Development of a Box for GPR Testing with Coarse Aggregates

Aaron J. Rubin, Corresponding Author
Department of Engineering Science,
Smith College, Northampton, MA 01063
Email: arubin@smith.edu

Lilliana Frantz
Department of Engineering Science,
Smith College, Northampton, MA 01063
Email: lfrantz@smith.edu

Almanzo Gao
Department of Engineering Science,
Smith College, Northampton, MA 01063
Email: agao@smith.edu

Ginger Silverman
Department of Engineering Science,
Smith College, Northampton, MA 01063
Email: gsilverman@smith.edu

Ashley Zhang
Department of Engineering Science,
Smith College, Northampton, MA 01063
Email: azhang@smith.edu

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ABSTRACT
Ground penetrating radar (GPR) is a nondestructive tool for investigating the subsurface. When used in laboratory testing, large boxes to contain the test specimen aggregate or soil are necessary. However, boxes created for GPR testing have some unique requirements such that they do not interfere with the sensitive GPR equipment. This paper presents the design and construction of economical boxes for GPR testing. Key design requirements for this test box were: minimal use of metal, compatible with a wide frequency range from 300 MHz to 1.6 GHz, capable of specimen saturation, capable of efficiently breaking down the specimen, and can be used for the preparation of hundreds of test specimens.. The literature does not contain many examples of test setups that would fulfill these objectives nor does it include specific instructions on how to create a box to achieve them. This paper presents the final economical design for laboratory testing of aggregate using GPR.
Keywords: Ground Penetrating Radar, Ballast, Aggregate, Testing Procedures

INTRO

Ground penetrating radar (GPR) is a common method of imaging the subsurface using electromagnetic waves. Measuring the time it takes for the wave to pass through subsurface materials in combination with dielectric mixing models can tell us the thicknesses of subsurface materials or the depth to identified targets. These methods are widely used in archaeology, geoscience, civil engineering, railroad engineering, and construction. However, these dielectric mixing models are imperfect and there is a need to test GPR devices in a laboratory setting.

Therefore, this study aims to improve the procedures of testing GPR devices with large box tests using aggregate material. The box outlined in this paper is approximately ½-cubic meter scale and is planned to be used as part of an NSF study (ERI: Dielectric Mixing Models for Coarse Aggregate, Award Number 2301588) relating to the relative permittivity of aggregate material from fine sand-sized particles up to particles 2 to 4 in (5.08 to 10.16 cm) in diameter. This paper includes a background of some previous attempts at GPR box testing of coarse aggregates, the specific design requirements needed, the design of two test boxes, and a discussion of some of the pros and cons of the constructed boxes.

BACKGROUND

Box testing of GPR devices in a laboratory setting goes back over 40 years. The well-known Topp et. al. (1), as an example, used specimens 20 to 100 cm thick. However, as is the case in Topp et. al., generally, the focus of the literature tends to be on the results of measurements versus the construction of test boxes or the placement of test materials. In the last decade or so, there have been other laboratory studies that have some good figures of test setups with GPR devices on sand-filled boxes. De Chiara et. al. (2) include three different test setups including a rebar-supported plastic box (1.10 m x 0.94 m x 0.47 m) for compacted dry railroad ballast, silt soil in a plastic box (0.53 m x 0.41 m x 0.40 m), and lastly a wooden box (0.50 m x 0.75 m x 0.52 m) for ballast-silt mixtures. The photos allow for a good idea of the overall approach, but the exact mechanism for saturation in the first rebar-supported plastic box is not shown. Liu et. al. (3) includes a very large box (4 m x 2 m x 1 m) filled with Ottawa sand. Liu et. al. (4) separately created a sandbox (0.95 m x 0.45 m x 0.40 m) with walls made of reinforced plastics. Lauro et. al. (5) also used fiberglass (1 cm thick) walls to create a box (1.5 m x 1.0 m x 0.30 m) that was elevated about 0.8 m above the floor to create an air gap below the test specimen. Prepared specimens were created with silica beads. Shamir et. al. (6) used three different types of boxes for their tests on soils. First, a plastic box (dimensions undefined but reported as 21 L volume), second, a wooden box (0.90 m x 0.50 m x 0.60 m), and lastly a metal box (2.0 m x 0.60 m x 0.60 m). At the bottom of the wooden and metal box, a combination of gravel and geotechnical fabric was placed to allow for saturation. The larger metal box was reported to have some issues with measurement - although this was attributed to the clay content in the soil by the authors and not by the material of the box. One commonality of all of these previous works using box testing is that the specimen material is of sand-sized particles. Wood and plastics are by far the most common materials to construct boxes for GPR testing.

There are far fewer examples of GPR testing on coarse aggregates. In general, many of the tests using railroad ballast material are prepared for cyclic loading (in metal boxes) or large-scale triaxial testing such as (7). These approaches are generally not useful models for GPR testing due to either box material type or specimen configuration. Bennett et. al. (8) suggest that most coarse aggregate and railroad ballast box testing use a combination of steel and wood as materials, however, using GPR equipment is not effective with that type of material. In order to complete the desired research, a specialized box for GPR testing must meet the following requirements:

1. The box will resist deformation caused by the material compaction;
2. The test material particle size will range from silt and sand up to gravels 2 to 4 in (5.08 to 10.16 cm) in diameter;
3. The materials used to build the box must not interfere with the GPR equipment (sensitive to metals for example);
4. The dimensions of the box must be suitable for a frequency range from 300 MHz to 1.6 GHz. The box must be thick enough to get readings with the lower frequency ranges which simultaneously being shallow enough that at higher frequency ranges the signal return is clear;
5. The box must be waterproof and leak-proof such that it can be saturated from the bottom of the specimen up;
6. After saturation, the box may be drained;
7. One or more sides can be readily disassembled for easy removal of the materials such that the box can be quickly taken down and rebuilt for subsequent testing.

METHODS

From the outlined design requirements, some were fairly straightforward to meet, while others were more difficult or contradictory. It was established early on that the box needed to be custom-produced. The main reason for this was when working with mixes of coarse aggregate, the specimen would be too heavy to easily dump. Also, the material would be difficult to dig out, especially with the larger particle mixes. Metal was eliminated as a construction material due to concerns of interference with the GPR. Wood was chosen over plastics or other synthetic materials due to cost and ease of construction.

When considering the overall specimen dimensions, three factors were considered: the frequency range of the GPR being used, the dimensions used by previous researchers, and the dimensions of commonly available plywood and lumber. The depth of our box was primarily set by the highest frequency used. Therefore, the 1.6 GHz antenna signal needed to clearly reflect off the bottom of the box while trying to maximize the depth to accommodate the largest particle sizes planned for testing and the lower frequency antennas. Ultimately, we settled on a depth of 24 in (0.61 m) which is in line with previous researchers' boxes and in line with the anticipated depth range for the 1.6 GHz antenna. For the width, the specimen had to be wide enough to accommodate our lowest frequency antenna, which had the largest dimensions. The 300 MHz antenna is 12.2 in (0.31 m) wide, so the width needed to be 24 to 30 in (0.61 to 0.76 m) so that the antenna would not be too close to the sides of the box. For the length of the box, we wanted to ensure that a radiogram could be recorded with our antenna and that the box had a long enough run using the largest (300 MHz) antenna. Ultimately, a length of 42 in (1.06 m) was selected. These dimensions place our box within the typical size used by previous researchers.

The primary design challenge for the box was that it needed to be both waterproof and watertight as well as have the ability to remove a side or sides to aid in specimen breakdown. As previously discussed, wood was selected for box construction because wood is cheap, lightweight, easily accessible, and relatively easy to build with. The one major shortcoming of using plywood for the sides is that it had to be waterproofed by hand. To do this, we used Flex Seal Liquid for the large flat areas and silicone sealant for the joints. Several layers of Flex Seal were applied to ensure an even and waterproofing coat. One concern with this design was that the box was intended to create hundreds of specimens, if the Flex Seal was scratched during testing by the coarse aggregates or compaction equipment, the waterproofing would no longer be effective. This meant that another material was necessary to protect the Flex Seal from the aggregate that would be filling the box. Three different geotextile materials were investigated: geotextile fabric, HDPE geomembrane pond liner, and geosynthetic clay liner. Geotextile fabric is used for silt management, isolation, and filtration at construction facilities, but it is not robust and was rejected due to concerns it would not be protective enough. Clay liners could not be used because the GPR equipment would send back signals from the clay that could interfere with the data we are collecting and the constructability of adding it to a vertical surface was deemed impractical. HDPE liner is the most robust material of the three and is relatively thin. Additionally, the HDPE liner is completely waterproof and would not interfere with the GPR signals. Therefore, HDPE liner was the chosen material to protect the Flex Seal on the interior of the boxes.

The last important detail to resolve was how to allow the box to be partially deconstructed after each test to empty the box. Dumping out the box was not considered viable because, with the assumed box dimensions, the test specimen alone could be 500 to 1000 kg. It was decided that from a safety perspective, allowing for the sides to be removed would be best. Previous work with a box that allowed for all four sides to be removed had yielded two main flaws: frequent leaks and it was time consuming to deconstruct the box and prepare it for a new specimen. To minimize leaks in the new box, only the long side of the box needed to be removable to make it easier to take out all the material. To accommodate the removal of a side (the “door”), a flange was created with 2x3s so that the long side plate could be secured to with clamps. Silicone vacuum grease was added to these surfaces to create a watertight seal. As a result of adding the flange, a lip was created on the bottom edge of the box. This lip was remedied by placing the box on a pallet where the lip could overhang. In addition to solving the geometric problem of the flange, there was an added benefit of creating an air layer below the box which helped identify the specimen thickness in the GPR data and provided a mechanism to raise and lower the box with a hand-operated pallet jack.

RESULTS

This section details the final box schematics as well as photos of key elements of the test box. The box-building process included creating an AutoCAD Drawing of the main design ideation as shown in Figure 1. The main parts of the box were composed of 0.75 in (1.91 cm) thick plywood and supporting 2x3 wood lumber. Elements were secured together with wood glue, trim nails, and structural screws at key locations.

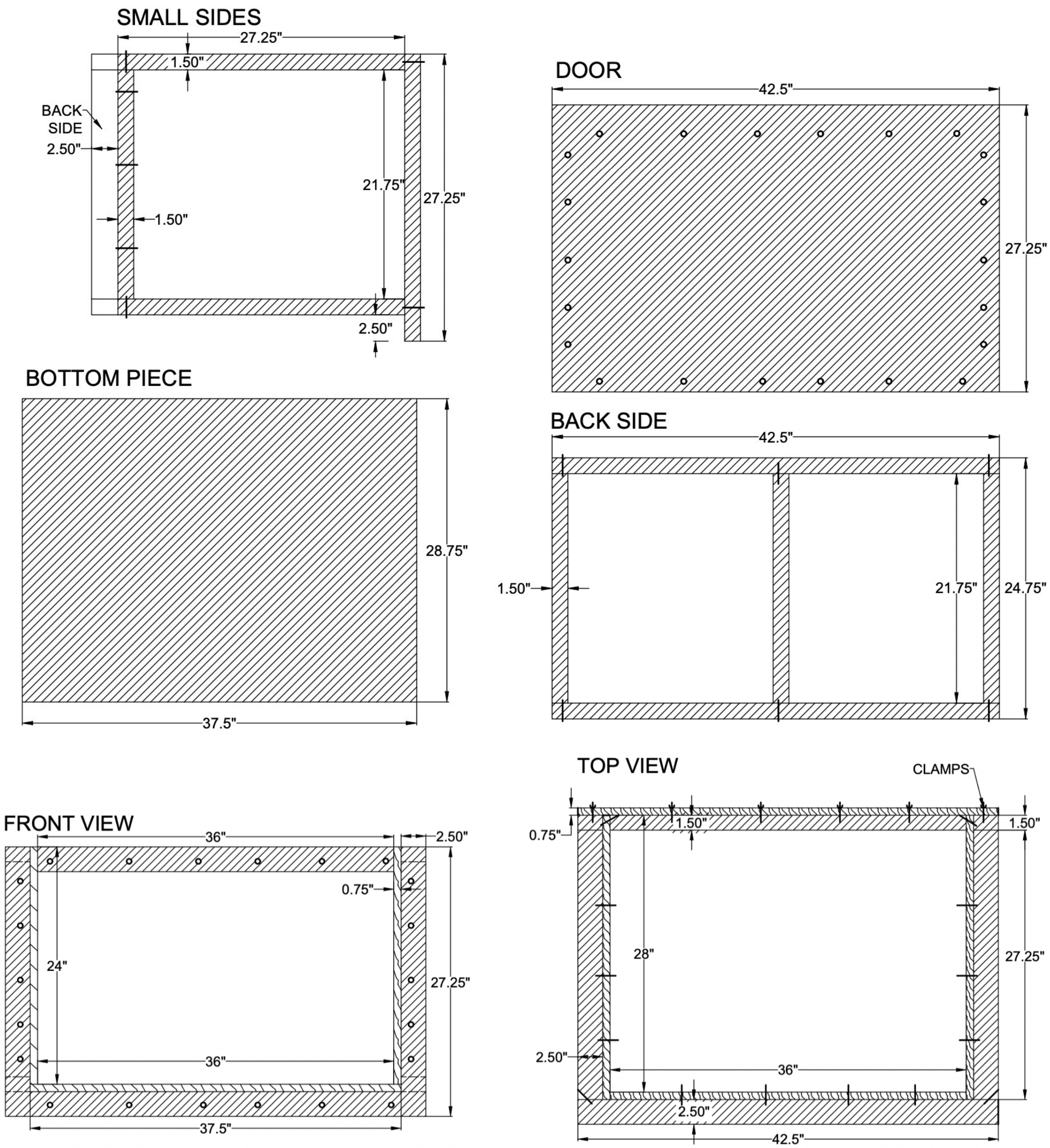

FIGURE 1 Box 1 Dimensions and Orthographic Projection from Two Views

All the 2x3s were measured and cut according to the AutoCAD Drawings to minimize the amount of wood waste. Each glued element was clamped to allow a 24-hour drying time. The 2x3 pieces were added to support the box, which reduced the deformation of the plywood sides when compacting specimens and filling with water.

FIGURE 2 Comprehensive Views of Box 1

Four coats of Flex Seal, common household sealant, and HDPE liner were applied to the wood pieces for waterproofing. This was found to be a very good waterproofing method at preventing leaking through the permanent joints of the box. A drain hole on the bottom piece was constructed for water flow (Figure 3). Over the drain hole, a geotextile fabric was glued under the HDPE liner to prevent particles from flowing into the pipe. The hose and right-angle pipe were connected underneath the box and pallet to allow water to flow freely in and out (Figure 4). The hose connection allowed for the box to be hooked up to a standard spicket. Plastic components were joined using the appropriate compound to chemically fuse the elements. Transitions between plastic and metal elements were sealed with silicone caulk. The water-tightness of the box was confirmed by filling the box up with water.

FIGURE 3 Waterproof Application on Box 1 Interior Sides

FIGURE 4 Right-angle Pipe underneath Box 1. The tub drain transitions from 2 in (5.08 cm) diameter pipe, to 1.5 in (3.81 cm) diameter pipe, down to a metal hose connection.

A silicone-based vacuum grease ("Super Lube") was applied between the front door and box before clamping the plywood to the front of the box (Figure 5). The clamps were evenly distributed on four sides of the front door and positioned midway through the 2x3s.

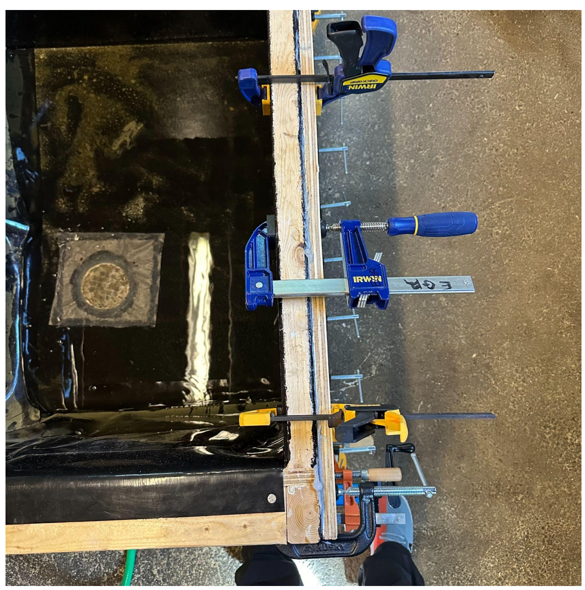

FIGURE 5 Super Lube between Plywood Front Door and Box 1 with Clamps. Note that the drain is protected by a layer of geotextile fabric to prevent soil from entering the drain.

Once Box 1 was completed, an improved second box was built (Figure 6, 7). Some improvements included the centering of the box on the pallet, reducing 2x3 and plywood waste, and decreasing the volume for easier filling and draining.

FIGURE 6 Comprehensive View of Box 2

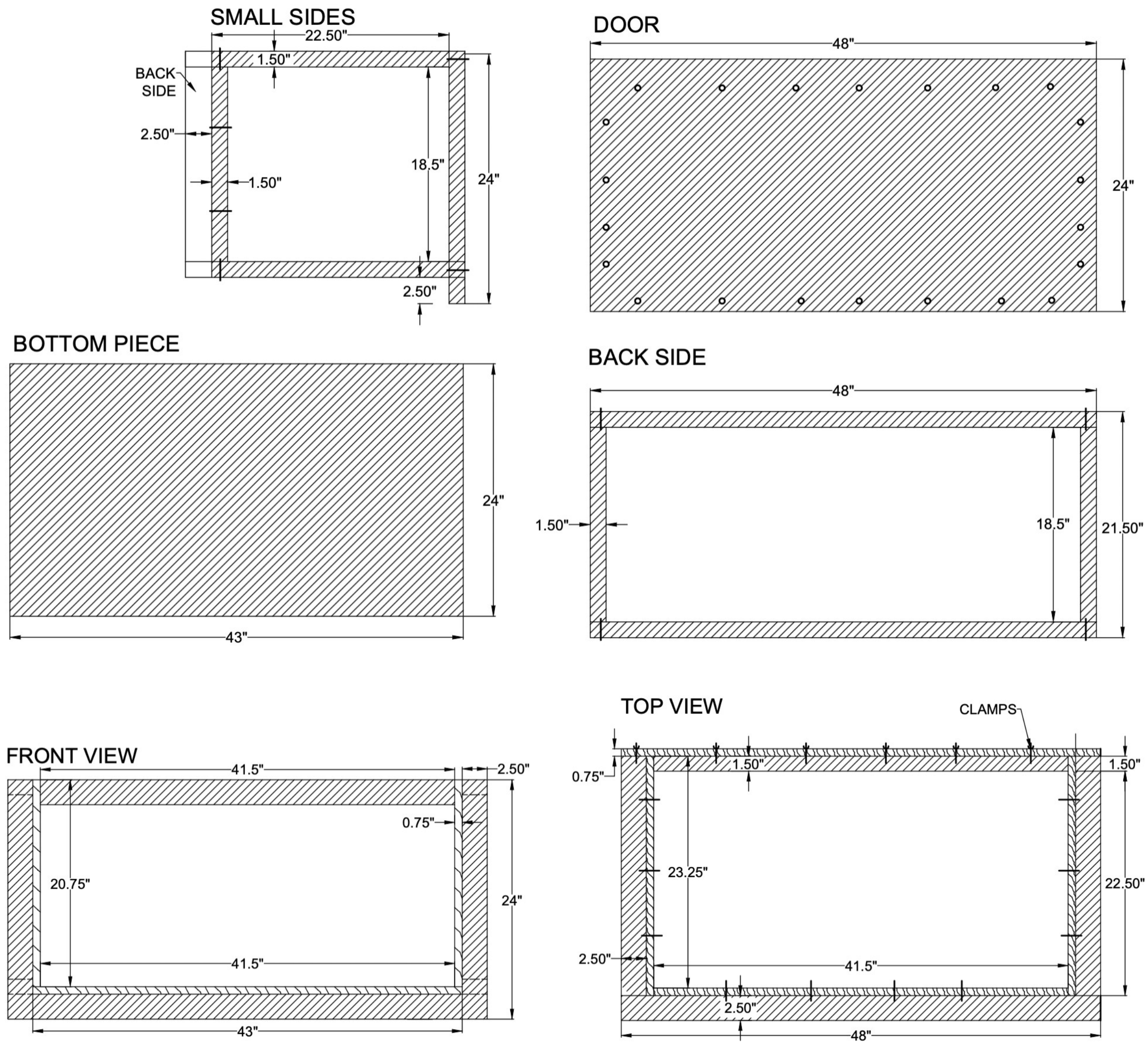

FIGURE 7 Box 2 Dimensions and Orthographic Projection from Two Views

The boxes were constructed out of readily available materials with the approximate following costs:

Two 4ftx4ft 0.75 in (1.91 cm) Plywood Sheets - $42
Five 2x3 8 ft (2.4 m) Planks -$15
Wood Glue -$5
Trim Nails -$25
Structural Screws - $15
Two Flex Seal Liquid 32Oz Cans - $70
20 mil HDPE pond liner - $40
Silicone Caulk - $10
PVC Plumbing elements - $25
Metal C-clamps - $150
TOTAL = $397

DISCUSSION
After constructing the first box, some shortcomings of the design became clear. The main concern was the box had to be lifted around 6 in (15.24 cm) off the ground using a hand pallet jack so that load cells could be placed underneath. The flange lip that hangs over the pallet causes weight to be distributed unevenly towards the detachable plate. The uneven weight distribution caused some tipping towards the front panel when the box was lifted (Figure 8) which made placing the load cells very difficult.

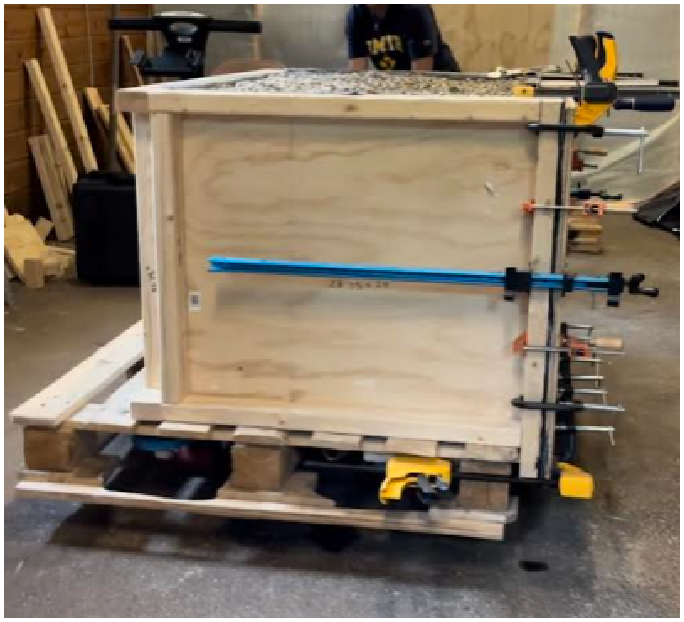

FIGURE 8 Box 1's Uneven Weight Distribution

Ultimately, two boxes would be built to speed up the testing process. While building the second box, we considered the shortcomings of the first box and centered the second box on its pallet. Centering the weight of the box was effective in reducing the tilting of the specimen during lifting (Figure 9). Additionally, placing 0.75 in (1.91 cm) thick plywood strips under the pallet and on the arms of the jack created enough space to easily place the load cells. Centering the box on the pallet made clamping more difficult, but the tradeoff was deemed to be successful due to the safety benefits gained by the stability and the ease in placing the load cells.

FIGURE 9 Box 2 Centered

One area of caution when using these boxes is during the compaction process of the aggregate. Although the HDPE liner protects the Flex Seal coating, it can tear when hand compaction with a tamper is done near the edges. Consequently, if the liner is ripped, the Flex Seal layer could be punctured and therefore be less effective in waterproofing the plywood sides of the boxes. However, not compacting near the edges could result in uneven specimen density. A significant amount of care is necessary during the compaction process which does slow down the process of specimen creation.

To date, over 50 specimens have been produced using the two boxes. As testing progressed, leaking has occurred while saturating some specimens. The leaking typically occurs at the flange/plate seam. This can typically be mitigated by tightening the clamps evenly and securely to create a better seal between the door and the flange of the box. Adding a thick layer of the silicone grease around the bottom edges of the box and the drain was also effective to stop leakage. When these steps were followed, the saturation process was generally successful with minimal leaking.

CONCLUSION

In this study, a waterproof and sturdy box was designed and built to contain coarse aggregates for GPR testing. The box is capable of being partially disassembled after a test to allow for the specimen aggregate to be efficiently removed from the box. The box is also capable of filling with water from the bottom up, allowing full saturation of test specimens. The box was economical to construct, costing less than $400 in materials. To date, the boxes have been used to create over 50 specimens and are working as intended. After two months of trials, this box design has proven to fulfill all the requirements of GPR testing while ensuring laboratory safety at the same time. The solidity and universal applicability of the box also allows us to conduct additional tests such as lightweight deflectometer and mini-cone testing.

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