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Geotechnical Physical Modeling for Education: Learning Theory Approach

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Abstract: As physical modeling sees increasing use in geotechnical engineering education, there is a need for a strategic approach for integrating this powerful simulation technique into courses in a way that ensures the greatest benefit for students. For this reason, a learning theory approach, which recognizes the natural learning cycle of students, has been developed. The approach is based on a modified version of the learning theorist David Kolb's "theory of experiential learning." The approach emphasizes a variety of learning styles and thus is appealing to a broad range of students. The approach is relatively easy to apply to traditional geotechnical engineering coursework and requires only a modest effort to adopt. It is expected that by using this approach when designing course modules, instructors can increase the likelihood that comprehensive learning will take place. While this paper focuses on physical modeling for geotechnical engineering, the approach presented here has educational applications to an array of other civil engineering topics.

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Introduction

Physical models have served important functions in engineering research, practice, and education for hundreds of years (Ferguson 1992). In geotechnical engineering, the first reduced scale physical models were used primarily for research, and usually in a 1-*g* environment. A key limitation to many of these studies was that the stress dependent behavior of soil was not properly accounted for in a 1-*g* environment, thereby making it difficult for quantitative interpretations of the experimental data to be made. The advent of modern geotechnical centrifuge modeling in the late 1980s addressed this limitation and greatly increased the acceptance and use of physical modeling for geotechnical engineering research. Physical modeling, especially in high gravity centrifuge environments, has evolved rapidly over the past several decades. Today, there are well established and validated laws of similitude to relate the behavior of reduced scale models to prototype earth systems (e.g., Santamarina and Goodings 1989; Iai 1989; Schofield and Steedman 1988; Culligan et al. 1996). Moreover, advances in system control, sensing, and experimental design have significantly improved the performance of test systems while minimizing the effects of instrumentation and boundary conditions on model response. Reviews of contemporary physical modeling practice have been presented by Paulin et al. (1993), Kutter (1995), Wood et al. (2002), and Garnier (2002), among others.

While physical modeling remains largely a tool for research, increasingly it is being used in both geotechnical engineering practice and education. For example, Becker et al. (1998) discuss how physical modeling was used to help design the foundation of the Confederation Bridge and Yang et al. (2004) highlights the role of centrifuge modeling for the seismic retrofit design of the George Massey Tunnel. Other recent practice-related applications of physical modeling are presented by Anderson et al. (2003) and Terashi et al. (2004). As an educational tool, physical modeling is now being used at universities worldwide to teach fundamental yet complex concepts of soil mechanics such as bearing capacity, lateral earth pressure, slope stability, and flow through porous media (e.g., Craig 1989; Mitchell 1998; and Dewoolkar et al. 2003). Moreover, the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program, a recent modeling initiative in the United States, includes a significant educational component (Anagnos and Fratta 2004) that is expected to further promote the use of modeling in education.

As the use of physical modeling in geotechnical engineering education grows, it is important to identify a strategic approach for introducing this simulation technique into courses in a way that ensures the greatest benefit for students. While it has long been recognized that students can improve their understanding of complex mechanisms and phenomena by engaging in highly visual, kinesthetic activities such as physical modeling, this alone does not ensure that comprehensive learning will occur (Wankat 2001). To maximize its educational benefits, physical modeling must be integrated into geotechnical engineering instructional modules in a manner that recognizes the natural learning cycle of students.

This paper reviews educational applications of physical modeling and presents a comprehensive but straightforward learning theory-based approach for integrating model demonstrations and experiments into geotechnical engineering instructional modules. There is convincing evidence that a student's understanding and retention of fundamental concepts will be enhanced if physical modeling is strategically integrated into coursework. Although this paper focuses on physical modeling for geotechnical engi-

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neering, the approach presented here has obvious applications to other civil engineering topics such as structures, mechanics, and hydraulics. In the latter part of the paper, an example of a physical modeling-based instructional module is presented to illustrate an application of this approach.

Benefits of Physical Modeling for Geotechnical Engineering Education

Laboratory instruction, which has traditionally played a prominent role in engineering education, allows students to develop skills in experimentation, data interpretation and synthesis, communication, and teamwork. In addition to these benefits, physical modeling offers some unique advantages pertinent to teaching geotechnical engineering.

1. Physical models clearly portray complex, nonlinear geotechnical mechanisms and phenomena that are otherwise difficult to visualize;
2. By directly observing geotechnical systems at the model scale, students develop an intuition and physical sense for the fundamental mechanisms that govern the behavior of these systems;
3. Small scale models may be tested to collapse, thereby allowing students to witness, first hand, failure mechanisms that are not seen in traditional soil mechanics laboratory sessions, which usually focus on element testing; and
4. Through back analysis of physical model experiments, students can directly assess the deviation between the predicted and actual performance of geotechnical systems.

From a pedagogical perspective, there is a significant body of research that suggests when used in conjunction with traditional instruction methods such as lectures, highly kinesthetic, interactive activities such a physical modeling can improve learning and motivate students. This is because integrated classroom-experimental instructional modules require students to use multiple perception modes (i.e., auditory, kinesthetic, and visual; Wankat and Oreovicz 1993), engage in a wide array of learning activities (Felder and Silverman 1988), and to participate in hands-on, “active” learning exercises (O’Sullivan and Copper 2003). Consider as an example data presented by Stice (1987) (compiled from an earlier study) that found when students learned by reading alone, their retention was only 10%. Similarly, hearing and seeing alone yielded retentions of 26 and 30%, respectively. Retention dramatically improved when students used several modes of perception and engaged in a variety of learning activities. Student retention increased to 50% when they both saw and heard instructional material, and 90% when then spoke about and used the instructional material. Other studies infer that physical modeling may provide motivation for learning. For example, learning constructivists have noted that laboratory demonstrations can have the effect of creating a “disequilibrium” in students, requiring them to revise their understanding and inspiring more in-depth learning of a subject matter (Bodner 1986; Wankat and Oreovicz 1993).

There are also broader applied benefits of physical modeling for education. By exposing students to this interesting and highly visual simulation technique, they may recognize civil engineering as a progressive, highly innovative discipline. This awareness may help draw and retain talented students to the profession. From a practical perspective, educational applications of physical modeling provides students with hands on experience with a technique that current trends indicate will see increasing use in practice for the analysis and design of complex geotechnical systems.

Applications of Physical Modeling for Geotechnical Engineering Education

Craig (1989) was one of the first to formally discuss physical modeling for geotechnical engineering education. He describes a modeling initiative that began in the mid-1970s at the University of Manchester where experiments were performed using an inexpensive “teaching centrifuge.” The teaching centrifuge, which has an effective radius of 300 mm and a centrifugal acceleration capacity of 500 *g*, includes a synchronized stroboscope that allows models to be directly observed during an experiment. Craig (1989) notes that the teaching centrifuge is used to illustrate concepts of slope stability, slope–foundation interaction, tunnel stability, and lateral earth pressure theory. Mitchell (1994, 1998) discusses use of a 2.25 m radius centrifuge to teach topics in geoenvironmental engineering such as unsaturated soil mechanics and contaminant transport. Mitchell (1994) reports that physical modeling activities often stimulate interest in geotechnical engineering among students. He notes that modeling can be particularly valuable for student independent projects. Caicedo (2000) describes an instructional centrifuge similar to that developed by Craig (1989) that is used to perform laboratory simulations of shallow foundations, pile and pile groups, and gravity, sheet pile, cantilever, and mechanically stabilize earth (MSE) retaining structures. In lieu of instrumentation, a grid is placed over the transparent side panel of the model container, which allows students to develop vectors of displacement that occur during an experiment. Caicedo (2000) also discusses modeling in the context of a “learning by doing” instructional module and describes a capstone course where student groups design a geotechnical system, test it to failure in the centrifuge, and later backanalyze the experiment. Bucher (2000) describes the use of physical model experiments conducted in a 1-*g* environment to illustrate concepts of lateral earth pressure, dam design, and flow though porous media. He suggests the use of enhanced visualization technologies such as video imaging, which would allow instructors to more effectively present model experiments to large groups of students (100–150) in real time.

Reflecting its growing popularity, several recent articles on educational applications of modeling were presented at the most recent International Conference on Physical Modeling in Geotechnics (Guo et al. 2002), which included work by Newson et al. (2002) and Madabhushi and Take (2002). This conference was preceded by a workshop on modeling for education, where presentations highlighted teaching applications of modeling at universities in North and South America, and Europe (Phillips and Goodings 2002). Newson et al. (2002) details a 350-mm radius, 400-*g* capacity instructional centrifuge with a digital video camera and stroboscope. The imaging system can be used to measure deformations during an experiment. Newson et al. (2002) discuss several teaching applications of the centrifuge including back-analysis of experiments involving bearing capacity, lateral earth pressure, and interface friction in soils. Madabhushi and Take (2002) discuss an 800-mm-diameter, 471-*g* capacity minidrum centrifuge used for graduate level instruction. The minidrum centrifuge is instrumented with pore-water pressure transducers, load cells, and displacement monitors, thereby allowing highly quantitative experiments to be performed. They describe two experi-

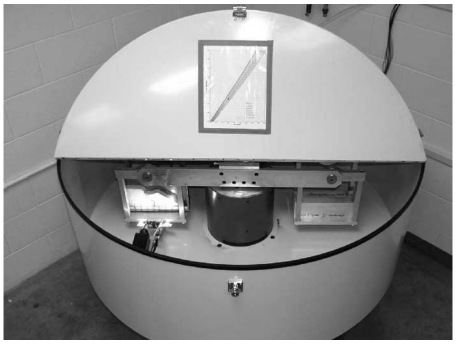

Fig. 1. Instructional centrifuge at Univ. of Colorado, Boulder. Photograph shows failed slope stability model in container to left (Photograph courtesy of Professor Dobroslav Znidarcic, used with permission).

ments involving embankments and shallow foundations on soft ground.

Most recently, Dewoolkar et al. (2003) detail the design and fabrication of a 610-mm-radius, 400-*g* capacity instructional centrifuge (see also Collins et al. 1997). The centrifuge includes a stroboscope for monitoring deformations during an experiment and a pneumatic actuator for applying loads to models. They also discuss applications of this device for undergraduate laboratory experiments involving slope-stability and lateral earth pressure. The centrifuge described by Dewoolkar et al. (2003) was recently redesigned and upgraded by Znidarcic and Ko (2005). The fabrication plans of this newer educational centrifuge, which is shown in Fig. 1, are available from the University of Colorado, Boulder (Znidarcic, private communication, 2005).

Table 1 summarizes these and other applications of physical modeling for geotechnical engineering education.

Table 1. Applications of Physical Modeling for Geotechnical Engineering Education

Reference(s)	Experimental device	Instructional topics
Craig (1989)	Centrifuge	Slop stability Shallow foundations Tunnel stability Lateral earth pressure theory
Mitchell (1994, 1998)	Centrifuge	Unsaturated soil mechanics Contaminant transport
Caicedo (2000)	Centrifuge	Shallow foundations Pile foundations Lateral earth pressure theory
Bucher (2000)	1-*g* modeling	Lateral earth pressure theory Dam design Flow though porous media
Newson et al. (2002)	Centrifuge	Shallow foundations Lateral earth pressure theory Interface friction in soils
Madabhushi and Take (2002)	Centrifuge	Slop and embankment stability Shallow foundations
Culligan and Nepf (2002)	1-*g* modeling	Contaminant transport (K-12 educational outreach)
Dewoolkar et al. (2003)	Centrifuge	Slope stability Lateral earth pressure theory Shallow foundations

Kolb's Learning Theory

Overview

In the 1970s and 1980s prominent learning theorists such as Mezirow (1978) and Freire (1973a,b) began to see critical reflection of an experience as a crucial step in the learning process. Building on this and other early work, Kolb (1985) introduced the "theory of experiential learning" as the basis for his model of the learning process. Kolb's (1985) learning model has since been applied to a variety of instructional levels (primary, secondary, high school, college, and adult education) and is popular in educational practice. Kolb described four elements of learning that were arranged in a circular model (Fig. 2): "concrete experience," "observation and reflection," "abstract conceptualization," and finally, "active experimentation." Kolb believed that comprehensive learning could only occur when students sequentially progress through each element of the learning cycle; students who shortcut the learning cycle using only their preferred learning elements learn significantly less. Upon completion, the entire learning cycle may be repeated, resulting in a deeper and more comprehensive understanding of the subject matter; in this sense, the model may actually be considered more spiral then circular (Wankat and Oreovicz 1993).

While many different learning theories have been proposed, Kolb's model, modified for teaching (McCarthy 1987) as described below, was selected for this research based on several considerations.

1. Kolb's (1984) model is conceptually similar to many other established learning theories (for example, those of Jean Piaget and Kurt Lewin) and therefore reflects a mainstream understanding of the learning process;
2. Kolb's model [as modified for teaching by McCarthy (1987)] has previously been applied in engineering courses (Stice 1987; Harb et al. 1993);

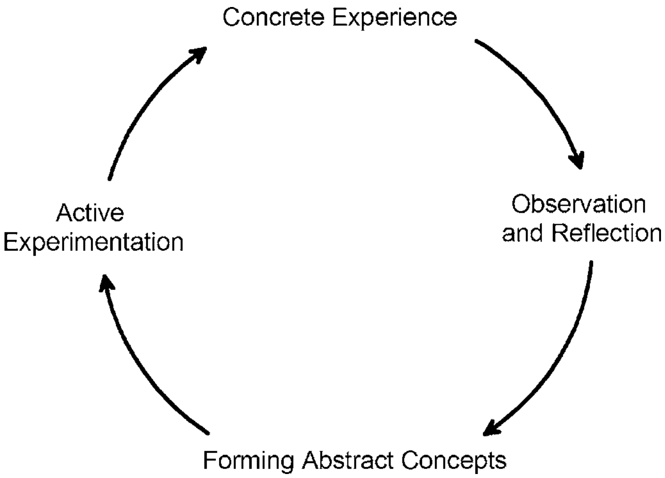

Fig. 2. Kolb's learning cycle showing four elements of learning [adapted from Kolb (1984)]

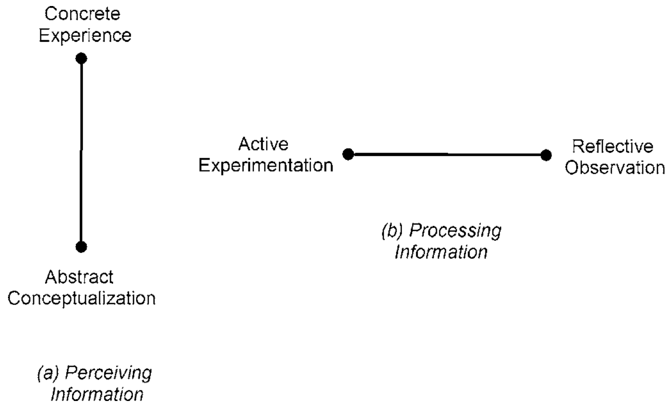

Fig. 3. Dichotomies in way individuals perceive and process information (adapted from Kolb 1984)

3. The model emphasizes a variety of learning styles and thus is appealing to a broad range of students;
4. The model is based on the "theory of experiential learning," which as its name suggests, emphasizes the importance of concrete experiences (e.g., laboratory activities) for learning;
5. The systematic nature of the learning cycle provides students with a greater awareness of their own learning process; and
6. The model is comprehensive, yet relatively easy to apply to geotechnical engineering instructional modules.

Learning models are, in many respects, analogous to mechanics-based models used to represent the behavior of engineering systems. The best models of any type capture the key elements, but often cannot fully describe every aspect of a system. Therefore it must be recognized that while the Kolb's model represents the most important parts of the learning process, the model may not fully describe the complete manner in which each individual learns. Criticism of and limitations to the Kolb's model are discussed later in the paper.

Kolb's Experiential Learning Model

Kolb's learning model (sometimes referred to as a "learning cycle") is based on dichotomies in the way individuals perceive and process information. The dichotomies are arranged orthogonally in the learning cycle (Fig. 3) and reflect a person's preferred style of learning. The vertical axis of the learning cycle is bounded by extremes in the way people perceive information, with some individuals preferring to have a concrete experience (e.g., laboratory experiment) while others favor more abstract conceptualization and analysis (e.g., developing analogies). The horizontal axis shows dichotomies in the way that information is processed. At the extreme, people can process information through active experimentation (e.g., simulations) or by reflective observation (e.g., discussion). Recognize that these are extremes in the way that individuals perceive and process information. While people may be weighted toward one of the extremes, most often they fall somewhere inbetween these limits. Regardless of individual preferences, Kolb (1984) considered the extremes in perceiving and processing information to be required steps necessary for comprehensive learning to occur.

Kolb's model was originally developed to explain the process by which people learn. McCarthy (1987) modified Kolb's model to make it directly applicable to planning teaching activities over a wide range of instructional levels (primary through high school education). The basic elements of McCarthy's (1987) modified learning model, which she calls the "4MAT system," are shown in Fig. 4. As McCarthy's modified learning model was developed specifically for instructional design, it is well suited for the current study. Fig. 4 shows four quadrants (or learning stages) formed by the orthogonal arrangement of the perceiving and processing dichotomies. Kolb and Fry (1975) believed that the learning cycle could be entered at any stage; however, the learning process is usually initiated by a concrete experience (CE) (Smith and Kolb 1986). Examples of CEs include witnessing a phenomenon, observing a laboratory experiment, or performing fieldwork. The CE forms the basis for the quadrant one learning stage, which emphasizes personal involvement with the problem. In

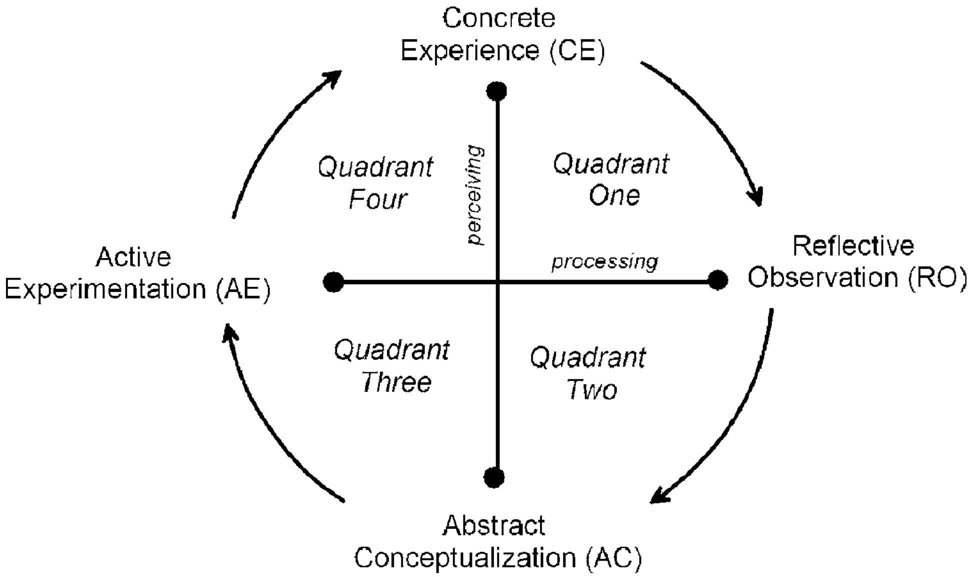

Fig. 4. Kolb's learning cycle as modified by McCarthy (1987) for teaching [diagram modified from McCarthy (1987)]

Table 2. Summary of Learning Cycle Elements

Learning cycle element	Concrete experience	Reflective observation	Abstract conceptualization	Active experimentation
Description[a]	Learner is actively experiencing an activity	Learner is consciously reflecting upon experience	Learner is being presented with or trying to conceptualize a theory or model of what was observed	Learner is trying to plan how to test model or theory, or is planning for a forthcoming experience
Example activities[b]	Laboratory sessions	Journal keeping	Lectures	Homework
		Discussion	Papers	Simulations
	Observations	Brainstorming	Analogies	Case studies
	Reading	Rhetorical questions	Projects	Experiments
	Examples		Reading	Analysis
	Field work			

[a] Adapted from Healey and Jenkins (2000).

[b] Modified from Svinicki and Dixon (1987).

stage one people generally rely on feelings rather than a systematic approach to problem solving and much of the learning that takes place results from specific experiences (Stice 1987). Perceiving occurs in a feeling mode, while processing occurs in a watching mode (Harb et al. 1993). McCarthy (1987) characterizes this stage with the question "why?" It is here that students also learn why the problem is important, thus providing the motivation for more in-depth study.

Having had a CE, students now begin reflective observation (RO) of the problem, which allows them to transform and internalize the information from stage 1, moving then to the second learning stage. Examples of RO activities include journal keeping, discussion of an observed phenomenon, or developing rhetorical questions about an event. The second stage can be characterized by the question "what?" (McCarthy 1987). In this stage people are searching for facts and begin to examine ideas from different perspectives. They rely on objectivity and careful judgment to form opinions and concepts, but do not yet take action (Stice 1987).

Students then begin abstract conceptualization (AC) of the problem, forming the basis of the third quadrant learning stage. At the university level, lecturing is the most common example of an AC activity. Other AC activities include writing papers and working on projects. McCarthy (1987) characterizes the third stage with the question "How?" (e.g., how do I analyze this phenomenon?). Learning now involves the use of logic and rationality rather than feelings, which served as the basis of earlier stages. Students then transition from thinking and rationalization to doing, or active experimentation (AE). Examples of AE include practice-oriented activities such as homework and problem solving.

The AE activities form the basis of the forth quadrant learning stage, which is characterized by the question "what if?" (McCarthy 1987). Students now begin to actively experiment with influencing situations and take a practical interest in understanding what really works (Stice 1987). They can now also begin to adopt what was learned in the first three stages to other situations. For example, they can predict the performance of a system having previously seen it, reflected upon this experience, and learned factual information on what governs its behavior. Students ultimately return to a CE, but now with a much greater understanding then when they first began the learning cycle. If a more comprehensive understanding of a subject matter is desired, students will return to the learning cycle and repeat the process. The learning cycle is summarized in Tables 2 and 3.

It has been suggested that Kolb's learning theory oversimplifies the learning process. For example, some researchers have suggested that learning can occur even if the stages are completed out of sequence (Sharp et al. 1997) or if stages occur simultaneously (Jeffs and Smith 1999). Rogers (1996) notes that some important aspects of learning such as goals, purposes, and decision making are not addressed in Kolb's model. Nevertheless, the basic learning process described by the model is generally well accepted in education practice and the learning cycle is recognized as an excellent framework for planning instructional activities and modules (Wankat and Oreovicz 1993; Tennant 1997).

Kolb's Learning Styles

It is widely recognized that people have different styles of learning (Felder and Silverman 1988) leading to individual preferences for learning activities (Kolb 1984). Recognizing this, Kolb (1985, 1999) formulated a theory of learning styles to identify, within the context of the learning cycle, an individual's preferred style of learning. He developed a self-scored learning style inventory that describes individuals as divergers, assimilators, convergers, or accommodators depending on their preference for perceiving (CE to AC) and processing (AE to RO) information. Willcoxson and Prossser (1996) found Kolb's learning style inventory to be highly reliable and indicated that there is evidence for it's validity.

Divergers are those who favor perceiving and processing information by CE and RO, respectively, and therefore prefer stage one learning activities. Divergers are good at problem identification, understanding people, and finding creative solutions to problems. Assimilators prefer RO and AC and favor quadrant two learning activities. Assimilators are skilled at organizing large amounts of information into logical forms and generally value the rational soundness of an idea over its practical value (Stice 1987). Convergers perceive and process information by AC and AE, placing their preferred learning activities in quadrant three. They generally like practical applications of ideas and theories, are good at deductive reasoning, and are recognized as good problem solvers and decision makers (Stice 1987). Research indicates that engineers in general, and civil engineers in particular, are usually categorized as convergers (Kolb 1981). The last type of learner, accommodators, favor the activities of the forth quadrant and prefer to perceive and process information by AE and CE. These individuals often learn primarily from hands-on experiences and tend to act more on feelings rather then logical analysis of a problem. In addition to the original reference, more detailed information on Kolb's (1985, 1999) learning types may be found in Stice (1987), Sharp et al. (1997), and Wankat (2001).

Table 3. Summary of Learning Stages

Learning stage	Quadrant One	Quadrant Two	Quadrant Three	Quadrant Four
Key question[a]	Why?	What?	How?	What If?
Instructor's role[a]	Motivator	Information giver	Coach/facilitator	Evaluator/remediation
Typical teaching objectives[b]	Introduce subject provide big picture	Provide students with information	Provide opportunity for students to apply material	Provide opportunity for self-discovery
	Provide meaning Generate enthusiasm Show interest	Organize and integrate new material	Help students develop problem solving patterns establish a safe learning environment	Provide opportunities for students to share discoveries
		Provide time for thinking and reflection	establish safe learning environment	Evaluate performance
Examples of student learning experiences[c]	Watching Observing Experimenting Listening	Receiving expert knowledge	Learning important skills	Adapting, modifying, and reworking
			Practicing	
		Establishing links between subjective experience and objective knowing	Using expert knowledge to get something done	Summarizing
		Seeing both the big picture and the supporting details		Creating new questions
			Doing Establishing the link between theory and application	Synthesizing confirming conclusions
		Organizing and classifying		Making new connections
			Seeing how things work	
		Comparing		Teaching
		Blending personal experiences with expert knowing	Predicting	
			Reaching conclusions	
		Patterning		
			Mastering skills	
Preferred learning style	Divergers	Assimilators	Convergers	Accommodators

[a] Adapted from McCarthy (1987).

[b] Adapted from Harb et al. (1993).

[c] Adapted from *About Learning* (2003).

While people have preferred styles of learning, they are capable of learning effectively in all four quadrants of the learning cycle. Indeed, Kolb (1984) argued that to be comprehensive, learning must occur in all stages of the learning cycle. Echoing this, Stice (1987) found that people learn most effectively when they develop learning skills in both their preferred and weaker learning stages. Thus, it is important to include a range of activities that appeal to all four of the learning styles when developing instructional modules. Research indicates that civil engineers are typically categorized as convergers and will therefore naturally gravitate toward AC and AE activities (Kolb 1981). However, overemphasis on quadrant three activities at the cost of less CE and RO will yield less than complete learning. Including CE and RO activities such as model demonstrations and analysis of model experiments into geotechnical engineering instructional modules will increase the likelihood that comprehensive learning will occur.

Discussion

Geotechnical engineering courses sometimes rely upon what McCarthy (1987) has termed the “pendulum style” of teaching, whereby instructional activities oscillate between quadrants two (lecture) and three (homework). Not only does this appeal to civil engineering students, who as convergers favor AE and AC (Kolb 1981), but it also fits the favored learning style of most civil engineering faculty, who generally teach to their preferred learning style (Wankat and Oreovicz 1993). Unfortunately, this approach to teaching is not likely to promote comprehensive learning. As noted above, by incorporating CE and RO activities such as physical model demonstrations and experiments into geotechnical engineering instructional modules, faculty can ensure that students are being trained in all four quadrants of the learning cycle. Rather than performing a single model experiment at the conclusion of a lesson or at a point in time selected for the convenience of the course schedule, it is recommended that modeling activities be sequenced in courses using the learning cycle.

Owing to their highly visual and kinesthetic nature, physical model demonstrations and experiments are well suited to serve as an initial CE to begin the learning cycle. Aside from providing motivation for students to learn about a topic, modeling activities provide students with the opportunity to reflect (RO) upon what they have witnessed during an experiment (e.g., by laboratory notebook keeping or class discussions about the witnessed phenomenon). This leads to traditional quadrant three and four instructional activities such as lecturing, problem solving, homework assignments, and class projects. Having experienced, re-

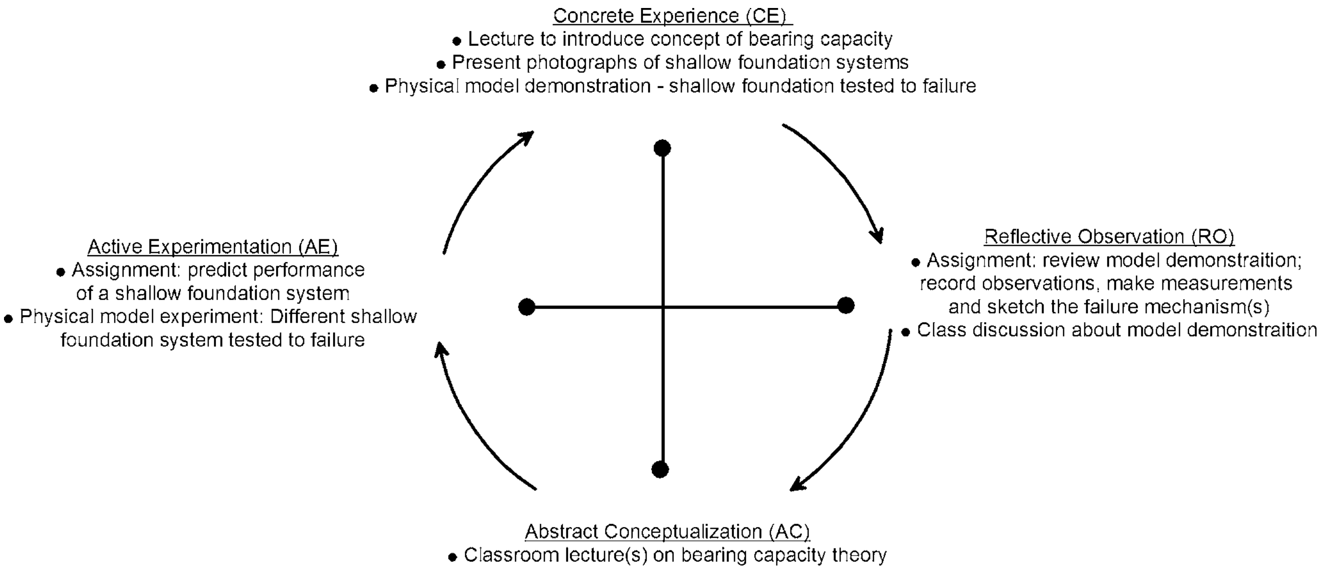

Fig. 5. Application of learning theory approach for development of instructional module on bearing capacity theory

flected upon, conceptualized, and practiced the subject matter, students are ready to progress to the final stage and consider, for instance, a physical model experiment in a more quantitative fashion. For example, rather then simply observing a modeling demonstration (the initial CE), students may predict the behavior of a geotechnical system, perform an experiment, and then compare the predicted and actual results. This may conclude the learning module, or if a deeper understanding of the subject matter is desired, lead to another rotation through the learning cycle. An example of an integrated physical modeling instructional module is presented below.

Example Application: Bearing Capacity Theory

Fig. 5 shows an example of how the learning cycle might be applied as an integrated physical modeling/classroom module for teaching a fundamental concept of foundation engineering, bearing capacity theory (e.g., Coduto 2001). The module begins with a brief lecture introducing the basic concept of bearing capacity. The lecture discusses the purpose of building foundations and includes photographs of actual shallow foundation systems. This is followed by a physical model demonstration where a reduced scale spread footing is progressively loaded until failure occurs, either by rapid, catastrophic movement (i.e., general shear failure in dense soil) or by excessive deformation (i.e., punching failure in loose soil). The demonstration is performed using a small geotechnical centrifuge and recorded through the clear side panel of the model container using digital video imaging, which allows students to see both surface and subsurface deformations. Visualization of the deformation patterns can be enhanced by using alternative layers of sand or clay of contrasting colors (e.g., Dewoolkar et al. 2003). If time does not permit an actual real-time demonstration, experiments can be performed in advance and video archives of the experiment can be presented and reviewed in class. This initial experimental activity provides a CE for the students and arouses their curiosities about the mechanism(s) that govern the behavior of the system, thus providing the motivation for more detailed study.

Archived video of the experiment is distributed to students, who are assigned the task of reviewing the demonstration in detail, recording observations, making measurements, and sketching the failure mechanism(s). These activities are performed using simple imaging analysis computer software, which allow for frame-by-frame review of an experiment and include particle tracking routines that capture the evolution of the foundation system during the test. Students later discuss their observations in class. These exercises require students to reflect (RO) upon the demonstration.

These activities are followed by a classroom lecture on bearing capacity theory (AC), and later by a classroom problem solving session (AE) and related homework assignment (AE). As part of the homework assignment, students are asked to predict the performance (deformation and/or load at failure) of a different type of footing (e.g., continuous, circular) supported on another soil type (e.g., clay, loose, or dense sand). This requires students to apply what they have learned in early stages to a related, but different type of shallow foundation problem. Finally, an instrumented physical model experiment that replicates the homework problem is performed, and students compare how well their predictions matched the experimental results. Students are asked to explain deviations, should they exist, between the theoretical and actual behavior of the system. Discrepancies may be attributed to inaccurate or incorrect estimates of soil or model parameters, use of an oversimplified analytical model, calculation errors, experimental limitations, etc.

Similar instructional modules can be developed for teaching other geotechnical engineering concepts such as groundwater flow, slope stability, lateral earth pressure, and deep foundation capacity, among others. Note that even without on-site access to physical modeling facilities, it is often possible to incorporate modeling into courses using digitally archived (both video and data) model simulation experiments that are now being made openly available on the internet through centrifuge research centers and repositories such as the NEESgrid (NEES 2006).

Summary and Conclusions

As physical modeling sees increasing use in geotechnical engineering education, there is a need for a strategic approach for integrating this powerful simulation technique into courses in a way that ensures the greatest benefits for students. For this reason, a learning theory-based approach, which recognizes the natural learning cycle of students, has been developed. The approach is based on Kolb's (1984) "theory of experiential learning" as modified for teaching by McCarthy (1987). The basic learning process described by the model is generally well accepted in educational practice and is recognized to provide an excellent framework for instructional design. The approach is relatively easy to apply and adapt into traditional geotechnical engineering coursework and requires only a modest effort to adopt. It is expected that by using this approach when designing course modules, instructors will increase the likelihood that comprehensive learning will take place.

The approach begins with a concrete experience, which emphasizes personal involvement with the problem and provides the motivation for more in depth study. This sets the stage for reflective observation of the problem, where students begin to examine ideas from different perspectives and rely on objectivity and careful judgment to form opinions and concepts. This leads to abstract conceptualization of the problem, where students use logic and rationality rather than feelings for learning. Students then move from thinking to doing, or active experimentation. Here students begin to actively experiment with influencing situations and take a practical interest in understanding what really works. Students ultimately return to a concrete experience, but now with a better understanding then when they first began the learning cycle. If a more comprehensive understanding of a subject matter is desired, students can repeat the process. This approach prevents what has been termed the "pendulum style" of teaching (i.e., when instructional activities oscillate between lecture and homework). While this paper focuses on physical modeling for geotechnical engineering, the approach developed here has direct application to the instruction of other topics in civil engineering such as structures, mechanics, and hydraulics.

There remains a need to demonstrate the effectiveness of this approach through student assessment and monitoring. For this reason it is recommended that those integrating physical modeling into geotechnical engineering courses develop formal assessment plans to document its effectiveness. The writer is currently overseeing such efforts at Drexel University.

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