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Employing Augmented Reality Throughout a Civil Engineering Curriculum to Promote 3D Visualization Skills

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Abstract

Use of Augmented Reality (AR) sandboxes has gained popularity in "please touch" science museums and introductory earth and environmental science courses to facilitate student visualization of concepts in three dimensions. University faculty who have access to AR sandboxes typically utilize them in discrete learning experiences (i.e., one specific activity, module, or course), rather than a series of interactions with the technology to introduce and then reinforce 3D visualization skills. A case study is presented herein of how student learning experiences with the AR sandbox have been woven throughout the undergraduate civil engineering curriculum at Villanova University. A series of progressive AR sandbox learning activities have been implemented in freshmen and junior-level civil engineering courses, and additional modules are planned for other courses in the sophomore and senior years. Planning and implementation of these modules has been a collaborative effort between faculty across multiple disciplines within the department (geotechnical, water resources, and structural engineering). The purpose of the AR sandbox interventions is to facilitate student engagement and improve understanding and ability to apply basic civil engineering concepts that require three-dimensional visualization skills, supporting the goal to graduate students who are professionally prepared to serve as effective engineers. Details are provided for three of the modules to allow for adaptation by faculty at other universities with access to similar technology. In the freshman-level course, Civil Engineering Fundamentals, students insert Plexiglas sheets in the sandbox and then create plan, profile, and cross-sectional views of elevation data. In the junior-level Soil Mechanics course taught in the fall, students build upon their prior experience with the AR sandbox and apply new concepts from lecture to evaluate slope stability and calculate earthwork volumes. In Hydraulic Engineering and Hydrology, taught in the spring of junior year, the learning module includes creating a watershed landscape in the sandbox and simulating rainfall to visualize flow patterns, directions, and travel time through the basin. Based on positive faculty and student feedback regarding the current AR learning experiences included in civil engineering courses at Villanova University, additional modules are planned for sophomore and senior-level courses to further enrich 3D-visualization outcomes from a curriculum-wide approach.

Introduction

Virtual Reality (VR) and Augmented Reality (AR) are visualization techniques now being examined in earnest for pedagogic benefit in a variety of STEM disciplines. The nature of this technology facilitates visualizing concepts in three-dimensions, and it has been shown to be effective in increasing student learning [1]. Previous research has shown a strong connection between spatial visualization skills and academic success in engineering [2], [3], and although definitions of spatial visualization skills can vary, it is generally accepted that such skills are important in engineering education [4]. In particular, dedicated instruction with concrete spatial activities has led to increases in spatial skills among civil engineering students [5]. Furthermore, interventions to improve spatial visualization skills are especially important for underrepresented minorities since they may come into college with a deficit of these skills [6].

The AR Sandbox is an earth sciences visualization tool that was developed at UC Davis in 2011 [7]. The Sandbox's basic design consists of a box of sand on a table with a short-throw projector and an altimetry sensor mounted above the sand. The altimetry sensor passes a 3D map of the sand surface to a software program that generates a color elevation map of the surface and projects it onto the surface of the sand. The software system also displays contour lines on the sand and can show virtual water flowing across the sand landscape according to fluid dynamics and the sand surface's shape. The system runs in real time and updates the projection, including changes in the flow of virtual water, as users reshape the sand with their hands. The virtual water is added to the landscape when users hold their hands cupped over the sandbox, and the water pours from the students' hands onto the surface. The AR Sandbox system has received positive reviews regarding its utility in undergraduate environmental science courses at multiple universities (e.g., [8], [9]). When compared to traditional laboratories, the AR Sandbox allowed students a deeper understanding of learning objectives [10]. Therefore, this technology provides an exciting opportunity to stress 3D visualization skills in engineering courses with laboratory elements.

An AR Sandbox was constructed in the Computer Science Department at Villanova University in 2016 (Figure 1), as part of an NSF grant. While accessible, this technology had been widely underutilized by instructors in disciplines outside of computer science, despite obvious connections to areas such as civil and environmental engineering (CEE) where many key concepts can be better visualized using this augmented reality. The CEE faculty have observed students struggling with three-dimensional concepts presented in sophomore and junior-level courses, such as interpretation of topographic maps and delineation of watersheds. Thus, we developed three modules that utilize the AR Sandbox to teach basic concepts in civil, geotechnical, and water resources engineering in a way that stresses visualization of core topics. These modules are integrated within the civil and environmental engineering undergraduate curriculum, taught at different times as to reinforce 3D visualization of different processes or features across sub-disciplines. This paper presents a case study describing the implementation of these AR Sandbox modules, including module setup, outcomes, and assessments, and presents future opportunities to create more sandbox modules within the curriculum. Additionally, we include recommendations for instructors at other institutions who are looking for ways to incorporate this technology in civil engineering courses.

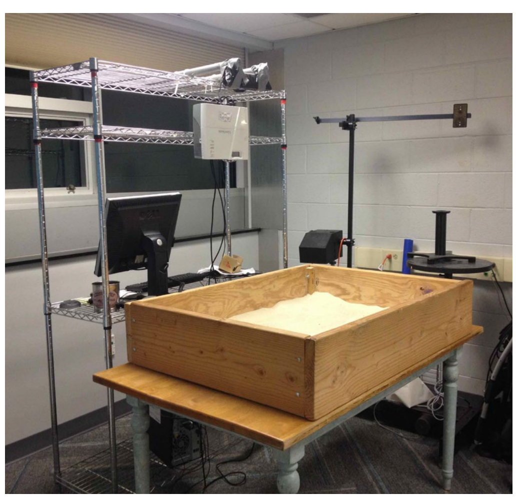

Figure 1. AR Sandbox at Villanova University.

Integration of AR sandbox in civil engineering curriculum

Currently, three AR Sandbox learning modules are being implemented within the Civil and Environmental Engineering (CEE) curriculum. Each module is explained in detail below and summarized in Table 1.

Table 1. Summary of AR sandbox modules described herein.

Module #	**1**	**2**	**3**
Year	Freshman	Junior	Junior
Course	Civil Engineering Fundamentals	Soil Mechanics	Hydraulic Engineering & Hydrology
Learning Outcomes	Scale and plot an elevation profile. Scale and plot an elevation cross section. Plot proposed and existing profiles together. Compare cut and fill.	Calculate fill and borrow volumes. Develop phase diagrams. Calculate factor of safety for slope stability. Create a 2D flow net and calculate seepage.	Delineate a watershed boundary. Calculate travel time with no channel. Calculate travel time with a defined channel.
Materials (in addition to sandbox)	Plexiglas board 24 in x 12 in Plexiglas board 12 in x 12 in 2 Coins Camera Dry-erase marker	Engineering paper Ruler Camera	Half of paper towel core Camera Stopwatch
Time Per Group	30 minutes	20 minutes	30 minutes
Students per Group	5-7	5-7	5-9

Module 1: Understanding Plan, Profile, and Cross Sectional Views of Elevation Data

<u>Overview</u>: The first AR sandbox module in the curriculum is taught in a freshmen (spring) course called Civil Engineering Fundamentals (Fundamentals). This course exposes students to the civil engineering discipline for the first time with an emphasis on tools and skills commonly used by civil engineers. Specifically, students utilize Microsoft Excel, AutoCAD, and ArcGIS to see how fundamental concepts related to surveying, statistics, and maps are applied in engineering [11]. A major theme in the course is the role of elevation data in civil engineering projects, particularly the relationship between plan, profile, and cross-sectional views, as well as scale. The ability to effectively visualize these different perspectives is facilitated by the three-dimensional quality of the AR Sandbox. The activity is run in 30 minute blocks with student groups rotating into the classroom to collect their data. The learning outcomes for this module include having students scale and plot elevation profiles and cross sections, plot existing and proposed profiles together on the same graph, and qualitatively assess relative requirements of cut and fill.

Activity: This is the first time that the students are exposed to the AR sandbox, so the module begins with several minutes dedicated to exploring the setup and capabilities of the sandbox. As students change the sandbox surface, they can clearly see how the contour lines and colors representing those elevations also change.

Following initial exploration, the instructor creates a landscape that generally slopes in one direction diagonally across the sandbox, but also includes several variations in the surface. Two points of interest are designated with coins on the sand surface, representing the beginning and end points of a roadway construction project. The primary module tasks require students to use two Plexiglas boards to simulate profile and cross section cut lines: one along the proposed roadway stretch between the designated points (profile) and one at the end (cross section). To start, students take a photo of the sandbox from above, which serves as the plan view for the assignment, showing the start and end points, contour lines, and associated color scale. Students then insert the larger Plexiglas board (24 in long by 12 in high) into the sand such that the board is located between the two coins and with its bottom flush against the bottom of the sandbox. The larger board acts as the profile cut line. Students then insert the smaller Plexiglas board (12 in x 12 in) at the end of the larger board, but perpendicular in orientation, thus acting as a cross section cut line. With several students supporting the Plexiglas boards, a student carefully moves sand away from the near side of the profile board, exposing the sand surface on the other side. Using a dark dry-erase marker, a student then traces the sand surface on the Plexiglas, creating a profile plot (Figure 2a). The same process is repeated for the smaller board, creating a cross section plot of the sand surface (Figure 2b). Both boards are then removed from the sandbox and placed in front of a whiteboard. Students take photos of each board which are then used to complete the follow-up tasks.

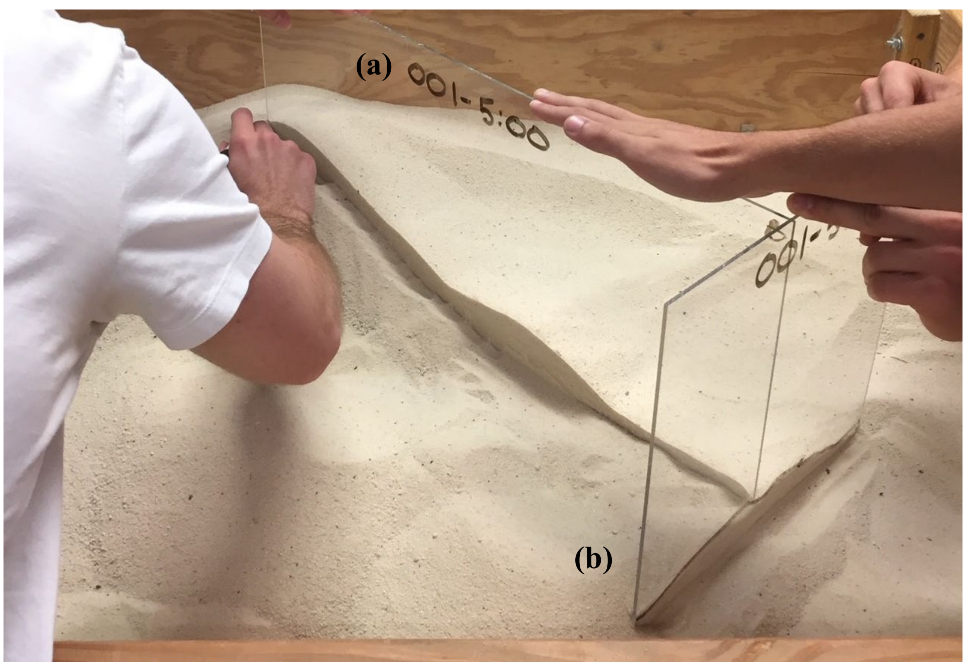

Figure 2. Plexiglas inserts to cut a profile (a) and cross section (b) in the sandbox during Module 1 on elevation data and views.

Assignment: The follow-up assignment requires use of the photos taken at the sandbox, placing a large emphasis on calculating and applying scale in addition to how the various views of elevation data are related. Students are told that the sandbox represented a scaled physical model of the area where the new road will be built. Instructors can specify any reasonable scale but given the dimensions of our Plexiglas boards and AR sandbox, the model scale was given as 1 in = 4 ft (vertical) and 1 in = 50 ft (horizontal), with an arbitrary datum elevation of 100 ft assigned to the sandbox bottom. Tasks are broken into the three different views:

- Plan view: Students must use the known length of the profile board (24 inches) and sandbox dimensions with the size of their image to determine the scale of their plan view photo.
- Cross section: Based on their photo, students must reproduce the cross section plot in Excel, plotting actual elevations versus distance. They are instructed on a minimal number of points that must be included in the plot, and that all significant changes in slope should be included to accurately represent the surface.
- Profile: Similar to the cross section plot, students must use their profile photo to reproduce the profile plot in Excel, plotting actual elevations versus distance. They are instructed on a minimal number of points that must be included in the plot (more points than for the cross section), and that all significant changes in slope should be included to accurately represent the surface.

To tie the activity back to the hypothetical civil engineering project of new road construction on this landscape, students use their plots produced in Excel to perform several additional tasks:

- Approximate the steepest existing slope along the profile and identify its location.
- Calculate the slope of the proposed road over the same profile given a starting and ending elevation and assuming a constant slope.
- Add the proposed road to the existing profile plot.
- Determine if the construction crew will need to bring additional soil to the site or haul excess soil away from the site to construct this segment of road. Students must explain their reasoning, including reference to their profile plot as support. No calculations are required.

The final question is a conceptual one focused on cut and fill, which to this point in the curriculum, has not yet been introduced. Therefore, this first module introduces a key civil engineering concept that is explored later in this course with AutoCAD, as well as later in the CEE program. Overall, this module demonstrates the physical meaning of profiles and cross-sections in a 3D landscape that is otherwise not possible when teaching these concepts in 2D.

Module 2: Earthwork, Slope Stability, and Seepage

Overview: The second sandbox module is taught in the junior year Soil Mechanics course. The course is typically scheduled as three 50-minute lecture periods per week. However, working within these 50-minute periods make scheduling of the AR sandbox module groups particularly challenging, such that each group only has 15-20 minutes with the sandbox. The sandbox module builds upon several topics covered within the course, including weight-volume relationships, borrow-fill problems, stress in soils, flow nets, and shear strength. Thus, the module is delivered towards the end of the semester. The activity is framed in the context of new embankment dam construction. Based on the proposed geometry, students are expected to (1) calculate fill and borrow volumes to construct the embankments; (2) develop phase diagrams as part of the borrow-fill calculations; (3) calculate factor of safety for slope stability; and (4) create 2D flow nets and calculate seepage and exit gradients.

Activity: The module begins with the instructor creating the proposed geometry of the embankment in the AR Sandbox, as shown in Figure 3a. There is a hypothetical reservoir area behind the dam, as can be seen by the depression in the sand, that will be filled with water later (as shown in Figure3b). The students measure the average length and width of the dam and take a photo of the slopes against engineering paper to determine the slope angle and approximate height. Students then discuss whether the geometry as shown is practical (coming to a peak as shown in Figure 3a) or if a flat crest width is required. In a corner of the sandbox, students see how steep they can make a pile of sand and compare this angle with the proposed embankment slopes. In the final portion, students hold their hands over the reservoir to fill it with water and take a plan-view photo.

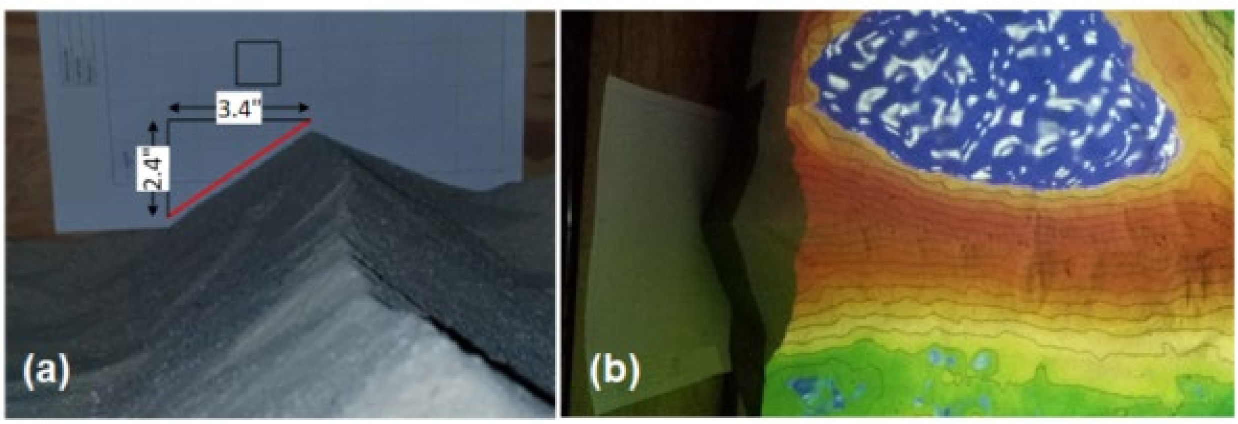

Figure 3. Sandbox in Module 2 with (a) instructor-prepared embankment dam initial slopes before accounting for 10-ft-wide crest and (b) plan view of filled reservoir for use in seepage analysis.

Assignment: Students are asked to complete the following tasks using the images and measurements taken during the activity:

- Sketch a cross section of the dam from the measured dimensions assuming the sandbox represents a 1/200 scale model. Modify the cross-section geometry to accommodate a 10-ft wide crest to allow for machinery and vehicles, while keeping the same footprint.
- Determine borrow-fill volumes to construct the proposed dam. Calculate the approximate total volume of compacted fill. Given properties of the proposed borrow soil, calculate the total volume to be excavated at the borrow source.
- Given shear strength properties (effective friction angle), comment on the factor of safety for the stability of the slopes.
- Draw a flow net and calculate seepage rates for the full reservoir condition assuming bedrock is located 60 ft below the base of the dam.

In addition to providing 3D visualization of a borrow-fill problem, use of the AR sandbox in this module also allows students to feel and create with coarse-grained particles (sand) and physically experiment with the angle of repose and maximum slope angles.

Module 3: Watersheds and other Basic Concepts in Hydrology

Overview: The third sandbox module is also taught in the junior year (spring) in Hydraulic Engineering & Hydrology (H&H) Laboratory. This course is currently the companion to a 3-credit, lecture-based H&H course, although the two classes are being combined into a single 4-credit H&H course starting in spring 2022. As currently formatted, H&H Lab is a course that stresses applications of hydrologic and hydraulic principles through both physical experimentation and computer workshops. The AR sandbox module in this course is taught during the first class meeting of the semester, with each student group having 30 minutes to complete the activity. By using this module to start the course, it creates a memorable experience while providing a broad introduction to basic hydrologic topics that will be covered throughout the semester in both the lab and lecture courses. The main emphasis of the module is watershed delineation, but other concepts such as contours, travel time, land cover, slope, and channels are all covered. However, the module is taught in such a way as to avoid much of these specific hydrology terms. Instead, students focus on visualizing these processes and conceptualizing their physical meaning; connections are made later in the semester once the terminology is introduced in the lecture course. Student learning outcomes include watershed delineation and determining travel time for water to leave a watershed with and without a defined channel.

Activity: The module begins with the instructor creating a landscape with a defined ridgeline encompassing much of the sandbox. It is important that the landscape has a defined outlet point near one corner of the sandbox and that the sand is generally sloping downward away from the ridges without forming a bowl shape (Figure 4). Once the landscape is created, students are asked questions regarding the contour lines shown in the sandbox, reflecting on what the spacing of contours reveals about slopes. Students then use their hands to create shadows over the sandbox, which simulates rain and subsequent overland flow on the sand, which is observed relative to the sandbox slope as well as the defined ridgeline. With the simulated water flowing in opposite directions away from the ridgeline, students visualize the concept of a watershed boundary. A discussion on the timing of water moving through the landscape ensues, with students asked to comment on what characteristics impact how long it takes water to move out of the watershed. Students select two locations along the ridgeline from which they believe water will take the longest to exit the watershed. They then simulate rainfall over those locations and time how long it takes for the water to flow to the outlet. Following a discussion on factors that influence the timing of water moving through a landscape, the instructor places a channel in the sand made from a molded paper towel roll core (Figure 4). The time procedure for the two locations on the ridgeline is then repeated.

Assignment: The quantitative tasks required for the follow-up assignment are based on using a color image of the sandbox from above (i.e., the plan view). Students delineate the watershed boundary on the image by hand, applying their knowledge of contours combined with what they observed in the sandbox regarding flow direction on a landscape. Once a watershed is drawn, students then estimate its drainage area within the sandbox (in square feet), first estimating the area on the image, then scaling up the image size to the known dimensions of the sandbox. To give context to this activity, students are then told that the sandbox represents a 1/300 scale physical model of a nearby watershed, so they must figure out the true watershed area in acres.

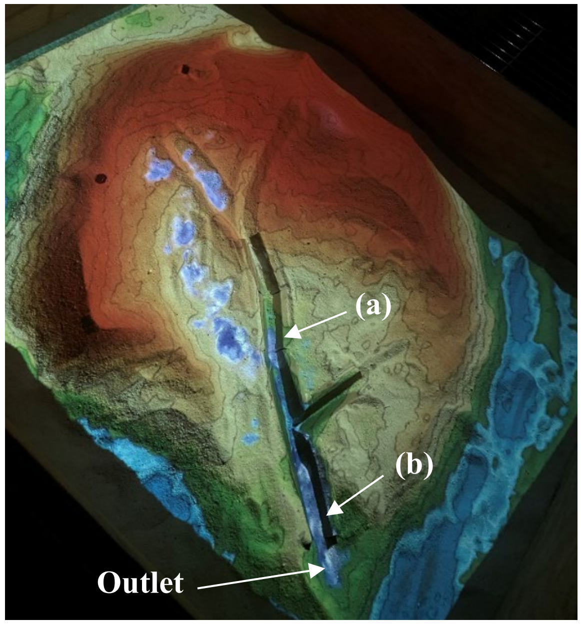

Figure 4. Sandbox in Module 3 showing the (a) watershed landscape and channel system and (b) simulated water flowing in the channel towards the outlet. Red and orange colors represent higher topography; blue and green colors represent lower topography.

Additional follow-up items are conceptual questions directed at core hydrologic topics that are introduced for the first time. These questions, and the associated hydrology concept that each question addresses, are as follows:

- Name two characteristics of a rainfall event that may change the volume of water that reaches a watershed outlet. (*rainfall intensity, duration, frequency*)
- Name three characteristics of a watershed that may change the volume of water that reaches its outlet following a rain event. (*watershed shape, land use, soil type, storage*)
- Name one factor that might affect the timing of water traveling through an actual watershed. (*travel time, time of concentration, slope, channel density and characteristics*)
- For a rain storm lasting two hours that rains uniformly over this watershed, sketch a graph of water volume passing through the outlet versus time. (*hydrographs, lag time*)

These follow-up questions can easily be modified based on the individual sandbox setup, but keeping the questions focused on key concepts that will be discussed further later in the course allows the instructor to reference the sandbox throughout the class, enhancing its effect on reinforcing concepts through visualization. Overall, this module provides students with a clear visual to help learn how to delineate watersheds. Consequently, the AR sandbox creates an experience otherwise not possible with traditional methods of teaching this concept, where the 3D reality of landscapes represented on 2D contour maps is often difficult to interpret.

Feedback and future module integration

Feedback from students on the current AR sandbox modules has been positive. While quantifiable assessment data is not currently available for these learning modules, anecdotal feedback suggests students found the activities beneficial and engaging. Common direct feedback from student comments included:

- One of the most memorable assignments this semester
- Liked the sandbox activity because it helped visualize calculations
- Found the activity very helpful and interesting
- Very effective visual and interesting way to view the topic
- Enjoyed breaking into small groups to do the activity

Faculty who have taught or observed these modules have shared similar feedback, highlighting that students seem engaged with the modules and that the sandbox creates a positive learning experience. On more than one occasion, faculty have noted that students stayed past their group time to continue exploring the sandbox capabilities.

This study is a work in progress, so assessments will be performed in the future to evaluate student learning in each module. Additionally, to continue integration of this technology into the CEE curriculum to improve visualization of key concepts, two more modules are planned to be added (Table 2): a module for Geology for Engineers (sophomore course) and a module in Foundation Design (senior course) are currently being developed.

Table 2. Schedule for integrating AR sandbox modules throughout the CEE curriculum.

Year	Semester	Course	Core concepts
Freshman	Spring	Civil Engineering Fundamentals	Contours; Plan; Profiles Cross sections; Scale
Sophomore	Spring	Geology for Engineers (*planned*)	Contours; Landforms
Junior	Fall	Soil Mechanics	Weight-Volume Relationships; Borrow-Fill Problems; Stress in Soils; Seepage; Shear Strength
	Spring	Hydraulic Engineering & Hydrology	Contours; Slope; Watersheds; Travel time; Channels; Scale
Senior	Fall	Foundation Design (*planned*)	Site Investigation; Retaining Walls; Shallow Foundations

Recommendations

Details on our modules have been provided for those with access to an AR sandbox who may be interested in implementing similar hands-on learning activities to reinforce core concepts through visualization. While access to a sandbox is certainly the biggest obstacle, there are numerous lessons that we have learned through implementation of the initial three modules. Our recommendations based on those lessons are described below.

Group size and timing: Given the size of typical AR sandboxes, the number of students that can use it at one time is limited. Through our module implementation, student groups were between 5 and 9 students. With our sandbox setup, students are clustered around three sides of the sandbox (with the controller on the other side). If student groups become too large, visibility can become an issue. Additionally, not all students are able to fully engage in the activities if they cannot get close enough to physically work with the sand. Coincident with student group size is the time allotted per group to complete the sandbox activity. This is directly linked with the course and the number of hours it meets each week. Module 1 and Module 3 described above are each taught during a 2 hour, 45 minute laboratory period, which allows for more time with each group. Conversely, Module 2 has been taught as part of a 3-credit course comprised of 50-minute class meetings. Therefore, sandbox activities were compressed, potentially impacting the benefits for the students. When planning sandbox modules, student group size should be limited as much as possible, and modules should ideally be taught in courses with longer meetings where staggered groups can each have adequate time.

Photo quality for follow-up assignments: With many of the assignment tasks in these modules requiring use of photos from the sandbox, photo quality can be an issue. For any scaling exercises based on those photos, it is important that photos are taken as squarely as possible, whether it be level from above the sandbox or straight from the side of the Plexiglas boards leaning against a whiteboard or wall. Ensuring proper photo angle will minimize issues that students encounter when using the photos for measurements or applying various scaling factors for calculations. Alternatively, it is beneficial if the sandbox controller can provide screenshot images from the operating computer when a landscape is set, showing the contour lines and associated color scale. Those images can be shared with the students for subsequent activities, providing some quality control for any plan view images of the sandbox. The drawback to this approach, which has been applied previously in Module 3, is that nothing on the actual sandbox surface will translate to the computer-generated image (e.g., coins marking points of interest, inserted channels, Plexiglas, etc.). In that case, students need to use photos they take in combination with the computer-generated images of the sand surface.

Uniformity/control of sandbox landscape: Having instructors set the primary landscape used for each sandbox module adds an element of control to the assignment. For example, the instructor can establish a landscape knowing that a defined watershed will exist, therefore ensuring that the activity can be completed as planned. The alternative approach would be to have students create their own landscape to investigate. While that promotes active-learning and creative thinking, it would present challenges for completing the module follow-up assignment and ensuring consistency between students doing the work. Additionally, with time generally a restrictive factor in teaching these modules, instructor-defined landscapes increase the likelihood of staying on schedule with groups cycling in and out.

Conclusions

An augmented reality (AR) sandbox was utilized in this study to develop three modules for use in undergraduate courses within the CEE department at Villanova University. The AR Sandbox offers opportunities to enhance student engagement and improve understanding. Further, these activities have the potential to enrich student aptitude for applying basic civil engineering concepts that require three-dimensional visualization skills, ultimately supporting the goal to graduate students who are professionally prepared to serve as effective engineers. Based on positive faculty and student feedback regarding the current AR learning experiences included in civil engineering courses at Villanova University, additional modules are planned for sophomore and senior-level courses to further enrich 3D-visualization outcomes from a curriculum-wide approach.

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