Engineering the World: Hands-on Experimentation for Civil Engineering K-12 Outreach

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Abstract

This paper details the development and application of a community outreach program designed to teach children about math, science, and the world in which they live. The program was titled "Engineering the World" and emphasized civil engineering applications. The program was offered in an inner-city middle school in Detroit, Michigan. The program was developed by civil engineering professors at Lawrence Technological University with the assistance of undergraduate engineering students. The activities were categorized by civil engineering discipline including construction, environmental, geotechnical, hydraulics, structural, surveying, and transportation. The paper describes details of several of the hands-on experiments and provides an assessment of the program including suitability of the activities for this age group. The activities were generally well received by the students. Recommendations for similar outreach programs are provided.

Introduction

It is well documented that children determine if they are "interested" in math and science by the time they are in middle school. Therefore, it is important to reach children at that age with fun, interactive, and interesting activities that improve the learning process. An outreach program was conducted with middle school students that emphasized civil engineering activities and concepts. The activities were developed to provide exposure to each of the conventional disciplines of civil engineering. Many of the activities were suitable for conducting competitions between individuals or teams of students. A summary of the original 8-module session is presented in Table 1.

The middle school at which the program was held was an inner-city school in Detroit, Michigan. Students in the program were enrolled in sixth, seventh, and eighth grades. Enrolling in the after school program required qualification of good academic standing by the students and almost all of the students were underprivileged minorities. Classes were scheduled for 20 students, yet regular attendance was between 8 and 12 students. The sessions were scheduled at the conclusion of the school day, from 2:30 until 5:00 pm one day per week. Classes were offered at the school two afternoons per week and the identical program was offered to two separate groups of students. Time was allotted during each session for a snack break.

Table 1. Original Schedule for "Engineering the World" Outreach Program

Session Title and CE Discipline	Emphasis of Presentation	Hands-on Activity
Is London Bridge Falling Down? Structural Engineering and Construction Engineering	Variety of materials including new ad composite materials Video of unique construction	Bridge construction (actual using construction kits and virtual using West Point Bridge Designer software)
Potholes in Motown Transportation Engineering	Variety of transportation facilities including airports, roadways, bridges, tunnels, canals, railroads, etc. Historical account of infrastructure	Tin foil boat competition Mixing of concrete
Don't Miss the Boat Hydraulic Engineering	Rivers, dams, canals, harbors, flood control, and sedimentation	Meandering river demonstration
Do You Dig Dirt? Geotechnical Engineering	Structure of soil	Shaking table for foundations, loose and dense sand structures, moisture in soils, geosynthetics demonstrations
Who's Trying to Get You? Environmental Engineering	Importance of clean water	Contaminant transport and landfill construction
From Inchworms to Light-years Surveying and Engineering Measurements	Importance of engineering measurements	Pacing vs. taping distances exercise

The instructors of the program were three faculty members from the Civil Engineering Department at Lawrence Technological University (authors of this paper). The faculty members shared teaching responsibilities and occasionally the sessions were co-taught by two faculty members. In addition to the faculty, undergraduate and graduate civil engineering students assisted with the planning and teaching activities. The faculty members were unable to secure a single assistant for the entire duration of the program; so multiple assistants were used (although, only one assistant was present for a given session).

Project Descriptions

Over the duration of the Engineering the World Program numerous projects were developed. Sessions were developed to emphasize each of the conventional specializations of civil engineering: construction, environmental, geotechnical, hydraulics, structural, surveying, and transportation. Individual sessions were formulated to emphasize hands-on activities (Figure 1). A number of the activities will be described in this section to help the reader understand the scope of the program.

Figure 1. Dr. Don Carpenter assisting students with steam-powered boat fabrication

Hydraulic Engineering Activities

A river model was constructed as a 20 in. wide by 48 in. long by 4 in. deep Plexiglas box filled with sand. The boxes are filled with a mixture of fine, medium, and coarse sand to allow the creation of three dimensional river systems. The flow through the model is accomplished by using a small submersible pump in a lower reservoir. For convenience and economics, the reservoir is simply a 20-gallon plastic storage container. Water is inserted into the upper portion of the modeling box through a small hose behind a diffuser. The diffuser slows the velocity of the water to resist excessive erosion at the point of entry. The box is set at a slight angle to facilitate flow through the river system. The water returns to the reservoir after leaving the model through a square notch in the end of the box. The water then recirculates through the system. The water needs to be occasionally exchanged because the unfiltered water becomes quite "muddy."

Students were asked to verbalize what they were seeing and how water flowing through the system was changing the environment. While they obviously did not use the proper terminology, they were pretty good in their descriptions. The system allowed students to visualize various river processes including sediment transport, bank and bed erosion, river evolution, flooding, etc. The use of non-uniform sand allowed students to visualize the transport of different sediment sizes as would be encountered in nature. Depending on the velocity of the water, students could see smaller grains of sediment being transported, with larger grains settling onto the bottom. Additionally, students had the opportunity to change their environment by adding scale features to the model such as boulders, gabions, logs, and bank vegetation. The boulders were simply small rocks; the gabions were wired baskets filled with gravel; the logs were cut dowel rods; and sponges anchored with toothpicks represented bank vegetation. The river model was easily changed to incorporate these features and see how the river adapted to the changes. Finally, after students have been given opportunities to alter the system, they were asked to construct a new river system and predict how it would react when water was added. Overall, they were quite successful in predicting where erosion and deposition would occur.

Perhaps the biggest challenge with the river model was patience. The students frequently wait long enough for the system to adapt to changes they had made. The other challenge was maturity. This experiment is very similar to playing in a wet sand box and some of the students treated as such instead of a scientific learning experience.

Structural and Construction Engineering

K'NEX kits are construction kits that use hard plastic components of various configurations to allow for building virtually any structural shape. K'NEX kits were used by the students to investigate aspects of structural and construction engineering by building models of bridges and skyscrapers. Initially, the students were asked to build simple structural shapes such as squares and triangles and to investigate what happens when they are "loaded." They then individually constructed a simple pier bridge. By performing these experiments, they were introduced to common terminology such loading, tension, compression, span, support, joint, connection, abutment, footing, etc. Once the students had background knowledge in the subject matter, they were split into teams and presented an engineering challenge with several restraints. The students then worked as a team to complete their project using the materials contained in a single K'NEX kit. In one session, the challenge involved a bridge and in another session, the challenge was based around a skyscraper. The K'NEX kits include blueprints for constructing various types of bridges and the students were allowed to use these blueprints to simplify the construction process.[1]

In the case of a bridge, the students were told to span a distance (14 in.) using a bridge design of their choice. The students were also informed that two prizes would be awarded: one award for the most aesthetically pleasing/interesting bridge and another award for the strongest bridge. The instructor and assistant judged which bridge was most aesthetic. The strongest bridge was judged by determining the number of science textbooks it could hold during a load test before collapsing (given lateral foundation support). A more interesting contest would have been a bridge weight to load weight ratio, but the students were more interested to see the ultimate load and failure. Each team had a set number of supplies so this limited the size of their construction. The strongest bridge was a variation of an elevated train truss structure and supported more than 20 textbooks before collapsing. The student really enjoyed the catastrophic failure of their creations. A cable stay bridge was awarded the most aesthetic.

In the case of the skyscraper, the students were given a rectangle of construction paper that represented a "city block" and that would be the maximum foundation footprint size for their building (i.e. in the final design, the K'NEX pieces at "ground level" must be contained by the border of the construction paper). Similar to the bridge assignment, the students were presented with two challenges with prizes awarded: an award for the tallest constructed building that could withstand a hurricane load (box fan) without toppling and the most volumetric office space given the foundation size and specified amount of materials. The K'NEX kits represented the internal structure and construction paper was attached to the side before wind loading. The tallest skyscraper reached almost 6 ft in height (taller than either member of the student design team which made for a comical load test with students standing on chairs). The award for most volumetric office space went to a team that ingeniously utilized cantilever structures.

Geotechnical Engineering Activities

A number of geotechnical engineering activities were conducted over the duration of two sessions of the program. Most geotechnical engineering activities were selected from the Soil Magic program developed through the sponsorship of ASCE. The Soil Magic program is a series of laboratory experiments that demonstrate many of the underlying principles of soil mechanics.[2] Those activities in which the students were physically involved in the experiment preparation or assisted with the test procedures appeared to be the most effective for delivering the concepts at hand.

The experiments outlined in Elton (2001) provide dramatic and often surprising behavior for soils.[2] In one of the activities, the students were challenged to understand the concepts of effective stress by observing how a rubber glove full of sand became rock-hard when subjected to vacuum pressure (iron glove experiment). This was a particularly entertaining activity as each student had an opportunity to personally shake hands with the iron glove. The concept of effective stress in soils was revisited using a demonstration of a bag of potato chips under loaded conditions (with pin holes introduced to the bag over time). In this case, the students enjoyed the "byproducts" of the experiment during the snack break. Some discussion in the class was developed to broaden the applicability of these simple demonstrations to real geotechnical engineering problems. The students appeared to appreciate the importance of laboratory exercises and saw the connection between a laboratory experiment and a field application.

Other geotechnical activities included demonstration of rock bolting and soil reinforcement mechanisms. Rock bolting was demonstrated using a bucket of gravel that remained in place after tipping the bucket upside down. This behavior was achieved through the action of applied compressive forces through the rock mass with bolts. Although the mechanics were beyond the students' conceptual understanding, they enjoyed assisting shoveling the gravel and tightening the bolts as well as hearing stories about tunneling for subways. The effectiveness of reinforced soil was demonstrated by hiding paper discs within one pile of sand next to a "control" pile of sand. The students could not guess why the reinforced sand pile (which appeared identical to the control pile) was able to hold substantially more weight before failing. The soil reinforcement demonstration was quite rapid because it had to be entirely set up ahead of time to maintain the element of surprise. This activity prefaced showing the students samples of geosynthetics and discussing a few aspects of ground modification engineering.

The student's favorite geotechnical activity was related to the principle of dilatancy. Students made a water-corn starch mixture (termed "ooblech" by Elton) that maintained form as a ball as long as they kept moving it from hand to hand. However, if the action stopped, the substance became viscous and ran down their hands and arms. The students were quite taken by this phenomenon and many requested to take their samples home. The instructors were entertained at the image of a sidewalk full of students having to continually move their samples from hand to hand as they walked home. We assured students that they could buy more of the magic powder at the grocery store.

West Point Bridge Designer Activities

A software package entitled West Point Bridge Designer (WPBD), developed by Steve Ressler of the United States Military Academy, was used for a number of sessions in the program.[3] We started the sessions that incorporated WPBD by introducing the students to basic engineering concepts such as tension, compression, deflection, bending moment, and stability. The instructor also devoted 15 minutes for discussing the various loads on bridges and the different types of bridges with the students. The students showed great interest and asked a lot of questions about bridges. Students were excited to learn bout how the different types of bridges transfer loads to the ground. They also showed great interest in guessing the different types of loads that bridges carry. The next step was to show the students how to use the WPBD software. At this stage, each student was assigned a computer and was allowed to start using the software. The instructors showed the students how to build the bridge and how to improve their designs using the reports to reach the best possible design.

The final step was the student competitions. In every session, we had two competitions and the first three winners were given a prize. In every competition, a different kind of bridge was assigned. In the first competition, the students were usually assigned a truss bridge and were allowed to use only the solid bar element. Each student would select a name for her/his bridge. The students were given 45 minutes to complete the design. A board with the names of the wining bridges was updated every 5 minutes. The winners were selected based on cost. During the last 5 minutes, the scoreboard was updated every minute. The winners were continuously changing until the very last minute.

In the second competition, the students were usually assigned a suspension bridge or a cable stayed bridge but were not restricted to any type of element for their bridge. Most students started by using solid bars, however, they were fast to find out that they could have different designs if they use hollow types or mix of solid bars and tubes. The students were very creative in their designs. Students were given approximately 1 hour to complete the second competition. The scoreboard was updated every 5 minutes for the first 55 minutes and every minute for the last 5 minutes.

Overall, the students showed great interest and asked if they could keep copies of the software. We distributed copies of the software to the students and scheduled an extra session for the WPBD Software activities. Students were encouraged to participate in a national competition for K-12 students nationwide that co-sponsored by and highlighted the sesquicentennial of ASCE and the bicentennial of the United States Military Academy. We did not confirm if any of the students actually participated in the national competition.

University Visit

A field trip to Lawrence Technological University was conducted at the end of each eight-week session. This session represented the culmination of the entire program and was a highlight for the students. This trip was used to demonstrate some large-scale experiments to the students. They toured various laboratories on campus including structural, geotechnical, materials, hydraulics, automotive, architectural, and chemistry. The students were quite interested in all the sites and activities of a college campus. A highlight of the university visit was the compressive load testing of the students' concrete cylinders that had been prepared at a program session approximately 4 weeks prior to the university visit.

Summary and Discussion

Program Successes

The instructors feel that the *Engineering the World* Program made a difference in the students' lives. Most of the class periods were held in the science room at the middle school. It was apparent that the science and engineering related activities that were presented in the program were substantially more interactive, hands-on, and entertaining than the conventional materials presented in their classes. Therefore, the students were able to see that science and engineering can be fun. Allowing the students to visit the Lawrence Technological University campus for the final session was also highly beneficial to the program. For many of the students, this was their first time visiting a college campus. The instructors were pleased with this visit in that dramatic and large-scale demonstrations (including concrete compressive strength tests, and steel yielding tests, hydraulic flume demonstrations, and dynamometer experiment) and experiments were easily accessible. The instructors were able to provide exposure to all the civil engineering laboratories and affiliated specializations of civil engineering during the visit to campus. We believe the program overall provided some image enhancement to engineering, and civil engineering profession in particular. The students left this program with a much better understanding of what civil engineers do for our society and how the principles of science and engineering can be applied to simple problems.

Program Challenges

Challenges associated with the program included maintaining student interest, identifying appropriate level for instruction, identifying and assisting with problematic student team dynamics, coordinating scheduling for the snack break, and continually improving the learning activities. Maintaining student interest was problematic at times. Activities were tailored to be hands-on, experimental, and often include competition. Students generally enjoyed the planned activities, although at times the underlying theory of certain activities escaped the group. Commonly, instructors would use brief and dramatic demonstrations of science and engineering principles to change the pace of the session and regain attention of the class. It was entirely understandable that the students were somewhat restless after a full day at school and it was occasionally difficult to maintain order in a room of 12 students when a couple needed individual attention.

Establishing the level of instruction was somewhat challenging in that sixth graders and eighth graders can have significantly different abilities (and the variable group attendance each week could greatly affect the appropriate level of instruction). Occasionally, the planned material was unintentionally beyond the students' abilities. One notable example of this was a visualization/drafting exercise in which the students were requested to draw plan, elevation, and side-views of relatively complex wooden blocks. The students had difficulty with the concepts of scaled drawings and hidden lines. The instructors learned that shorter duration activities were generally more successful at keeping the attention of the students. The shorter duration activities also presented less risk of devoting too much time to an activity that was not at the appropriate level (either too simple or too difficult).

Team dynamics presented numerous challenges, as the students were not always cooperative with sharing program resources. To the best of our abilities, we tried to develop individual or team-based activities to provide a majority of individual hands-on experiences rather than large-group activities. Periodically, personality differences would affect the quality of team performance. The instructors tried to identify problematic team member combinations and attempted to avoid these team assignments in future sessions.

Although the schedule for a snack break sounds like a minor point, it was a source of problems for the program. The break period was not always consistent with a logical break in the learning activities. On occasion, the instructors were left to fill relatively small amounts of time waiting for the break and on other occasions, compromise the flow of learning activities for the service of a snack.

A primary intention at the onset of the program was to complete one 8-week set of sessions and conduct a thorough assessment to highlight areas needing improvement. Poole et al. (2001) conducted a similar thorough assessment of an outreach program that consistent with the philosophy of ABET's Criteria 2000.[4] We conducted a self assessment and planned appropriate changes to the activities (some broad teaching methodology style changes and other highly detailed changes related to specific activities). The instructors felt well prepared for the second run of the program. The instructors were quite surprised to find a large number of repeat students for the second offering of the program. Although we were encouraged that the students enjoyed the program enough to return, we were a bit overwhelmed at the prospect of developing entirely new learning material for a second eight-week program (a demand of the repeat students) with very little lead time. In the end, the instructors saw this turn of events as the greatest single challenge of the program.

Program Discussion

To assess the program the students were asked to participate in a round table discussion regarding what they had learned (or recall) from the engineering projects of the previous several months. Overwhelmingly, students enjoyed the program and their experiences. While this is nice to know, it obviously does not correlate with learning. Furthering probing seemed to indicate a majority (upwards of 75%) of the students generally understood what civil engineering is and how engineers affect their world. This was one of the goals of the program, so in that aspect, the program was a success. When asked if they wanted to be engineers (and/or civil engineers) when they grow up, the overall response was fair. Some students were very enthusiastic about engineering when others seemed a little more cavalier. Finally, to really try to test their learning, students were asked to pose a thoughtful question to their peers that related to the experiments they had performed. A well thought question was rewarded with a prize (candy) and a correct answer was also rewarded with a prize. While only a handful of students (approximately 25%) actually won prizes for posing or answering questions, their questions (and subsequent answers) were extremely interesting. For example, one student asked the question "if a bridge beam is loaded from above, what side of the beam is in tension and what side is in compression?" Another student asked "how does sand size effect sediment transport?" This was a very qualitative and informal testing procedure but it was great to see the students recalled concepts that, in some cases, they had learned month's prior. This was very rewarding from an educator's viewpoint.

Recommendations for Similar Programs

The faculty members learned a great deal by completing these modules and are interested in passing along lessons learned to those undertaking similar outreach initiatives. The main recommendations can be classified as allowing flexibility in program organization and planning, maintaining high entertainment value and hands-on emphasis for activities, providing recognition to the students for their accomplishments, and obtaining and managing program resources.

Flexibility in program planning and delivery is critical. The young students make improvisation in program delivery necessary. It helps to be prepared for quick changes to program plans. If students are disinterested or not enthusiastic about a given activity, the disinterest can linger and affect the atmosphere of the entire session. Sometimes the simplest activities were the most successful at achieving student awareness of engineering principles.

Hands-on activities tended to be the most successful. Whereas the instructors need to be cognizant not to leave any students out of the planned activity (as to risk that student pursuing potentially disruptive activities not related to the program), the instructors also need to identify those capable and highly interested students (so as to capture their enthusiasm and allow this to spread to the entire group). If a student or group of students is entirely unwilling to participate in the planned activities, discipline becomes an issue. Billed as an after school program, the instructors were interested in keeping a friendly atmosphere and rapport with the students. The lack of presence of a school authority figure in the classroom changes the behavior of the students considerably. Therefore, an after school outreach program has a distinctly different feel than a K-12 outreach program conducted during school hours. First, the students are somewhat more restless and secondly, the students' expectations are more aligned with playing than maintaining a conventional classroom setting. The instructors of this program found that competitions were particularly effective as using the student's after school energy towards effective learning exercises.

Recognition to the students for their accomplishments was a natural extension of the competitions. Prizes were awarded for best designs, proper calculations, and correct answers to questions related to the subject matter. The students very much enjoyed the personal recognition and the pursuit of prizes enhanced the competitive environment. The prizes were generally selected to relate in some manner to the subject matter so that additional learning was encouraged beyond the classroom sessions. In some cases, personalized certificates were prepared after the competition and distributed the following week in an awards ceremony.

In addition to the prizes, relatively inexpensive learning tools were often distributed to the entire class. On occasion, these learning tools ("gifts" rather than prizes) were used during the sessions and the students were allowed to take their "experiment" home with them. Three examples of learning tools that were distributed that were used in the sessions include retractable measuring tapes (that were used in an engineering measurements session), silly putty (as part of an engineering materials session), and freshly planted vegetable and flower seeds for the students to grow at home (as part of a sustainable development session). On other occasions, learning tools that were not directly related to the program content (such as drafting supplies, pens, and pencils) were distributed at the end of the session. The students enjoyed these token souvenirs and the cost to the program was minimal. In addition, the prospect of distributing "gifts" provided some friendly leverage for maintaining good behavior during the session. A special gift (a university logo T-shirt) was given to each student on the last day of the program during the tour of the Lawrence Tech campus. The students very much enjoyed this and the instructors feel this gift will leave a lasting impression of the program.

Obtaining resources for such a program is an entirely separate undertaking from developing the educational program. We were fortunate that the program was generously funded through the university by external sources. This funding provided access to learning materials. It was necessary to bring basic laboratory supplies to the school, as the resources available at the school were rather limited. At times, we ended up carrying more than an entire carload of supplies and equipment to conduct a given session. The geotechnical engineering, river model, and concrete mixing sessions were particularly cumbersome to conduct at a remote location (at the middle school). We would consider running these sessions at the university in the future to facilitate the entire process including cleanup. The benefit of conducting the concrete mixing at the middle school was that the students took "ownership" of their concrete cylinders and were proud to compete in a compressive strength test competition using products of their own workmanship.

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