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Light Water Reactor Sustainability Program

Large Scale Laminar Box Test Plan

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July 2016

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ABSTRACT

This report describes the test plan for large-scale laminar box tests planned for fiscal year (FY) 2017. Initial large-scale geotechnical laminar box (GLB) tests are planned for September at the University at Buffalo (UB) State University New York (SUNY). The need for GLB testing was identified in numerical modeling performed in FY 2014. Five sets of tests will be run in the GLB with increasing amplitude for each test set. This experimental test program will gather data from approximately 20 unique tests. The data from these test runs will be compared with numerical blind prediction models. These comparisons will be used to validate the soil constitutive models in these codes. This will build confidence in the numerical predictive capability when performing site-response analysis and understanding how earthquake waves pass through soil.

ACKNOWLEDGEMENTS

The Light Water Reactor Sustainability Program at INL commissioned this report. Input on the geotechnical laminar box capability was provided by University of Buffalo.

Large Scale Laminar Box Test Plan

FIGURES

ACRONYMS

DOE	Department of Energy
ERG-EH	External Hazards Experimental Group
EPRI	Electric Power Research Institute
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability
MOOSE	Multiphysics Object Oriented Simulation Environment
NPP(s)	nuclear power plant(s)
PRA(s)	probabilistic risk assessment(s)
R&D	research and development
RIMM	risk-informed margins management
RISMC	Risk-Informed Safety Margin Characterization
SSCs	structures, systems, and components

Large Scale Laminar Box Test Plan

1. INTRODUCTION

The purpose of this report is to describe the test plan for large-scale geotechnical laminar box (GLB) tests planned for September at the University at Buffalo (UB) State University New York (SUNY). The need for GLB testing was identified in Fiscal Year 2014 in Spears and Coleman (2014). This report started development of a nonlinear soil-structure interaction (NLSSI) methodology using commercially available tools. The conclusions of that report point to GLB testing to resolve open-ended questions discovered during numerical simulations. The conclusions state that:

- *An abrupt change in the tangent stiffness of the soil at the transition from loading to unloading or vice versa will generate a high-frequency acceleration response. It is unclear whether this transition, in reality, is abrupt or smooth and, if abrupt, whether equivalent-linear methods can capture this affect in site response and SSI analyses. Dynamic, large-strain testing of soils is needed to characterize soil behavior for linear and nonlinear modeling. Large-scale, large-strain site-response and SSI testing is also needed, which can be performed in a geotechnical laminar box such as the one shown in* Figure 1.
- *Equivalent-linear analysis appears to suppress the high-frequency response at high strain levels, whereas the nonlinear methods do not. This issue could be resolved through validation using the experiments in a geotechnical laminar box.*
- *Nonlinear analyses predict higher levels of shear strain (in the soil column considered) than the equivalent-linear analyses. This is an important observation for buried structures and needs to be verified and validated in a controlled laboratory environment. The aforementioned laminar box could be used for this purpose.*

Figure 1: University at Buffalo geotechnical laminar box

Based on continued development of numerical tools to perform NLSSI analysis and on the conclusions of Spears and Coleman (2014) planning for GLB testing was initiated. The test, which is actually a set of around 20 runs, will be used to characterize one-dimensional (1D) wave passage in soil medium and to validate the numerical tools under development. A process for validation of numerical tools is discussed in Coleman *et al.* (2016). That document discuss three levels of experimental testing to build a predictive numerical capability, 1) unit, 2) benchmark, and 3) subsystem. Figure 2 describes what physical behavior must be validated in the numerical tools to develop a predictive capability. The GLB test will be both benchmark and subsystem experiments. It will be used to provide data that will be used to validate linear and nonlinear numerical soil behavior and characterize 1D cyclic wave passage effects.

Figure 2 presents a process for developing a predictive NLSSI capability. The large-scale GLB experimental test will fit into the Soil Site Response box in Figure 2.

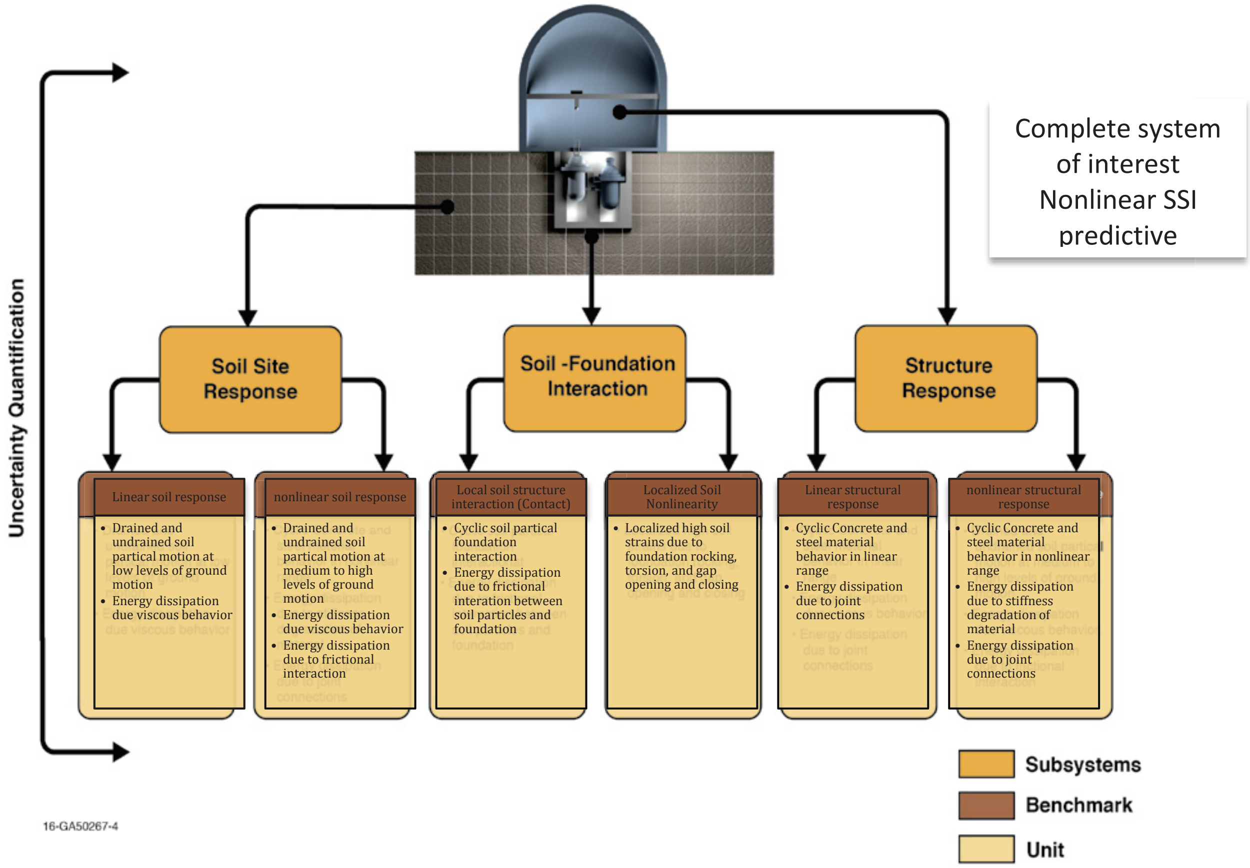

Figure 2: Validation process for developing a predictive capability of site response and SSI numerical tools

1.1 Outline of this Report

Section 2 provides details on the GLB geometrical configuration, Section 3 provides details on the soil used in the test including material properties and a description on filling the GLB box. Section 4 gives details on the instrumentation that will be used in the tests, Section 5 describe the GLB runs and sequencing, and Section 6 provides details on the numerical analysis that will be performed prior to and after GLB tests.

2. LAMINAR BOX CONFIGARATION

The Geotechnical Laminar Box (GLB) is located in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at University at Buffalo. The SEESL is a large indoor physical-testing facility able to accommodate a variety of civil and geotechnical engineering experiments. The SEESL has dedicated personnel, equipment and structures capable of performing many different types of physical experiments. SEESL has the following pieces of equipment:

- Three Earthquake Simulators, also known as Shake Tables
- One 3.6-m x 3.6-m with 5 degrees-of-freedom (DOF), 50-ton payload
- Two relocatable 7.0-m x 7.0-m platforms with 6 DOF, 50-ton payload each
- A two stories bi-axial Shaking Table system used as Non-structural Component Simulator
- A 175 m^2 Strong Reaction Wall for horizontal loading devices for large scale testing
- A 340 m^2 Strong Testing Floor for vertical reactions and tie downs of large scale models
- **A Uniaxial Laminar Box for 1.0 g soil testing (GLB), GLB could be reconfigured for 2D and 3D tests**
- Reconfigurable assemblies of Static and Dynamic Servo-controlled Actuators
- A High Performance Hydraulic Power Supply with 6,000 liters per minute flow
- Local and Wide Area Gigabit Networks interfaced and supported by NEESit services
- Tele-presence & operation capabilities for local/wide area collaborations in real time
- Advanced & Pseudo-Dynamic, and Static Testing with Real Time Dynamic Hybrid Testing
- MTS 810 Servo-hydraulic Universal Testing Machine

F-55 Ottawa sand (material properties discussed later) will be placed in the GLB pictured in Figure 3. The GLB is composed of 40 laminate rings stacked on top of each other separated and independently floating by ball bearings. These laminates minimize the lateral stiffness of the box and allow the wave to pass through soil as it would naturally in the real world. The boxed is lined with a custom 2.67-mm thick assembly of Firestone EPDM rubber. This rubber liner contains the saturated-soil material inside the GLB and prevents spillage of soil through the bearing-gaps between laminates.

Input ground motion is applied to the bottom of the GLB. The motion can either be simple sinusoidal waves or complex earthquake time series. The GLB is a uniaxial laminar box meaning that the input motion is applied in one direction, however the box could be modified to input 2D or 3D motion. The base of the GLB is forced in to motion by two MTS 110,000-lbs dynamic hydraulic actuators that are attached to the SEESL strong floor. The motion applied to the GLB base propagates up through the soil column to the free top of the GLB. The laminates are free to move laterally due to the frictionless bearings thereby allowing shear deformation of the soil.

The hydraulic actuators are displacement controlled and operated by MTS Model 79.10 Multipurpose TestWare and Series 793 Application Software (MPT). The interior dimensions of the GLB are 196 inches (E-W direction), 108 inches (N-S direction) and is 240 inches tall. Each laminate including space for the bearings is 6 inches in height (there are 40 laminates). Safety limits the maximum height the box can be filled, therefore soil in the box is filled to less than 20 feet. This yields a total maximum interior-testing volume of approximately 108 cubic yards.

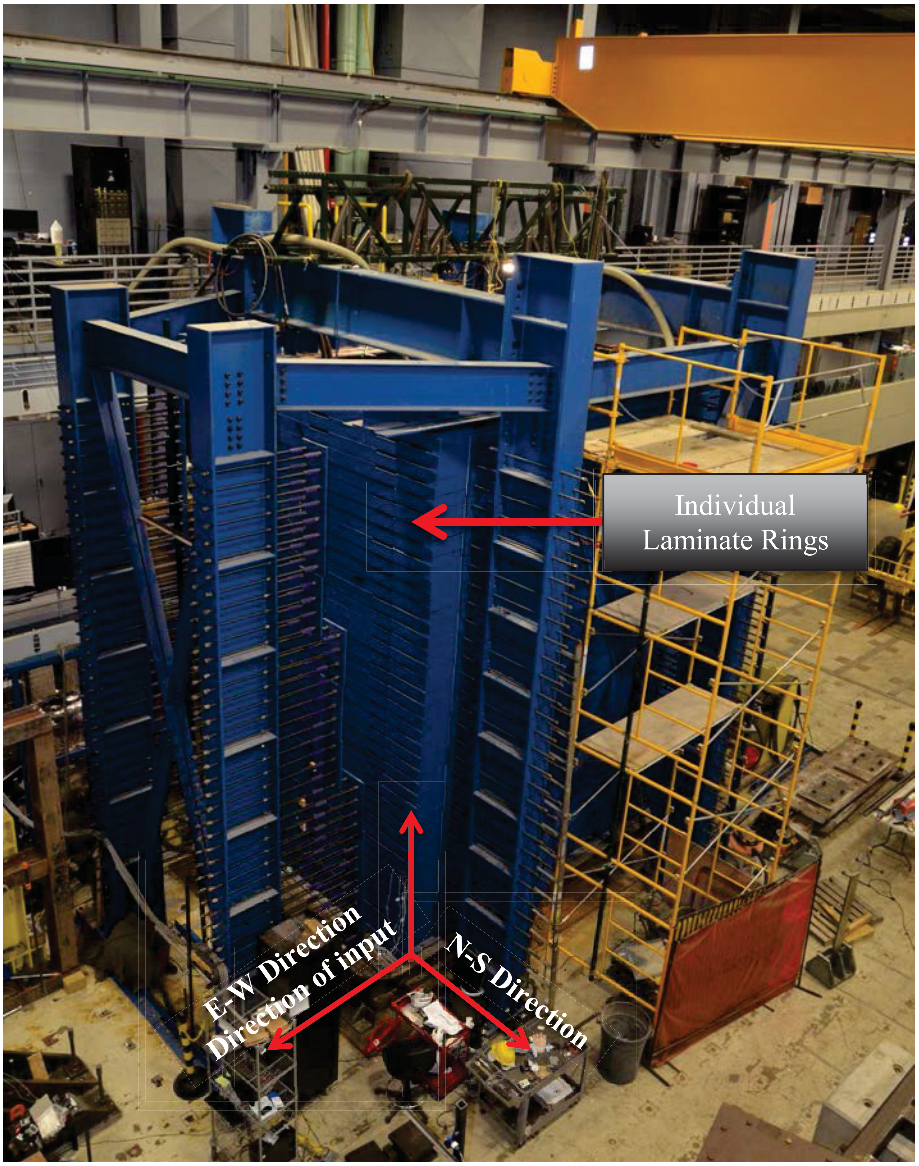

Figure 3: GLB in SEESL

3. SOIL INFORMATION AND PLACEMENT IN BOX

The material used in this experiment is Ottawa F-55 sand. Ottawa F-55 is medium size grain sand with the mean particle side (D_{50}) equal to 0.258 mm with less than 1% fines. The sand grains are mainly rounded of clear colorless quartz, diamond-like in hardness, pure silica (silicon dioxide) uncontaminated by clay, loam, iron compounds, or other foreign substances. The maximum and minimum void ratios of the sand are 0.800 and 0.608, respectively, and its permeability coefficient fluctuates between k = 5x10-3 cm/sec and k = 1.2x10-2cm/sec for a range of void ratios between 0.646 and 0.723.

Table 1: Ottawa F-55 sand properties (Thevanayagam *et al.* (2003) and NEES (2009))

Specific Gravity	2.67
e_{min} =	0.61
e_{max} =	0.80
Typical Unit Weights, e_{min} (most dense)	
Dry, lbs/ft^3	103.4
Saturated, lbs/ft^3	127.0
Dry, kN/m^3	16.3
Saturated, kN/m^3	20.0
Typical Unit Weights, e_{max} (most loose)	
Dry, lbs/ft^3	92.4
Saturated, lbs/ft^3	120.1
Dry, kN/m^3	14.5
Saturated, kN/m^3	18.9

The Ottawa F-55 sand used in the SEESL laboratory is physically and chemically altered due to the repeated use and outdoor exposure. Figure 4 shows optical 50x-microscope photographs of fresh F-55 sand (left) and used sand (right), from the GLB storage tanks. Sieve analysis also shows possible changes in the grain size distribution. Therefore the dynamic properties of the SEESL sand is slightly different from the natural sand. Therefore dynamic test are planned on this material to gather initial dynamic soil properties. This is discussed in more detail below.

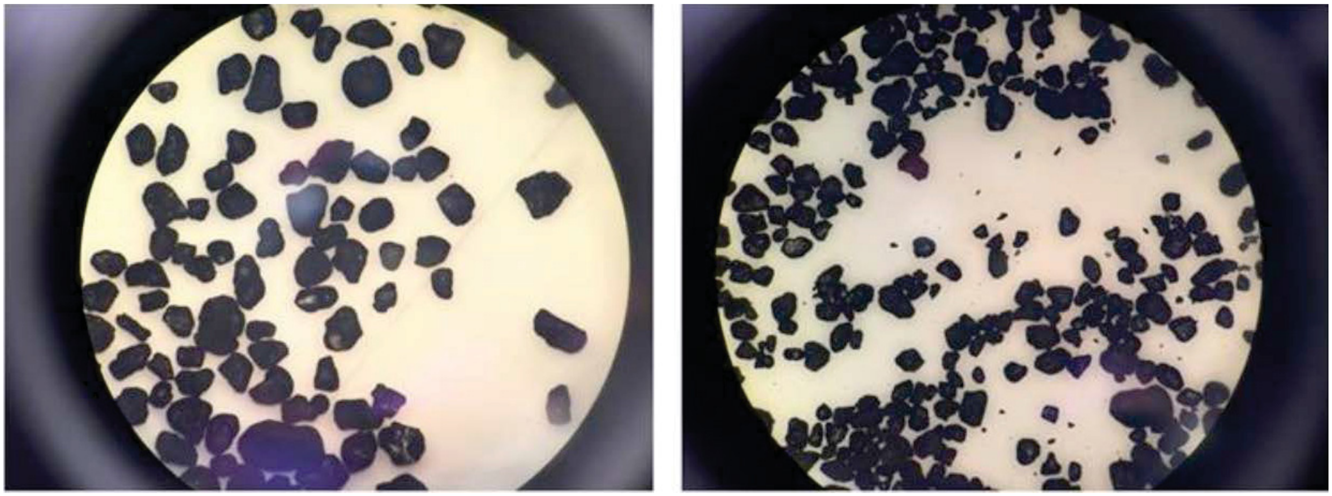

Figure 4: Natural Ottawa F-55 Sand (Left) and Used SEESL Ottawa F-55 Sand (Right)

3.1 Dynamic Properties

In the 1970s experimental tests on soils showed a degradation in soil stiffness and an increase in damping during dynamic testing. Testing to develop dynamic properties for sand produced a range of degradation data for a range of sand properties from dry to saturated (Figure 5). Typical stiffness degradation values and increasing in damping of Ottawa sand is provided in Figure 6.

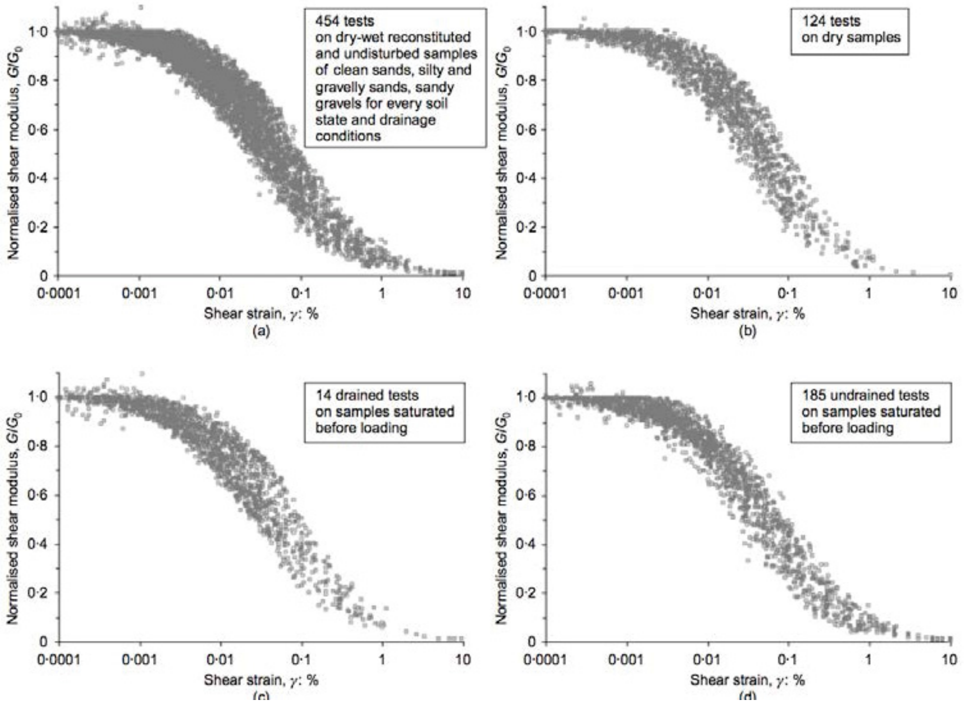

Figure 5: Shear modulus values for 454 tests on sand Oztoprak and Bolton (2013)

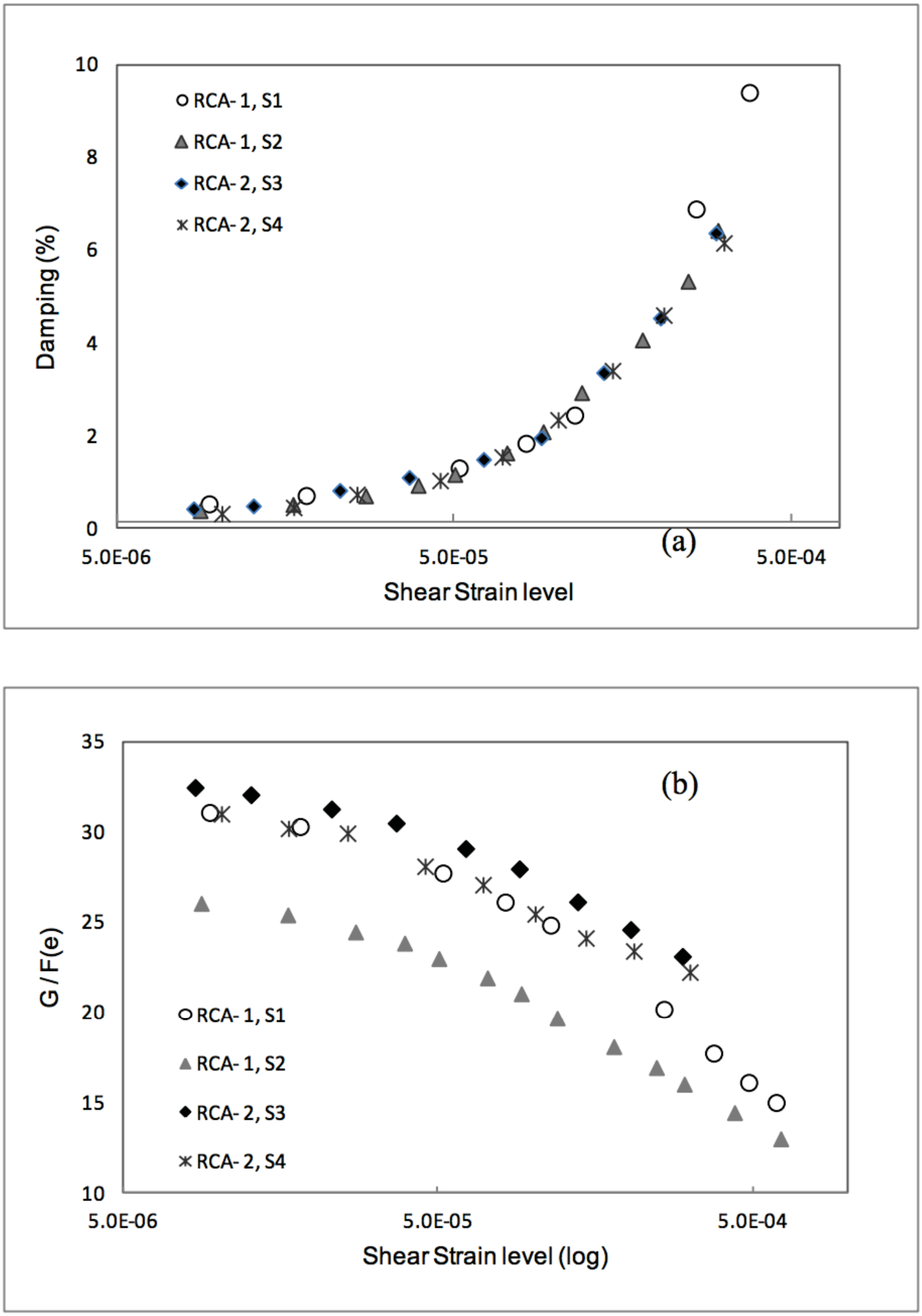

Figure 6: Dynamic soil properties for Ottawa Sand (Moayerian (2012))

Dynamic material property data for the SEESL Ottawa F-55 sand will be gathered using a newly purchased cyclic triaxial machine. This machine will also be used to gather dynamic material property data after each set of GLB tests. The Advanced Dynamic Triaxial Testing System (DYNTTS) is a high-end testing apparatus combining a triaxial cell with a dynamic actuator capable of applying load, deformation and stresses at up to 10Hz. The axial axis is screw-driven from an integral base unit housing the motor drive. Axial force and axial deformation are applied through the base of the cell. Figure 7 shows the cyclic triaxial machine at University at Buffalo.

Figure 7: Cyclic Triaxial Machine at University at Buffalo

3.2 Soil Placement in Box

Ottawa F-55 sand is pumped into the GLB using hydraulic slurry processes. The sand is pumped out of three large steel containers (SSTs) that are placed outside of the SEESL. The SSTs are 7-ft square by 24-ft long (Figure 8). This pumping procedure is labor intensive requiring multiple technicians and several days to complete for both the filling and emptying of the GLB (Figure 10 is looking inside the GLB during the filling process). Three-inch slurry lines transfer the sand from the SSTs to the GLB (Figure 9 shows a cross-section of the GLB). A plan view of the SEESL and the GLB slurry layout is shown in Figure 11.

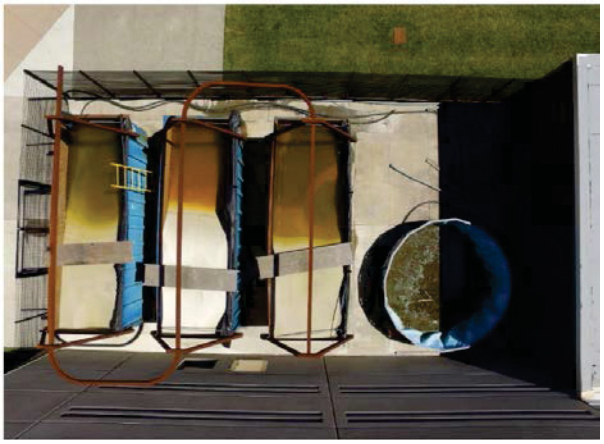

Figure 8: SSTs that hold the sand

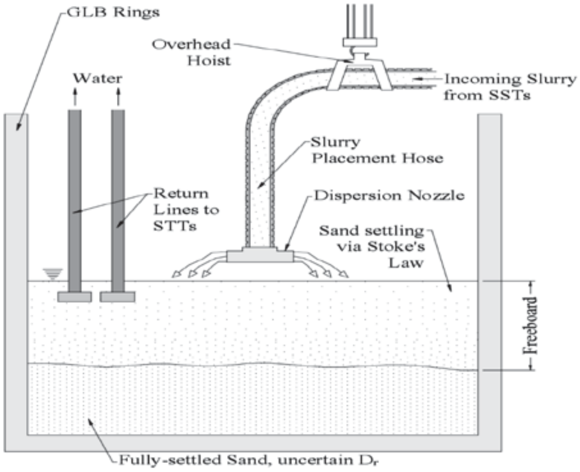

Figure 9: Cross-section of filling process in GLB

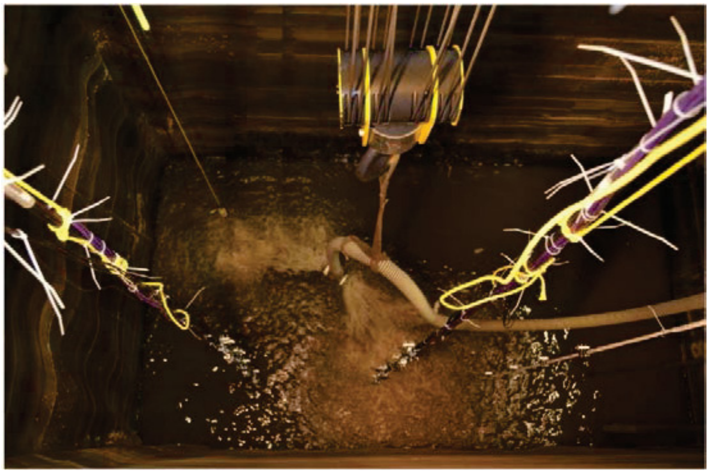

Figure 10: Looking down inside GLB during filling

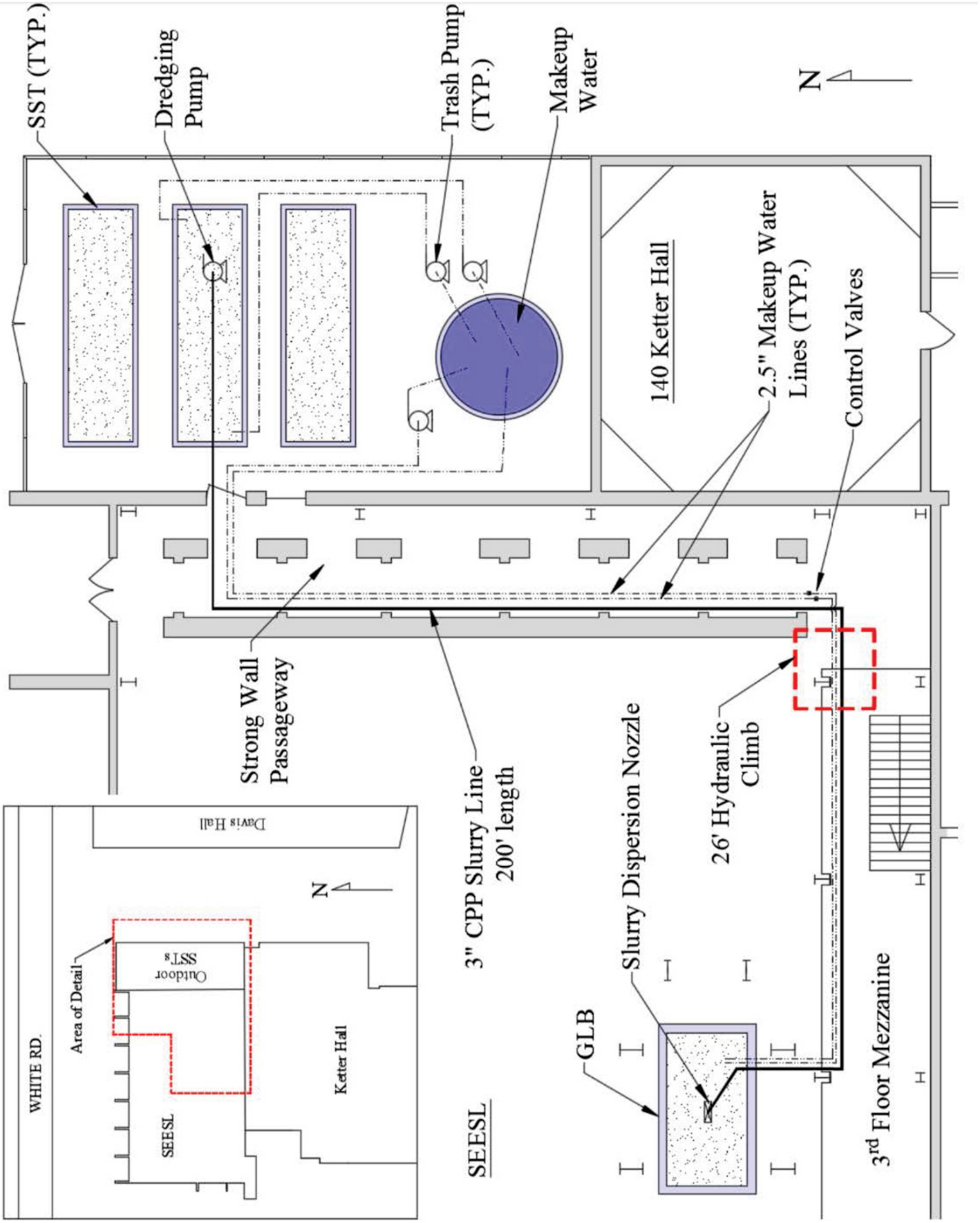

Figure 11: SEESL layout for filling GLB

4. INSTRUMENTATION

Instrumentation is placed in the GLB to enable observation of real time soil shear wave velocity (SWV) and track the input wave as it propagates through the soil column. To accomplish this a number of instruments are required including; Bender elements (BE), displacement transducers (string-pots), accelerometers, pore water pressure (PWP) sensors, and shape accel arrays. The following subsections will describe this instrumentation and briefly discuss its layout in the GLB.

The primary data acquisition system used to acquire data during GLB testing is Pacific Instrumentation, Inc.®. The string-pots, accelerometers, and PWPs are monitored through this setup using Pacific's PI660-6000 Professional Test and Measurement Software. This software acquires the test data, allows immediate plotting of results and allows for text-file conversion for post-processing in other more-available data analysis programs such as MATLAB®.

The BE's use a Data Acquisition (DAQ) Personal Computer (PC). The DAQ PC the BEDAQ software. This software provides a Graphical User Interface (GUI), program that operates and controls the signals to and from the transducers. This software dually organizes the type of signal sent to a transmitter and then monitors the received signals from selected receivers.

4.1 Bender Elements

The BE system at UB is composed of hardware and software components. A Bender Element (BE) is a common piece of equipment used in experimental soil mechanics testing used to measure the mechanical properties (Figure 12). COLLETTI (2016) shows an approach for capturing real time shear wave velocity during geotechnical laminar box (GLB) tests. Bender Elements are capable of predicting/measuring the Shear Wave Velocity, usually abbreviated as either SWV or Vs, of a soil specimen in the GLB. In the GLB tests bender elements are used to measure the changes in Vs through the duration of the experimental. By mapping the changes in the soils physical properties the dynamic behavior of soil can be better understood. The BEs will be buried inside the soil that is place in the GLB and used to measure the Vs of the contents.

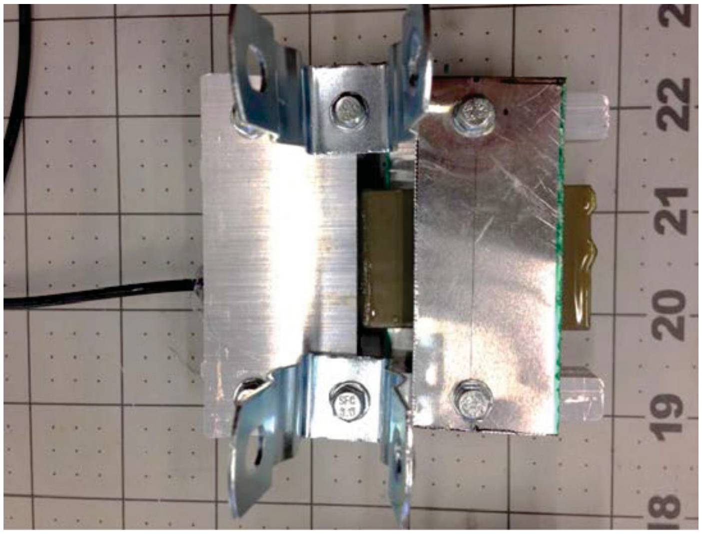

Figure 12: Fully assembled Bender Element with protective flashing

Before filling the BEs are placed in the empty GLB. This is accomplished by attaching them to two different structures; 1) a set of transmitters attached to a Measurand Shape AccelArray (SAA) named SAA1, and 2) a set of transmitters and receivers were attached to another SAA named SAA2. Sand is then pumped from the outdoor SSTs and is placed inside the GLB via a hydraulic filling process. This allows the BEs to be cast inside the soil media.

The SAA devices are pieces of instrumentation that when embedded in soil are able to capture the deformation of the material. SAAs are long and slender devices made of links and nodes. The SAAs that will be used are 20-ft long and each node in these SAAs are separated by 10-in long links. The SAAs have accelerometers located throughout the device. The SAAs are hooked up to a computer in the SEESL where the data is acquired by a software called SAARecorder. Therefore, the SAAs capture the exact location of all of its nodes during the experiment. A photograph of the BEs attached to the SAAs and PVC inside the GLB is seen in Figure 13.

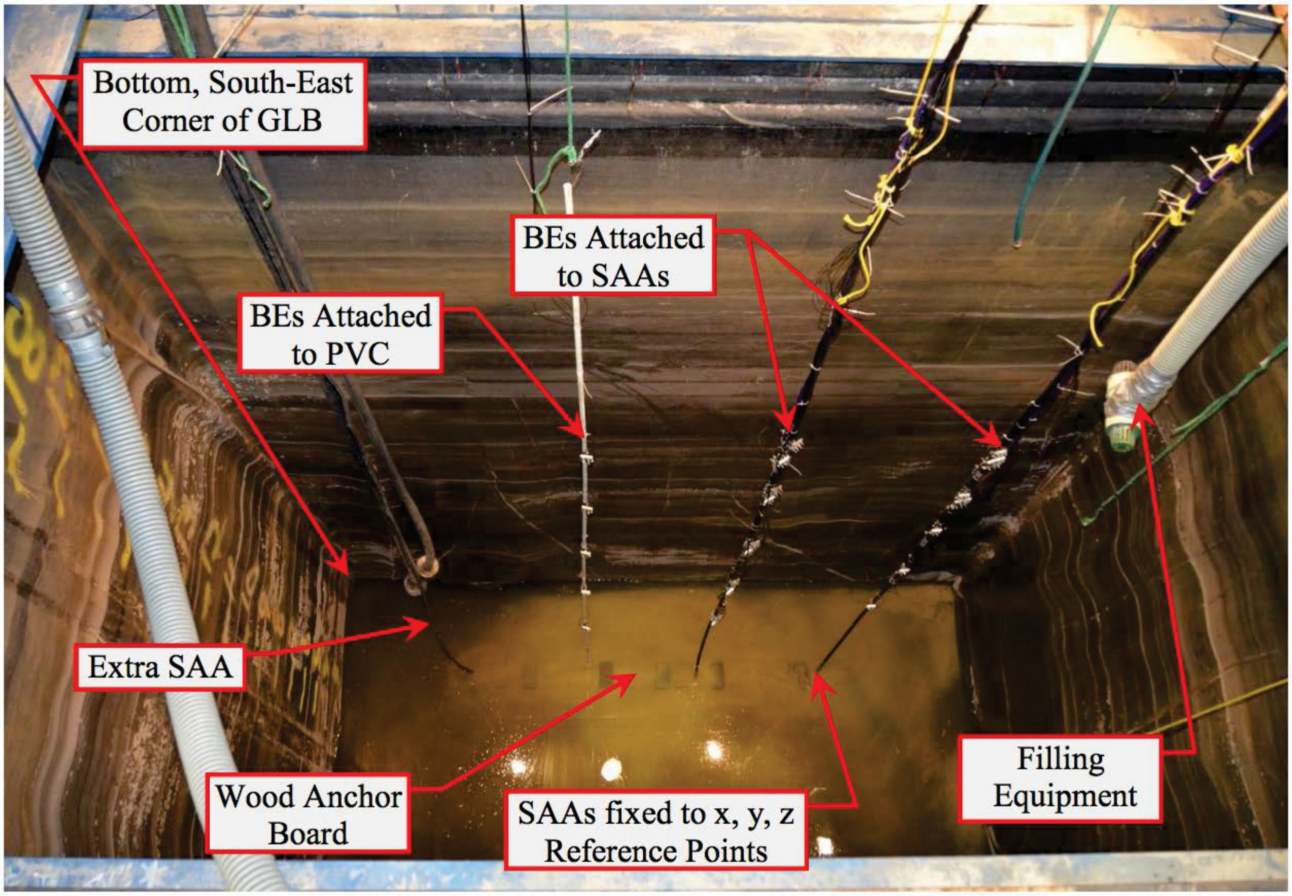

Figure 13: Location of Bender Elements in the GLB

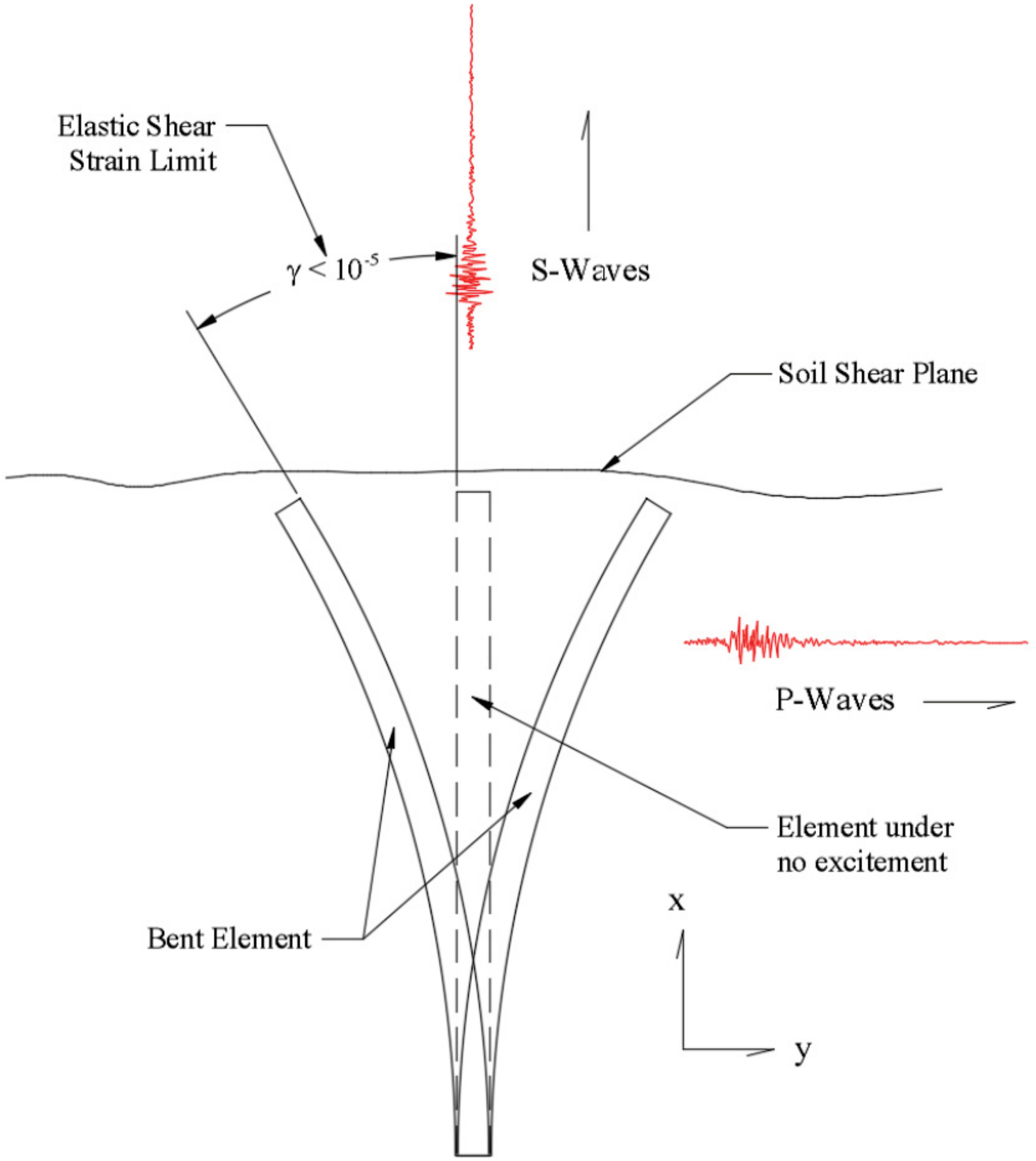

Figure 12 - Top, x-y plane, view of an Excited BE (NTS)

Figure 14: View of an excited BE

It is estimated that 22 BE transducers will be placed in the GLB. There will be 12 transmitters and 10 receivers.

To detect a shear-wave at least one transmitter and one receiver must be present and their exact locations known in some global coordinate reference frame. Knowing the coordinates of the BEs then the direct distance between the two transducers may be calculated via Pythagoras' equation. After the BEs are buried in the soil the transmitter is used to create a small elastic pulse. The transmitting BE physically moves and therefore deforms the soil matrix. Located at a know distance away is the receiving BE. The shear-wave travels through the soil and comes in contact with receiver. Therefore, until the shear-wave reaches the receiving BE there is no voltage measurable. If the time can be measured, between the initial pulse of the transmitter and the acceptance of the shear-wave at the receiver, then a linear SWV can be calculated between the two elements.

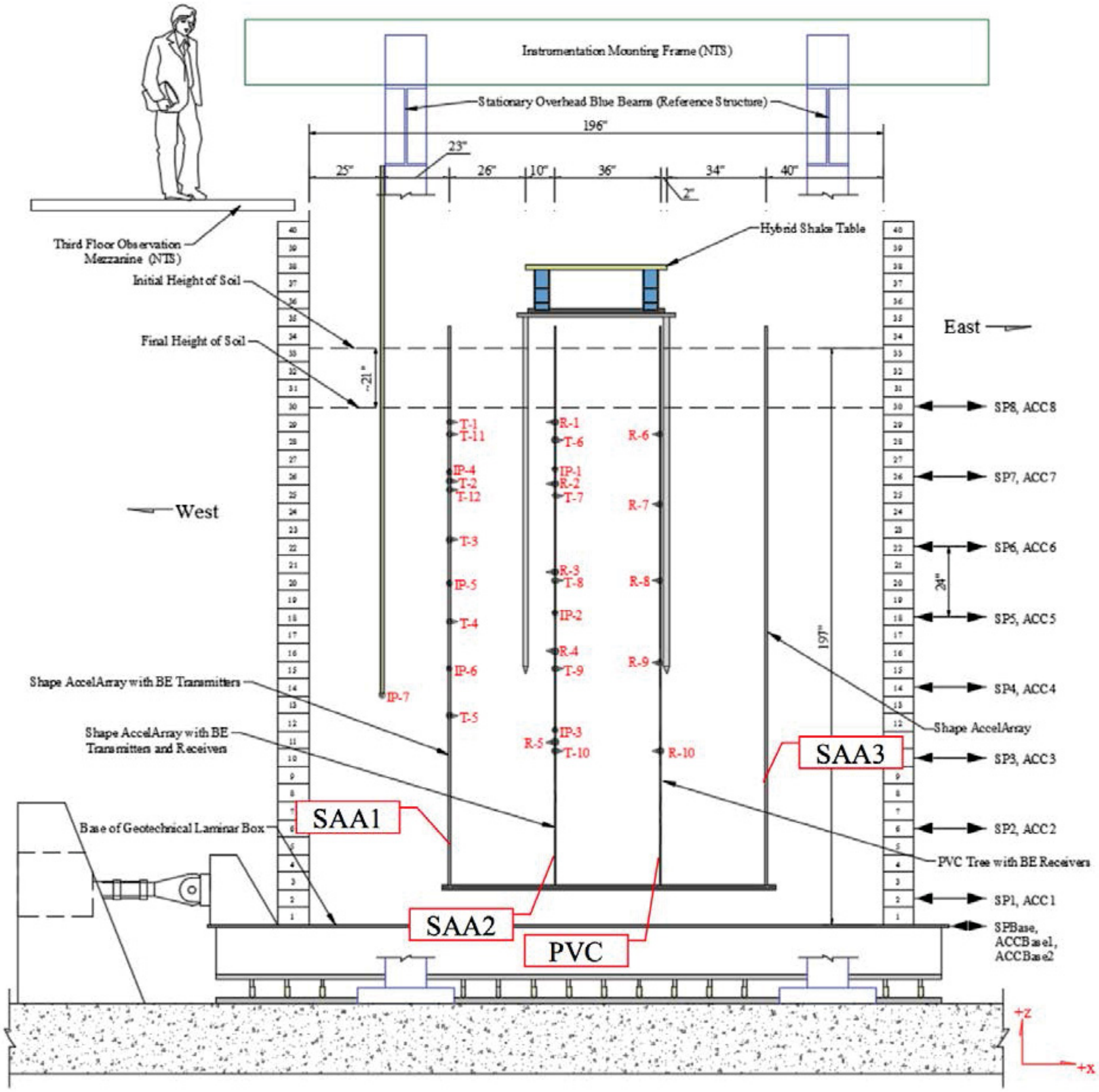

Figure 15: Cross section view of SAA's and BE's embedded in the GLB

4.2 Displacement Transducers and Accelerometers

The base of the GLB and eight of the 40 laminates will be instrumented with displacement and acceleration transducers. These devices measure the movement and acceleration of the base. The actual motion imposed on the GLB base and soil model is different then the input motion due to losses in the hydraulic system and frictional resisting forces in the actuating and base motion setup. Therefore, the base displacements and acceleration transducers measure the actual changes in the state of the GLB base. The input MPT computer commands therefore are just an approximate actuating signal and the true GLB motions are measured using these transducers attached to the base.

The displacement of the base, laminates and HST are measured using Firstmark Controls® Model 162-3405 Position Transducers, also known as "string-pots." The accelerations of the base, laminates and HST are measured using Honeywell-Sensotec® Model JTF accelerometers.

4.3 Pore Water Pressure Sensors and SAAs

The pore water pressure is measured using 194-mm long, 32-mm diameter, 250-kPa capacity Geokon® Model 3400 piezometers. The pore water piezometers (PWPs) are calibrated using a custom SEESL setup involving a Dayton® 1ZMG5 pressure vessel and a 690-kPa capacity Groebner® digital pressure gauge.

Embedded in the soil model were three Measurand® ShapeAccelArrays (SAAs). The SAA devices are long-slender rope-like pieces of instrumentation, made of links and nodes, that when embedded in the soil are able to capture the deformation of the geomatrix. The SAAs used in this experiment were 6-meters long with each node separated by 250-mm long rigid links. The nodes are instrumented to provide the location of the SAA assemblies at all times.

5. LAMINAR BOX RUNS

Once the GLB is filled, the water will be allowed to drain out of the box via drain ports in the bottom. This will allow for the sand to reach its normal in-place moisture content of around 20%. Five series of tests will be run each with increasing amplitude. The input motion will be simple sine wave inputs for four of the five tests and the fifth set will be run using an actual earthquake time series. The input sign motion will have an amplitude of about 0.025g's and a wavelength of approximately 4 Hz. The idea is at low levels of shaking (i.e. test set 1 and 2) the dynamic soil material properties will not change between experimental runs and that the dynamic properties will be similar. As the higher amplitude motion is input the dynamic properties will change and only one or two tests can be performed with known properties.

Table 2: Planned test series

Test Series	Initial V_s desired	Number of runs	Amplitude of Sine Wave (g's)
1	250 ft/s	7	0.025
2	TBD after Tests Series 1	7	0.04
3	TBD after Tests Series 2	3	0.08
4	TBD after Tests Series 3	2	0.14
5	TBD after Tests Series 4	1	0.25

The motion will be input at the base of the GLB using two MTS® Model 244.41S displacement-controlled hydraulic actuators. Each actuator is rated for 500-kN of force. The maximum static and dynamic stroke of the actuators are, respectively, 304.8 and 254 mm. MTS® Model 661.23 500-kN force transducers (load cells) are in-line with the actuators thereby giving complimentary load vectors to pair with the input displacement motions.

The base motions are controlled with MTS® Model 793.10 MultiPurpose TestWare and Series 793 Application Software. The SEESL GLB base motions are divided in to different categories called Record Motions.

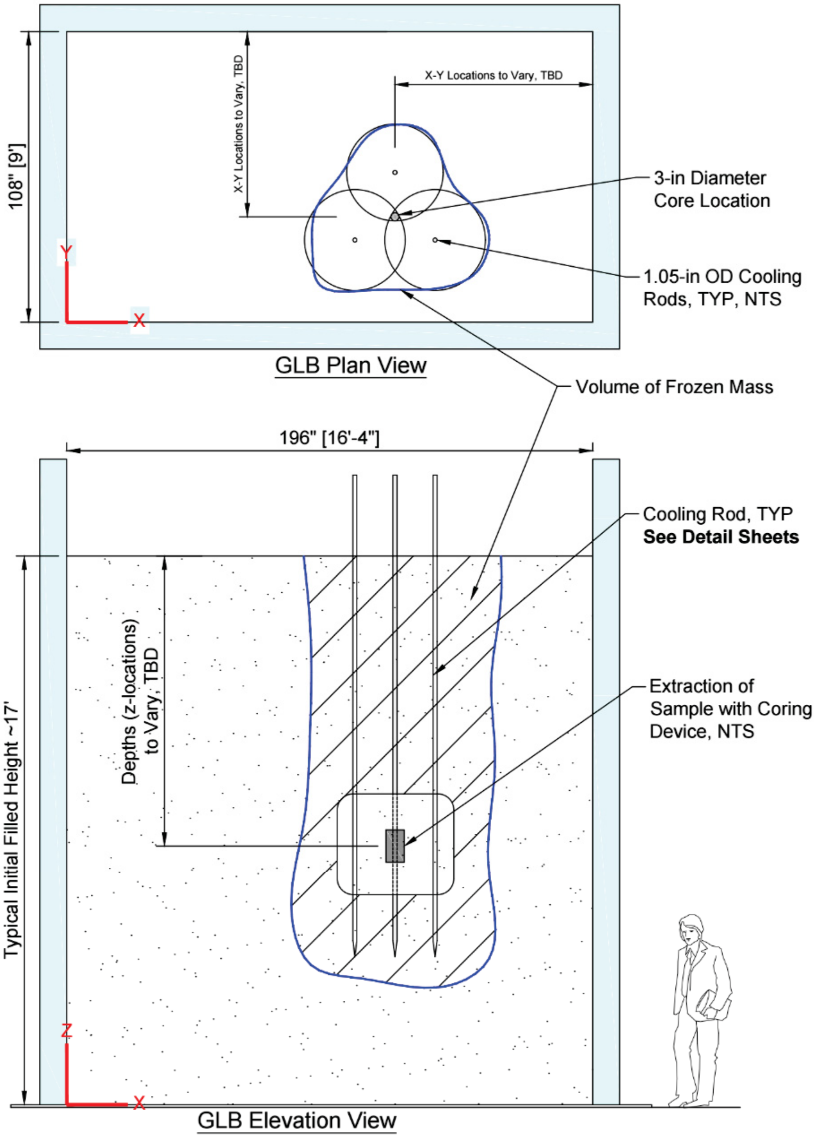

Figure 16: Ice core extraction layout

5.1 Gathering Soil Properties after Each Test

Bender elements will be used to measure shear wave velocity during the experimental tests. The SWV will be used to calculate the shear modulus. At the end of each series of test an Artificial Soil Freezing (ASF) technique will be used to extract soil cores. These cores will then be tested in the cyclic triaxial machine to determine the dynamic soil properties. A core from each test series will be sent to INL for examination in a CAT scan machine to identify any shear banding. A nominal layout for extracting the frozen cores is shown in Figure 16.

6. NUMERICAL ANALYSIS

Numerical models of the GLB test will be built in three software programs, 1) MASTODON/MOOSE, 2) ABAQUS, and 3) LS-DYNA. Initial blind model runs will be performed to predict the shear wave behavior in the GLB and the response spectrum at the free surface. These initial tests will be compared with the experimental test results when those results have been gathered. These comparisons will be used to validate the soil constitutive models in these codes. This will build confidence in the numerical predictive capability when performing site-response analysis and understanding how earthquake waves pass through soil.

7. REFERENCES

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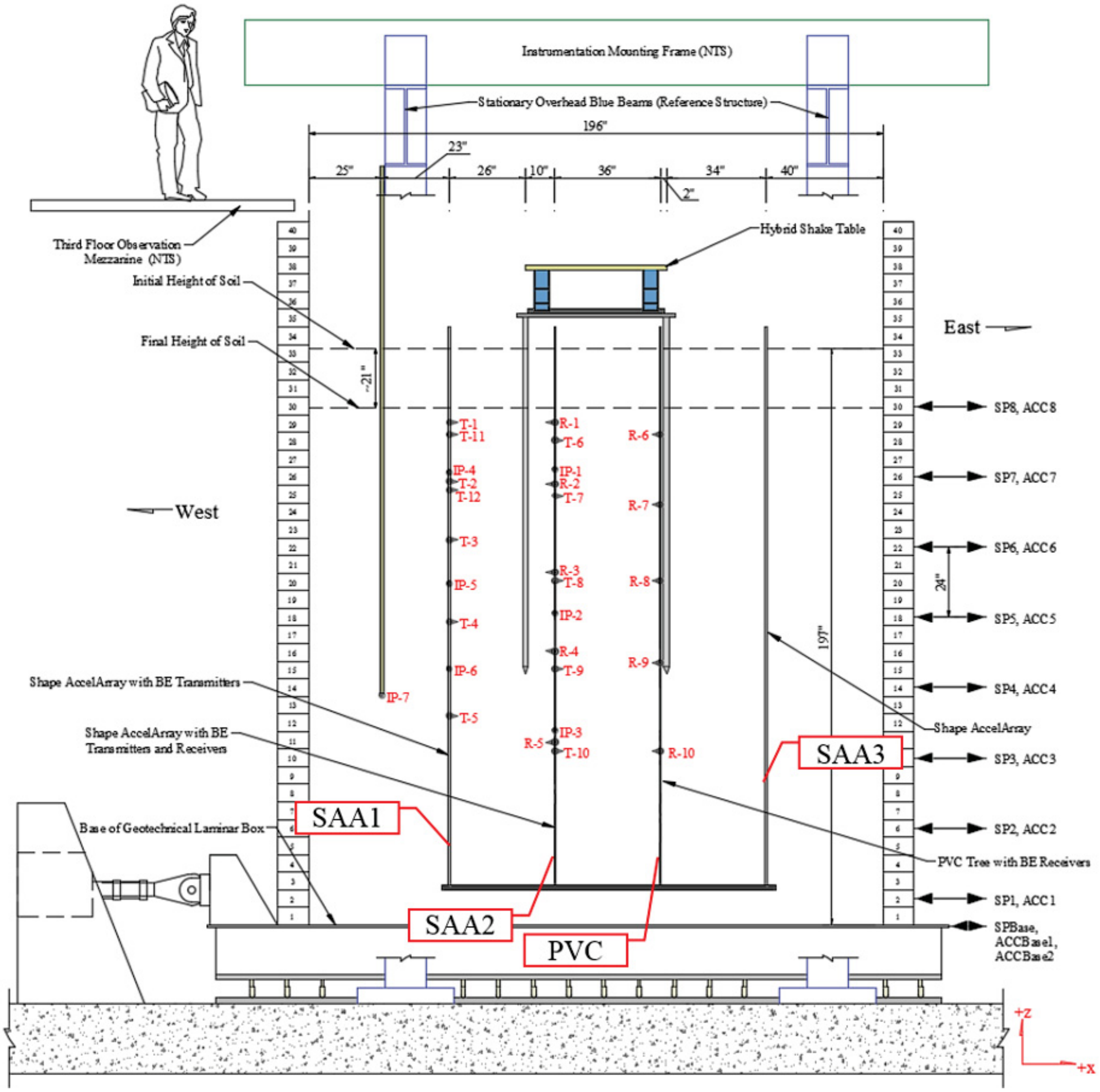
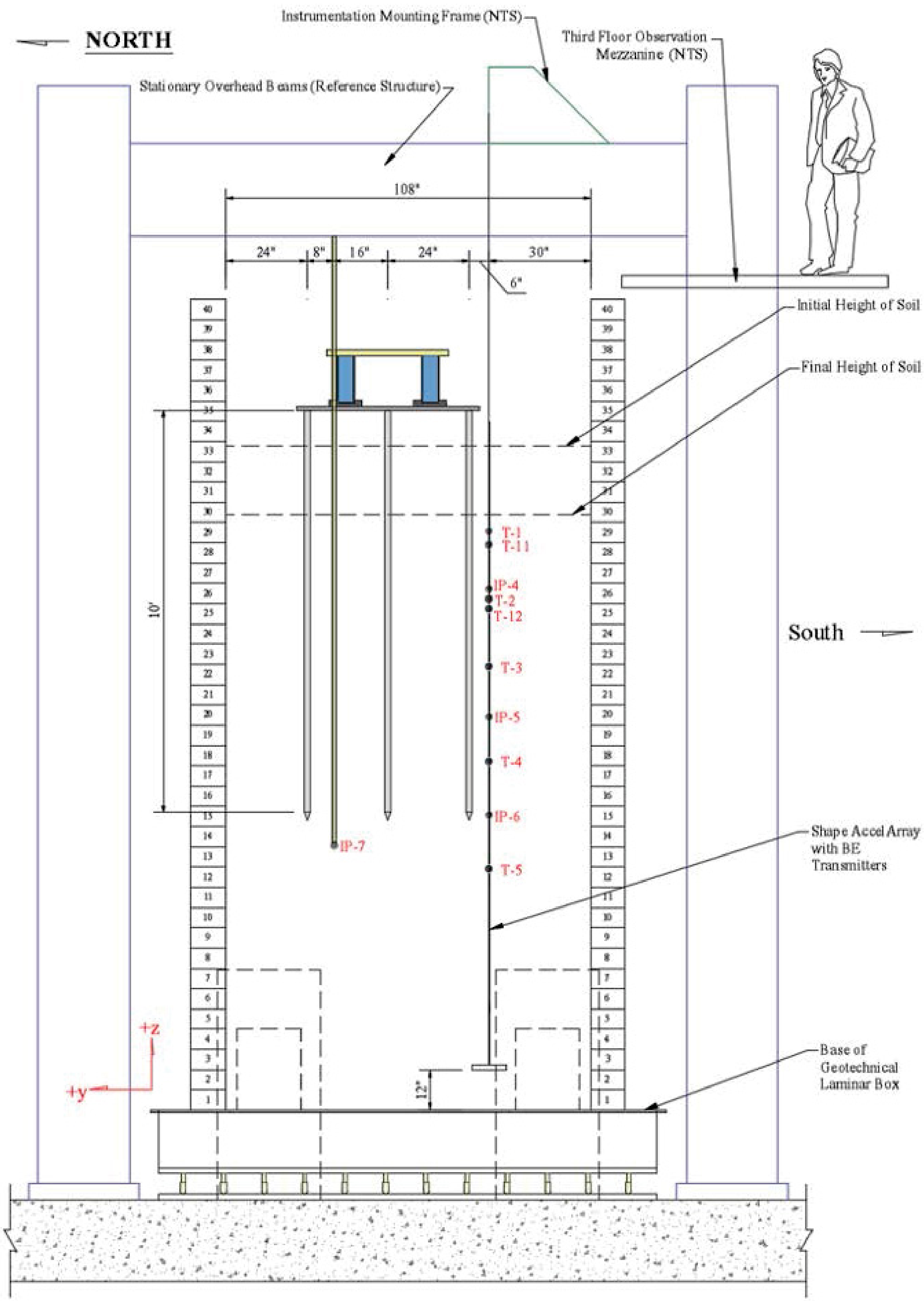
APPENDIX A: LAMINAR BOX DRAWINGS




NORTH
Instrumentation Mounting Frame (NTS)
Third Floor Observation Mezzanine (NTS)
Stationary Overhead Beams (Reference Structure)
108"
24"
8"
16"
24"
30"
6"
Initial Height of Soil
Final Height of Soil
10'
40
39
38
37
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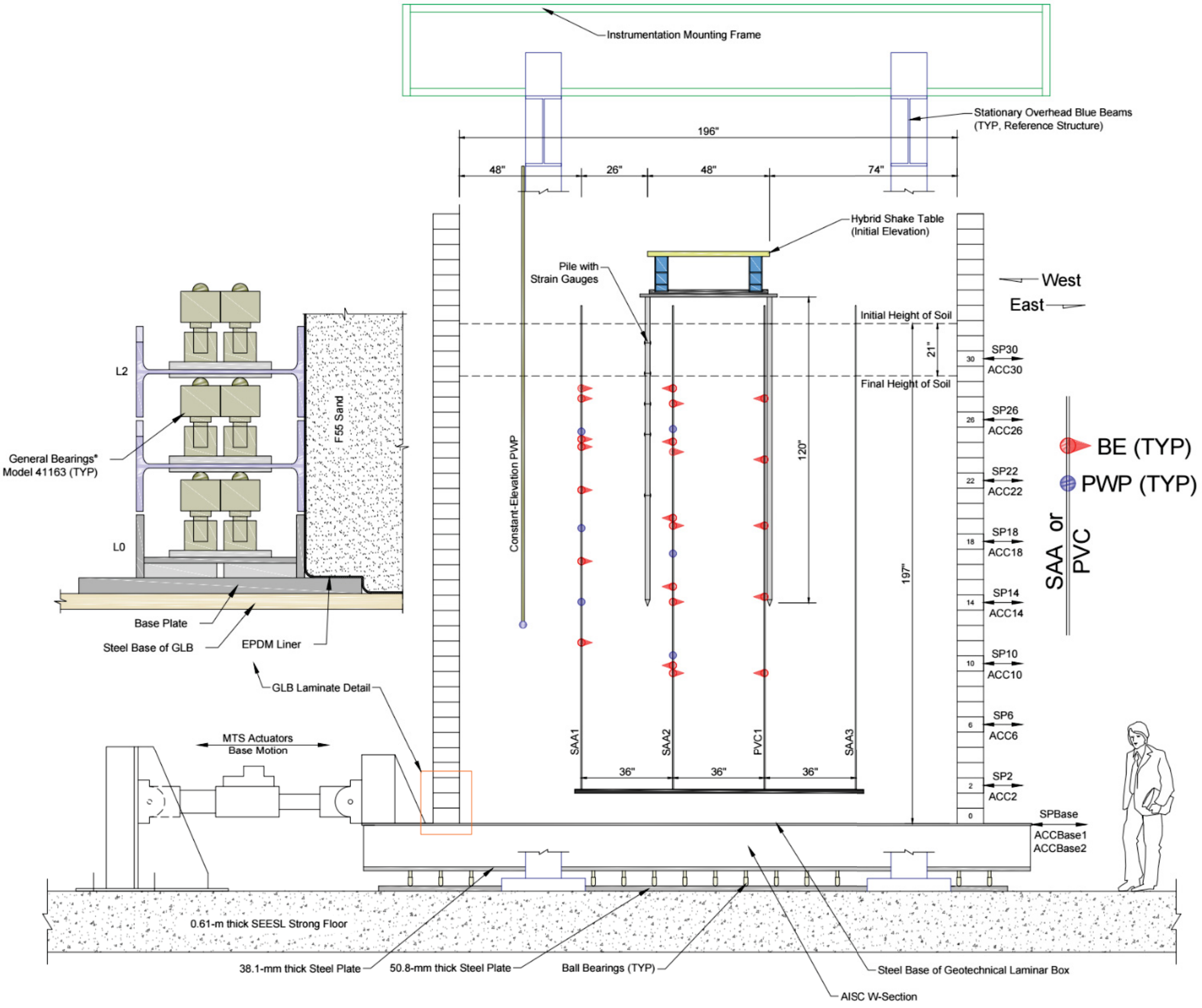
T-11
IP-4
T-2
T-12
South
T-3
IP-5
T-4
IP-6
IP-7
T-5
Shape Accel Array with BE Transmitters
+z
+y
12"
Base of Geotechnical Laminar Box


Instrumentation Mounting Frame
Stationary Overhead Blue Beams
(TYP, Reference Structure)
196"
48"
26"
48"
74"
Hybrid Shake Table
(Initial Elevation)
Pile with
Strain Gauges
West
East
Initial Height of Soil
21"
Final Height of Soil
120"
197"
SP30
ACC30
SP26
ACC26
SP22
ACC22
SP18
ACC18
SP14
ACC14
SP10
ACC10
SP6
ACC6
SP2
ACC2
SPBase
ACCBase1
ACCBase2
30
26
22
18
14
10
6
2
0
BE (TYP)
PWP (TYP)
SAA or
PVC
Constant-Elevation PWP
SAA1
SAA2
PVC1
SAA3
36"
36"
36"
L2
L0
General Bearings*
Model 41163 (TYP)
F55 Sand
Base Plate
Steel Base of GLB
EPDM Liner
GLB Laminate Detail
MTS Actuators
Base Motion
0.61-m thick SEESL Strong Floor
38.1-mm thick Steel Plate
50.8-mm thick Steel Plate
Ball Bearings (TYP)
Steel Base of Geotechnical Laminar Box
AISC W-Section