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# Modernized Approach For Generating Micro-Layering And Macro-Heterogeneous Structures In Porous Media For Use In Transmitted-Light Method Flow Visualization Experiments

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# MODERNIZED APPROACH FOR GENERATING MICRO-LAYERING AND MACRO-HETEROGENEOUS STRUCTURES IN POROUS MEDIA FOR USE IN TRANSMITTED-LIGHT METHOD FLOW VISUALIZATION EXPERIMENTS

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ABSTRACT:

Image capturing in flow experiments has been used for fluid mechanics research since the early 1970s. Interactions of fluid flow between the vadose zone and permanent water table are of great interest to researchers because this zone is responsible for all recharge waters, pollutant transport and even irrigation efficiency for agriculture. Griffith, et al. (2011) developed an approach where constructed reproducible "geologically realistic" sand configurations are deposited in sand-filled experimental chambers or cells for light-transmitted flow visualization experiments. This method creates reproducible, reverse graded, layered (stratified) thin-slab sand chambers for visualizing multiphase flow through porous media. Reverse-graded stratification of sand chambers mimic many naturally occurring sedimentary deposits. Sand-filled cells use light as nonintrusive tools for measuring water saturation in two-dimensions (2-D). Homogeneous and heterogeneous sand configurations can be produced to visualize the complex physics of the unsaturated zone. The experimental procedure developed by Griffith, et al. (2011) was designed using now outdated and obsolete equipment. We have modernized this approach with new PARKER daedal linear actuator and programed projects/code for multiple configurations. We have also updated the camera with new software and image processing software. Modernization of transmitted-light source, robotic equipment, redesigned experimental chambers, and newly developed analytical procedures have greatly reduced time and cost per experiment. We have demonstrated the functionality of the new equipment to generate micro-layers and macro-heterogeneous sand-filled chambers.

## Dedication and Thank You:

Thank you to Matt Lowe and his machine shop on campus and to John Massey of the ARS National Sedimentation Laboratory for distilling my thoughts into tangible pieces of hardware used in this experiment. I have learned much in the way of fabrication from you both.

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This thesis is dedicated to my family. The people who lift me up and are always in my corner. To Kit, my wife, every day I am more in awe of your strength and steadfast faith. To my mother, the no. 1 fan I will ever have. To the memory of my father, Kevin Jones, and his passion for the sciences. Finally, to my grandparents, to the ones who instilled the bedrock of my values and ethics. These are my dedications.

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# 1. INTRODUCTION

Fluid flow research often uses imaging methods to discern the complex mechanics inherent in flow systems. Transmitted-Light Method (TLM) for flow visualization experiments analyze two-dimensional digital or digitized images taken within thin-slab chambers or cells of porous media. Experimental cells filled with translucent porous media are mounted and light is transmitted through the cell as photographs are captured from a camera, recorder, charge-coupled device (CCD), or more recently a scientific complementary metal oxide semiconductor camera (sCMOS). This technique has been used to evaluate wetting front instability in a variety of cross-section sand configurations and infiltration conditions (e.g., Hill and Parlange, 1972; Hoa, 1981; Glass, et al., 1989b; Samani, et al., 1989; Liu, et al., 1994; Detwiler, et al., 1999; DiCarlo, et al., 1999; Wang, et al., 2000; Walker, et al., 2000; Mortensen, et al., 2001; Niemet, et al., 2002; Yarwood, et al., 2002; Weisbrod, et al., 2003; Parker, et al., 2006; Griffith, et al., 2011). Transmitted light intensity is inversely proportional to the thickness of the slab (Griffith, 2008). Intensity increases in saturated regions of transparent fluid with relatively high indices of refraction ($H_2O$), and decreases as light is scattered in aerated porous regions (unsaturated regions). These nonintrusive tools for characterizing water saturation have been contrasted with X-ray transmission and found to be highly correlative at a far lower cost (Tidwell and Glass, 1994; Niemet and Selker, 2001).

Griffith, et al. (2011) developed an approach for constructing reproducible, ‘geologically realistic’ sub-laminae and macro-heterogeneous sand structured chamber configurations for

TLM experiments. A list of figures used in this thesis are found in Appendix A. An apparatus was created to emplace randomized sand inside thin-slab chambers with micro-layering and reverse-grading of grains, mimicking many natural sedimentary features (Figure 1). The reverse-graded and micro-layered structure (sub-laminae bedding) of grains in nature are characteristic of fluvial environments and have complicated flow paths in which large volumes of water move through relatively small sections of the subsurface (Figure 2). Figure 3 is a close-up image of the Ancestral Rio Grande River outside Albuquerque, NM and shows this type of structural development. Multiple productions of different "microlayer" samples were generated and analyzed to evaluate reproducibility of the sample preparation procedure. The original equipment used in this procedure has become obsolete and essential hardware has suffered complete failure (Appendix B).

The objectives of this thesis are to: 1) construct a laboratory space for flow visualization experiments, 2) redevelop the approach for generating heterogeneous sand-filled chambers with new equipment, 3) acquire and apply a new light source, 4) design a new mounting system for sand-filled chambers, 5) develop a new chamber design, 6) construct a darkroom for conducting experiments, and 7) conduct a series of example experiments demonstrating the capabilities of our new flow-visualization equipment and approach with a new laboratory procedure (Appendix C). The following section discusses and compares outdated and new equipment.

We have acquired new equipment to replace obsolete hardware and developed a new procedure reproducing the results of Griffith, et al. (2011) with these updates. Newly acquired hardware includes the current year model Parker daedal linear actuator (Robotic arm), a new light source, new chamber design and a chamber mount. An updated procedure for image acquisition and analysis using Micro-Manager and ImageJ (open-source products) is also included. During this time, we moved into a new lab space in the University extended Jackson Avenue Center (JAC); this new space is dedicated to flow visualization and hydrogeology research.

This thesis documents the new equipment design and demonstrates use of the equipment for multiphase flow experiments. Updates to this approach will enable future researchers to perform multiphase imaging experiments in porous media under realistic geological conditions at lower cost and less experimental set-up time, using readily upgradable equipment and software.

# 2. BACKGROUND

Recharge of the permanent water table through the unsaturated (vadose) zone is very important in the understanding of our water usage and possible movement of contaminants into the groundwater and soils. Water movement and contaminant transport within the unsaturated zone is very dynamic and not intuitive. Over the course of time researchers have tried to gain a better understanding of the mechanisms at play, including physical and numerical models to determine the dominant physical features and experimentation and field studies to support these findings. This research is important because water storage is low, but recharge high in regions where sandy soils constitutes a large portion of the continental land mass (Figure 4).

In the 1960s and '70s, researchers such as Hill and Parlange (1972) discovered the recharge waters to the saturated zone do not move in a uniform "sheet" through the media of the unsaturated zone but take preferential pathways. These "unstable wetting fronts" move large volumes of water at rapid rates through soil horizons and make the numerical modeling of small grid-block recharge models inherently more complex. Richard's equation for unsaturated flow and other continuum approaches cannot describe this infiltration. The goal of many research hydrologists and soil scientists at this time was to better understand unstable wetting fronts and characterize what conditions such infiltration occurs (Raats, 1973; Hoa, 1981; Glass and Steenhuis, 1984, Glass, et al., 1989a,b,c; Samani, et al., 1989).

Visualization of water flowing or infiltrating into porous media has become an integral branch of hydrologic studies, and there have been many innovative and novel approaches to this task. The approach we use for porous media transport visualization was developed and refined by Robert J. Glass, a researcher with Sandia National Laboratories (Glass, et al., 1989b). This method is known as the Transmitted-Light Method and is a non-invasive, cost effective means of visualizing the wetting front and capturing the flow in images (.tiff files) for analysis. This method creates geologically realistic reverse-grade sand layers within a glass paneled chamber or cell (Figure 5). The configurations of the sand layers in the cells can be manipulated and a variety of fluvial-like structures created. Griffith (2008) proved the reproducibility of this method with the original equipment donated to the department by Sandia. Light passing through the boundaries of different media traveling from its source to the sCMOS camera is refracted between the boundaries, as described by Snell's law.

The original scope of this thesis was to use the methods and equipment developed by Griffith (2008, 2011) to quantify the influence of capillary heterogeneity on the dissolution rate of gaseous $CO_2$ in water-saturated thin-slab, sand-filled chambers; however, the original equipment experienced complete failure and our laboratory space was moved several times over the span of two years (Appendix B). The delays associated with the acquisition of new equipment, the design and development of new experimental procedures, and the repeated laboratory moves necessitated a change in the thesis scope. Figure 6 is a blueprint of the new laboratory at the JAC.

# 3. METHODS

## 3.1) Comparison of Outdated and new Equipment

The daedal linear actuator (robotic arm), controller (compumotor) and computer running X-ware failed in 2014. This was the original equipment donated to the Geology and GE Department by Sandia National Laboratory (SNL). The original arm was purchased in 1994 and controlled by an obsolete computer and outdated version of X-ware Terminal Emulator (version 2.0) via DOS interface system. We evaluated our needs, contacted Parker, met with our local distributor and found a replacement for the original arm. The new generation Parker daedal linear actuator (OSPE32) with standard carriage has a maximum load capacity of 300 Newtons (N) and total stroke distance of 1.5 meters (Figure 7). This updated robotic arm uses C3 ServoManager and CoDeSys version 2.3 for development and implementation of our Programing Language Controller (PLC) for Windows 7. An operation manual for calling a program, manipulating parameters, and executing the operation can be found in Appendix D, and a version of the program used in this thesis can be found in Appendix E.

The original light source was a massive box, housing an array of 21 fluorescent light bulbs (Figure 8). This was too heavy to move (when assembled) without the use of a forklift and wastes excessive amounts of energy due to heat loss. The excessive heat loss from this light source called for a mounted external cooling system. Powering the array and cooling system was difficult and constituted a safety hazard. The “lightbox” was in need of weight-support beams and required the operational “darkroom” have an open wall for heat exhaustion. This method required the entire lab to be dark so not to interfere with the CCD imaging. The darkroom is now closed completely allowing little light from the laboratory in during experimentation.

The new light source is a 0.609 $m^2$ flat LED panel (Figure 9) that delivers a light output of 3300 Lumens (lm) at an output of 44 watts (w). The standard lifetime on this piece of equipment is roughly 50,000 hours. The internal radiator distributes heat produced from the array such that brightness from the panel is enhanced. The included diffusion plate is designed to give an even distribution of light across the entire panel. This panel is now attached directly to the visualization stage and mounted in with the chamber (Figure 10) for experimentation, this reduces the need for multi-mount housings and is mobile.

The original mounting system for sand chambers was attached directly to the lightbox. Now that the old light-box has been replaced, this procedure exclusively enlists the use of the visualization-stage mount. This mount is created from unistrut metal framing systems with four casters to move the mount freely and safely around the lab space. This mount houses the chamber, light source and the tubing for fluid infiltration (Figure 11). It has a rotating stage so that future researchers will be capable of altering gravity effects while capturing flow images.

The new chamber is made from performance polymer plastic replacing the steel spacers creating a much lighter chamber (Figure 12). The original chambers were designed with steel spacers, glass panels, and steel C-clamps holding the assembly together (Figure 12). Sand is still deposited via a removable chamber top and the bottom of each chamber houses a manifold. The U-shaped manifold of the new chamber has a keyed-in top with fewer seams than the original design. This design is sealed with six Dewalt large trigger clamps and waterproofed with silicon sealant. Because the scope of this thesis changed, we chose not to fabricate a vacuum sealed chamber for $CO_2$ diffusion experiments; instead I shifted focus to developing updated experimental apparatuses and developing a new experimental procedure. This chamber design is perfect for this application as it is lighter and takes far less time to breakdown and clean between experiments.

CCD cameras are the most commonly used cameras in quantitative imaging. This is because the instruments are designed for low noise, excellent linearity, uniformity and resistance to blooming (glare that is caused by a shiny object reflecting too much light into the camera lens). These instruments operate on the fundamental property that a photon incident on the device produces an electron–hole pair in a region of silicon that is biased to some potential (Clemens, 2001). The CCD camera had to be replaced as well. We upgraded from a Photometrics COOLSnap HQ to the PRIME sCMOS, also a product of Photometrics (Figure 13). This camera is more sensitive with a larger field of view with high trigger speeds and less noise from signal to noise contrasts.

The updated image processing technique uses Matlab's micro-manager and imagej software where images are acquisitioned into micro-manager and analyzed in imagej. These images are stored as separate images in a compressed folder. The .tiff files are layered together to create a movie of the infiltration of the chamber. Analysis of images is based on grayscale pixels with intensity values ranging from 0 to 255, where 0 represents black and 255 is pure white. Saturation of the sand occurs in pixels at the white end of the grayscale. Areas with a large pixel value are lighter (near 255) and represent zones of large pores (i.e. larger grain size); darker sections indicate areas of smaller grains (small grains scatter light more, decreasing the light intensity).

The new darkroom is constructed from unistrut framing and duvetyne fabric (Figure 14). Duvetyne is a twill fabric with velvet-like nap at one side. It is mainly used in the film industry as it is the ideal material for blocking light. It is highly opaque (roughly 98% opacity) and easier to work with than any vinyl sheeting. Since the light source is now an energy efficient LED panel the darkroom can be completely covered, allowing the experimenter to leave the laboratory overhead bulbs on.

The updates outlined in this paper are intended to improve upon a well-developed experimental procedure and incorporate modern hard and software. Modernization of this experimental design will allow for continued research using the TLM and provides an inexpensive platform that is easily altered to meet experimental design needs and is readily upgradable.

### 3.2) New Laboratory Procedures

The sand-filled chambers and subsequent experiments shown here illustrate the capabilities of our new equipment and procedures. Geologically realistic thin-slabs bring the field into the laboratory setting, where parameters are manipulated and underlying physical process of depositional structures better understood.  The experimental procedure (Appendix C) has been modified from Griffith (2008) and Glass et al. (1989b). Appendix D is a procedure for using the C3 ServoManager and CoDeSys compiler software, while Appendix E is a copy of the original program. Appendix F is a set of laboratory notes outlining programs by file name, a brief description of the sands structure developed by that program and giving the declared parameters of the program.

The chambers used in this procedure are built from two glass panels, with a polymer plastic manifold between the panels. The new chamber is designed to have the same sized spacing and internal volume as the old chambers.  We begin by cleaning the two glass plates and cutting out the two new neoprene sheets and cheesecloth for each experiment (Appendix C). Placing a sheet of neoprene on each side of the manifold between it and the glass panels. The chamber is held together via 8 large trigger clamps (Figure 12). The old chamber design consisted of two side rails (spacers) sandwiched between two glass plates. The rails contained an inset O-ring to seal the edges of the chamber, and a steel strip was then placed on the outer edges of the glass. A piece of angle-iron was then slipped over the edges of the chamber, and a series of screws were used to press the glass plates together, compressing the O-ring seal. This approach required extreme care, as differential pressures from the tightening of the screws could result in one of the glass panels breaking (Figure 15). Though the trigger clamps are cumbersome, they do not risk shearing the glass panels. The chamber's manifold is divided into two pieces, a lower U-shaped half with two ports for fluid exiting and a keyed-in top with three ports for fluid infiltration. When building the chambers, we place a layer of cheesecloth (to impede grains falling into and clogging the port holes) at the bottom before filling with sand and at the top after chamber filling is complete. This chamber is easy to move from filling apparatus to the visualization-stage and can be broken down and cleaned very fast.

Homogeneous sand packs are created for the new chamber by dumping sand directly through a rectangular randomizer with V-shaped trough (Figure 16) (Griffith, et al., 2011). The sand falls through five bored holes in the V-shaped trough through a series of three screens designed to keep grains randomized during their fall. This process is difficult and requires patience, as a perfectly homogeneous chamber rarely happens on the first attempt. Any buildup of grains on one side or the other while filling, or non-uniform flowrate of falling grains will cause structuring within the chamber. This is best avoided by raking the grains in the trough to maintain a level surface and therefore an evenly distributed volume across all bore holes. A homogeneous pack could take many attempts, and images are taken to compare each attempt.

Generating micro-layers and macro-heterogeneous structured chambers begins by cleaning and randomizing a known volume of sand in desired sieve size range. Randomizing sand for the sandfiller requires dumping premixed and randomized sand into the hopper-filler (Figure 17); (Appendix C). Randomized sand is held by a hopper that is housed on the sandfiller carriage; sand flow is impeded by a swinging gate (Figure 18). The sandfiller apparatus is a linear actuator belt-driven robotic carriage fastened to a unistrut carriage with sand chamber keyed in at the bottom (Figure 19). The carriage holds the hopper of randomized sand and feeding tube, which are lowered into the chamber and, when initiated, delivers sand at a constant flow rate (Figure 20). The carriage is supported by a caster that moves horizontally along the unistrut frame. The frame is suspended by a cable and pulley system for controlling drop height of the sand deposited into the chamber. The linear actuator is controlled by PARKER compumotor via C3 ServoManager software and projects are programmed via CoDeSys V2.3 compiler.

To begin the chamber fill, place the chamber in the sand-filler mount, lower the feeding tube into the chamber, swing down the gate (into the closed position) and attach the filled hopper to its mount above the gate. When the program is enabled and initialized, the actuator moves in a back-and-forth horizontal motion, delivering the sand inside the chamber in configurations predetermined by programmed projects written in CoDeSys V2.3. The project allows control of the actuator position, margins (boundaries), input velocity, deceleration to the margins, acceleration from margins, and number of passes across the chamber. All these parameters are available for manipulation in nineteen preset profile passes (Appendix E). The code compiler (CoDeSys) uses IEC 61131-3 industrial programming language in structured text.

After the chamber is filled with sand it is moved to the darkroom and mounted in the visualization-stage for imaging (Figure 11&14). The chamber is keyed-in, then the light panel added to the stage, in between the chamber and light source is a cutout frame that is designed to use only the region of light sized to the chamber glass, to block light from the rest of the LED panel during experimentation. Now the camera can be powered up and the computer can be used to capture images.

In order to avoid damaging the camera, the following procedure must be used to operate the camera:

1) Power up the camera, wait until orange LED stops flashing on back of camera.
2) Remove the lens cap from the focal lens.
3) The computer may be powered up after the orange LED with label [Initializing] has gone off.

It is not recommended to boot up the computer before powering up the camera, as the camera will not be recognized by the computer.

Experiments can be conducted once the computer controlling the camera is powered up and all soft parameters are set. The user must click the Micro-Manager icon and select a preset camera configuration. If you wish to setup a new configuration, do so by finding Tools from the toolbar and scroll down to Hardware Configuration. Follow the instructions for selecting a camera, naming it and selecting parameters to go on the Micro-manager dashboard.

The user must click Live to see the chamber inside the darkroom, adjust the movable stage or the camera to get a best fit inside the frame. Adjust exposure rates to get the best dry image. We found that exposures of 25-30 milliseconds (ms) is good to get a sufficiently variable light intensity for most situations. Now, select the rectangle tool from the ImageJ window and decide on the region of interest (ROI) you wish to capture. Open the multi-dimensional acquisition window to begin capturing a series of images, set the number of images and frame rate. A rate of 400 images at 1 sec/image is sufficient to capture jumps between layers and after capillary barriers (Figure 21). The disk space needed to hold such a large number of highly detailed images can be reduced by selecting a smaller ROI than the full frame and making certain the file directory is compressed. The user must then choose the file directory in which to save the images. Be sure to select single image capture and not image stacking, this type of acquisition (single image) is easier to manipulate when analyzing the images later. Make any notes needed for this experiment, changes in parameters include: type of structure, grainsize variation, infiltrating flowrate, lens exposure time, number of images captured and the frame rate of capturing. To capture images, hit the acquire button in multi-dimensional window and turn on the water valve to begin infiltration of the chamber.

Prior to conducting an experiment, the sands within the chamber must be consolidated. This is accomplished by repeatedly filling and draining the chamber with water. As the chamber drains, capillary forces pull the sand grains together, consolidating the pack. Take dry images, saturated images, drain the chamber and dry by infiltrating with desiccated air, retake dry images for comparison (Appendix C). Repeat this process and compare the images after each drain and fill. When dark sand grains no longer move between successive fill and drain cycles, the chamber is sufficiently consolidated to conduct an experiment. This process must be repeated a minimum of three times.

Procedures for use of the new equipment are found in Appendix C. Throughout the experimental procedure there are controllable parameters for creating structured chambers that must be addressed and fully understood. The controllable parameters are sand properties, drop height of feeder tube during depositing, the flow rate of sand through the feeder tune into the chamber, and how and where the feeder tube delivers the sand.

Throughout the course of this work, we used an evenly distributed grain size. Grainsize variations are detected in the imaging as lighter (large grains) and darker (small grains) regions because light is refracted through the quartz many more times in an area of small grains than large ones. Distribution and shape of sand effect the capillarity and pore size within the chamber. We sought out clean and uniform sand from vendors and bought from Accusand (wholesaler from Wisconsin, USA) for its very clean and pure sand with rounded and highly spherical grains.

Drop height is the elevation from the bottom of the feeding tube to the point of deposition in the chamber. The drop height is maintained by using a hand crank attached to the cables and pulleys to lift the actuator. How far grains fall determines how much they bounce when hitting the bottom. This, in turn, determines sorting. Drop height is crucial to develop reproducible cells for experimentation and must be maintained. We have found that 10 cm is a good height but should be manipulated depending on desired structures. Whatever height chosen, it must be maintained throughout the chamber filling by use of the hand crank.

Flow rate is maintained by the feeder funnel and has not been adjusted throughout the course of this experiment. This small, plastic funnel fits into the bottom of the hopper and its opening diameter sends sand out of the hopper and into the feeding tube at approximately 10 g/sec.

The last of the controllable parameters, how and when sand is delivered, is controlled via the ServoManager and CoDeSys projects for manipulation of the actuator carriage and has the most effect on structure characteristics. CoDeSys projects are written in structured text for use in the IEC 61131-3 program compiler. A list of the variety of projects we created can be found in Appendix F. All projects used are alterations of the original program from Appendix E. The actuator runs through a series of ‘profiles’ in which the editor can manipulate parameters (starting position, ending position, velocity of carriage, acceleration and deceleration from the boundaries, and jerk acceleration and deceleration) to create a variety of sand structures within the chamber.

We have developed an updated experimental approach to creating micro-layering and macro-heterogeneity in sand filled chambers and visualizing fluid flow through the chambers. This approach is for used for research into the complex physical mechanisms involved in moisture transport through the vadose zone and other multiphase flow problems. We created six different chambers with a variety of grain structures and one homogenous chamber. We infiltrated these chambers and captured the infiltration and movement of the wetting front through the layering.

# 4. EXAMPLE EXPERIMENTS

Micro-layers are achieved by programming the actuator project to move across the width of the chamber, to decelerate as it reaches the boundary and accelerate back in the opposite direction. Figure 22 is a test of the parameters (boundaries, velocity, acceleration, and deceleration) for creating mirco-layering. This chamber's project ran 4 profiles with all profiles having a constant velocity of 50 mm/sec except for the last on (5 mm/sec) where a distinct 'table top' structure is formed.

Buildup of deposited grains at the margins results in convex structures (Figure 5). This can occur by the feeder tube being to near the margins, or because feeder tube movement into and away from the margin happens too quickly. Concavity occurs under the opposite conditions where the movement at margins is to slow and dumps too many grains. We corrected the structural issues of Figure 5 by reducing the acceleration and deceleration values (Appendix F).

If the margins are not symmetrical with respect to the chamber center the layers possess a slope, where slope direction is upward toward the side closest to the chamber margin and downslope is toward the shallow side (Figure 23).

Stationary delivery (pauses) are not a parameter built into the programmed projects, but mounds can be created by other means (executing a profile to move a very short distance over many passes, or by toggling a 'hard stop' from the debugger window on ServoManager). Mounds created by processes known as granular avalanches where the large grains lag while the smaller grains propagate forward, known as the shock wave and size segregation of avalanches (Gray and Hutter, 1997). If the ‘hard-stop’ option is chosen, it requires that the carriage run through the Homing sequence and then the project be restarted to continue a fill.

Infiltration begins by taking a dry reference image (Figure 24). Then you must set parameters for multiple image capturing in the multi-dimensional acquisition tool of micro-manager. When parameters are selected for visualizing the flow, hit acquire and begin infiltrating the chamber. Infiltration will begin as a point source. Flow is pulled laterally by capillary forces in each layer (Figure 24c)

Capillary heterogeneities in the structuring of grains determines flow direction and soil moisture retention. Water stopped moving laterally after breaking the capillary barrier in the first mound structure. By Figure 24f the figure flow has reached the bottom of the chamber and draining of the upper micro-layers has begun. The water movement is concentrated in the finer grains of each successive mound and does not propagate laterally any longer.

Figure 25 is the first chamber created with a mixture of micro-layering and macro-heterogeneity. The macro-heterogeneity in this cell is from point source deposition of grains where we hard-stopped the actuator to allow the feeder tube to stay stationary, creating the four mounds present. We see infiltration beginning with at the open port valve (Figure 25b). Fingered flow is dominated by gravity forces, but some horizontal movement is induced by the capillary heterogeneity in the micro-layers (Figure 25c&d). By Figure 25d&e, the finger encounters a capillary barrier of coarse-grained material and moves downward to the right along the capillary barrier. We see that another finger has propagated through the lower micro-layers (Figure 25e).

The second chamber constructed with micro-layered and macro-heterogeneous structures has mounds on the left and right margins, as well as a mound in the center of the chamber (Figure 26a). For this experiment, we adjusted the flowrate of infiltrating waters and saw much more of a stable wetting front across the extent of the chamber (Figure 26b&c). Figure 26d we had cut off all valves, draining of the top layers began, fingers developed in the lower part. At the end of the experiment, you can see that the top half of the chamber is draining, and all preferential flow of the water is concentrated at the margins or through the center of the chamber (in the finer grained material) (Figure 26e).

Figure 27 is unique because we packed the top 2.54 cm of the chamber with unstructured fine-grained sand. In Figure 27b, horizontal stratification has led to strong horizontal capillary forces that pull water away from the body of the finger. Figure 27c shows the effects of placing unstructured fine grains at the top of the chamber, as the fine-grained unit is close to saturation. Multiple figures arise as the capillary forces give way to gravity forces. Preferential flow begins to occur at the margins. Note zones of trapped air near the center of the finger. Water begins to move through the large, coarse-grained center mound (Figure 27d). A finger penetrates the top of the mound, but the flow rate into the chamber is sufficiently high that flow along the top of the mound (a capillary barrier) occurs. Figure 27e, two more fingers penetrate the coarse-grained mound, and the central finger reaches the micro-layered zone. Strong horizontal capillary forces are present in the micro-layered zone. The wetting front has moved completely through the chamber (Figure 27f) and, if given time, capillary pull would fill all the micro-layers with moisture.

Figure 28 is a test of sloping layers. In this chamber, strata dip mainly from right to left, with the exception of a broad zone near the middle which dips from left to right. This configuration is dominated by macro-heterogeneity and contains many capillary barriers. The wetting front begins from a point source and very quickly starts moving to the right. The wetting front/finger encounters and coarse-grained mound and flow is directed down gradient to the right (Figure 28b&c). Two fingers develop and penetrate the mound. Both fingers encounter a capillary barrier and begin to merge (Figure 28d). The fingers enter the right dipping strata and begin to merge. Gravity forces direct the wetting font toward the right (Figure 28e). At the end of the experiment, the finger has moved from the center of the chamber to the right, and the upper part of the wetted zone is draining (Figure 28f).

Figure 29a is the dry image from a test to develop parameters for creating straight micro-layers in a chamber. This chamber displays three profiles of microlayers and one profile of very thick (table top) layers. Gravity forces dominate in the very large ‘table top’ layers, the coarser zones act as capillary barriers, and capillary forces pull the water horizontally in the fine-grained layers (Figure 29b&d). The finger then brakes through into the micro-layers, and the capillary heterogeneity in the layers leads to strong lateral movement (Figure 29d). In Figure 29e, the wetting front has reached the bottom of the chamber, note the strong horizontal capillary forces have pulled water laterally in the micro-layers and drainage in the fine layers near the top.

# 5. SUMMARY/FUTURE EXPERIMENTATION

Objectives reached during the course of this thesis were to: 1) construct a new laboratory space for flow-visualization research in the field of hydrology (room D01 of the JAC), 2) redevelop the approach for generating micro-layers and macro-heterogeneity in sand-filled chambers with modernized equipment, 3) acquire and apply a new light source for experimentation, 4) design a new mounting system for housing the sand-filled chamber and light source, 5) develop a new chamber design for flow-visualization experiments, 6) construct a darkroom for experimentation, and 7) conduct a series of example experiments demonstrating the functionality and capability of our new equipment and laboratory (outlined above). These objectives have been met and approved by the Department of Geology and GE.

Future researchers will find many parts of this procedure can be improved upon. Removing the chance for human error is always encouraged in experimentation, where reproducible results are the foundation. Replacing the hand crank with an automated gear for lifting the actuator and maintaining a level drop height is one such example.

It is interesting to note that in the sand cleaning and drying procedure, we took no effort in removing all relative humidity from the samples. Investigation is needed of this background humidity effect of capillary action during infiltration of the cell?

The study is needed of our original scope to visualize $CO_2$ diffusion into fully saturated, vacuum sealed chambers. These experiments can reveal the impact of capillary heterogeneity on the dissolution rate of $CO_2$ gas in aquifers.

Above all, the research produced in the new hydrogeology flow-visualization laboratory will have wide use as an educational tool for future students of this field.

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LIST OF APPENDICES

# Appendix A:

# Figures

## List of Figures

FIGURE PAGE

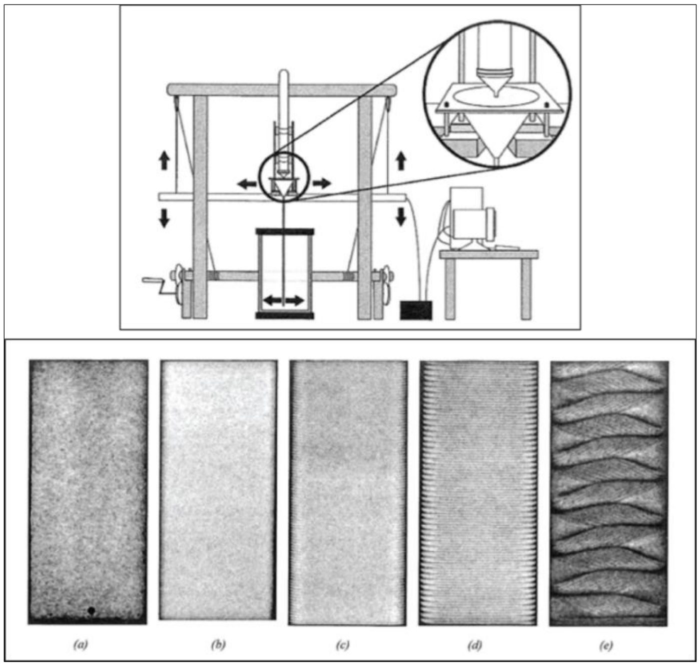



Figure 1: Conceptual design of the Sandfiller apparatus and types of chamber configurations capable of producing: (a) homogeneous, (b) thin-layered, (c) medium-layered, (d) thick-layered, (e) cross bedding (Griffith, et al., 2011).

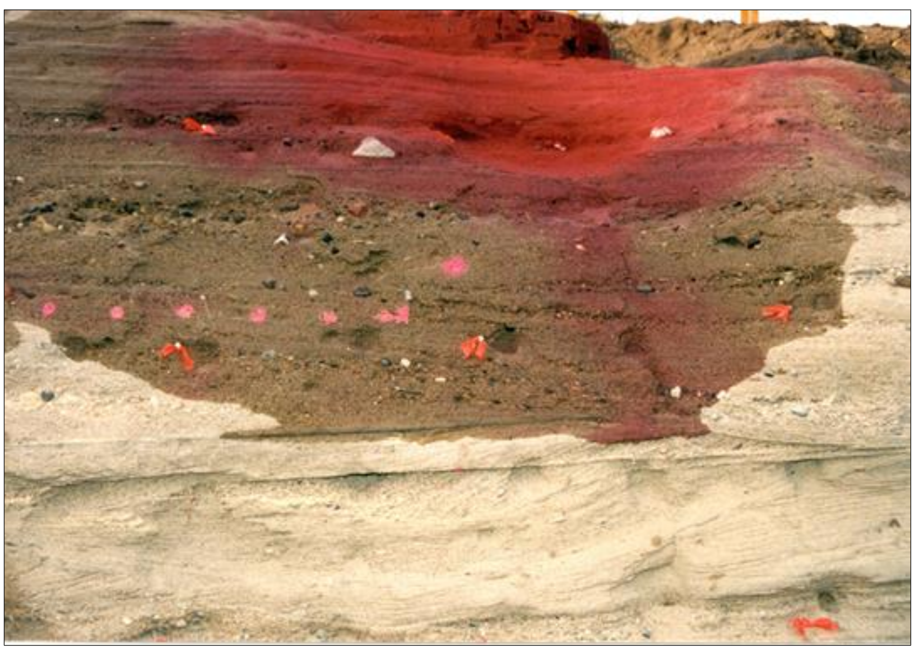
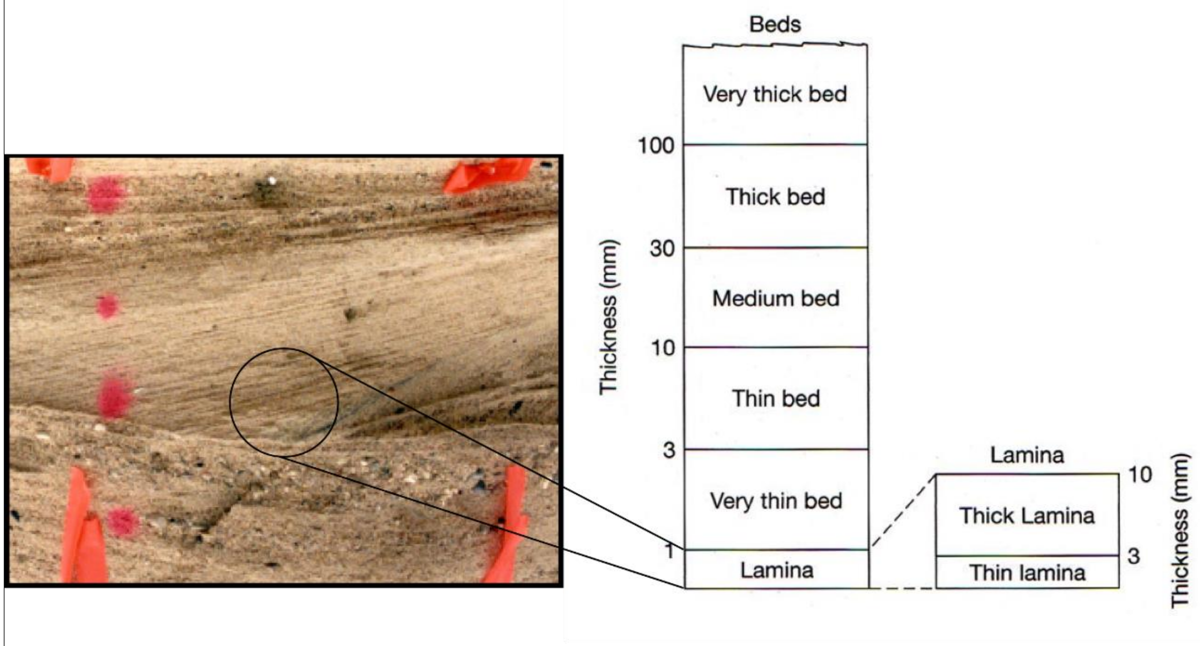


Figure 2. Fluvial outcrop where a tracer test has been performed. This section of the Ancestral Rio Grande River shows how recharge waters move through preferential flow paths through the subsurface.




From Boggs, Principles of Sedimentology and Stratigraphy, 5th ed., Figure 4.1, p. 67

Figure 3. Reverse-graded and micro-layered (sub-laminae thick) bedding of grains in a characteristic fluvial environment, this facies is of the Ancestral Rio Grande River outside Albuquerque, NM. Diagram of scales describing bedding thickness in sedimentary structures. (Griffith, et al., 2011; Boggs, 2012).

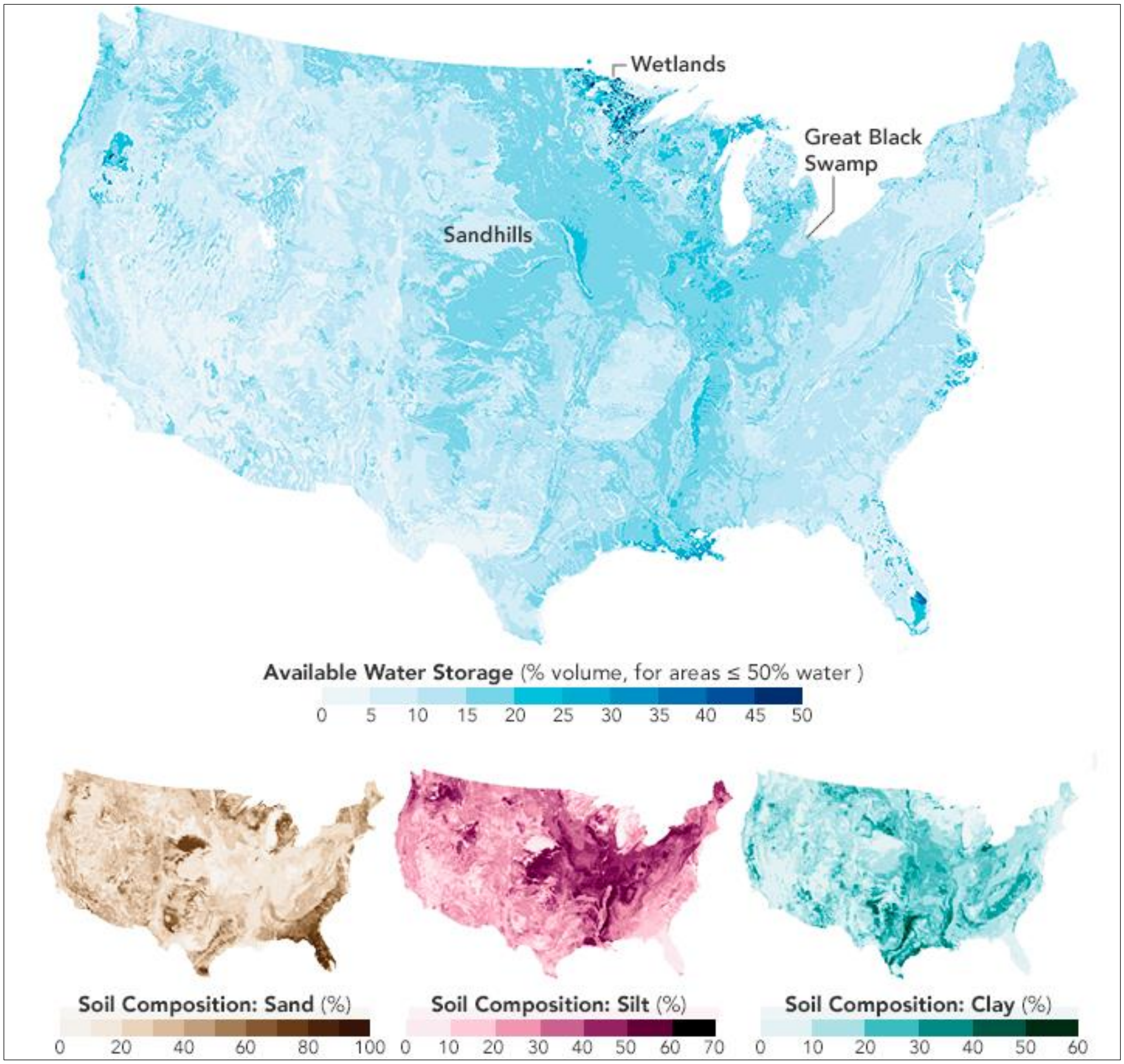


Figure 4. NASA landsat image map of water storage and the three main soil compositions. Water is stored in fine grained material and tends to drain or transport through sandy soils (Stevens, 2018).

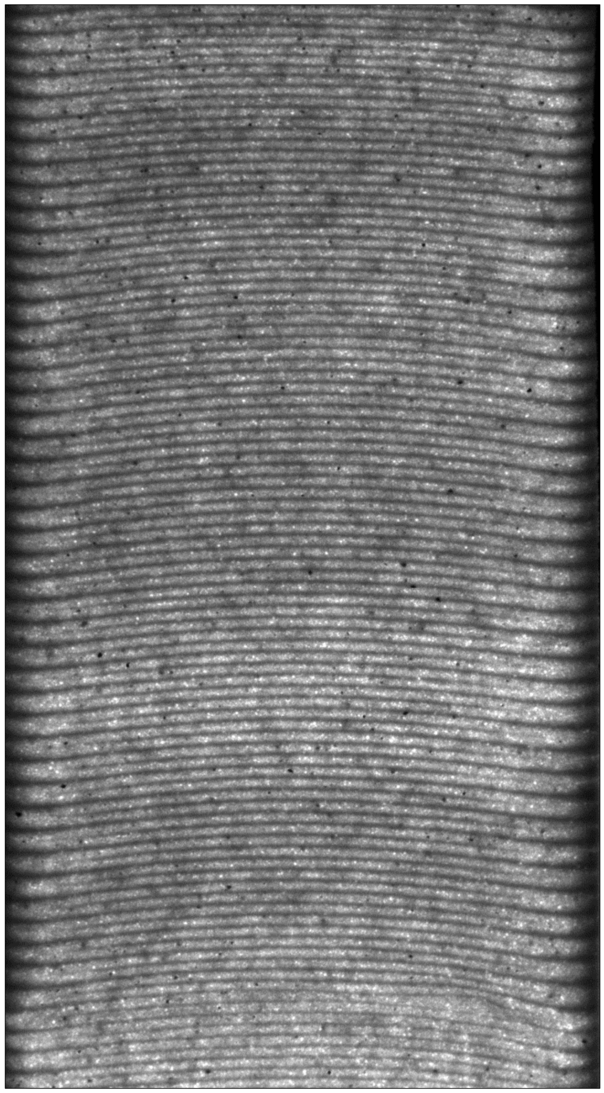


Figure 5. Example of geologically realistic reverse-grade sand layers within a glass paneled chamber or cell.

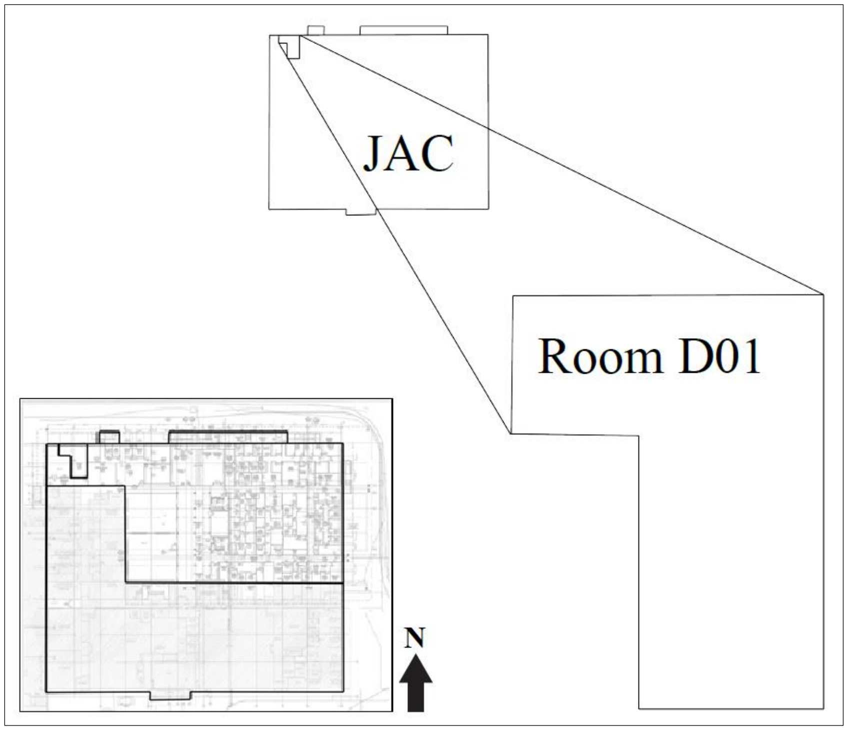



Figure 6. Blueprint and layout of new laboratory and experimental equipment. The Jackson Avenue Center (JAC) was completed in two stages, you can see our new laboratory (D01) in the northeast corner.

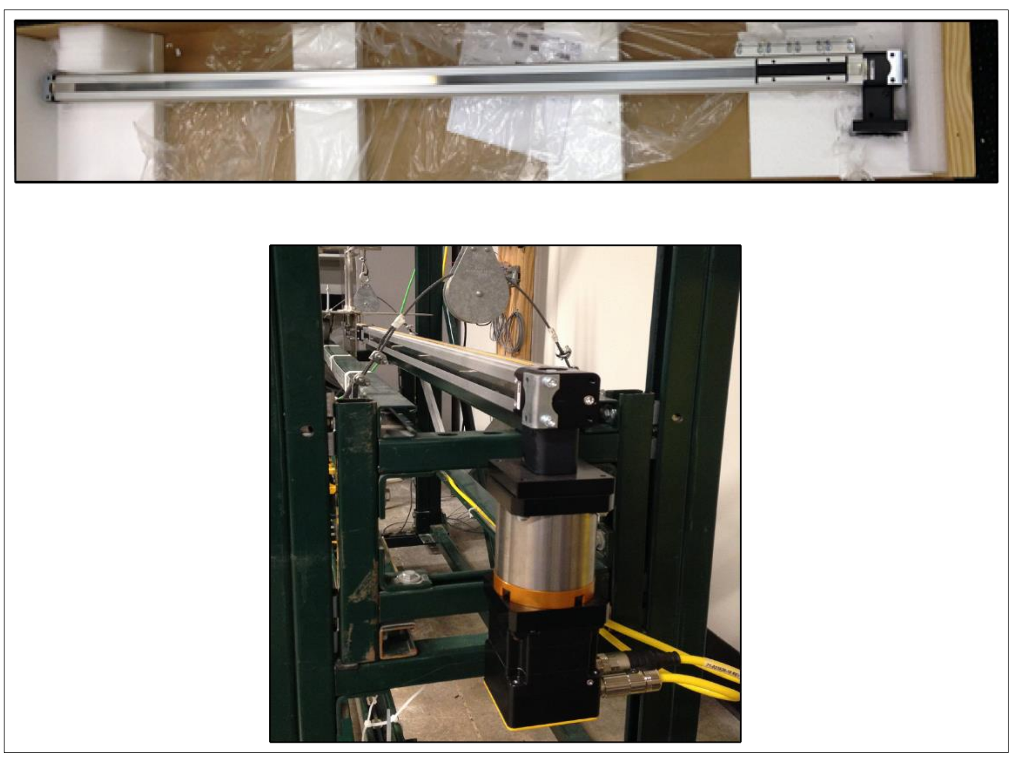


Figure 7. New generation PARKER linear actuator (OSPE32) in the box and attached to the vertical carriage of the sandfiller apparatus.

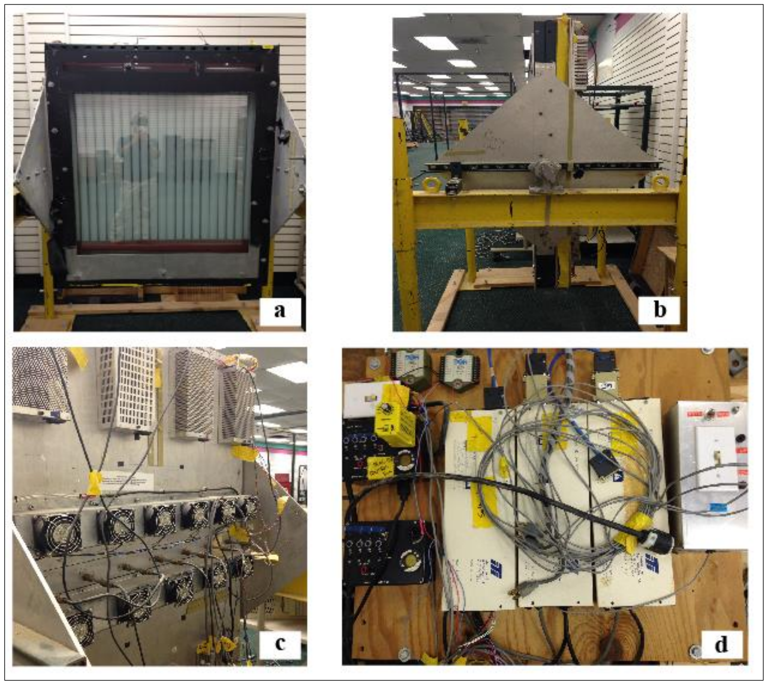



Figure 8. Outdated light assembly: (a) lightbox – front view; (b) lightbox – side view; (c) cooling system; (d) electrical control housing.


Figure 9. LED light panel: (a) front, and (b) back view. This is a 2x2 ft. 3300 lumens panel with built in diffuser plate.

Figure 10. LED panel in the visualization stage.

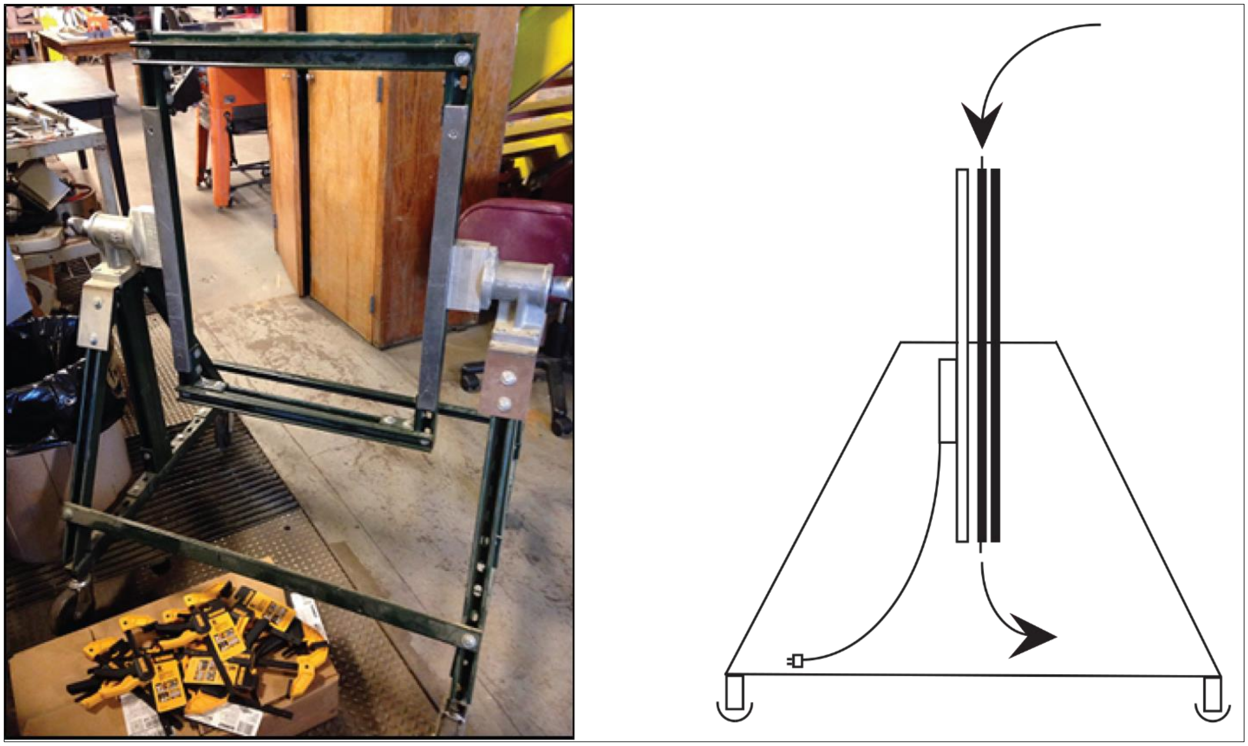


Figure 11. Rotating-visualization stage created from Unistrut metal framing systems with four casters to move the mount freely around the lab space. The diagram of the rotating-visualization stage with chamber and light panel attached. The arrows indicate portholes on the chamber and the flow direction of fluids.

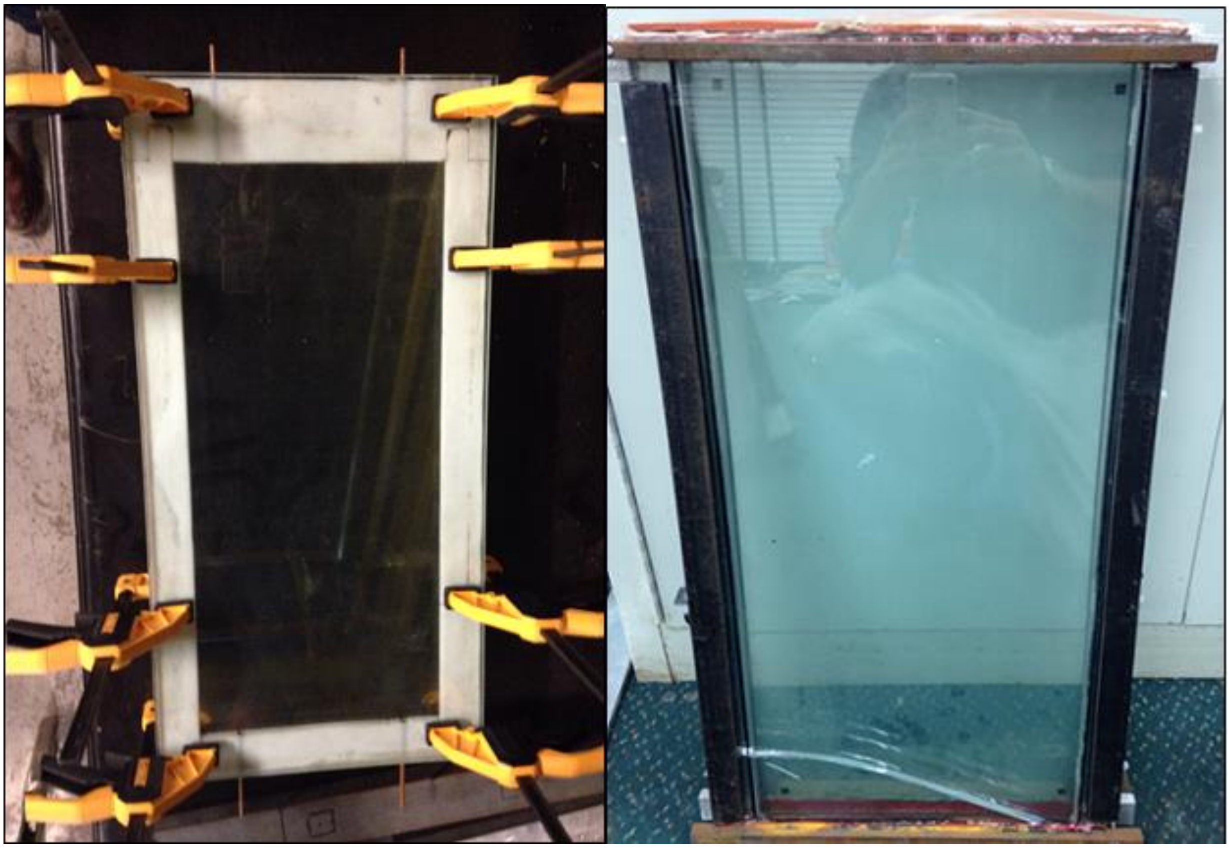


Figure 12. New chamber design (left) beside the old design (right). The new chamber consists of a high-performance light weight polymer plastic acting as panel spacer and manifold with port holes in the top and bottom.


Figure 13. New Photometrics PRIME sCMOS (scientific complimentary metal-oxide semiconductor) camera.

Figure 14. The laboratory's new darkroom.

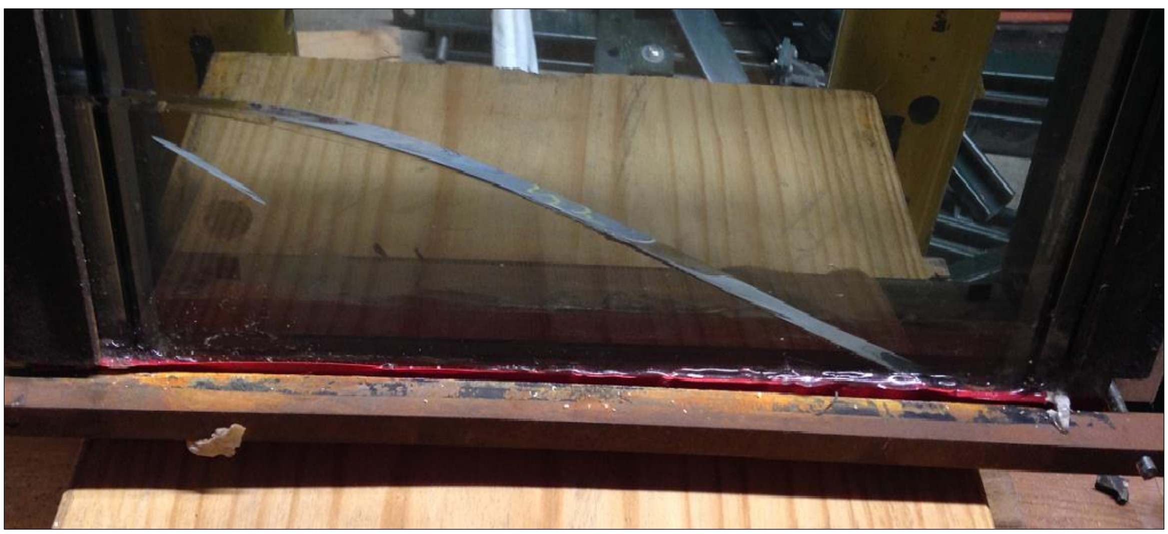


Figure 15. Example of tightening the C-clamp down in the wrong way, results in shearing the glass panel in the original chamber design.

Figure 16. Creating homogeneous chambers by dumping sand directly through a rectangular randomizer with V-shaped trough.

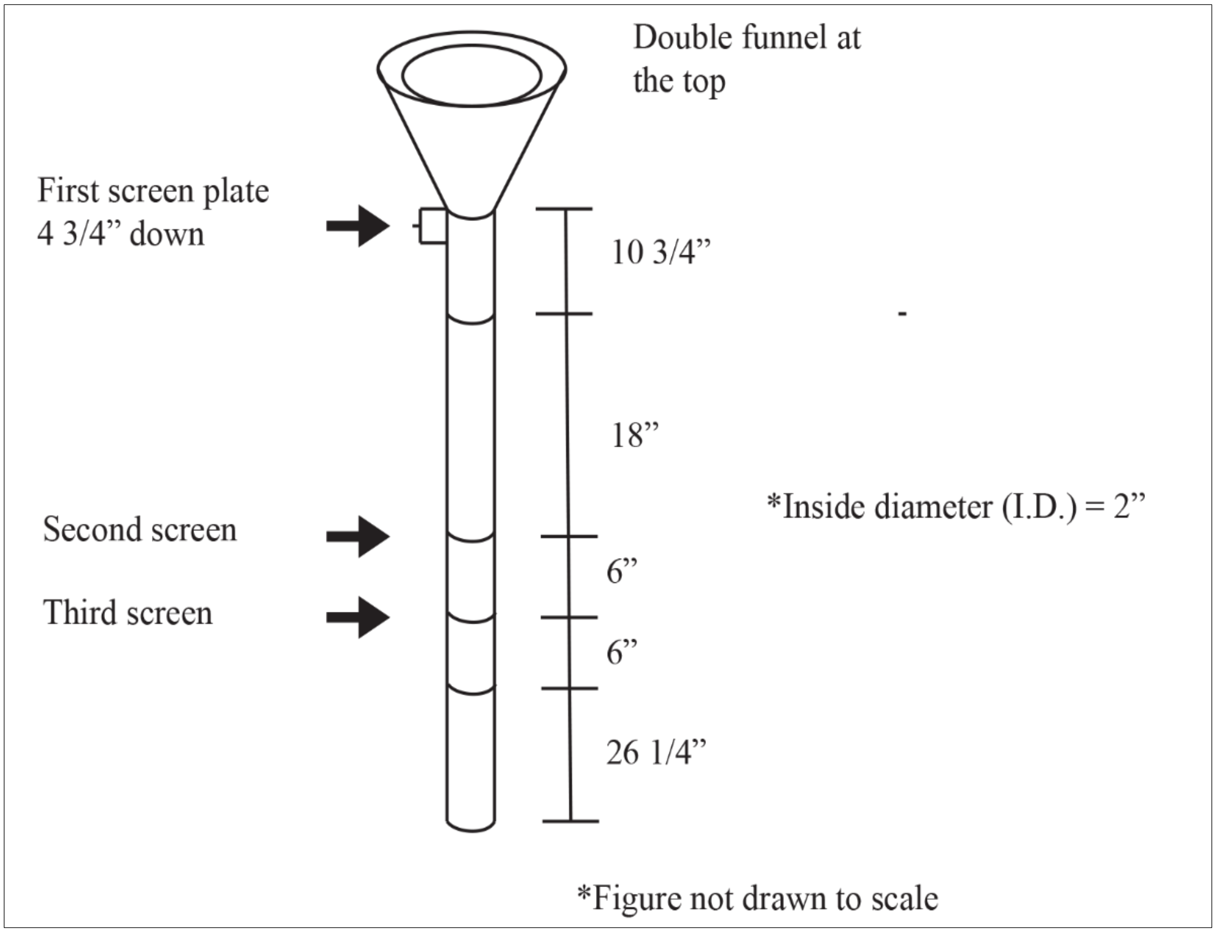


Figure 17. Diagram of the carriage hopper-sandfiller. This device is composed of five pieces of PVC with screens in the tube at varying intervals. Not drawn to scale.

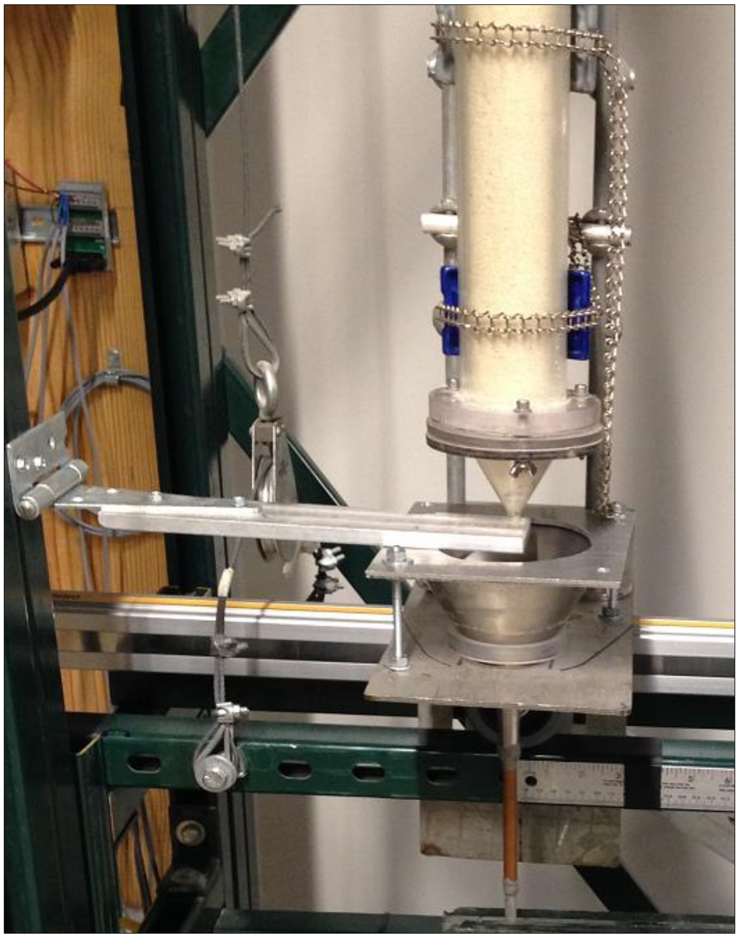


Figure 18. Randomized sand is held by a hopper that is housed on the sandfiller carriage, sand flow is impeded by a swinging gate.

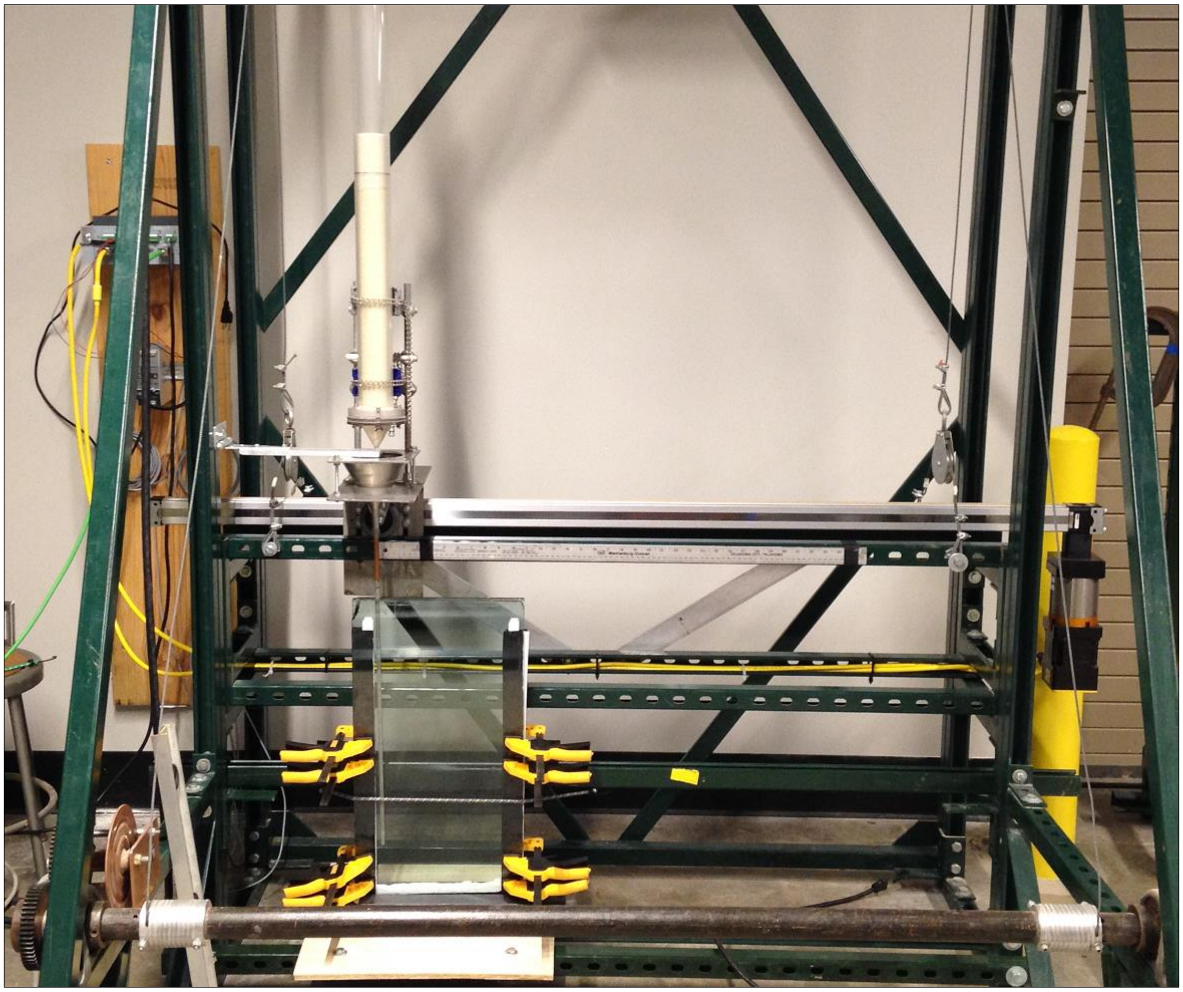


Figure 19. Sandfiller apparatus with chamber keyed-in and ready to be filled.

Figure 20. While filling the chamber sand is delivered at a constant flowrate and the feeder-tube is maintained at a constant drop height.

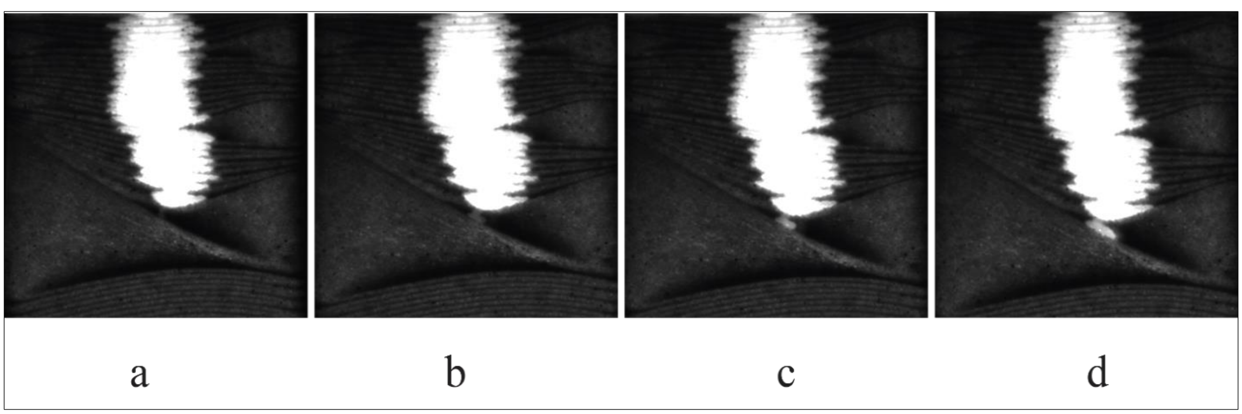



Figure 21. Visualizing the Haines jumps at lens exposure of 25 milliseconds and capturing images every second.

Figure 22. Variety of micro-layers with a table-top structure overlain.

Figure 23. Sloping in layers occurs when the feeder tube does not move across the entire width of the chamber.

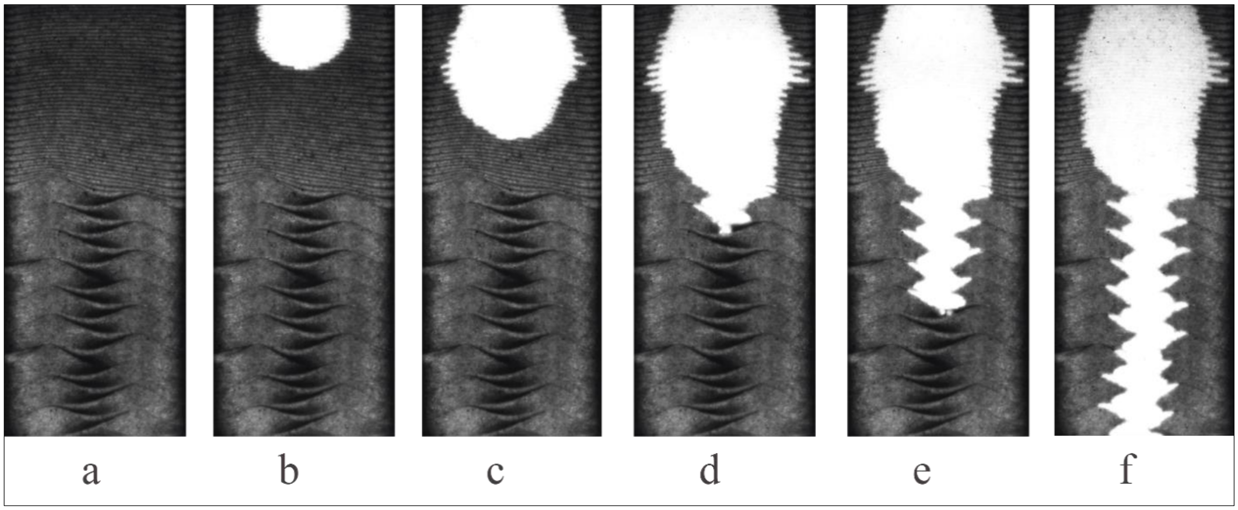



Figure 24. a) Dry mound structures overlain by micro-layers, b) beginning infiltration from a point source injection. c) Capillary forces begin to take hold and move moisture laterally through the micro-layers. d) Breaking through the second mound or capillary barrier down. Water movement is being concentrated into the middle of the chamber in the finer grains. f) The unstable wetting front (finger) has reached the bottom of the chamber. Flow from the water reservoir has been cut off and the micro-layers are beginning to drain.

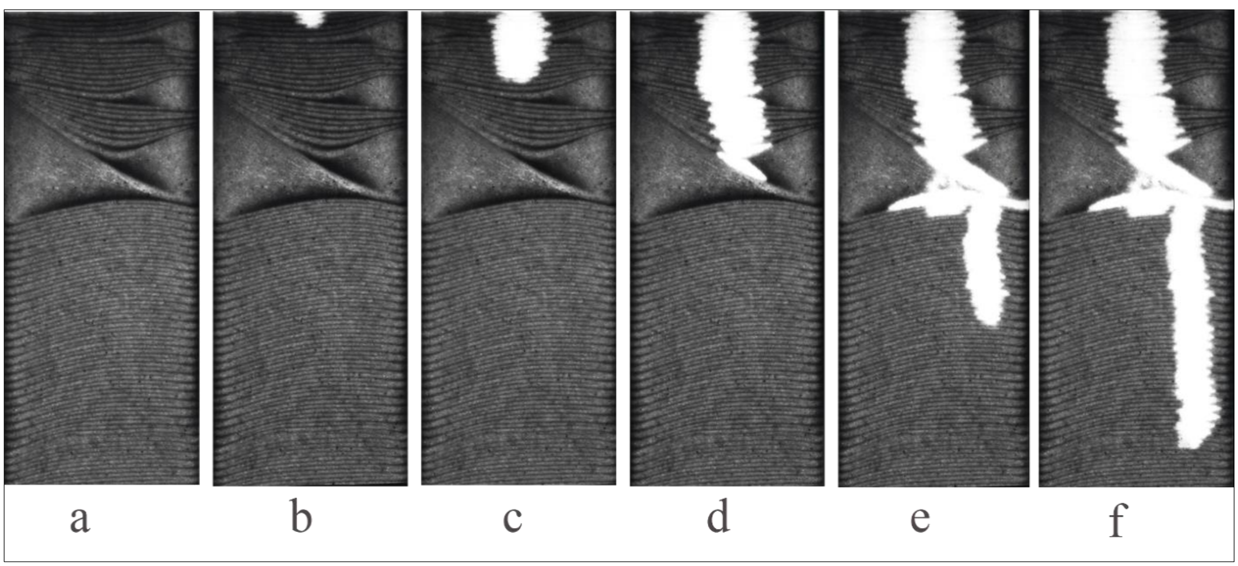



Figure 25. Infiltration and figure flow of a micro-layered and macro-heterogeneous chamber.

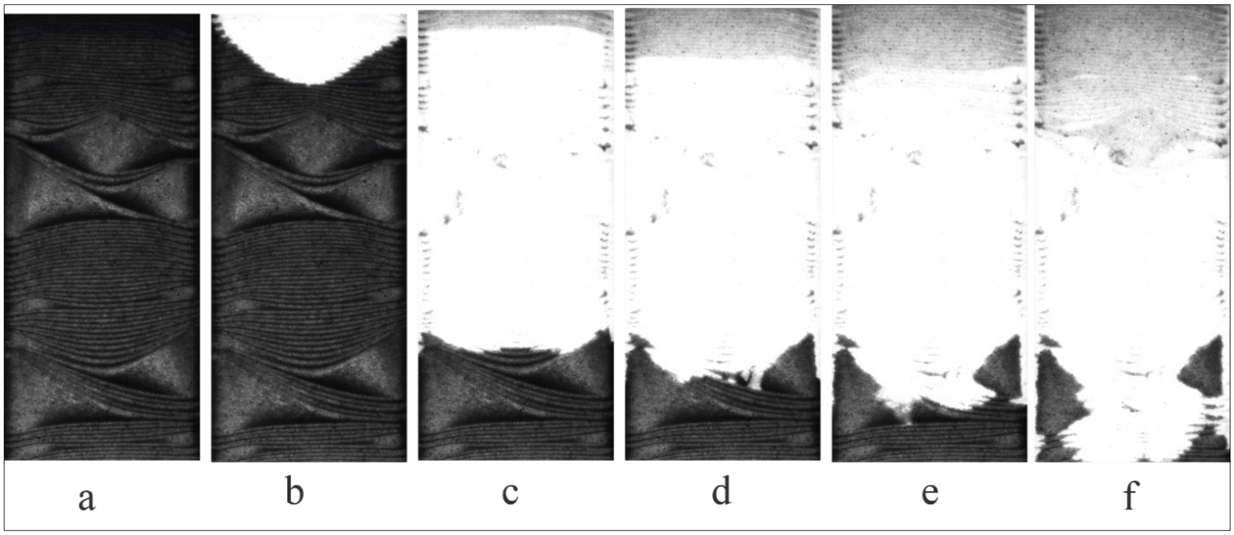


Figure 26. Here adjusted the infiltration rate and resulted in a more stable wetting front.

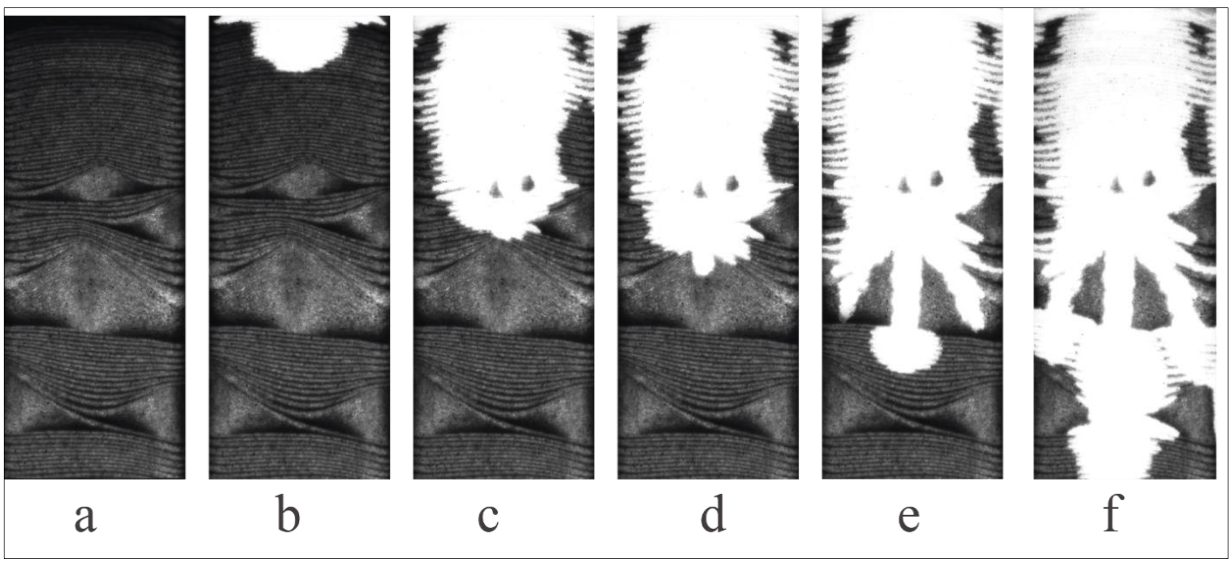


Figure 27. Preferential flow becomes divided into three fingers between d-e.

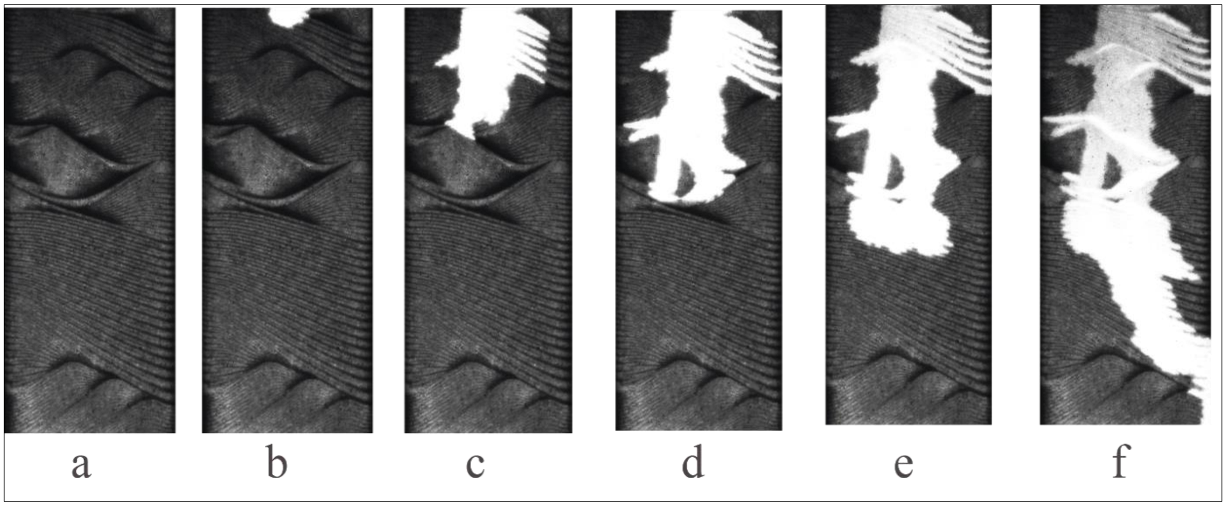


Figure 28. Preferential flow moving down sloped layers.

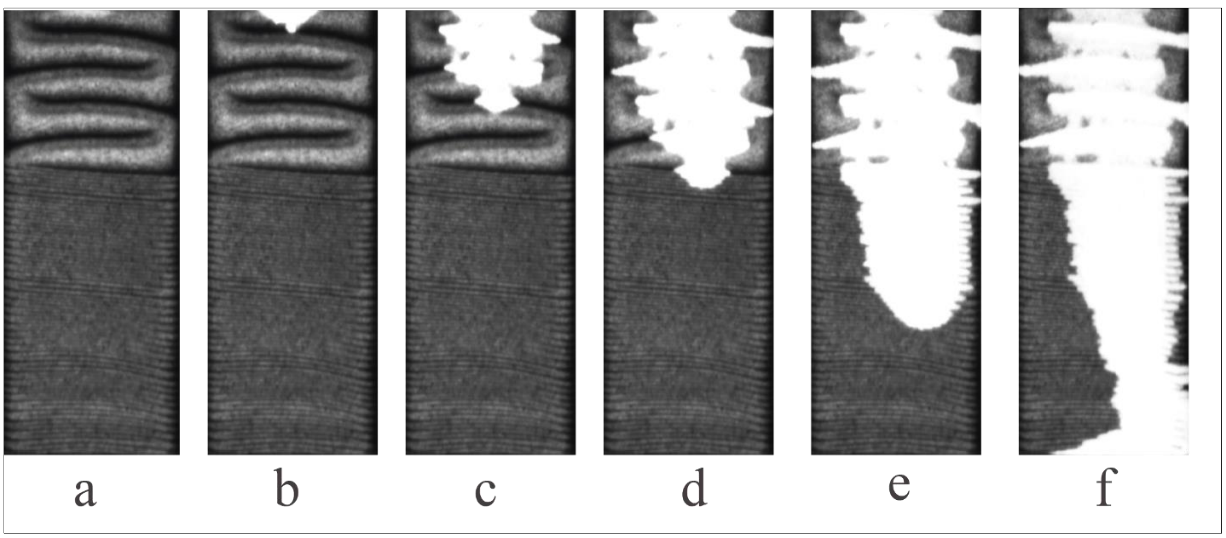


Figure 29. Test of micro-layering with thick (table top) structure at the top of the image.

# Appendix B:

# Delays with Thesis

Delays:

Table B-1 presents a timetable showing the issues and delays during the course of this thesis. On the second day of being in the lab and learning the operation of equipment, the original PARKER linear actuator failed and would not respond to DOS commands or the operations software (X-ware). Soon after the year model 2000 Gateway desktop failed as well. We then began a year-plus long process to acquire a new robotic actuator. During this time, a fellow graduate student was with personnel from Ole Miss Facilities Management and was told of a demolition project and new construction that would begin in the JAC (in the area where our lab was located). We began a process of coordinating the move to a temporary location (one without power and water) with Facilities Planning. In addition, we worked with Facilities Planning to design the new laboratory space. Over the course of our tenure in the temporary space, I presented a proposal of this thesis to the Geology and GE Department. The final move to a permanent laboratory happened May 2017, and all utilities were operational in that space by June of that year. Finally, the original CCD camera failed to communicate with newer computers, and no software solution was available. As a result, we acquired an updated scientific imaging device (Photometerics – PRIME sCMOS).

TABLE B-1. TIMETABLE

| | |
|---|---|
| Began graduate courses……………………………………………....... | August 2013 |
| Settled on thesis topic………………………………………………….. | January 2014 |
| Received keys to original laboratory…………………………………... | Junes 2014 |
| Controller, computer and PARKER linear actuator failure…………… | October 2014 |
| Began shopping for replacement actuator……………………………... | November 2014 |
| Quote received for updated actuator…………………………………... | October 23rd, 2015 |
| First notice of JAC demolition……………………………………… | November 11th, 2015 |
| Sole Source verified for actuator, quote approved…………………….. | March 30th, 2016 |
| New PARKER actuator arrives to Procurement………………………. | June 14th, 2016 |
| Moved lab equipment to temporary facility…………………………… | July 10th, 2016 |
| Thesis Proposal………………………………………………………... | February 25th, 2017 |
| Move from storage into permanent space……………………………... | May 1st, 2017 |
| Permanent space complete with data lines, power and water…………. | July 1st, 2017 |
| CCD camera failure………………………………………………… | November 27th, 2017 |
| Sole Source and approval to order new camera……………………….. | December 13th, 2017 |
| Arrival of camera to Procurement……………………………………... | January 25th, 2018 |
| Scheduled professional Industrial Programmer's assistance………….. | February 28th, 2018 |
| Vendor application to Procurement …………………………………... | March 9th, 2018 |
| Consulting time with Jerry Sorrells…………………………………… | March 26th-28th, 2018 |
| Defense draft to committee……………………………………………. | April 26th, 2018 |
| Defense Presentation…………………………………………………... | May 1st, 2018 |

# APPENDIX C:

# GENERAL LABORATORY PROCEDURE

**PRECAUTIONS WITH EQUIPMENT**:

1. Photometrics Camera Prime sCMOS –
   - Extremely sensitive to Electrostatic Discharge (ESD)
     - Remember this is high voltage equipment – turn the camera on FIRST and power down camera FIRST
     - Never connect/disconnect any cable while the camera is on
     - No need to power down computer while camera is on
     - Avoid "transient voltage spikes" – i.e. arc lamps (not needed in our context)
     - 1" of space around the camera's fan – Do not open at any point
     - Do not use a C-mount lens with optics that extend behind the flange of the lens
   - All repairs required are done at Photometrics only. Opening the camera will void its warranty.
2. Chambers glass panels –
   - Should be mounted or placed on thick rubber sheet
   - These are the last two unbroken panels in lab
   - Take care
3. Computer for Communicating with Sandfiller (ServoManager) –
   - Clean and defrag the (C:) drive every day (this device is nearly out of memory and will move slow at times)
4. PARKER linear actuator –
   - Plugin to wall
   - Wait for green LED on ServoManager to begin flashing
   - Insert the USB into computers USB port and wait for green LED from the RS232 cable (green cable)

**CAMERA TIPS AND USE:**

- Use 60mm lens, 12-bit digitizer, > 1k X 1k resolution
- Beware the manifold shadow
  - Take test images often, exposure time >10 and <100 ms
- Should always be operated in a clean, dry environment
  - System's ambient operating temp. (0˚C to 30˚C) with 80% relative humidity, noncondensed
- Images acquired as .tif files
- For 'saturated' experiments imaging is taken every 30 secs, otherwise capture at 1 sec intervals

**CLEANING**:

1) Chamber Glass –
   - Chamber will have to be disassembled and cleaned immediately after use
   - Clean hands, wash with Dawn or alcohol (if using glass)
   - Lightly apply to the chamber with clean hands
   - Rinse with de-ionized water
2) Photometrics Camera –
   - Exterior surfaces of the camera may be cleaned with a dry, lint free cloth

- While cleaning imaging window, only use a filtered compressed-air source (hand held cans are not recommended as they may spray propellant onto window)
- Do not touch imaging window

3) Sand –Dirty sand could greatly influence capillarity.
   - Boil in 0.5% of lab glass cleaner for 0.5 – 0.75 hrs
   - Rinse with warm tap water for 15 mins
   - Boil in tap water for 15 mins
   - Wet sieve for 1 minute with tap water – using 1982 g of sand per chamber
     a. Sieve Sizes: [No. 12, No. 20, No. 30, No. 40, No. 70]
   - Dry (60-70)˚C for 6 hrs
   - Cover till use

## sCMOS Camera Alighment Tips:

- Use 35mm lens, 12-bit digitizer, > 1k X 1k resolution
  - When using 35 mm lens things progress much more quickly than with 60 mm
- Beware the manifold shadow
  - Take test images often, exposure time >10 ms

## Randomizing Sand:

- Combine equal parts of known and clean sieved industrial sand into bucket (bucket must be 3X or more the volume of sand being mixed)
- Stir initially, secure a top to the bucket with ratcheting nylon strap
- Flip 180˚ no less than 20X to achieve a "perfect drop" with each flip (pouring of sand results in sorting)
- Do not pour sand from bucket.
- **Homogeneous Pack:** Detach the top and collect scoops from the bucket with scooper for chamber filling, remember DO NOT pour the sand but dump it. Avoid sorting.
- Weak sorting can be corrected by stirring the sand in scooper.

## Experimental Procedure:

Always begin the experimentation by cleaning and organizing sand you will use. A good rule is to clean 3X the volume of sand you think will be necessary. Another way to cut experimentation time is to have all neoprene sheet and cheesecloth precut.

1. Homogenous Chamber –
   - Clean individual pieces of chamber, allow to dry.
   - Assemble chamber
     - Using new neoprene sheet and cheesecloth for every experiment
   - Weigh empty chamber
   - Randomize Homogeneous Sand
     - Detach the top and collect scoops from the bucket with scooper for chamber filling, remember DO NOT pour the sand but dump it. Avoid sorting.
     - Weak sorting can be corrected by stirring the sand in scooper

- To Achieve Homogeneity:
  - Dump, do not pour mixed sand evenly across the V-shaped trough of chamber extension
  - Use the extension with the same internal cross-sectional area as chamber
    i. 27 cm X 1 cm (internal dimensions)
  - Try and maintain a constant flow rate, sand should rise evenly within the chamber while avoiding micro-layering
  - Avoid any clogs in the trough as gaps in flow rate produce layers
  - Monitor flow to prevent unintended heterogeneity from developing
  - Avoid vortexes or sorting in the trough by raking to maintain a level surface
- Assure a nice dense pack by lifting the chamber 1 cm and dropping it (50X) onto matted flooring (several flattened cardboard boxes and some towels)
- Flow rates measured in grams per minute (g/min), record the flowrate.

2. Structured/micro-layered packs –
   - Randomizing sand for structured cells
     - Combine equal parts of known and clean sieved industrial sand into bucket (bucket must be 3X or more the volume of sand being mixed)
     - Stir initially, secure a top to the bucket with ratcheting nylon strap
     - Flip 180˚ no less than 20X to achieve a "perfect drop" with each flip (pouring of sand results in sorting)
     - Take large and small funnel (combine the two by putting the smaller one into the larger funnel) to the hopper-filler
     - Attach the hopper to the bottom of the hopper-filler
     - Dump sand into the funnels at the top while maintaining a gap for air to move
   - Weigh empty chamber
   - Filling Chamber with sand:
     - Remove hopper from actuator carriage
     - Lift actuator carriage with crank
     - Place empty chamber in sandfiller mount
     - Guide actuator carriage and the delivery funnel down into the chamber
     - Drop gate into place
     - Fill hopper with randomized, clean sand
     - Attach hopper to the actuator carriage
     - Power up computer, follow programming procedure
     - Run program
   - Weigh full chamber
   - Calculate bulk density
   - Calculate porosity (grain density = 2.65 $^{g}/_{cc}$ )
   - Mount Chamber to visualization stage
   - Turn on Camera
     - Wait for orange LED to stop flashing
   - Turn on computer
- Take Dry/Reference Image(s) before infiltration
  - Take high-exposure reference image to illustrate pack characteristics
- Drain & Fill(s) – Effort to reduce pore space/pack the media
  - Seal chamber and flood from the bottom with desiccated air
    - Displacing the air in pore spaces
  - Gradually introduce de-aired and de-ionized water through the bottom
    - Allowing the air to escape through open ports at the top of the manifold

- Repeat drains and fills 3x
    - flushing at least three pore volumes upward through the sample
    - Record pore volume quantity
- Gravity drain, then dry by pulling desiccated air downward through the chamber until completely dry
- Capture dry reference image
- Repeat the process once more or up to 4x, depending on the size of the chamber
- Capture images of draining and dry (last time around)
- Confirm settling is complete
    - Via imaging (when dark grains stop moving)

- Saturate Chamber
    - Induce gravity driven flow
    - Avg. 400 saturation images at 1 second intervals
    - Estimate saturation hydraulic conductivity, Table 3-3. Griffith (2008)
- Capture Images

All procedures modified from Griffith (2008) and Glass et al (1989b)

# APPENDIX D:

# SANDFILLER SOFTWARE PROCEDURE

## Sandfiller Procedure

Make sure the X1 port on the C3 is plugged into must always be plugged into the gray outlet box hanging from the ceiling. This is the "mains" power for the servo drive, and it must remain connected at all times to operate the Sandfiller.

Plug the SOLA power supply into the wall. Wait for the green LED to begin flashing on the Compax3.

Make sure the green RS232 cable is connected to the X10 port of the Compax3.

Insert the RS232-USB adaptor into the desktop's USB port.

Double click the **C3MGR2_R09-70** icon on the desktop

Inside if C3 ServoManager, on the Toolbar click **File** → **Open** and open the **SandfillerDriveConfig_v1.00** configuration for C3 ServoManager.

Find the **Open/Close com port** icon on the toolbar and click it. The banner on the bottom-right of the program window will be highlighted and will indicate which port the device is connected to.

Minimize the C3 ServoManager and double-click the **Projects and Configs** file icon. Open the **SANDFILLER_vX.XX.pro** file that you wish to execute in CoDeSys.

The program has 19 profiles that execute in sequence, where each profile consists of configurable parameters for:

a) Position 1
b) Position 2
c) Velocity
d) Acceleration
e) Deceleration
f) Number of Profile Passes, where a pass is from Position 1 to Position 2 or vice versa

The profiles can be customized from the variable declaration window by changing the initial values. Simply scroll to the appropriate profile run in the variable declaration window of CoDeSys 2.7.

After customizing the profile variables, click **Project → Rebuild All** from the toolbar. Choose *All Versions* and click Compile. (The compile results are displayed in the output window. If there are no errors or warnings, move on.)

Maximize the C3 ServoManager interface and find the **IEC61131-3 Programming (Codesys)** tree in the left window of the manager. Expand the file by clicking on the box with the plus sign.

Open the **Link IEC61131-3 project** and link the controller with your rebuilt project. When the project is linked the box displaying your project file will turn green.

Move up the CoDeSys tree one spot to **IEC61131-3 Debugger** and open the debugger window.

Find the Compax3 Login/Logout icon on the toolbar (it looks like a serial adapter). Click to initialize.

Find the **Download** button on the right-hand side of the debugger window and click it. Click **Yes**.

The Debugger is the control window for operating the Sandfiller and your new program. The first thing you must do to execute your program is to enable the drive. Drag your mouse to the first row in the list of variables and double click on the **FASLE** value for **PLC_PRG.XCMDENABLE**.

This opens a window asking if you want to overwrite the variable. Choose the **TRUE** option and click Ok. (You should hear the drive enabled, which means current is applied to the motor.)

Drag the mouse down to the next row, for **PLC_PRG.XCMDHOME** and double-click. Change the value to **TRUE** and the carriage/sand-hopper will move to the HOME position as determined by the home switch on the actuator.

Now, the drive is energized and the arm's carriage/sand-hopper is at the HOME position and ready to begin filling a cell. Scroll down one more row and double-click to change the **FASLE** value for **PLC_PRG.XCMDSTART** variable to **TRUE**. Program execution will start, and the cell will start filling with layers. The program will step through each profile and make the specified number of passes for each profile. To skip a profile, simply set the number of passes to zero.

If at any time you must stop the program while it is executing scroll one row down to the **PLC_PRG.XCMDSTOP** variable and change its value to **TRUE**. This stops the program completely and you must begin again at Step 15 with HOMING of the sandhopper. (NOTE: If you stop the program, it will not begin again at the point which you stopped. The cell must be emptied, the sandhopper refilled with sand and the issue resolved. Then the program can begin again from HOME.)

# APPENDIX E:

# EXAMPLE PROJECT IN CODESYS

# EXAMPLE CODESYS PROJECT

```
PROGRAM PLC_PRG
VAR

	(*Command Variables*)
	xCmdEnable		:	BOOL;
	xCmdHome		:	BOOL;
	xCmdStart		:	BOOL;
	xCmdStop		:	BOOL;
	xCmdReset		:	BOOL;

	(*Par Values*)
	(*diStopDecel		:	DINT:= 10000;
	diStopJerk		:	DINT:= 1000000;*)
	(*Status Variables*)
	iState			:	INT:= 0;		(*state of the program*)
	iProfile	:	INT:= 1;			(*profile that is being executed*)
	iPass			:	INT:= 1;	(*profile pass that is being executed*)
	xAxisReferenced		:	BOOL;	(*indicates if the axis has been referenced*)
	tElapsedTime		:	TIME;	(*time that the last layering process took to
complete*)

	(*Function Blocks*)
	fbTimer			:	TON;		(*timer function block*)
	fbEnable		:	MC_Power;	(*function block to enable the drive*)
	fbHome			:	MC_Home;	(*function block to reference the axis*)
	fbStop			:	MC_Stop;	(*function block stops the axis during a
move*)
	fbReset			:	MC_Reset;	(*function block resets any errors on the
drive*)
	fbMoveAbs		:	MC_MoveAbsolute;	(*function block to make absolute
position moves*)

	(*Move Parameters - the rest of the variables below are sets of parameters for the 19 allowable move
profiles.
	Array processing and data structures are not supported on the Compax3 drive/controller, therefore, the
profiles
	are individually defined and initialized here (strictly typed). Each profile's parameters can be adjusted
	to change the layers' physical profiles. All 19 profiles are executed on each move. If a profile's number of
passes, i.e.
	_x_iProfilePasses is equal to zero, then the profile will be ignored.*)

	(*Generic Profile - the numbered profiles below are loaded to the generic profile during runtime.*)
	rPos1			:	REAL;		(*mm - the first position the axis
will move to. This should generally be zero (0) for the first profile since the sand will start at the home position.*)
	rPos2			:	REAL;		(*mm - this is the second position
the axis will move to.*)
	rVelocity		:	REAL;		(*mm/s - the constant velocity that
the axis will accelerate to and then maintain until it starts the deceleration part of the move profile.*)
	diAccel			:	DINT;		(*mm/s^2 - the acceleration of the
move.*)
	diDecel			:	DINT;		(*mm/s^2 - the deceleration of the move.*)
	diJerkAccel		:	DINT;		(*mm/s^3 - the jerk of the acceleration. This
value is the derivative of acceleration and limits the rate of change of the acceleration.*)
```

```
	diJerkDecel		:	DINT;		(*mm/s^3 - the jerk of the deceleration. Also
limits the rate of change. For both, the lower the value, the slower the acceleration.*)
	iProfilePasses		:	INT;		(*moves - number of passes the profile will
run. One pass is from position 1 to position 2. Position 2 back to 1 would be a second pass.*)

	(*Profile #1*)
	_01_rPos1		:	REAL:= 0;		(*mm - this value should generally
be zero since every fill run will start from the home position.*)
	_01_rPos2		:	REAL:= 62;		(*mm*)
	_01_rVelocity		:	REAL:= 50;		(*mm/s*)
	_01_diAccel		:	DINT:= 10000;		(*mm/s^2*)
	_01_diDecel		:	DINT:= 10000;		(*mm/s^2*)
	_01_diJerkAccel		:	DINT:= 1000000;		(*mm/s^3*)
	_01_diJerkDecel		:	DINT:= 1000000;		(*mm/s^3*)
	_01_iProfilePasses	:	INT:=	19;		(*passes - an even number will end
where the profile started. An odd number will end at the second position.*)

	(*In general, the subsequent profile should start where the previous profile ends.*)
	(*Profile #2*)
	_02_rPos1		:	REAL:= 62;		(*mm - this should generally be
equal to _01_rPos2, or _01_rPos1, whichever one the previous profile ended on..*)
	_02_rPos2		:	REAL:= 124;		(*mm*)
	_02_rVelocity		:	REAL:= 50;		(*mm/s*)
	_02_diAccel		:	DINT:= 10000;		(*mm/s^2*)
	_02_diDecel		:	DINT:= 10000;		(*mm/s^2*)
	_02_diJerkAccel		:	DINT:= 1000000;		(*mm/s^3*)
	_02_diJerkDecel		:	DINT:= 1000000;		(*mm/s^3*)
	_02_iProfilePasses	:	INT:=	19;

	(*Profile #3*)
	_03_rPos1		:	REAL:= 124;		(*mm - same as above, this should
generally be the same as _2_rPos2, or wherever the previous profile ended.*)
	_03_rPos2		:	REAL:= 186;		(*mm*)
	_03_rVelocity		:	REAL:= 50;		(*mm/s*)
	_03_diAccel		:	DINT:= 10000;		(*mm/s^2*)
	_03_diDecel		:	DINT:= 10000;		(*mm/s^2*)
	_03_diJerkAccel		:	DINT:= 1000000;		(*mm/s^3*)
	_03_diJerkDecel		:	DINT:= 1000000;		(*mm/s^3*)
	_03_iProfilePasses	:	INT:=	19;

	(*Profile #4*)
	_04_rPos1		:	REAL:= 186;		(*mm*)
	_04_rPos2		:	REAL:= 250;		(*mm*)
	_04_rVelocity		:	REAL:= 50;		(*mm/s*)
	_04_diAccel		:	DINT:= 10000;		(*mm/s^2*)
	_04_diDecel		:	DINT:= 10000;		(*mm/s^2*)
	_04_diJerkAccel		:	DINT:= 1000000;		(*mm/s^3*)
	_04_diJerkDecel		:	DINT:= 1000000;		(*mm/s^3*)
	_04_iProfilePasses	:	INT:=	19;

	(*Profile #5*)
	_05_rPos1		:	REAL:= 250;		(*mm*)
	_05_rPos2		:	REAL:= 240;		(*mm*)
	_05_rVelocity		:	REAL:= 50;		(*mm/s*)
	_05_diAccel		:	DINT:= 10000;		(*mm/s^2*)
	_05_diDecel		:	DINT:= 10000;		(*mm/s^2*)
```

```
_05_diJerkAccel        :    DINT:= 1000000;    (*mm/s^3*)
_05_diJerkDecel        :    DINT:= 1000000;    (*mm/s^3*)
_05_iProfilePasses     :    INT:=  51;

(*Profile #6*)
_06_rPos1              :    REAL:= 240;        (*mm*)
_06_rPos2              :    REAL:= 0;          (*mm*)
_06_rVelocity          :    REAL:= 70;         (*mm/s*)
_06_diAccel            :    DINT:= 100;        (*mm/s^2*)
_06_diDecel            :    DINT:= 100;        (*mm/s^2*)
_06_diJerkAccel        :    DINT:= 1000;       (*mm/s^3*)
_06_diJerkDecel        :    DINT:= 1000;       (*mm/s^3*)
_06_iProfilePasses     :    INT:=  11;

(*Profile #7*)
_07_rPos1              :    REAL:= 0;          (*mm*)
_07_rPos2              :    REAL:= 350;        (*mm*)
_07_rVelocity          :    REAL:= 70;         (*mm/s*)
_07_diAccel            :    DINT:= 100;        (*mm/s^2*)
_07_diDecel            :    DINT:= 100;        (*mm/s^2*)
_07_diJerkAccel        :    DINT:= 1000;       (*mm/s^3*)
_07_diJerkDecel        :    DINT:= 1000;       (*mm/s^3*)
_07_iProfilePasses     :    INT:=  0;

(*Profile #8*)
_08_rPos1              :    REAL:= 0;          (*mm*)
_08_rPos2              :    REAL:= 350;        (*mm*)
_08_rVelocity          :    REAL:= 70;         (*mm/s*)
_08_diAccel            :    DINT:= 100;        (*mm/s^2*)
_08_diDecel            :    DINT:= 100;        (*mm/s^2*)
_08_diJerkAccel        :    DINT:= 1000;       (*mm/s^3*)
_08_diJerkDecel        :    DINT:= 1000;       (*mm/s^3*)
_08_iProfilePasses     :    INT:=  0;

(*Profile #9*)
_09_rPos1              :    REAL:= 0;          (*mm*)
_09_rPos2              :    REAL:= 350;        (*mm*)
_09_rVelocity          :    REAL:= 70;         (*mm/s*)
_09_diAccel            :    DINT:= 100;        (*mm/s^2*)
_09_diDecel            :    DINT:= 100;        (*mm/s^2*)
_09_diJerkAccel        :    DINT:= 1000;       (*mm/s^3*)
_09_diJerkDecel        :    DINT:= 1000;       (*mm/s^3*)
_09_iProfilePasses     :    INT:=  0;

(*Profile #10*)
_10_rPos1              :    REAL:= 0;          (*mm*)
_10_rPos2              :    REAL:= 350;        (*mm*)
_10_rVelocity          :    REAL:= 70;         (*mm/s*)
_10_diAccel            :    DINT:= 100;        (*mm/s^2*)
_10_diDecel            :    DINT:= 100;        (*mm/s^2*)
_10_diJerkAccel        :    DINT:= 1000;       (*mm/s^3*)
_10_diJerkDecel        :    DINT:= 1000;       (*mm/s^3*)
_10_iProfilePasses     :    INT:=  0;

(*Profile #11*)
_11_rPos1              :    REAL:= 0;          (*mm*)
```

```
_11_rPos2               :       REAL:= 350;         (*mm*)
_11_rVelocity           :       REAL:= 70;          (*mm/s*)
_11_diAccel             :       DINT:= 100;         (*mm/s^2*)
_11_diDecel             :       DINT:= 100;         (*mm/s^2*)
_11_diJerkAccel         :       DINT:= 1000;        (*mm/s^3*)
_11_diJerkDecel         :       DINT:= 1000;        (*mm/s^3*)
_11_iProfilePasses      :       INT:=  0;

(*Profile #12*)
_12_rPos1               :       REAL:= 0;           (*mm*)
_12_rPos2               :       REAL:= 350;         (*mm*)
_12_rVelocity           :       REAL:= 70;          (*mm/s*)
_12_diAccel             :       DINT:= 100;         (*mm/s^2*)
_12_diDecel             :       DINT:= 100;         (*mm/s^2*)
_12_diJerkAccel         :       DINT:= 1000;        (*mm/s^3*)
_12_diJerkDecel         :       DINT:= 1000;        (*mm/s^3*)
_12_iProfilePasses      :       INT:=  0;

(*Profile #13*)
_13_rPos1               :       REAL:= 0;           (*mm*)
_13_rPos2               :       REAL:= 350;         (*mm*)
_13_rVelocity           :       REAL:= 70;          (*mm/s*)
_13_diAccel             :       DINT:= 100;         (*mm/s^2*)
_13_diDecel             :       DINT:= 100;         (*mm/s^2*)
_13_diJerkAccel         :       DINT:= 1000;        (*mm/s^3*)
_13_diJerkDecel         :       DINT:= 1000;        (*mm/s^3*)
_13_iProfilePasses      :       INT:=  0;

(*Profile #14*)
_14_rPos1               :       REAL:= 0;           (*mm*)
_14_rPos2               :       REAL:= 350;         (*mm*)
_14_rVelocity           :       REAL:= 70;          (*mm/s*)
_14_diAccel             :       DINT:= 100;         (*mm/s^2*)
_14_diDecel             :       DINT:= 100;         (*mm/s^2*)
_14_diJerkAccel         :       DINT:= 1000;        (*mm/s^3*)
_14_diJerkDecel         :       DINT:= 1000;        (*mm/s^3*)
_14_iProfilePasses      :       INT:=  0;

(*Profile #15*)
_15_rPos1               :       REAL:= 0;           (*mm*)
_15_rPos2               :       REAL:= 350;         (*mm*)
_15_rVelocity           :       REAL:= 70;          (*mm/s*)
_15_diAccel             :       DINT:= 100;         (*mm/s^2*)
_15_diDecel             :       DINT:= 100;         (*mm/s^2*)
_15_diJerkAccel         :       DINT:= 1000;        (*mm/s^3*)
_15_diJerkDecel         :       DINT:= 1000;        (*mm/s^3*)
_15_iProfilePasses      :       INT:=  0;

(*Profile #16*)
_16_rPos1               :       REAL:= 0;           (*mm*)
_16_rPos2               :       REAL:= 350;         (*mm*)
_16_rVelocity           :       REAL:= 70;          (*mm/s*)
_16_diAccel             :       DINT:= 100;         (*mm/s^2*)
_16_diDecel             :       DINT:= 100;         (*mm/s^2*)
_16_diJerkAccel         :       DINT:= 1000;        (*mm/s^3*)
_16_diJerkDecel         :       DINT:= 1000;        (*mm/s^3*)
```

```
	_16_iProfilePasses		:	INT:=	0;

	(*Profile #17*)
	_17_rPos1			:	REAL:= 0;		(*mm*)
	_17_rPos2			:	REAL:= 350;		(*mm*)
	_17_rVelocity			:	REAL:= 70;		(*mm/s*)
	_17_diAccel			:	DINT:= 100;		(*mm/s^2*)
	_17_diDecel			:	DINT:= 100;		(*mm/s^2*)
	_17_diJerkAccel			:	DINT:= 1000;		(*mm/s^3*)
	_17_diJerkDecel			:	DINT:= 1000;		(*mm/s^3*)
	_17_iProfilePasses		:	INT:=	0;

	(*Profile #18*)
	_18_rPos1			:	REAL:= 0;		(*mm*)
	_18_rPos2			:	REAL:= 350;		(*mm*)
	_18_rVelocity			:	REAL:= 75;		(*mm/s*)
	_18_diAccel			:	DINT:= 10000;		(*mm/s^2*)
	_18_diDecel			:	DINT:= 10000;		(*mm/s^2*)
	_18_diJerkAccel			:	DINT:= 1000000;		(*mm/s^3*)
	_18_diJerkDecel			:	DINT:= 1000000;		(*mm/s^3*)
	_18_iProfilePasses		:	INT:=	0;

	(*Profile #19*)
	_19_rPos1			:	REAL:= 0;		(*mm*)
	_19_rPos2			:	REAL:= 250;		(*mm*)
	_19_rVelocity			:	REAL:= 50;		(*mm/s*)
	_19_diAccel			:	DINT:= 10000;		(*mm/s^2*)
	_19_diDecel			:	DINT:= 10000;		(*mm/s^2*)
	_19_diJerkAccel			:	DINT:= 100000;		(*mm/s^3*)
	_19_diJerkDecel			:	DINT:= 100000;		(*mm/s^3*)
	_19_iProfilePasses		:	INT:=	0;		(*moves*)

END_VAR

(*
Aaron Jones & Jerry Sorrells -  3/28/2018
*)

fbEnable.Enable:= xCmdEnable;					(*enables the drive if the command is set to true,
disables the drive if it is false*)

IF xCmdStop AND fbEnable.Status THEN
	xCmdStop:= 0;
	iState:= 5;
END_IF

CASE iState OF

	0: (*IDLE*)
		IF fbEnable.Status THEN								(*Make
sure the drive is enabled before allowing any other commands.*)

			IF xCmdHome THEN
	(*User command to go to the home state.*)
				xCmdHome:= 0;
	(*Reset the user command so it doesn't get held high and the user*)
```

```
                    iState:= 1;                 (*doesn't have to reset it every time.*)
                END_IF

                IF xCmdStart AND xAxisReferenced THEN           (*If the axis is referenced and the
start command is given by the user, *)
                    xCmdStart:= 0;              (*then reset the command, *)
                    iState:= 2;
                END_IF

            END_IF

        1: (*HOME_STATE*)
            fbHome.Execute:= TRUE;
            IF fbHome.Done THEN
                fbHome.Execute:= FALSE;
                xAxisReferenced:= TRUE;
                iState:= 0; (*go to IDLE*)
            END_IF

            IF fbHome.Error THEN
                fbHome.Execute:= FALSE;
                iState:= 8;                     (*if error occurs, go to reset*)
            END_IF

        2: (*LOAD PROFILE*)

            CASE iProfile OF                    (*This case statement is loading the profiles to the
generic parameters based on which profile is to run next.*)

        (*This entire case statement could really be collapsed for program space and viewability purposes, but
doing*)
                1:      rPos1                   := _01_rPos1;
        (*so would make it very difficult to read. No one should really need to read or modify it, but it's left in this
format*)
                        rPos2                   := _01_rPos2;
        (*just in case someone in the future wants to know what's happening here.*)
                        rVelocity               := _01_rVelocity;
                        diAccel                 := _01_diAccel;
                        diDecel                 := _01_diDecel;
                        diJerkAccel             := _01_diJerkAccel;
                        diJerkDecel             := _01_diJerkDecel;
                        iProfilePasses          := _01_iProfilePasses;

                        iPass:= 1;
                        iState:= 3;
                        fbTimer.IN:= TRUE;

                2:      rPos1                   := _02_rPos1;
                        rPos2                   := _02_rPos2;
                        rVelocity               := _02_rVelocity;
                        diAccel                 := _02_diAccel;
                        diDecel                 := _02_diDecel;
                        diJerkAccel             := _02_diJerkAccel;
                        diJerkDecel             := _02_diJerkDecel;
                        iProfilePasses          := _02_iProfilePasses;
```

```
        iPass:= 1;
        iState:= 3;

3:      rPos1                   := _03_rPos1;
        rPos2                   := _03_rPos2;
        rVelocity               := _03_rVelocity;
        diAccel                 := _03_diAccel;
        diDecel                 := _03_diDecel;
        diJerkAccel             := _03_diJerkAccel;
        diJerkDecel             := _03_diJerkDecel;
        iProfilePasses          := _03_iProfilePasses;

        iPass:= 1;
        iState:= 3;

4:      rPos1                   := _04_rPos1;
        rPos2                   := _04_rPos2;
        rVelocity               := _04_rVelocity;
        diAccel                 := _04_diAccel;
        diDecel                 := _04_diDecel;
        diJerkAccel             := _04_diJerkAccel;
        diJerkDecel             := _04_diJerkDecel;
        iProfilePasses          := _04_iProfilePasses;

        iPass:= 1;
        iState:= 3;

5:      rPos1                   := _05_rPos1;
        rPos2                   := _05_rPos2;
        rVelocity               := _05_rVelocity;
        diAccel                 := _05_diAccel;
        diDecel                 := _05_diDecel;
        diJerkAccel             := _05_diJerkAccel;
        diJerkDecel             := _05_diJerkDecel;
        iProfilePasses          := _05_iProfilePasses;

        iPass:= 1;
        iState:= 3;

6:      rPos1                   := _06_rPos1;
        rPos2                   := _06_rPos2;
        rVelocity               := _06_rVelocity;
        diAccel                 := _06_diAccel;
        diDecel                 := _06_diDecel;
        diJerkAccel             := _06_diJerkAccel;
        diJerkDecel             := _06_diJerkDecel;
        iProfilePasses          := _06_iProfilePasses;

        iPass:= 1;
        iState:= 3;

7:      rPos1                   := _07_rPos1;
        rPos2                   := _07_rPos2;
        rVelocity               := _07_rVelocity;
        diAccel                 := _07_diAccel;
        diDecel                 := _07_diDecel;
```

```
        diJerkAccel          := _07_diJerkAccel;
        diJerkDecel          := _07_diJerkDecel;
        iProfilePasses       := _07_iProfilePasses;

        iPass:= 1;
        iState:= 3;

8:      rPos1                := _08_rPos1;
        rPos2                := _08_rPos2;
        rVelocity            := _08_rVelocity;
        diAccel              := _08_diAccel;
        diDecel              := _08_diDecel;
        diJerkAccel          := _08_diJerkAccel;
        diJerkDecel          := _08_diJerkDecel;
        iProfilePasses       := _08_iProfilePasses;

        iPass:= 1;
        iState:= 3;

9:      rPos1                := _09_rPos1;
        rPos2                := _09_rPos2;
        rVelocity            := _09_rVelocity;
        diAccel              := _09_diAccel;
        diDecel              := _09_diDecel;
        diJerkAccel          := _09_diJerkAccel;
        diJerkDecel          := _09_diJerkDecel;
        iProfilePasses       := _09_iProfilePasses;

        iPass:= 1;
        iState:= 3;

10:     rPos1                := _10_rPos1;
        rPos2                := _10_rPos2;
        rVelocity            := _10_rVelocity;
        diAccel              := _10_diAccel;
        diDecel              := _10_diDecel;
        diJerkAccel          := _10_diJerkAccel;
        diJerkDecel          := _10_diJerkDecel;
        iProfilePasses       := _10_iProfilePasses;

        iPass:= 1;
        iState:= 3;

11:     rPos1                := _11_rPos1;
        rPos2                := _11_rPos2;
        rVelocity            := _11_rVelocity;
        diAccel              := _11_diAccel;
        diDecel              := _11_diDecel;
        diJerkAccel          := _11_diJerkAccel;
        diJerkDecel          := _11_diJerkDecel;
        iProfilePasses       := _11_iProfilePasses;

        iPass:= 1;
        iState:= 3;

12:     rPos1                := _12_rPos1;
```

```
        rPos2              := _12_rPos2;
        rVelocity          := _12_rVelocity;
        diAccel            := _12_diAccel;
        diDecel            := _12_diDecel;
        diJerkAccel        := _12_diJerkAccel;
        diJerkDecel        := _12_diJerkDecel;
        iProfilePasses     := _12_iProfilePasses;

        iPass:= 1;
        iState:= 3;

13:     rPos1              := _13_rPos1;
        rPos2              := _13_rPos2;
        rVelocity          := _13_rVelocity;
        diAccel            := _13_diAccel;
        diDecel            := _13_diDecel;
        diJerkAccel        := _13_diJerkAccel;
        diJerkDecel        := _13_diJerkDecel;
        iProfilePasses     := _13_iProfilePasses;

        iPass:= 1;
        iState:= 3;

14:     rPos1              := _14_rPos1;
        rPos2              := _14_rPos2;
        rVelocity          := _14_rVelocity;
        diAccel            := _14_diAccel;
        diDecel            := _14_diDecel;
        diJerkAccel        := _14_diJerkAccel;
        diJerkDecel        := _14_diJerkDecel;
        iProfilePasses     := _14_iProfilePasses;

        iPass:= 1;
        iState:= 3;

15:     rPos1              := _15_rPos1;
        rPos2              := _15_rPos2;
        rVelocity          := _15_rVelocity;
        diAccel            := _15_diAccel;
        diDecel            := _15_diDecel;
        diJerkAccel        := _15_diJerkAccel;
        diJerkDecel        := _15_diJerkDecel;
        iProfilePasses     := _15_iProfilePasses;

        iPass:= 1;
        iState:= 3;

16:     rPos1              := _16_rPos1;
        rPos2              := _16_rPos2;
        rVelocity          := _16_rVelocity;
        diAccel            := _16_diAccel;
        diDecel            := _16_diDecel;
        diJerkAccel        := _16_diJerkAccel;
        diJerkDecel        := _16_diJerkDecel;
        iProfilePasses     := _16_iProfilePasses;
```

```
                    iPass:= 1;
                    iState:= 3;

            17:     rPos1               := _17_rPos1;
                    rPos2               := _17_rPos2;
                    rVelocity           := _17_rVelocity;
                    diAccel             := _17_diAccel;
                    diDecel             := _17_diDecel;
                    diJerkAccel         := _17_diJerkAccel;
                    diJerkDecel         := _17_diJerkDecel;
                    iProfilePasses      := _17_iProfilePasses;

                    iPass:= 1;
                    iState:= 3;

            18:     rPos1               := _18_rPos1;
                    rPos2               := _18_rPos2;
                    rVelocity           := _18_rVelocity;
                    diAccel             := _18_diAccel;
                    diDecel             := _18_diDecel;
                    diJerkAccel         := _18_diJerkAccel;
                    diJerkDecel         := _18_diJerkDecel;
                    iProfilePasses      := _18_iProfilePasses;

                    iPass:= 1;
                    iState:= 3;

            19:     rPos1               := _19_rPos1;
                    rPos2               := _19_rPos2;
                    rVelocity           := _19_rVelocity;
                    diAccel             := _19_diAccel;
                    diDecel             := _19_diDecel;
                    diJerkAccel         := _19_diJerkAccel;
                    diJerkDecel         := _19_diJerkDecel;
                    iProfilePasses      := _19_iProfilePasses;

                    iPass:= 1;
                    iState:= 3;

            20:     iState:= 0; iProfile:= 1; iPass:= 1; tElapsedTime:= fbTimer.ET; fbTimer.IN:=
FALSE;

        END_CASE


    3: (*MOVE_TO_POS_TWO*)
        IF iProfilePasses = 0 THEN                  (*If the profile has zero passes, then drop
through and ignore it,*)
            iProfile:= iProfile + 1;                (*increment the profile number, and *)
            iState:= 2;                             (*go load the next profile.*)
        ELSE
            fbMoveAbs.Position:= rPos2;             (*Else, go to the second position first. The
assumption is we're already at position 1.*)
            fbMoveAbs.Execute:= TRUE;
            IF fbMoveAbs.Done THEN                  (*Wait until the move is done, then*)
                fbMoveAbs.Execute:= FALSE;          (*toggle the execute*)
```

```
                    IF iPass = iProfilePasses THEN      (*If this was our last pass for the profile,*)
                        iProfile:= iProfile + 1;        (*then increment the profile*)
                        iState:= 2;                     (*and go load the next one.*)
                    ELSE
                        iPass:= iPass + 1;              (*Increment which pass we're on*)
                        iState:= 4;                     (*and go to position one.*)
                    END_IF
                END_IF

                IF fbMoveAbs.Error THEN
                    fbMoveAbs.Execute:= FALSE;
                    iState:= 8;                         (*go to the error state*)
                END_IF
            END_IF

        4: (*MOVE_TO_POS_ONE*)
            IF iProfilePasses = 0 THEN                  (*This is the same as above. If the profile
has zero passes, then drop through and ignore it,*)
                iProfile:= iProfile + 1;                (*increment the profile, and *)
                iState:= 2;                             (*load the next profile.*)
            ELSE
                fbMoveAbs.Position:= rPos1;             (*Else, go to the first position. We're
currently at the second at this point in the program.*)
                fbMoveAbs.Execute:= TRUE;
                IF fbMoveAbs.Done THEN                  (*Wait until the move is done and then*)
                    fbMoveAbs.Execute:= FALSE;          (*toggle the execute for the function block
to work the next time around.*)
                    IF iPass = iProfilePasses THEN      (*If this is our last pass for the profile,*)
                        iProfile:= iProfile + 1;        (*then increment the profile*)
                        iState:= 2;                     (*and go load the next one *)
                    ELSE
                        iPass:= iPass + 1;              (*Increment which pass we're on*)
                        iState:= 3;                     (*and go to position two.   *)
                    END_IF
                END_IF

                IF fbMoveAbs.Error THEN
                    fbMoveAbs.Execute:= FALSE;
                    iState:= 8;                         (*go to the error state*)
                END_IF
            END_IF

        5: (*STOP STATE*)
            fbStop.Execute:= TRUE;
            IF fbStop.Done THEN
                fbStop.Execute:= FALSE;
                iState:= 7;                         (*stop and then go to cleanup*)
            END_IF

            IF fbStop.Error THEN
                fbStop.Execute:= FALSE;
                iState:= 8;                         (*go to the reset state*)
            END_IF

        6: (*RESET STATE*)
            fbReset.Execute:= TRUE;
```

```
        iState:= 7;                                  (*reset the routine and go to the cleanup state*)

    7: (*CLEANUP STATE*)
        fbHome.Execute:= FALSE;
        fbMoveAbs.Execute:= FALSE;
        fbStop.Execute:= FALSE;
        fbReset.Execute:= FALSE;
        fbTimer.IN:= FALSE;
        iProfile:= 1;
        iPass:= 1;
        iState:= 0;

    8: (*ERROR STATE*)
        xAxisReferenced:= FALSE;                     (*force a re-home if the error state is entered*)
        IF xCmdReset THEN                            (*wait on the user to issue the reset command*)
            xCmdReset:= 0;
            iState:= 6;
        END_IF

END_CASE

(*******************************************************************All function blocks are called
here*******************************************************)

fbEnable(Axis:= AXIS_REF_LocalAxis);
fbHome(Axis:= AXIS_REF_LocalAxis, Position:= 0);
fbMoveAbs(Axis:= AXIS_REF_LocalAxis, Velocity:= rVelocity, Acceleration:= diAccel, Deceleration:= diDecel,
Jerk:= diJerkAccel, JerkDecel:= diJerkDecel);
fbStop(Axis:= AXIS_REF_LocalAxis, Deceleration:= 10000, Jerk:= 1000000); (*values hardcoded here because the
number of allowable 32-bit variables was exceeded*)
fbReset(Axis:= AXIS_REF_LocalAxis);
fbTimer(PT:= T#30m);
```

# APPENDIX F:

# CHAMBER FILLING NOTES

Sandfiller Notes: Date: 4/20/2018

Project: SANDFILLER_V1.01
Type: Microlayered Cell
Profile Settings:

Profile 1 -

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 1000 | (mm/sec^2) |
| Decel | 1000 | (mm/sec^2) |
| JerkAccel | 10000 | (mm/sec^3) |
| JerkDecel | 10000 | (mm/sec^3) |
| ProfilePass | 110 | (#) |

Note: we have fine-tuned the micro-layering. This can also be found in profile 3 of SANDFILLER_V1.06

Project: SANDFILLER_V1.02
Type: Micro-Thick-Micro layered Cell
Profile Settings:

Profile 1 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 36 | (#) |

Profile 2 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 25 | (mm/sec) |
| Accel | 5000 | (mm/sec^2) |
| Decel | 5000 | (mm/sec^2) |
| JerkAccel | 500000 | (mm/sec^3) |
| JerkDecel | 500000 | (mm/sec^3) |
| ProfilePass | 38 | (#) |

Profile 3 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 36 | (#) |

Notes: Adjust margins and accel/decel from margins. The third profile is not pictured as there were only a few layers. The 2nd profile took more time and a larger portion of the chamber than intended.

Project: SANDFILLER_V1.03
Type: Layers and Capillary barriers (avalanches)
Profile Settings:

Profile 1 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 10 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 100000 | (mm/sec^2) |
| Decel | 100000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 2 –

| | | |
|---|---|---|
| Pos1 | 10 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 100000 | (mm/sec^2) |
| Decel | 100000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 3 –

| | | |
|---|---|---|
| Pos1 | 215 | (mm) |
| Pos2 | 0 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 100000 | (mm/sec^2) |
| Decel | 100000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 35 | (#) |

Profile 4 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 5000 | (mm/sec^2) |
| Decel | 5000 | (mm/sec^2) |
| JerkAccel | 500000 | (mm/sec^3) |
| JerkDecel | 500000 | (mm/sec^3) |
| ProfilePass | 36 | (#) |

Notes: Here we are attempting to eliminate the lag effects of automated gate and testing the effects of manipulating acell, decel, and jerk values (notice: profile 4 is half the value on these parameters as the profiles before it.)

We incorporated stops and restarts from the computer controller to produce the avalanches. (notice: these stops and restarts are not programmed in the project, but accomplished via toggles on the controller.)

Project: SANDFILLER_V1.04 & V1.04.1
Type: Micro-Layer with Macro-Heterogeneity
Profile Settings:

Profile 1 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 10 | (#) |

Profile 2 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 20 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 3 –

| | | |
|---|---|---|
| Pos1 | 20 | (mm) |
| Pos2 | 25 | (mm) |
| Velocity | 20 | (mm/sec) |
| Accel | 5000 | (mm/sec^2) |
| Decel | 5000 | (mm/sec^2) |
| JerkAccel | 500000 | (mm/sec^3) |
| JerkDecel | 500000 | (mm/sec^3) |
| ProfilePass | 10 | (#) |

Profile 4 –

| | | |
|---|---|---|
| Pos1 | 20 | (mm) |
| Pos2 | 195 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 5000 | (mm/sec^2) |
| Decel | 5000 | (mm/sec^2) |
| JerkAccel | 500000 | (mm/sec^3) |
| JerkDecel | 500000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 5 –

| | | |
|---|---|---|
| Pos1 | 195 | (mm) |
| Pos2 | 200 | (mm) |
| Velocity | 20 | (mm/sec) |
| Accel | 5000 | (mm/sec^2) |
| Decel | 5000 | (mm/sec^2) |
| JerkAccel | 500000 | (mm/sec^3) |
| JerkDecel | 500000 | (mm/sec^3) |
| ProfilePass | 10 | (#) |

Profile 6 –

| | | |
|---|---|---|
| Pos1 | 200 | (mm) |

| | | |
|---|---|---|
| Pos2 | 0 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 20 | (#) |

Project: SANDFILLER_1.05
Type: Crossbedding with micro-layered beds
Profile Settings:

Profile 1 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 2 –

| | | |
|---|---|---|
| Pos1 | 215 | (mm) |
| Pos2 | 161 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 25 | (#) |

Profile 3 –

| | | |
|---|---|---|
| Pos1 | 161 | (mm) |
| Pos2 | 107 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 25 | (#) |

Profile 4 –

| | | |
|---|---|---|
| Pos1 | 107 | (mm) |
| Pos2 | 53 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 25 | (#) |

Profile 5 –

| | | |
|---|---|---|
| Pos1 | 53 | (mm) |

| | | |
|---|---|---|
| Pos2 | 0 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 25 | (#) |

Profile 6 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 40 | (#) |

Note: These came out more like sloped layers

Project: SANDFILLER_V1.04.2
Type: mounds under layers
Profile Settings:

Profile 1 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 164 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 2 –

| | | |
|---|---|---|
| Pos1 | 164 | (mm) |
| Pos2 | 157 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 79 | (#) |

Profile 3 –

| | | |
|---|---|---|
| Pos1 | 157 | (mm) |
| Pos2 | 47 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 4 –

| | | |
|---|---|---|
| Pos1 | 47 | (mm) |
| Pos2 | 54 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 79 | (#) |

Profile 5 –

| | | |
|---|---|---|
| Pos1 | 54 | (mm) |
| Pos2 | 164 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 6 –

| | | |
|---|---|---|
| Pos1 | 164 | (mm) |
| Pos2 | 157 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 79 | (#) |

Profile 7 –

| | | |
|---|---|---|
| Pos1 | 157 | (mm) |
| Pos2 | 47 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 8 –

| | | |
|---|---|---|
| Pos1 | 47 | (mm) |
| Pos2 | 54 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 79 | (#) |

Profile 9 –

| | | |
|---|---|---|
| Pos1 | 54 | (mm) |
| Pos2 | 164 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |

| | | |
|---|---|---|
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 10 –

| | | |
|---|---|---|
| Pos1 | 164 | (mm) |
| Pos2 | 157 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 79 | (#) |

Profile 11 –

| | | |
|---|---|---|
| Pos1 | 157 | (mm) |
| Pos2 | 47 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 12 –

| | | |
|---|---|---|
| Pos1 | 47 | (mm) |
| Pos2 | 54 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 79 | (#) |

Profile 13 –

| | | |
|---|---|---|
| Pos1 | 54 | (mm) |
| Pos2 | 0 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 1 | (#) |

Profile 14 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 60 | (#) |

Type: manipulation of Velocity, Accell and Decel
Profile Settings:

Profile 1 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 10000 | (mm/sec^2) |
| Decel | 10000 | (mm/sec^2) |
| JerkAccel | 1000000 | (mm/sec^3) |
| JerkDecel | 1000000 | (mm/sec^3) |
| ProfilePass | 16 | (#) |

Profile 2 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 1000 | (mm/sec^2) |
| Decel | 1000 | (mm/sec^2) |
| JerkAccel | 100000 | (mm/sec^3) |
| JerkDecel | 100000 | (mm/sec^3) |
| ProfilePass | 16 | (#) |

Profile 3 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 50 | (mm/sec) |
| Accel | 100 | (mm/sec^2) |
| Decel | 100 | (mm/sec^2) |
| JerkAccel | 10000 | (mm/sec^3) |
| JerkDecel | 10000 | (mm/sec^3) |
| ProfilePass | 40 | (#) |

Profile 4 –

| | | |
|---|---|---|
| Pos1 | 0 | (mm) |
| Pos2 | 215 | (mm) |
| Velocity | 5 | (mm/sec) |
| Accel | 2500 | (mm/sec^2) |
| Decel | 5000 | (mm/sec^2) |
| JerkAccel | 250000 | (mm/sec^3) |
| JerkDecel | 500000 | (mm/sec^3) |
| ProfilePass | 30 | (#) |

# VITA

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## EDUCATION

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The University of Mississippi School of Engineering
Thesis: Modernized Approach for Generating Micro-Layering and Macro-Heterogeneous structures in porous media for use in Transmitted-Light Flow Visualization Experiments

Bachelor of Science, Geological Engineering, August 2013
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USDA/ARS National Sedimentation Laboratory — June 2016 – Present
Engineering Technician for the Water Quality and Ecology Research Unit responsible for compilation and processing of water quality data of Roundaway lake and watershed south of Clarksdale, MS.

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University of Mississippi Teaching Assistant — August 2013 – May 2017
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Graduate Research Assistant - Vicksburg, MS for Dr. Gregg Davidson

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