C4.1
column12=averagerecoverabledeflection; %column number 12 in report form C4.1
column13=averagerecoverablestrain; %column number 13 in report form C4.1
column14=ones(length(column13),1);%column number 14 in report form C4.1 in kPa, later✓
divided by 1000 to make into MPA
for v=1:length(column13)
    column14(v,1)=(column8(v,1)/column13(v,1))/1000;% yeilds resilient modulus for each✓
of the last 5 cycles in each step
end

%% plot of resilient modulus through test
x=96:100:1496;
xx=97:100:1497;
xxx=98:100:1498;
xxxx=99:100:1499;
xxxxx=100:100:1500;
M_new=[x;xx;xxx;xxxx;xxxxx];
xaxis=reshape(M_new,75,1);

% figure (11)
% scatter(xaxis,column14,10,'black');% (x,y,size of points)
% hold on
% title('Resilient Modulus Throughout Test')
% xlabel('Total Cycles')
% ylabel('Resilient Modulus (MPa)')
% %mr=polyfit(xaxis,column14,1);%(x,y,power of the function)
% %linefit=((mr(1,1)*xaxis)+(mr(1,2)));
% %linefit=((mr(1,1)*xaxis.^2)+(mr(1,2)*xaxis)+(mr(1,3))));
% %plot(xaxis,linefit,'blue');
% hold off
% % axis([xmin xmax ymin ymax])
% %axis([0 1500 0 7500000])

%% plot of target load and actual load

AA=(1:1:length(column14));
AAA=(transpose(AA));
tload1=[0.339 0.678 1.017 0.565 1.129 1.694 1.129 2.259 3.387 1.129 1.694 3.387 1.694✓
2.259 4.518];%%these are the target cyclic loads from the standard (kN)
tload2=[0.339 0.678 1.017 0.565 1.129 1.694 1.129 2.259 3.387 1.129 1.694 3.387 1.694✓
2.259 4.518];
tload3=[0.339 0.678 1.017 0.565 1.129 1.694 1.129 2.259 3.387 1.129 1.694 3.387 1.694✓
2.259 4.518];
tload4=[0.339 0.678 1.017 0.565 1.129 1.694 1.129 2.259 3.387 1.129 1.694 3.387 1.694✓
2.259 4.518];
tload5=[0.339 0.678 1.017 0.565 1.129 1.694 1.129 2.259 3.387 1.129 1.694 3.387 1.694✓
2.259 4.518];
tload_new=[tload1;tload2;tload3;tload4;tload5];

```

```
targetload=reshape(tload_new,75,1);

%%resilient modulus through test

% figure (12)
% plot(xaxis,targetload,'black')
% scatter(xaxis,targetload,250,'black')
% title('Comparison of Actual Applied Cyclic Load and Target Cyclic Load')
% xlabel('Total Number of Cycles')
% ylabel('Load (kN)')
% hold on
% scatter(xaxis,column5,250,'red','+')
% plot(xaxis,column5,'red')
% legend('Target Load','Actual Applied Cyclic Load');
% axis([0 1600 0 6])
% hold off
%
% figure (13)
% scatter(AAA,targetload/area,'black')
% title('Comparison of Actual Applied Cyclic Stress and Target Cyclic Stress')
% xlabel('Number of Cycles')
% ylabel('Stress (kPa)')
% hold on
% scatter(AAA,column5/area,'red','+')
% plot(AAA,column5,'red',)
% legend('Target Stress','Actual Applied Cyclic Stress');
% hold off

%% calculating the %difference between the target load and the actual applied load

difference=(column5-targetload);
difference2=(difference./column5)*100;%%gives a column of % differences

% % figure
% % scatter(AAA,difference2)
% % xlabel('Number of Cycles')
% % ylabel('Difference')
% % %
% xlswrite('MatlabReport Form C4.1SI.xlsx',column3,'e19:e93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column4,'f19:f93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column5,'g19:g93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column6,'h19:h93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column7,'i19:i93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column8,'j19:j93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column9,'k19:k93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column10,'l19:l93')
% % % % % xlswrite('MatlabReport Form C4.1SI.xlsx',column11,'m19:m93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column12,'n19:n93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column13,'o19:o93')
% xlswrite('MatlabReport Form C4.1SI.xlsx',column14,'p19:p93')
% % % % % xlswrite('MatlabReport Form C4.1SI.xlsx',averagepermanentstrain,'q19:q93')
```

```
% xlswrite('MatlabReport Form C4.1SI.xlsx',area,'f5:f5')
% xlswrite('MatlabReport Form C4.1SI.xlsx',height,'f8:f8')
% % % % % % %xlswrite('MatlabReport Form C4.1SI.xlsx',sample_material(1,:), 'c6:c6')
% % % % % % %xlswrite('MatlabReport Form C4.1SI.xlsx',sample_number,'c4:c4')
% % % % % % %xlswrite('MatlabReport Form C4.1SI.xlsx',testdate,'c8:c8')
```

5. Appendix C: Cyclic Liquefaction Sample Preparation

This appendix includes the sample preparation procedure used to perform the energy-based cyclic liquefaction tests.

The method used for the remainder of this thesis is a mixture of the slurry deposition method which is vibrated at low frequencies. The author uses a split mold, and PVC pipe filled with a known mass of soil, as shown in the picture below.

Figure 5.1. Energy-based cyclic liquefaction soil preparation.

The author then slowly lifts the PVC pipe allowing the soil to pluviate into the water filled membrane. A metal plate is then placed on the split mold. A standard proctor hammer is dropped from a height of 3 inches onto the plate. This action allows for a repeatable and consistently made soil preparation method. The number of drops by the standard proctor hammer is changed to achieve different relative densities. A top cap and porous stone is installed on the sample, and the triaxial cell is assembled. A small effective stress of approximately 18 kPa is placed on the sample for placement into the load frame.

6. Appendix D: Energy-based Cyclic Liquefaction Test Procedure

This appendix includes details on the testing procedure for the energy-based liquefaction testing in this thesis. This includes inputs to the computer in order to perform the required test, along with the set-up of the triaxial cell.

The cyclic Instron Wavematrix testing method was used for cyclic liquefaction testing. In this test procedure an amplitude and number of cycles were assigned. The amplitude is based on the target cyclic stress ratio according to the equation below.

$$Amplitude = CSR * 2 * \sigma' * A_s \quad (6.1)$$

Where A_s is the cross sectional area of the sample, and σ' is the effective confining pressure. The number of cycles is set at a large number (10,000) to ensure that the test does not end before the sample is liquefied. The Waveform Starting Phase is set for 180 degrees; this causes the test to begin in compression.

Figure 6.1. Energy-based test method sequence menu.

Once an amplitude is calculated, the sample is placed into the Instron 8872 load frame. The triaxial cell is bolted to the base of the load frame, and the triaxial cell piston is fixed to the piston of the Instron. While fixing the load frame piston to the triaxial cell, the computer is programmed to hold a load of approximately 1 lb. This is to prevent the soil from feeling any load due to tightening the connection. The triaxial cell is filled with water and both the top and bottom porous stones are flushed as shown in the figures below.

Figure 6.2. Triaxial cell being filled with water.

Figure 6.3. Top and bottom porous stones being flushed.

The back pressure is then increased to approximately 30 psi while the cell pressure is increased to approximately 34 psi. Volume readings for both the triaxial cell and the sample specimen are recorded at this time. The pore pressure is raised to 60 psi and the cell pressure is raised to 64 psi and the readings are then recorded again. The readings allow the user to track the change in volume throughout this procedure. As the back pressure is raised, the confining pressure and computer load are also changed to keep the same effective stress on the sample at all times. The sample remains under

back pressure saturation for approximately 30 to 60 minutes. At this point a B-parameter check is performed to ensure saturation. If fully saturated the water in the cell is removed through the burette system so that only a pressure differential of approximately 1 psi is developed. This process usually takes 1 to 2 hours. There was concern that by draining the water out of the cell and replacing it with air that some of the air may permeate through the membrane. If this happened the sample would lose saturation and thus have a dampened pore pressure response during the cyclic testing. A B-parameter check was performed on one sample after the cell had been drained of its water to ensure air was not permeating through the membrane. This B-parameter check was satisfactory and was the only B-parameter performed while the cell was drained.

Once the water is removed, the sample is consolidated to the appropriate effective confining pressure. The consolidation phase is performed for approximately 5 minutes. After consolidation the final pore water pressure reading is recorded. The pore water pressure valve is closed and the cyclic test is performed.