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Investigation of Casting Methods of Photoelastic Particles to Study the Geomechanics of Granular Media

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Honors Research Project

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Abstract

In real-world scenarios, shape and size of soil particles vary for every location where structures are built. A challenge faced in today's world is being able to correctly predict how different samples of soil media will behave under loading conditions based on their size, shape, and morphology present at a given location. Due to the varying micro-scale properties of soil particles, the interparticle forces transferring through the soil media will not stay consistent based on on-site location. This occurs through a complex interaction between geostatic and external stresses due to the weight of overlaying soils and foundations, fluid flow through the granular media, surrounding structures including the foundations systems and numerous other factors including thermal-chemical-hydro-mechanical processes.

The research being performed under professor Nariman Mahabadi will attempt to model soil particles of various shapes and sizes, and then create a testing chamber where future tests will be conducted on the particles utilizing differing flow and loading conditions. Once force and flow are applied to the modeled particles, the concept of photoelasticity, which will be explained in further detail, will be used to enable a visual observation of the stresses and force chains experienced by each soil sample being tested.

The main objective of conducting the research is to construct a bench scale chamber (10.5cm x 8cm x 1cm) that will be used for modeling the soil particles. Soil particles of varying shapes will then be cast ranging in size from 0.25-0.5cm diameter. Proceeding, a testing chamber with the dimensions of 11" x 11" x 5/8" will be fabricated to house the particles where loading and flow conditions can be induced on the soil media being tested. Through utilizing photoelastic principles, the tested soil media can be observed to see how the stress distribution will behave within the sample.

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I. Introduction

Geotechnical work is performed in all civil engineering projects across the world. When any structure is to be built, the ground beneath the structure must be analyzed to determine the engineering behavior of the soil and the design of foundation geosystems are carried out accordingly to ensure that the ground will be able to support the stress-induced upon it by the structure. Engineering classification of soil plays a critical role in the prediction of the behavior of geomaterials. Coarse grain soils are defined as having a diameter larger than 4.75mm. Within this classification, granular soils are listed with types of granular material being gravel, sand, and loamy sand. Due to these soil types having little to no clay content, they are classified as the weakest type of soil when looking at unconfined compressive strength as well as being extremely permeable. Through the research being conducted, modeled granular soil media will be created and a testing chamber will be fabricated to perform future tests under differing flow and loading conditions for the observation of interparticle interactions within the sample. This will also allow the observer to witness how force chains within the tested media will vary based on the varying shapes and sizes of the particles. Another advantage of the proposed photoelastic chamber is to validate the particle levem computational models such as Discrete Element Method (DEM) models for complex hydro-mechanical interaction.

Due to the extensive nature of the overall work, the goals and objectives of this project are focused only on the process for the casting of various-shaped particles and to create a transparent chamber where the casted particles can be tested in future semesters. The concept of photoelasticity will mainly be used for final testing; However, it must also be utilized in the trial phase of creating the soil media to ensure that the particles being cast exhibit the photoelastic properties being looked

for. Thus, the concept of photoelasticity and how it applies to the testing of the soil media will be covered in this report.

II. Photoelasticity

Photoelasticity will be one of the main concepts being considered with the research in both trial and testing phases. Photoelasticity as described in an article published by the University of Cambridge's science department states, "The photoelastic effect (alternatively called the piezo-optical effect) is the change of refractive index caused by stress" [4]. Within the research, photoelasticity will be applied to the modeled soil media and then observed to visually see the stress state of each particle within the testing chamber. Photoelasticity can be used to show stress concentrations in irregular geometries through the utilization of observing the changes in optical properties under mechanical deformation [14], which will be the loaded soil media within the research. Refer to **Figure1** below for a visual representation of a polarizing device.

(a) (b)

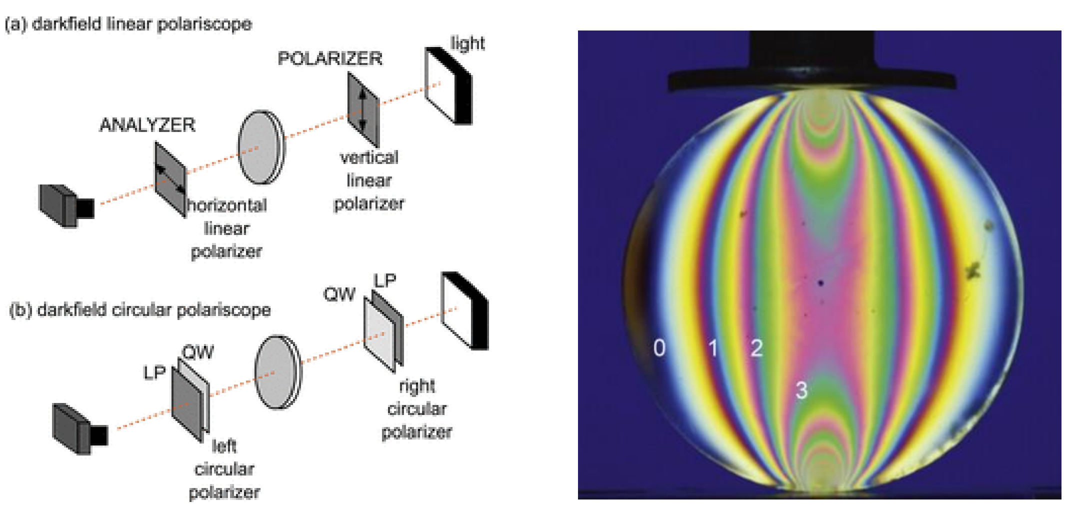

Figure 1: Polarizing device and particle with photoelastic properties [14]

Multiple properties of photoelasticity must be observed. The first property is the concept of birefringence. The phenomenon behind birefringence is that light passing through birefringent material experiences two refractive indices, otherwise known as double refraction, and upon the application of stresses, the photoelastic material will exhibit birefringent properties [14]. This means that the magnitude of the refractive indices at each point in the material is related directly to the state of stresses at the point being observed [14]. These stresses and birefringent properties can be observed under a polariscope device.

"The basic principle of a darkfield polariscope is to place a photoelastic sample between a polarizer and an analyzer of the opposite polarization" [14]. Initially, unpolarized light will be used and passed through the polariscope where it will become polarized. When the polarized rays of light pass through the photoelastic material, the electromagnetic wave components will travel along two principal stress directions, causing a separate refractive index [14]. While formulas can be derived to achieve the magnitude of these relative stresses, an image processing technique developed in Mahabadi's lab will automatically populate the magnitude and orientation of these contact forces [13]. Then, the light will pass through the final sheet of the polarizer where this concept can be used to analyze the results. By studying the fringe pattern, stress states can now be determined at every single particle and the entire chamber within the sample being tested [14].

For a material to be photoelastic, it must be transparent and be of crystalline material. A crystalline material is a material in its most stable state; The atoms are oriented in a way where they are closely packed together, and the total potential energy is at a minimum [3]. Many materials can be considered photoelastic, however, the closer they are to being classified as a crystalline material, the more accurate the results will be when using photoelasticity for determining stresses. Within the research, it was initially assumed that a PL-1 castable liquid resin would be used as the

photoelastic material [6]. However, a complication arose in using the PL-1 liquid, and it was determined that photoelastic particles could be 3D-printed using an *Anycubic PhotonS* printer. The printer uses a liquid resin that hardens as the object is printed, giving the final product similar qualities to that of the PL-1 castable resin.

III. Materials and Procedure

Research activities began in the summer of 2020. To begin, a plan for the semester was laid out, as well as goals and objectives being set for current and future semesters. To begin, an initial goal was set of being able to generate an idea to feasibly model soil particles using readily available materials at The University of Akron's disposal. After multiple weeks of collaboration, it was originally assumed that machine shop fabrication of a chamber made out of a thick acrylic sheet would be used, which would then be used to cast the silicon mold. The silicon mold that is created could then be used to cast the individual soil particles. The reason this intermediate step must be taken is because the acrylic chamber would have little to no flexibility, thus making it impossible to remove small pieces of casted material acting as the soil particles. It was determined that a 1/2" thick sheet could be used. The acrylic sheet could then be cut to model the design for silicon mold creation. Once the chamber was designed, collaboration with multiple machine shops in the Akron area occurred. After receiving multiple quotes from companies around the Akron area exceeding $1000 for a singular acrylic sheet being fabricated, it was concluded that this would not be the most cost-effective way of proceeding. Further collaboration occurred, and it was determined that the lab could purchase a resin 3D printer that could be used for this project in addition to future projects. This would also allow in-house modifications to be made as needed, as well as a multitude of molds to be created. Through the utilization of SolidWorks, an original chamber with the dimensions of 21cm x 21cm x 1cm would be used to cast our silicone mold.

When looking at the model to be 3D-printed, it can be described as a hollow basin with a solid base, and variously shaped protrusions jutting out from the bottom of the basin to a height of 0.2cm. These variously shaped protrusions would act as soil particles. Once the chamber is printed, silicone could then be poured into the hollow chamber, and once cured, it would be removed. This leaves out hollow shapes in the middle of the silicon mold with a height of 1cm which will be used for casting the soil particles out of a photoelastic resin. **Figure 2** shows the design of the 3D-printed chamber.

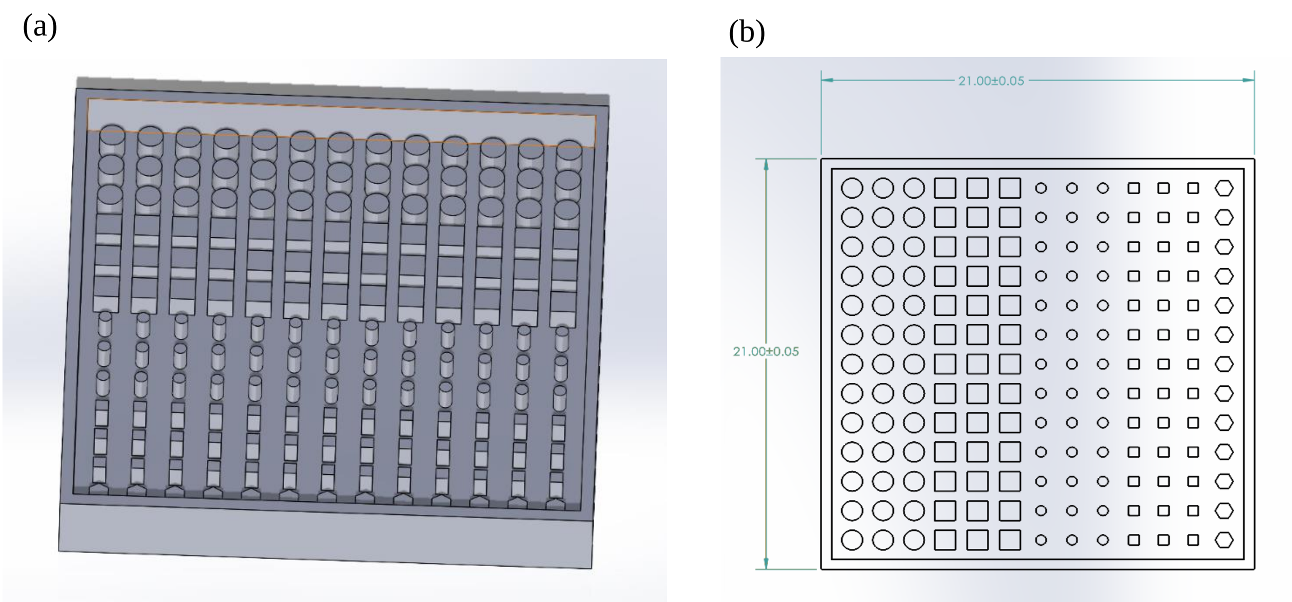

Figure 2: Design of 3D-printed chamber to be used for silicon casting with outer dimensions of 21cm x 21cm x 1cm, and various shaped protrusions with a diameter ranging from 0.05-0.1cm and height of 0.2cm

Due to Covid-19, work restrictions, and remodeling of the soil lab, work was halted for the summer semester of 2020 with a plan to continue in the spring semester of 2021. The initial goal for the semester was met of coming up with a plan to feasibly model soil particles using resources readily available.

The research was continued in the spring semester of 2021. A new set of final goals and objectives were defined as being able to have a working sample of high-quality soil particles, as well as having designed and fabricated a testing chamber to house the soil media where photoelasticity tests can begin at a later date. Beginning the semester, work was continued with the idea of utilizing a 3D-printed chamber to make a silicon mold. Due to the previous mold design exceeding the maximum dimension restrictions of the *Anycubic PhotonS* 3D-printer, a new mold design was utilized using the dimensions of 10.5cm x 8cm x 1cm. The previous model of 21cm x 21cm x 1cm was scaled accordingly to meet the new restraints. New dimensions were not used as this procedure was being conducted as a trial run to observe the results of the chamber. With the dimensions being adjusted, the design was sent to the 3D printer for creation. **Figure 3** presents the visual results of the printed chamber. The chamber was deemed to be of high quality and could be used in making the silicon mold.

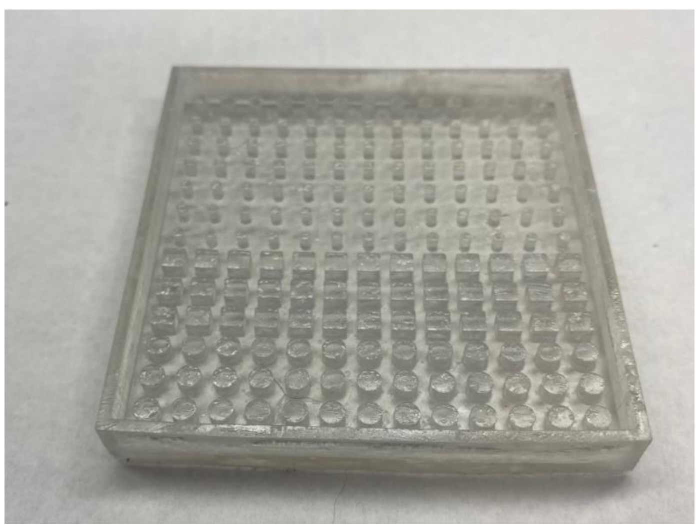

Figure 3: 3D-printed chamber for silicon mold

Proceeding, silicon was to be ordered. After further collaboration, a two-part silicon kit was ordered from Amazon to be used in the lab. The silicon selected was due to its high

workability, easy mix ratio, and fast curing time [10]. The silicon kit was ordered and received within the same week and lab work continued. The two-part silicon kit was utilized, mixing the two parts in a 1:1 ratio as instructed, with a quantity of silicon that would exceed the volume of the 3D-printed chamber. Before placement of the silicon, the 3D-printed chambers were layered with a releasing agent to ensure that once the silicon was cured, it would be easily removed from the chamber. Once mixed, the silicone was poured into the 3D-printed molds and left to cure overnight. During the following lab session, the silicon molds were removed easily and visually analyzed to see that the three molds cast were of high enough quality to begin preliminary soil particle testing. **Figure 4** illustrates the fabricated silicon mold.

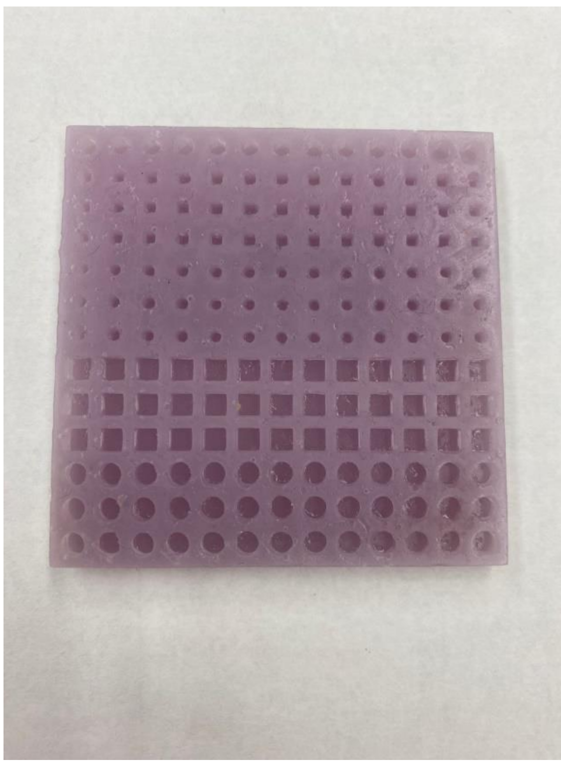

Figure 4: Silicon mold casted from 3D-printed chamber with voids ranging from 0.05-0.1cm diameter and a height of 0.2cm

Moving forward, the utilization of PL-1 liquid plastic was to be used for the casting of the various shaped soil particles. PL-1 is a resin/hardener that can be used for the creation of contourable PhotoStress sheets as defined by the instruction manual [6]. By following the manual, a ratio of resin to hardener was determined amounting to the total volume of voids that needed to be filled within the silicon mold. These voids that are filled with the PL-1 liquid will act as the modeled soil particles. Once the resin/hardener was placed in the three high-quality silicon molds, they were left to cure. During the next lab session, the results were analyzed. **Figure 5** presents visual results of the first batch of modeled soil particles. The result was deemed unacceptable, which will be explained in further detail within the results and discussion section of the report.

Figure 5: Soil particles cast from silicon mold with a diameter of 0.05cm-0.1cm and a height of 0.2cm

The last objective to be met through the final semester of conducting research is to design and construct a chamber that can house the modeled soil particles for photoelastic analysis. Two requirements of the chamber need to be met. The first is that the chamber needs to be nearly 100% transparent to allow for observation of the particles, and it needs to have the strength capacity to overcome the outward force induced on the outer walls of the chamber during testing. Through

research and browsing of *McMaster-Carr,* it was determined that clear acrylic sheets would be ideal for the creation of the chamber. For the design, two simple ideas were drafted where the acrylic sheets would be used. For the first design, three acrylic sheets will be used. The two outer walls of the chamber will have a thickness of 1/4", while the center sheet will have a thickness of 1/8" (0.31cm). The two outer sheets will be solid and have dimensions of 11" x 11" x 1/4". The 1/8" thick sheet is to have a cut made to act as the void where the soil particles will sit and be tested. The second chamber will only utilize two 1/4" thick acrylic sheets. The top sheet will have a 0.25" diameter hole cut out of the center for the introduction of a push-to-connect connection where fluid injection can then be introduced into the system.

Further steps describing how the chambers are to be assembled will be described in the results and discussion section of the report. In addition, the acrylic material ordered was 'Clear Scratch- and UV-Resistant Cast Acrylic Sheet' [8] in both 1/4" and 1/8" thicknesses for the chamber. The listed properties of the acrylic sheet are defined as a clear, high strength, and multipurpose material, which were all properties deemed necessary for a high-quality chamber [8].

IV. Results and Discussion

Casting of Soil Particles

Once the original idea of utilizing a machine shop for fabricating a chamber was deemed unreasonably expensive, it was determined a 3D-printed chamber could be used to cast the silicon mold. The original chamber (**Figure 2)** has dimensions of 21cm x 21cm x 1cm. Once made, it will allow silicon to be poured within the chamber and then left to cure. Once cured the silicon can be removed from the chamber, which when removed will be left with voids of various shapes as seen protruding out from the bottom of the basin. These voids can then be used to cast the soil particles.

Moving forward, the *Anycubic PhotonS* 3D printer was ordered and delivered to the lab. The reason this printer was chosen was due to the specification matching closely to what was needed at the time, as well as a potential use for future projects. The printer uses self-curing resin, about one second per layer of resin. Layer resolution is specified as 25-100µm, as well as coming with a 405nm photosensitive resin [7]. Once received, a design for the chamber to be printed was made utilizing SolidWorks. The original chamber needed to be modified to meet the constraints of the 3D printer. Due to this procedure being within the trial phase of creating the silicon mold, the entire model was simply scaled down to meet the 10.5 x 8 x 1cm constraints.

Once scaled down in SolidWorks, the model was sent to the 3D printer to be made. After being printed, two test trials needed to be run to calibrate the printer for printing the highest quality of chamber possible. On the third attempt, a chamber was made that was deemed acceptable for housing the silicon mold to be cast **(Figure 3)**.

The chamber printed was of fairly high quality considering the intricacy of the piece. Due to the printer using a hardening resin, it is possible to make objects of such dimensions with small diameter measurements. Now that the chamber is fabricated, it is ready to be used for casting the silicon mold. As explained in the materials and procedure section, silicon was ordered from amazon to be used. The silicon came in a two-part mixture, being mixed in a 1:1 ratio and then poured in its mold and left to complete its 6-hour curing process [10]. Simple calculations were made to ensure the quantity of silicon to be mixed would exceed the volume of the chamber to be filled. 380ml of silicon was needed to fill three chambers including a 10% addition of excess material. 190ml of part A and 190ml of part B of the silicon mix was used. Moving forward, the silicon was mixed in a container before being poured into three 3D-printed chambers. The three chambers were layered with a releasing agent to ensure the silicon would be easily removed once

cured. The excess silicon was disposed of properly, and the silicon molds were left overnight to cure. When coming back to the lab, the silicon finished curing, and the molds were removed from their 3D-printed chambers (**Figure 4**).

Now that the silicon molds were created, test trials of casting soil particles from the molds were ready to begin. Before placement of the PL-1 liquid plastic within the silicon molds, a test trial was conducted to see how the resin/hardener system would act once mixed. For the PL-1 liquid plastic, a two-part mixture is used. The two parts consist of a resin component and a hardener component [6]. The hardener to resin ratio is defined as 18-20 pph of hardener to resin [6]. If 100 grams of resin is used, 18-20 grams of hardener is needed. For the test trial, a total of 20 grams of resin mixture was needed, with 16.66 grams being resin, and 3.34 grams being hardener. Instructions were followed using the instruction bulletin IB-233, which is referenced in the report and can be used for further detail in the resin mixing process. Temperature requirements were met for mixing, and the heating plate was used to heat the resin and hardener to 90 degrees Fahrenheit before mixing [6]. Once mixed, a temperature of 125 degrees Fahrenheit needs to be reached before placement into the silicon molds [6]. During the first trial, it was determined the heating plate will not be needed after the resin and hardener are mixed. As the resin and hardener are mixed and stirred continuously, an exothermic reaction occurs with the air causing the mixture to rise in temperature immediately [6]. Due to the small amount of PL-1 mixture being used, only 20 grams, the heating plate caused the mixture to rise in temperature too quickly. Once the resin and hardener were mixed, they immediately began to harden and set due to the rapid increase in temperature.

This led to trial 2 where the same amount of resin and hardener were to be used. However, the heating plate will only be used to heat each component, the resin, and the hardener, to 90 degrees Fahrenheit before mixing. Once mixed, the heating plate will no longer be used as it is

assumed the exothermic reaction occurring with the outside air will raise the temperature accordingly. With the listed assumptions in mind, trial 2 was performed. 16.66 grams of resin and 3.34 grams of hardener were heated to a temperature of 90 degrees Fahrenheit. Once the temperature requirement was met, the two components were mixed in a separate beaker. The mixture was continuously stirred, with a thermometer being read continuously within the beaker. After a few minutes, the temperature requirement of 125 degrees Fahrenheit was met. The mixture was then immediately poured into the voids of the silicon mold (**Figure 4)**. The curing process as stated by instruction bulletin IB-233 requires a full 24-hours is needed, so results were observed in the following lab section.

After removing the soil particles from their respective silicon molds, multiple observations were recorded (**Figure 5)**. First, the transparency of the particles was fairly poor. While being semi-transparent, one of the key concepts of using photoelasticity is that the sample being tested within the polarizer is to be as transparent as possible. The soil particles created had a slight yellowish tinge. In addition, the PL-1 bulletin states the transparency of sheets immediately after casting will have excellent transparency and will begin to darken after time. This means that for long-term testing, soil particles will continuously need to be created as older samples will lose their transparent properties. Second, the physical quality of the particles was relatively low. After closely examining the particles, there appeared to be rough edges and inconsistencies within the geometries of the particles. This could be due to air voids when pouring the PL-1 mixture into the silicon molds or the quality of the silicon molds being too low to achieve high-quality casted soil particles. Lastly, the size of the particles was deemed to be too small. With future considerations of the testing chamber in mind, the original dimensions of 0.25-.5cm in diameter and 0.25cm in height are to be used.

While the quality of the particles was deemed to be relatively low, they were still tested using the polarizer device. Two particles were grabbed simultaneously using a pair of needle-nosed plyers and were observed behind the polarizing sheet. A phone with white light displayed was placed on the table and the first polarizing sheet was placed over the phone. The particles were then held above the first sheet and a small amount of pressure was applied using the plyers. The second polarizing sheet was held above the particles as pressure was applied, and observations were made on the particles. By applying varying small amounts of pressure on the particles, the stress distribution was easily seen within each particle. This signified the polarizing method will work, however a new method of casting the soil particles was utilized.

Further research was performed on the concept of photoelasticity, and more ideas were generated as to how to cast the soil particles in a simpler manner where less room for error would occur. The first thought presented was to simply print the particles individually from the 3D printer. Rather than print a chamber, which would then be used for creating a silicon mold that would be used for casting soil particles, why not mitigate two steps. If the products coming out of the printer were observed to show photoelastic properties, the two intermediate steps of creating a silicon mold and casting the particles from such mold could be skipped. This leaves much less room for error. To solidify the idea, the original 3D-printed chamber used for casting the silicon mold was tested under the polarizer. Pressure was applied on either wall of the chamber, and the photoelastic properties were observed.

A new resin was ordered for the 3D printer. ‘405nm High Precision Fast Curing UV Photopolymer Resin for LCD 3D Printing, 500g Clear’ was ordered through amazon [11]. The product is described as being a high precision, fast curing resin containing high-quality pigments showing high stability in humid environments [11]. Once the resin was received, new dimensions

of 0.25-0.5cm diameter and 0.25cm height particles were sent to be printed out. View **Figure 6** for a visual representation of the printed particles.

Figure 6: Image depicting individually printed out soil particles with a diameter of 0.5cm and a height of 0.25cm

Comparing the results seen in **Figure 6** to **Figure 5**, it is seen that the final quality of the particles is much higher than before. First, the particles are much more transparent. There is no yellowish tinge, and the observer can see through the particles. Second, the physical quality of the particles is higher. The edges are smoother, there are little to no air voids, and the geometry matches closely with the desired shape. Lastly, the size is more practical for the applications used within the lab. Force chains will be clearer in each particle with the increase in size. These results match the original objective of creating soil particles of various shapes that produce photoelastic properties. For future testing, thousands of these individual particles will be created, with various shapes and sizes being considered. Reference the appendix to visually see the particles being tested in a polarizing device.

Creation of Testing Chamber

Now that the goal of generating a method to create various shaped soil particles has been met, a testing chamber is to be designed to house the soil particles for future photoelastic testing. Multiple requirements needed to be met in the design of the testing chamber. First, the chamber needs to be 100% transparent. This will allow the soil particles tested with the chamber to be easily seen when placed in the polarizing device. Second, with the new height of particles being 0.25cm, the void of the testing chamber must exceed this dimension. Third, the chamber must be able to withstand the outward pressure applied on the outer walls of the chamber once pressure is applied to the soil media being tested.

With these requirements in mind, a testing chamber was designed. After some research, it was determined, clear, acrylic sheets would be a perfect material for meeting the requirements listed above. Utilizing McMaster-Carr, Clear Scratch UV-Resistant Cast Acrylic Sheets [8] were ordered. The properties of the acrylic sheets are defined as a clear, high strength, multipurpose material which were all deemed necessary for meeting the design requirements of the testing chamber. In addition, the product has a light transmission rate of 92% and a tensile rating of 10,000+ psi [8]. These values well exceed the transparency and pressure requirements needed to be met by the testing chamber. Six, 12" x 12" x 1/4" thick sheets were ordered to be used as the outer walls of the chamber. Two, 12" x 12" x 1/8" sheets were ordered to be used as the inner portion of the testing chamber. The 1/8" thickness is equivalent to 0.312cm, which slightly exceeds the 0.25cm height of the particles being created. This will allow the soil particles to be placed in the chamber with additional room on either side for fluid injection. The quantity of material will allow for two testing chambers to be created. The two additional 1/4" thick sheets not utilized can then be used as fluid injection sheets, where a 0.25" diameter hole can be drilled out of the middle

of the chamber where water can be introduced into the system to observe the effects on interparticle forces within the tested media.

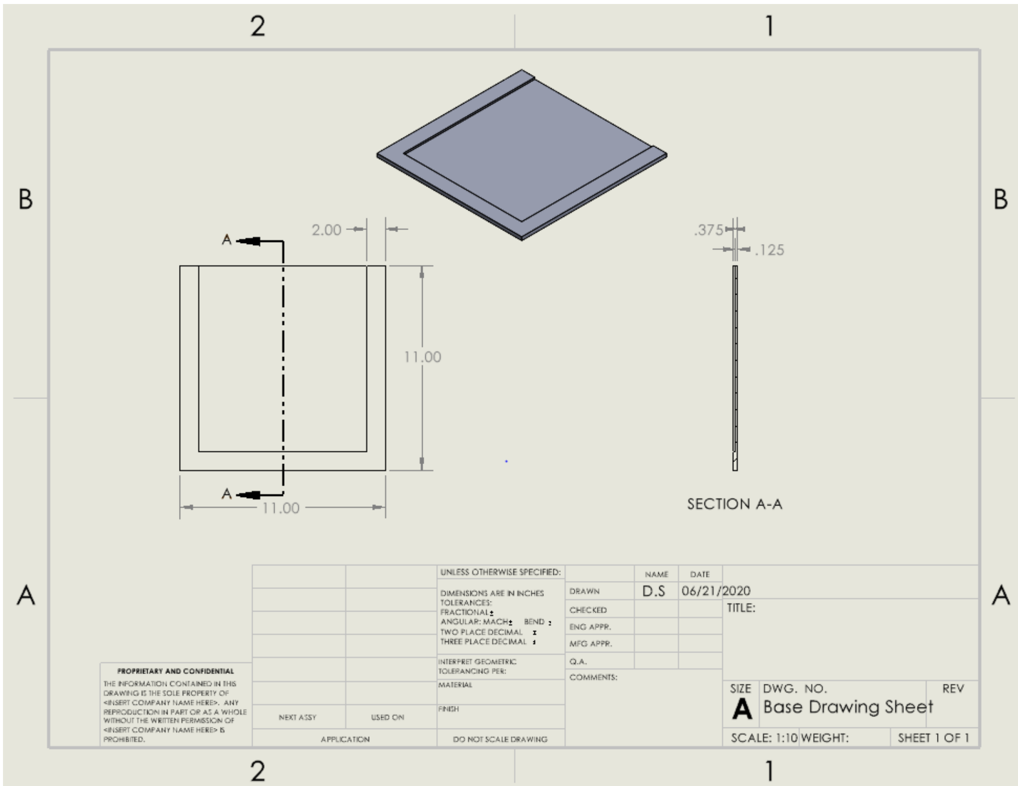

Figure 7: Testing chamber drawing sheet detailing the dimensions (in inches) of the chamber, with one outer wall and the center sheet present

As seen in **Figure 7** above, the main testing chamber will consist of three pieces. The figure depicts one outer wall with the 1/4" thickness and the center 1/8" thick sheet, excluding the second 1/4" outer wall so the observer can view the open orientation of the chamber. The center acrylic sheet with a thickness of 1/8" will also be an 11" x 11" sheet. The sheet will have a rectangular portion cut out, 9" in width and 10" in depth, measured from the center of one side of the outer walls. This will leave the 1" wide strip of 1/8" thick acrylic sheet that will be placed along the outer edge of the 1/4" thick base sheet (**Figure 7)**. Once the cut middle section is placed on top of the base sheet, the top 1/4" thick acrylic sheet will be placed over the 1/8" thick section. The three

sheets will then be screwed together using ‘18-8 Stainless Steel Hex Head Screws’ [10] ordered from McMaster-Carr. These screws were selected due to their high thread count (28) for more thread engagement between the screw and the plastic as well as their high strength rating. One screw will be used per corner, totaling to four screws being used per chamber. Each screw will be a distance of 0.5” O.C in both the x and y directions measured from any given corner. This ensures the chamber will be properly sealed shut with no chance of failure once pressure is applied to the tested soil media.

Due to an excess of two 1/4" sheets being left after the fabrication of the two main chambers, one additional chamber will be made for fluid injection into the tested media. The same material and dimensions will be used as the main chamber, however, only two 1/4" thick sheets will be used with no middle acrylic sheet. This leaves room for the introduction of a closed circular rubber barrier, centered around the push-to-connect connection, between the two outer walls at any desired height more than the height of the 0.25cm particles. This rubber barrier will act as a confining space for the particles to sit in between the two 1/4” thick sheets. Water can then be injected at rapid rate to the media to observe the corresponding stress to the sample. The distance between the two acrylic sheets can also be adjusted so that there can be a miniscule gap between the rubber and upper acrylic sheet to allow for water to escape the confined area. Refer to **Figure 8** for the final fabrication of a single testing chamber.

(a) (b)

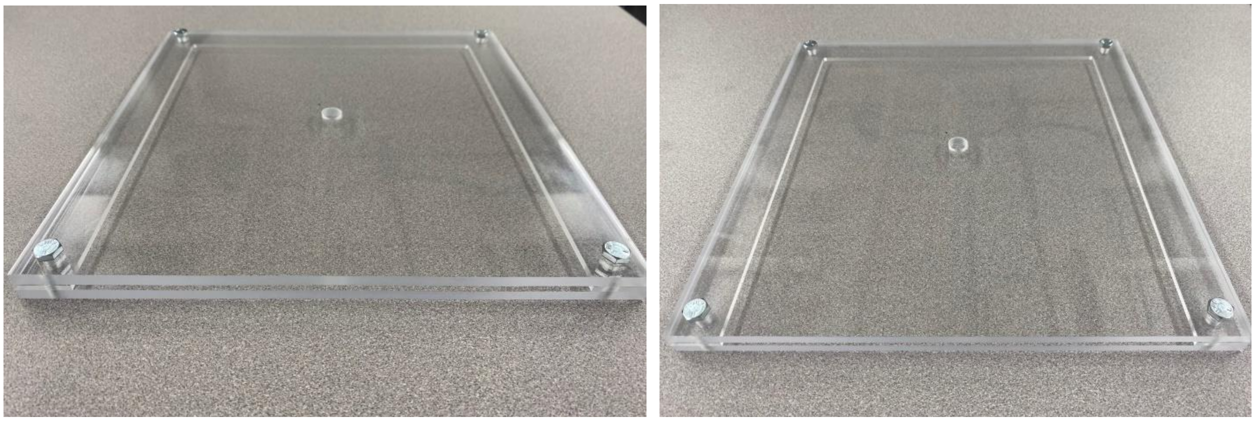

Figure 8: Final Testing Chamber with dimensions of 11" x 11" x 5/8" and a centered ¼" NPT hole on the top acrylic sheet for a push-to-connect connection

V. Conclusion

Geotechnical work is performed in all civil engineering projects across the world. Within the geotechnical field comes the classification of soil types and properties attributed to their respective classification. Granular material consists of gravel, sand, and loamy sand with a diameter greater than 4.75mm. Due to these soil types having little to no clay content, they are classified as the weakest type of soil when looking at unconfined compressive strength in addition to being extremely permeable. Within granular soil, force chains experienced within the soil media can differ solely based on the size and shape of the media present. Through the research performed, granular soil media was modeled and will be tested in the future to analyze how the different geometry of the soil will affect interparticle interactions within the sample. The results can hopefully be used to model real-world scenarios where soil makeup is known, and based on the observed media, the force experienced within the soil can be predicted and the results can be utilized for real-world design practices.

The first goal of the research was to generate a simple method for creating granular soil media of varying shapes and sizes which can later be tested and analyzed using the concept of photoelasticity. Through trial and error, a method was achieved and approved to be acceptable. Beginning, it was assumed that 3D-printing a chamber would house a silicon mold that could then be used to cast the soil particles. After lab trials were performed, this method was concluded to be unsuccessful as there were too many intermediate steps leading to poor quality of the final product. The original method was modified, and it was determined that the soil particles could be made directly using the *Anycubic PhotonS* 3D printer. The clear resin that the printer utilizes was analyzed under the polarizer, confirming the display of photoelastic properties. The final quality of particles can be visually seen referencing **Figure 6**. In future semesters, thousands of these particles can be printed, accumulated over time, and analyzed in the testing chamber fabricated within this research.

The second goal of the research was to design and fabricate a testing chamber that will house the casted soil particles for future photoelastic testing. Once the process of creating soil particles was solidified and the dimensions of the soil particles were finalized, creating the testing chamber was relatively simple. Three design requirements needed to be met including the testing chamber having close to 100% transparency, having a void thickness of greater than 0.25cm, and being able to overcome the outward pressure exerted from the soil media being on the outer walls. A final testing chamber was designed, deemed acceptable, and fabricated which is depicted in **Figure 8**. The goals originally set out when beginning the research have now been met, and the remaining research can be carried out in the upcoming semester proceeding the fall semester of 2021.

VI. Recommendations

Due to the preliminary steps of the research being completed, future semesters can be focused on the physical testing of varying soil media. A solid method of creating soil particles was generated, and a testing chamber was fabricated to house the soil particles and perform the tests. I recommend that a mass amount of soil particles be printed. 1000's of particles can be printed, 100 or more of each shape, so that an excess number of particles are present at all times. This will allow any given makeup of soil media to be placed within the testing chamber, analyzed, and compared to previous and future results. If multiple tests are to be conducted simultaneously, additional acrylic sheets can be ordered, and new testing chambers can be fabricated using the same process detailed in the procedure and discussion section.

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Appendix

Figure A1: Depiction of 3D-printed soil particles being analyzed under polarizing device.

The above figure visually shows two final product soil particles being tested within the polarizing device. Pressure was applied using plyers, and the forces experienced within the particles can be seen from the refracting light. The darker the orange color observed, the more stress that is experienced in that portion of the particle.

Stress on 3D printed
individual particles.M(

The above video is included to depict the forces experienced within two soil particles when increasing and decreasing pressure is applied.

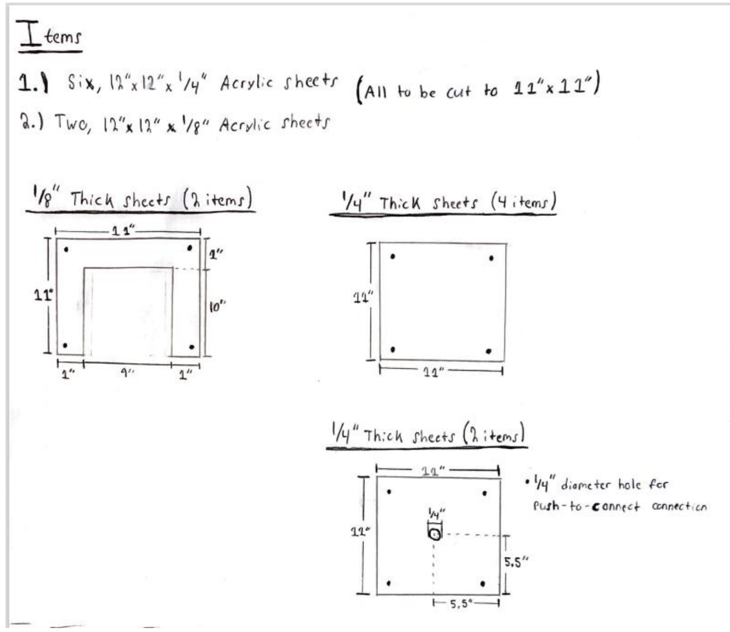

Figure A2: Item sheet necessary for completion of the Testing Chambers

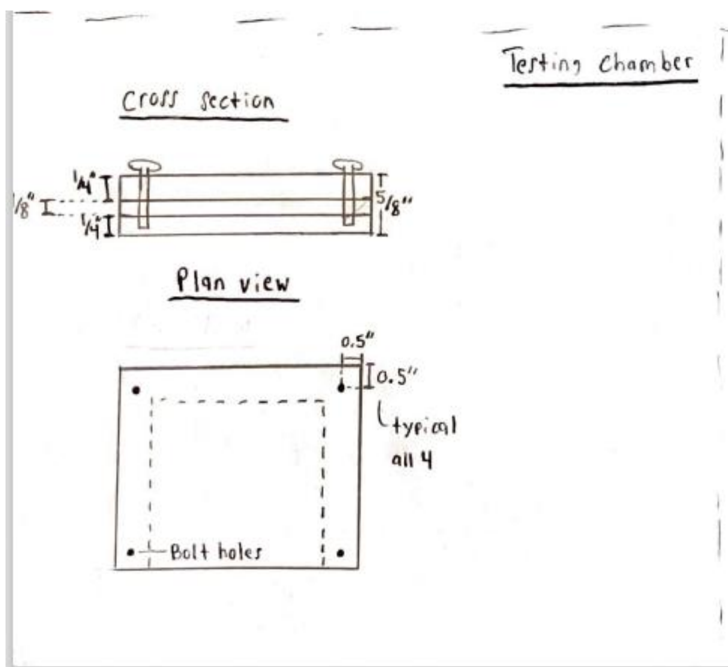

Figure A3: Testing Chamber supplemental drawing sheet