

Geotechnical Engineering Curriculum Modules for High School Math and Science Classes

Beena Ajmera, Ph.D., P.E., M.ASCE¹; Sarah L. Crary, Ph.D.²; Ryan Wenaas³;
Jill Wold⁴; Matthew Stone⁵; and Thomas Jorgenson⁶

¹Assistant Professor, Dept. of Civil, Construction, and Environmental Engineering, Iowa State Univ., Ames, IA. Email: bajmera@iastate.edu

²Assistant Director, Office of Teaching and Learning, North Dakota State Univ., Fargo, ND. Email: sarah.crary@ndsu.edu

³Maths Teacher, Davies High School, Fargo, ND. Email: wenaasr@fargo.k12.nd.us

⁴Science Teacher, Sheyenne High School, West Fargo, ND. Email: jwold@west-fargo.k12.nd.us

⁵Science Teacher, Sheyenne High School, West Fargo, ND. Email: mtstone@west-fargo.k12.nd.us

⁶Science Teacher, Sheyenne High School, West Fargo, ND. Email: jorgensoth@gmail.com

ABSTRACT

High school science and math classes can often seem irrelevant to the everyday lives of students leading to difficulties in engaging students in these topics. Moreover, limited opportunities for hands-on learning can further perpetuate perceptions of subject matter difficulty and result in limited exposure to available career paths. By incorporating hands-on curriculum modules in geotechnical engineering, it is possible to overcome these issues while providing students with real-world applications making the material more engaging and meaningful. This paper presents two curriculum modules developed as part of the National Science Foundation-funded Research Experiences for Teachers (RET) site at North Dakota State University. These modules—one for a high school science class and one for a high school math class—were developed with the aim of promoting science, technology, engineering, and mathematics education (STEM), while inspiring students to consider careers in geotechnical engineering. The lessons are designed to align with the Next Generation Science Standards and include hands-on activities along with real-world applications to enhance student understanding of the subject matter. The effectiveness of these modules was evaluated through formative and summative assessment and student surveys. The results indicate that the modules can effectively engage students in geotechnical engineering by connecting the math and science concepts from their classes and increase their interest in STEM fields. These curriculum modules are a valuable resource for high school math and science teachers looking to integrate engineering into their classes.

INTRODUCTION

High school math and science education play a pivotal role in shaping the readiness and success of students in science, technology, engineering, and mathematics (STEM) fields. Mathematics provides a framework for logical reasoning and problem-solving. It equips students with the quantitative skills which are essential for interpreting data, making accurate measurements, conducting experiments, and modeling complex phenomena. The sciences foster curiosity, nurture scientific inquiry, and encourage the exploration of cause-and-effect relationships. Through hands-on experiments, data collection, and analysis, students develop

observation skills, learn to formulate hypotheses, design experiments, and interpret results. In addition to teaching students subject-specific knowledge, math and science classes instill critical skills and competencies that are highly valued in STEM fields including problem-solving, critical thinking, logical reasoning, and data analysis (NAESM 2016). Moreover, they cultivate creativity, perseverance, and the ability to approach challenges with a systematic and analytical mindset.

Despite the importance of high school science and math education, students often face several challenges leading to difficulties and struggles with these subjects reducing their desire to pursue STEM careers. One common challenge is the lack of relevance that students perceive in math and science concepts. When students fail to see the practical applications or understand how these subjects relate to their everyday lives, they may struggle to engage and develop a genuine interest (Osborne et al. 2003). The abstract nature of math and science concepts can be difficult to grasp for some students. These subjects often require students to think critically, reason logically, and understand complex theories and formulas. Thus, the shift from concrete to abstract thinking can be a significant hurdle for many students (Rittle-Johnson and Schneider, 2014).

Limited opportunities for hands-on learning experiences further contribute to the struggles that students face in high school math and science classes. Traditional instructional methods, which primarily rely on lectures and abstract problem-solving, may not fully engage students. However, McNeill and Krajcik (2011) and Hake (1998) found that the incorporation of hands-on activities and practical applications can resolve some of those issues. Furthermore, Hidi and Renninger (2006) showed that the creation of connections between academic content and real-world contexts can enhance student motivation and engagement.

In this paper, two curriculum modules – (1) Slopes Failures and Integration and (2) Testing the Effects of an Earthquake on the Structural Integrity of a Building – developed as part of the National Science Foundation funded Research Experiences for Teachers (RET) site at North Dakota State University are presented. These modules aim to address the challenges of engaging high school students in science and math education by incorporating hands-on activities and real-world applications in geotechnical engineering. By aligning with the Next Generation Science Standards and AP Standards set by College Board as well as by integrating engineering principles into high school curricula, these modules offer an innovative approach to enhance student understanding, interest, and motivation in STEM fields.

CURRICULUM MODULE FOR HIGH SCHOOL AP CALCULUS AB CLASS

The curriculum module developed for the AP Calculus AB classes was intended to revise the traditional instructor-led lecture-based instruction of integration. In this traditional instructional approach, the instructor stands at the front of the classroom and delivers information, explanations, and contents to the students in a primarily one-way communication style. The module developed in this study is more hands-on allowing students to interact with the concepts and take ownership of the learning. It also provides greater connectivity to the real-world applications in geotechnical engineering by connecting the College Board standards for AP Calculus AB to slope failures. In particular, this module addressed the standards related to: (a) approximating areas with Riemann sums, (b) interpreting the behavior of accumulation functions involving area, (c) finding antiderivatives and indefinite integrals: basic rules and notation, (d) Riemann sums, summation notation, and definite integral notation, (e) the fundamental theorem of calculus and definite integrals, (f) applying properties of definite integrals, (g) finding the

average value of a function on an interval, (h) finding the area between the curves expressed as functions of x , and (i) integration using substitution.

As shown in Table 1, there are six sections within the new curriculum module. Each section covers concepts related to one to three different “I Can” statements (MacDuff et al. 2010). These statements explain the goal of the learning activities in a student friendly manner. In the process, they result in the separation of the lesson into a series of smaller learning objectives that allow teachers to focus their efforts. Furthermore, they are intended to allow students a mechanism to check the progress of their learning within a lesson and throughout the unit (MacDuff et al. 2010).

Table 1. “I Can” Statements in the New AP Calculus AB Curriculum Module

Section	Topic	“I Can” ...
1	Area under a curve	- Approximate the area under a curve using Riemann sums - Find the area under a curve using geometric formulas - Interpret the behavior and meaning of functions involving area
2	Antiderivative	Find the antiderivative of basic functions including all polynomials, some rational and some trigonometric functions
3	Indefinite and definite integrals	- Express a definite integral in summation notation - Evaluate indefinite integrals - Evaluate definite integrals using the fundamental theorem of calculus
4	Properties of definite integrals	- Apply properties of integrals to simplify and help solve them - Find the average value of a function - Find when a function is equal to its average
5	Area between curves	Find the area between two curves
6	Integration by substitution	- Evaluate a definite integral using substitution - Apply the second fundamental theorem of calculus

While the instruction of the new curriculum module still incorporated traditional instructor centered classroom lectures, several discovery learning labs were also added. In these labs, students worked together to solve several assignments that required the use of 3D physical graphs and a measuring device. In the implementation of this module, the instructor created these physical graphs using craft foam. The measuring device was a clear acrylic sheet with a coordinate grid. Both items are pictured in Figure 1.

In the first exercise students develop their own methods to find the area under a curve. They must make sure that their proposed method is repeatable, leading to the development of the Reimann sum method to find areas under curves. In the next exercise, students determine the total rainfall, a common trigger of slope failures, from the graphs depicting the amount of rainfall over time. In the last exercise, craft foam shapes were used to represent the topography of a slope before and after it failed. Students used the concepts they learned to determine the total area of

the soil mass involved in the failure as one of the input parameters for a simplistic factor of safety calculation using the ordinary method of slices.

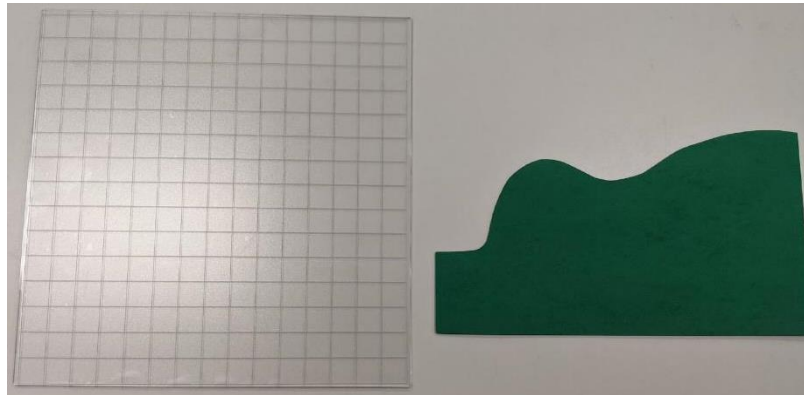


Figure 1. Example of Props Used by Students during the Discovery Learning Labs

Due to space limitations, this paper only presents an overview of this curriculum module. However, all of the details associated with the unit including all handouts, lecture notes, homework assignments and teaching instructions can be found in Wenaas et al. (UR).

CURRICULUM MODULE FOR HIGH SCHOOL EARTH SCIENCE CLASS

In the curriculum module developed for the high school earth science class, students simulated the role of civil engineers and applied the engineering design process to construct a building in an earthquake-prone area. The module is aligned with three Next Generation Science Standards: (1) HS-ETSI-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering, (2) HS-ETSI-3: Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts, and (3) HS-ESS3-2: Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios. Upon the completion of this curriculum modules, students should achieve the following five learning objectives: (a) understand the components of the engineering design process, (b) describe the effects of both vertical stress and shear stress on a structure, (c) work collaboratively to create a structure within the specified design constraints, (d) explain trade-offs in the design process using cost-benefit analyses, and (e) communicate the outcome of the design process to all parties involved.

The module begins with a PowerPoint presentation on soil characteristics, where students are introduced to terms such as pore pressure, porosity, and permeability. Loading on a soil mass is also discussed. Next, students complete an activity to study the difference between porosity and permeability of different types of soils. In a low cost set-up, students measure the porosity of the soils by examining the amount of water the pore spaces can hold through measurements of how much water can be held by the soil without creating a pool of water on top. In the second part, students measure the permeability of the soil by determining how long it takes water to move through the soil mass and exit at the bottom of the beaker, while maintaining a constant head on the soil, as shown in Figure 2.



Figure 2. Photographs of the Low-Cost Porosity and Permeability Labs.

The porosity and permeability labs are followed by a PowerPoint presentation that covers information about waves, refraction, Mohorovicic Seismic Discontinuity and how earthquake waves propagate through soils. This section also includes resources for how engineers stabilize buildings in seismically active areas. After the lecture, students perform an earthquake damper activity, where they determine the optimal length and weight of the damper (weight on a string) to reduce the effects of an earthquake on a building. Students use a model of building built from dowel rods to represent the columns and wood sheets to represent the slabs, as pictured in Figure 3. This activity involves the use of the Pasco Sparkvue app, which uses an accelerometer in an iPad located at the top of the building to provide various outputs. Using bungee cords, students pull the building away from the base and release it to simulate an earthquake. A 1 kg weight is placed on the base to prevent the building from rocking. Students record the duration of the building shaking. This activity has two learning goals. First, the students do a series of earthquake trials to determine the optimum weight of the damper where the building shakes for the least amount of time. Once they have the optimum weight, they use that weight and change the lengths of the string to determine the optimum length of the string to minimize the shaking duration.

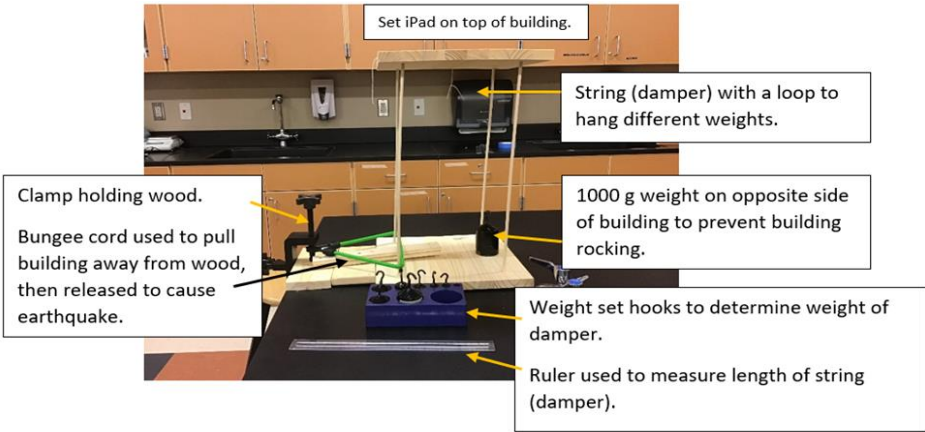


Figure 3. Set-up for Earthquake Damper Activity.

The last part of this module is a performance assessment using the engineering design process. Students work in teams of four to act as civil engineers to design, construct and test their building on a shake table. Each team is a firm that has been tasked with designing an earthquake safe building in San Francisco. The buildings should be constructed from pasta noodles, toothpicks, bendable straws, marshmallows, and hot glue. Each material is associated with a cost, which the team must keep track of during the construction process. The designed building must meet several specifications. Specifically, it must fit onto a 15 cm x 15 cm footprint and have at least four floors (a minimum height of 30 cm). The weight of the building cannot exceed 300 g. It must be able to hold a 1.1 kg weight on the shake table. Teams must also take photographs to show how the building was constructed and where the different materials were used.

Once students have a design, they move to constructing their building. Students had to work together to ensure that the building was constructed within the time constraints of the classroom schedule. For this module, students were given three days to design and construct their buildings. The buildings were then tested on a shake table and the time to failure was recorded for each building. Students then looked at where their buildings failed and determined how they could improve its design to be more earthquake-resilient.

The shake table used was constructed by the teachers that implemented the curriculum modules in their classrooms. Their goal was to develop a shake table that was not cost-prohibitive for others that might be interested in using this module in the future. In fact, it was a very simple system in which super balls were placed between two wooden boards held together by rubber bands and clamps. Some pictures of the system are provided in Figure 4.

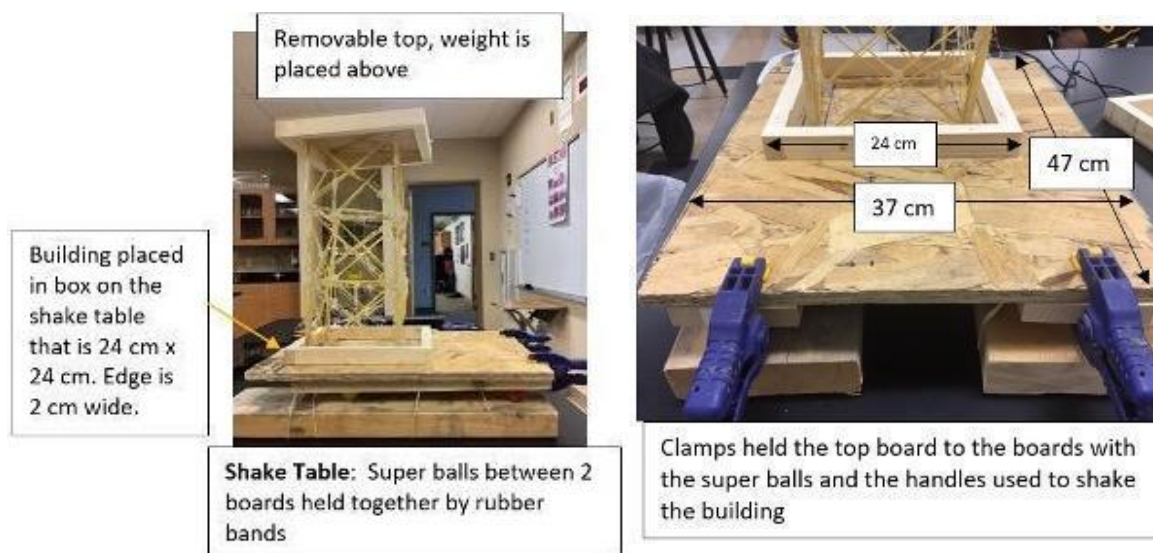


Figure 4. Pictures of the Shake Table Developed for the Implementation of the Earth Science Curriculum Module.

In the last section of the module, the students presented their findings. In their presentations, students showed how they used their materials, shared the total cost and the length of time the building survived. In addition, they discussed the modifications that they would make to the building based on the observations of the failed systems. Students developed their presentation with the intent of presenting to the San Francisco developing company to win the bid to construct the building. Thus, a professional quality was expected for their presentations.

Only a summary of the curriculum module is provided due to the limited space available. However, details of the instructions provided to the students, along with all the PowerPoints, grading rubrics and other relevant information associated with this curriculum module can be found in Wold et al. (Accepted – In Press).

OUTCOMES OF THE CLASSROOM IMPLEMENTATIONS

Methods. With IRB approval, brief self-report surveys were administered to the students right before the teacher taught the new modules that were developed. The same survey was, then, administered again immediately after the units were completed. The surveys were either administered on paper or online and consisted of six Likert scale items. The Likert scale ranged from strongly disagree (1) to strongly agree (6). In addition to the Likert scale items, the survey also collected basic demographics. In particular, the data presented in this paper came from the classes that two teachers taught, one in science and one in math. Independent sample *t*-tests were run comparing student responses on the six Likert scale items on: (1) gender (i.e., women and men), (2) Race (i.e., BIPOC (Black, Indigenous and People of Color) and White), (3) grade (i.e., juniors and seniors in high school), and (4) discipline (i.e., math and science).

Results. The demographic breakdown of the students surveyed as part of the classroom implementations of the curriculum modules is provided in Table 2. This table also summarizes the results of the independent sample *t*-tests that were found to be statistically significant for gender, race, grade and discipline. Those items that were not statistically significant are not reported in this paper due to space limitations. To assess the significance of the difference between the scores in each item, Cohen's *d* as calculated to determine the effect size. The Cohen's *d* values are also reported in Table 2.

The results associated with gender indicate that male students were more likely to agree to have an interest in learning about civil engineering than women students. Additionally, they disagreed less strongly with women students about their interest in a career in civil engineering and their knowledge about civil engineering topics. These results are shedding additional light on the gender disparity that exists in the interest and intention to pursue civil engineering among high school students. Such disparities can contribute to the underrepresentation of women in STEM fields. Furthermore, the higher interest and knowledge among the male students may indicate the continued perpetuation of an existing gender gap in civil engineering and other STEM disciplines.

There are several effective strategies to address gender disparities that include recruitment and outreach activities, educational interventions, highlighting successful women professionals as role models and addressing biases and stereotypes. However, most strategies are often geared towards high school students, when perceptions and stereotypes may have already contributed to gender disparities leaving a lasting impact on the next generation of STEM professionals. As such, it may be more effective to implement these strategies earlier and more frequently in K-12 education allowing time to reinforce and support the ideas before students make career decisions.

From Table 2, it is clear that white students are more likely to agree to an interest in pursuing a career in a STEM discipline than BIPOC students. Although the population was predominantly white, the results are still significant in that there is a disparity that needs to be addressed. In particular, the lack of representation and diversity in STEM professions is captured by the results. Furthermore, this lack of interest among BIPOC students may continue to contribute to the existing disparities and limit the perspectives and experiences brought to the profession.

Many BIPOC students do not see themselves reflected in their teachers who are usually white, therefore they do not see themselves as engineers. The need to address systemic barriers that hinder participation of BIPOC students in STEM disciplines is underscored by the results presented in this study (Paz 2022).

Table 2: Statistically Significant Results Between Pre- and Post- Likert Surveys in Implementing Classrooms

Item	<i>N</i>	Mean (SD)	<i>N</i>	Mean (SD)	<i>t</i> -Test	<i>p</i>	Cohen's <i>d</i>
Gender							
	Women		Men				
I am interested in learning about Civil Engineering.	27	2.26 (0.98)	55	3.16 (1.34)	1.91	0.050	1.34
I am interested in pursuing a career in Civil Engineering.	27	1.85 (0.66)	55	2.78 (1.27)	3.56	0.001	1.11
I am knowledgeable about Civil Engineering topics.	27	2.26 (1.20)	55	2.98 (1.37)	2.34	0.050	1.31
Race							
	White		BIPOC				
I am interested in pursuing a career in a STEM discipline.	70	3.59 (1.65)	12	2.50 (1.09)	2.20	0.05	1.58
Grade							
	Junior		Seniors				
I am knowledgeable about STEM topics.	41	3.37 (1.32)	40	4.03 (1.37)	2.21	0.05	1.34
Discipline							
	Math		Science				
I am interested in learning about STEM disciplines and topics	34	5.00 (0.95)	51	3.12 (1.44)	6.71	0.001	1.27
I am interested in learning about Civil Engineering.	34	3.26 (1.38)	51	2.59 (1.22)	2.38	0.050	1.28
I am interested in pursuing a career in a STEM discipline.	34	4.50 (1.50)	51	2.67 (1.26)	6.08	0.001	1.36
I am knowledgeable about STEM topics.	34	4.24 (0.99)	51	3.37 (1.45)	3.02	0.050	1.29

High school seniors were found to be more likely to agree with their knowledge about STEM topics than high school juniors. This may be attributed to several factors. First, seniors will have had more an additional year of courses to engage with STEM subjects and explore a broader range of topics as compared to juniors. They may have also taken more advanced courses, participated in extracurricular activities, or pursued independent study leading to a deeper understanding and familiarity with STEM concepts. Second, the curriculum in high schools is designed to build upon foundational knowledge each year with more advanced concepts being introduced in later grades. Thus, high school seniors will have accumulated a greater breadth and depth of knowledge in STEM subjects over time enabling them to feel more confident about their understanding. Finally, high school seniors are often further along in the process of considering college and career goals as this usually begins in their junior year when they begin to look at colleges. This may lead to the perception their knowledge of STEM topics is more solidified leading to more confidence about their knowledge about STEM topics.

From a disciplinary perspective, math students were more likely than science students to agree to having an interest in STEM disciplines and topics, an interest in learning about civil engineering, and an interest in pursuing a career in a STEM discipline and their knowledge about STEM topics. This may be partially attributed to the differences in the disciplines. High school math curricula often have a structured and progressive nature with students starting with Algebra I continuing to Geometry and then finishing with Algebra II, building on foundational concepts and providing clear pathways for advanced study. This focused and sequential approach to learning can enhance the confidence and knowledge in STEM-related topics of high school math students. In contrast, science curricula may cover a broader range of subjects with physical science and biology being required courses in North Dakota. Students may then select a variety of classes for their remaining coursework. Many science courses do require more hands-on experimentation, which could potentially impact the self-perception of knowledge in specific STEM disciplines among the students.

A second factor affecting the statistically significant differences with the disciplines might be tied to the perceived relevance and application. Mathematics is widely recognized as a fundamental tool in various STEM fields. Math students may perceive their skills as more directly applicable to a range of STEM disciplines, including civil engineering. This perceived relevance and practicality can contribute to a higher interest in pursuing STEM careers and a greater sense of confidence in their knowledge about STEM topics.

It is important that the authors note that the explanations provided here are general observations. As such, they may not apply uniformly to all genders, races, grades, and disciplines. Individual interests, teaching quality, and personal motivations can also influence levels of interest, knowledge, and confidence in STEM disciplines. However, the authors still believe that the results obtained from the implementation of the two new curriculum modules are valuable and highlight some important shortcomings in the K-12 educational system that impacts the diversity within STEM fields in college classrooms and in the industry.

CONCLUSIONS

High school math and science education is crucial for preparing students for success in STEM fields. Math equips students with problem-solving skills and quantitative abilities necessary for data interpretation and modeling, while science encourages curiosity and exploration of cause-and-effect relationships through experiments. These subjects also teach

critical skills valued in STEM, such as problem-solving and data analysis, and foster creativity and perseverance. However, students often struggle with math and science due to a perceived lack of relevance and the abstract nature of the concepts. Limited hands-on learning opportunities further hinder engagement. To address these challenges, this study presents two curriculum modules developed to integrate hands-on activities and real-world applications in geotechnical engineering, aligning with the relevant standards and enhancing student understanding and motivation in STEM.

The new curriculum module developed for the high school AP Calculus AB classes aimed to revise the instruction of integration by incorporating real-world applications from geotechnical engineering. The module covered various topics related to integration, such as areas with Riemann sums, interpreting accumulation functions, finding antiderivatives, and applying properties of definite integrals. The module was divided into six sections, each focusing on specific learning objectives represented by "I Can" statements. In addition to traditional lectures, discovery learning labs were included, where students used 3D physical graphs and a measuring device to solve assignments.

The curriculum module for high school earth science class involves a simulation where students act as civil engineers designing a building in an earthquake-prone area. They must consider a budget and limited materials to construct a structure that can withstand a weight and survive an earthquake test on a shake table. By analyzing collapse points, students improve their designs and present their findings to compete for a project bid.

Both of the developed curriculums were implemented into high school classrooms. Surveys conducted before and after the implementations were used to assess students' interest and knowledge in STEM disciplines, particularly civil engineering. The results indicated gender disparities, with male students showing higher interest and knowledge in civil engineering compared to female students. This highlights the existing gender gap and underrepresentation of women in STEM fields. Additionally, white students were more likely than BIPOC students to express interest in pursuing a STEM career, indicating a lack of diversity and representation. High school seniors demonstrated greater knowledge about STEM topics than juniors, likely due to more exposure and advanced coursework. Math students also displayed higher interest and knowledge in STEM disciplines compared to science students, potentially influenced by the structured nature and perceived relevance of mathematics to STEM fields. The results from the surveys emphasized the need to address systematic barriers and implement strategies earlier in K-12 education to foster diversity and interest in STEM fields.

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