

PHYSICAL MODELS FOR EXPERIENTIAL LEARNING IN GEOTECHNICAL ENGINEERING

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ABSTRACT

Physical models constructed to support experiential learning of geotechnical concepts are utilized by Algonquin College students enrolled in the Bachelors of Building Science program. This paper describes a model used to visualize the effective stress theory and to introduce the concept of vertical stress profiles. Another physical model highlighted in this paper consists of a scaled model of a pump test in an unconfined sand aquifer.

These physical models support experiential learning styles where the students are actively involved with their in-class experience. The models also provide a practical basis for discussion and analysis of geotechnical topics such as soil liquefaction, slope stability and bearing capacity of soils. When demonstrated in class, these models deliver both visual and tactile evidence of fundamental principles in soil mechanics. The models support the application of experiential learning methodologies to assimilate theory by active experimentation.

RÉSUMÉ

Les étudiants inscrits au programme de Baccalauréat en science du bâtiment au Collège Algonquin utilisent des maquettes pour accompagner l'apprentissage expérientiel des notions de base de la géotechnique. Cet article présente une maquette utilisée pour visualiser la théorie de la contrainte effective et comme introduction au concept du profil de la contrainte verticale ainsi qu'une maquette d'un test de pompage effectué dans une nappe libre constitué de sable.

Ces maquettes soutiennent une pédagogie active par laquelle les élèves sont directement impliqués dans leur apprentissage en classe. Les maquettes fournissent également une plateforme concrète pour la discussion et l'analyse des notions de base en ce qui a trait à la liquéfaction des sols, la stabilité des pentes et la capacité portante du sol. Lors de leur utilisation en classe, ces maquettes fournissent des exemples visuels et tactiles des notions de base de la mécanique des sols. Les maquettes soutiennent l'application des méthodes d'apprentissage expérientiel pour assimiler la théorie par une expérimentation active.

1 INTRODUCTION

The evolution of Geotechnical Engineering is based on the analysis of empirical and observational findings (Chowdhury and Flentje, 2007) of soil behaviour. It is therefore not surprising that geotechnical education is well-suited for experiential learning methodologies. The author has incorporated this approach to supplement other traditional styles of academic education for students enrolled in the 2nd year course ENG2100–Geotechnical Engineering for the Building Science degree program at Algonquin College, in Ottawa, Canada.

According to Kolb's model of experiential learning (Kolb, 1984) the process of effective learning involves four distinct stages: 1. *Concrete experience*, where the learner finds a new experience or expands on an existing experience; 2. *Reflective observation*, where the learner reflects on the experience and any inconsistencies between the experience and current understanding; 3. *Abstract conceptualization*, where the learner creates or modifies an existing abstract concept – analyzing the concepts and forming conclusions and generalizations; and, 4. *Active experimentation*, where the learner plans and tries out what was learned and is able to apply the new knowledge to other situations.

The model suggests that for effective learning all four stages must be completed, as illustrated in Figure 1:

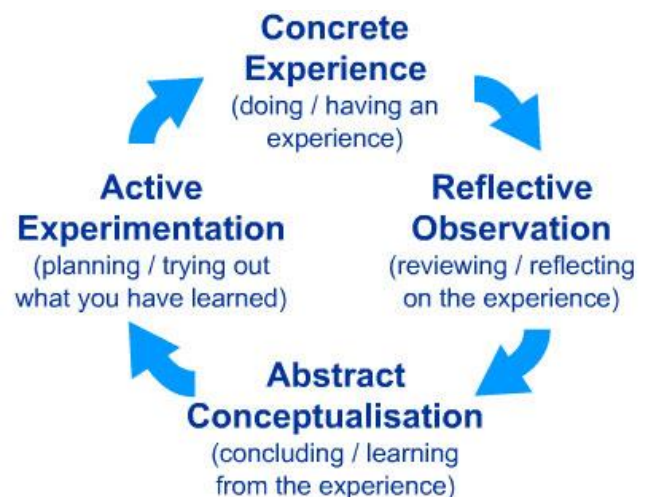


Figure 1. A 4-stage learning cycle (McLeod, S. 2013)

Another constructivist teaching strategy for effective learning in science is the **5E** instructional model that was developed in 1987 by the Biological Sciences Curriculum

Study (Bybee et al. 2006). The **5E** model advocates the application of five components of the learning process illustrated in Figure 2:



Figure 2. The **5E** instructional model cycle (NASA eClips 2019)

In the **5E** model the learner can experience five distinct stages that can be applied to individual lessons or to entire subjects. The learner can build the understanding of the topic covered through the following five stages: 1. Engage is designed to capture the learners' interest and assessing prior understanding. 2. Explore allows the learners to immerse themselves in the concepts and enhance their understanding. 3. Explain provides the learners with an opportunity to communicate and discuss what they have learned. 4. Elaborate allows the learners to apply their new knowledge and extend their understanding of its implications. 5. Evaluate provides both learners and teachers with feedback on how much learning has occurred.

Different learners may adopt one or more modalities for assimilating new information and experiences; Visual, Auditory or Kinesthetic. The Kinesthetic modality is based on movement or action and tactile feeling. Learners' preferences can vary and normally one (or two) of these learning styles is dominant. While a preferred learning style is often associated with different disciplines (e.g. visual and architecture, auditory and law, kinesthetic and engineering), the individual preference for learning style may not always to be the same for all tasks.

This paper describes two physical models that are used to support experiential strategies for learning geotechnical concepts by Algonquin College students enrolled in the Bachelors of Building Science program. The behaviour of soils (a multi-phase material that includes solid, liquid and gas) is often less intuitive to the novice learner than other single-phase materials used in building construction. Therefore, these models prove to be most valuable to engage learners and particularly those that adopt the Kinesthetic modality.

2 EFFECTIVE STRESS MODEL

2.1 Effective Stress Principle

Terzaghi's principle of Effective Stress is described by a very simple mathematical expression in Equation 1 (Terzaghi and Peck 1987):

$$\sigma' = \sigma - u \quad [1]$$

where, σ' = effective or interparticle stress,
 σ = total stress, and
 u = the pore (water) pressure or neutral stress.

In spite of the mathematical simplicity of Equation 1, it may prove somewhat difficult for the novice learner to fully understand the concept of effective stress in soils, since the behaviour of geotechnical materials may not be as intuitive relative to other construction materials.

2.2 Demonstration Model

A portable physical model (Figure 3) was constructed to aid Algonquin College students to visualize the effective stress theory developed by Karl Terzaghi and explore the mechanics of soils.

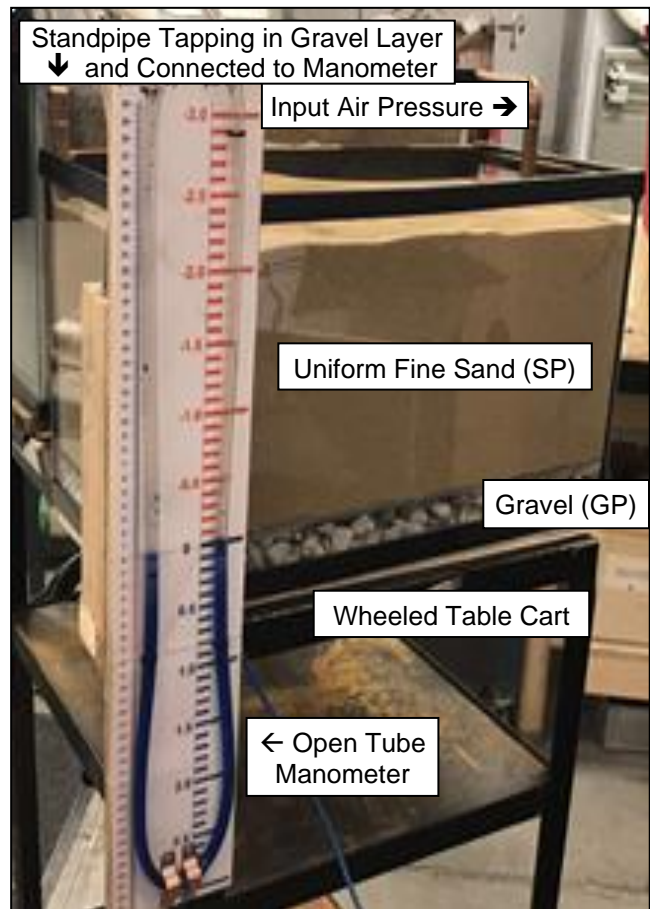


Figure 3. Effective stress demonstration model

The model shown in Figure 3 consists of a standard fishtank (45 cm wide x 25 cm long x 30 cm high) filled with uniform sand placed over geosynthetic filter materials and a manifold of perforated pipes embedded in a gravel layer. The manifold is fed by an air supply line that is equipped with a shut-off valve and a regulator to produce various ranges of either positive or negative pore pressure. A standpipe connected to an open-tube manometer displays the pressure head (cm) at the bottom of the sand layer. The manometer's dual-scale is also calibrated to display pore pressure levels in units of kiloPascal (kPa). As seen in Figure 3, positive pressures are labeled in blue, whereas suction is labeled with negative numbers in red. The model is also equipped with a digital pressure gauge to display changes in pore pressure at the bottom of the sand while the top of the sand layer is kept open to atmospheric pressure.

The following Figure 4 shows some details of the model construction from the bottom up:

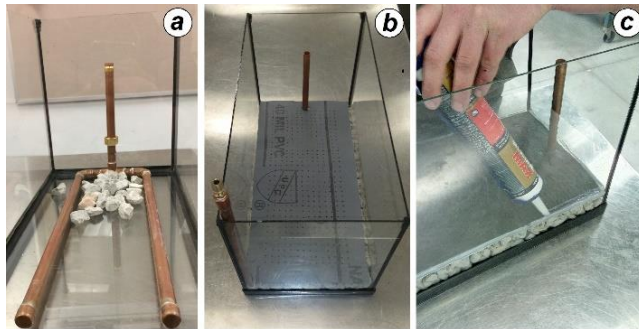


Figure 4. Construction details of the effective stress model

The manifold consists of 13-mm diameter perforated copper pipes embedded in a layer of poorly graded gravel (Figure 4a). The gravel is covered by a composite layer of plywood and PVC membrane (Figure 4b) that has small perforations arranged along a square grid pattern. The perforated composite PVC/Plywood facilitates the even distribution of air pressure through the sand, which is critical for the model performance. Figure 4c shows the silicon sealing that minimizes the escape of air pressure through the glass side-walls. Finally, the model is filled with dry, brown, fine uniform sand. The particle size distribution for the brown sand are presented in the following Figure 5:

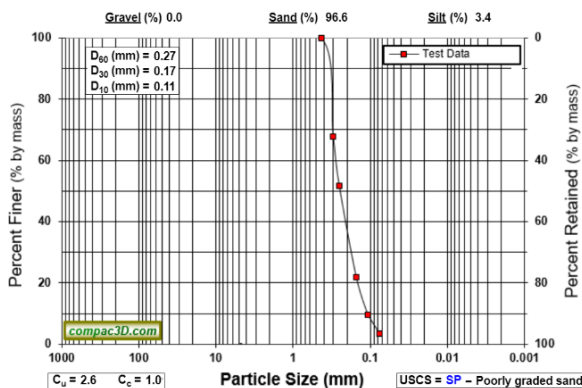


Figure 5. Particle size analysis (from Compac3D, 2014)

The results of a particle size distribution analysis conducted on the brown sand (Figure 5) indicate that the material is classified as SP – poorly graded sand in accordance with the Unified Soil Classification System (USCS).

The model's operator may select various ranges of positive or negative pore pressure. Thus, the operator can demonstrate that effective stress theory can account for either weakening or strengthening of the granular soil as the pore pressure is adjusted from neutral to either positive or negative, respectively. In the author's experience, this model can support all aspects of the **5E** experiential learning cycle, and it is particularly useful to Engage students with visual and kinesthetic learning styles. Through visual, action and tactile sensations, the engaged learner can Explore, Explain and Elaborate on various applications of the geotechnical theory. Finally, the instructor and/or learners can Evaluate the gained knowledge and experience by means of surveys, quizzes, discussions or other methodologies.

The interactive nature of the effective stress demonstration model has proven to be very useful for students to participate in all five stages of the 5E model, as evidenced by the video clips posted at the following links:

- o <http://bit.ly/2DFjSTY> (Ferguson et al. 2016) and
- o <http://bit.ly/2NkcWCM> (Iskandar et al. 2019)

2.3 Geotechnical Profiles Visualization in Real-Time

The visualization and understanding of vertical stress profiles are key requirements for solving most geotechnical problems, including slope stability, bearing capacity, soil liquefaction, consolidation and groundwater seepage. Geotechnical profiles normally consists of a 2-dimensional graph of total, neutral and effective vertical stresses plotted versus depth.

The derivation of the geotechnical profiles is based on the following equations:

$$\sigma_v = \gamma z \quad [2]$$

$$u = \gamma_w d \quad [3]$$

$$\sigma'_v = \sigma_v - u \quad [4]$$

where, σ_v = total vertical stress

γ = unit weight of soil,

z = depth below ground surface,

u = pore (water) pressure or neutral stress

γ_w = unit weight of water,

d = depth below the groundwater table, and

σ'_v = effective vertical stress.

The geotechnical profiles corresponding to the sand layer are shown in Figure 6. The total vertical stress (σ_v) increases linearly with overburden depth (z) as defined by Equation 2. As suggested in Figure 6, the unit weight can also be demonstrated in class by taring a 4-inch diameter standard Proctor (ASTM D698, 2012) mold having a volume of 943.9 cm³ and weighing it filled with dry sand (mass of 1600 g), giving a dry unit weight $\gamma = 16.6$ kN/m³.

The pore pressure also varies linearly with depth (z) from atmospheric conditions at surface to the value displayed by the open-tube manometer at the bottom of the sand layer.

Since the air line is provided with a shut-off valve and a regulator, the model's operator can select various ranges of either positive or negative pore pressure at the base of the bottom of the sand. The open-tube manometer shown in Figure 4 provides a visual display which is supplemented by a digital pressure sensor that monitors the pore pressure. An Arduino micro-processor is used to interface the pressure sensor with a computer in order to display in real-time the geotechnical profiles shown in Figure 6.

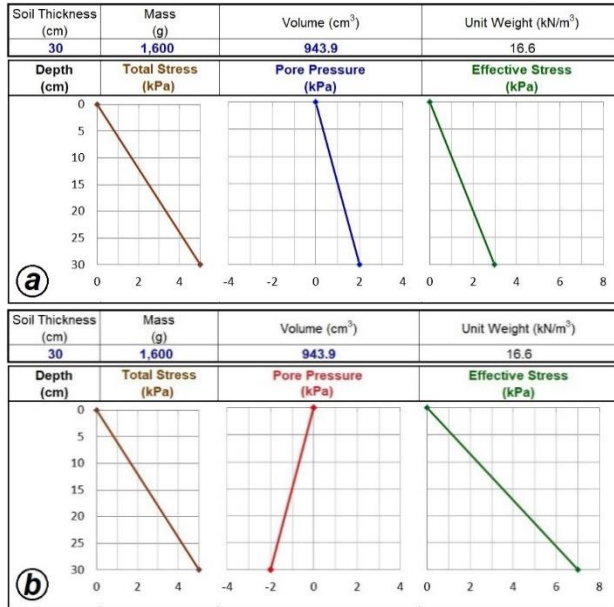


Figure 6. Interactive geotechnical profiles

3 HYDROGEOLOGIC MODEL

3.1 Pump Test Theory

Geotechnical applications such as dewatering or contaminant migration may require the performance of a pump test, schematically shown on the following Figure 7:

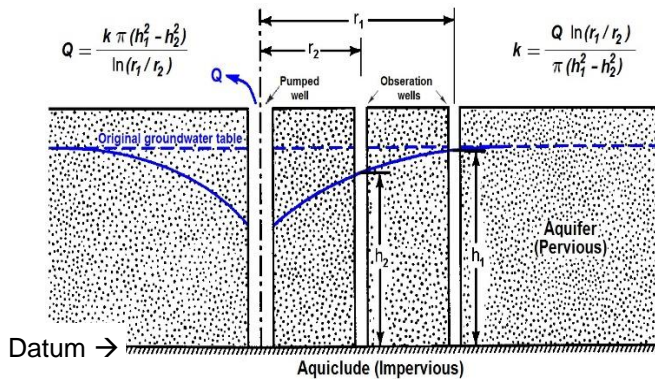


Figure 7. Schematic of pump test in unconfined aquifer (adapted from Coduto et al. 2010)

The flow rate, or the hydraulic conductivity, of an unconfined aquifer can be expressed by Equations 5 and 6 (Coduto et al. 2010) as follows:

$$Q = k \pi (h_1^2 - h_2^2) / \ln(r_1 / r_2) \quad [5]$$

$$k = Q \ln(r_1 / r_2) / \pi (h_1^2 - h_2^2) \quad [6]$$

where,

- Q = flow rate to the pumped well
- k = hydraulic conductivity of aquifer
- r₁ = radius to farthest observation well
- r₂ = radius to nearest observation well
- h₁ = total head in farthest observation well
- h₂ = total head in nearest observation well

Equations 5 and 6 apply within the unconfined aquifer's cone of depression and they require that the datum be located at the bottom of the aquifer. These equations may present a higher level of complexity to the novice learner and the concepts can be affirmed with the following hydrogeologic physical model.

3.2 Pump Test Demonstration Model

A portable physical model of a pump test was constructed using a similar fish-tank to the one used for the effective stress model described in section 2.2. The glass tank was 45 cm wide x 25 cm long x 30cm high and was filled with uniform brown sand, as shown in the following Figure 8:



Figure 8. Pump test demonstration model

The model includes a vertical layer of 25-mm gravel that is located along the side of the tank and serves as a recharge zone. The gravel is separated from the brown sand by geosynthetic filter material. The pumped well and observation wells consist of PVC pipes slotted in halves and affixed to the front glass panel using clear silicone. All wells are perforated at 25-mm centers and wrapped with a filter fabric to reduce the clogging by the surrounding sand.

The pump test demonstration can start with a fully saturated sand layer where the original water table is horizontal under static conditions. The model's operator can highlight this condition by injecting a food coloring dye into each of the PVC wells as shown in Figure 9a. The pump test can then be conducted by withdrawing groundwater from the pumped well using a syphon pump

(or equivalent means) to remove groundwater at a constant flow rate. As the pump test progresses, the water levels at the pumped and observation wells drop until they all reach a steady level corresponding to a steady flow rate.

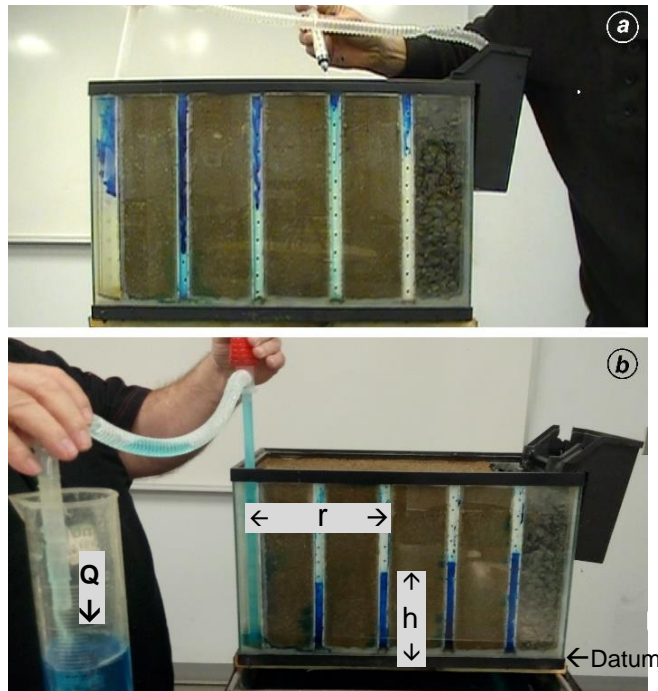


Figure 9. Pump test demonstration in progress

The model demonstrates that pumping the well in the unconfined aquifer causes dewatering of the material within an inverted, roughly cone-shaped volume, called the cone of depression or cone of influence. The height of the dyed water above the base of the sand (datum) defines the total head at each observation (Figure 9b). The flow rate can be measured using a graduated cylinder and stopwatch to compute the volume of water withdrawn over given a period of time. The learners can actively participate in the measurements of flow rate (Q), hydraulic head (h) and radial distance (r) to the pumped well at two observation wells. Then, the hydraulic conductivity (k) of the sand can be estimated using the equations provided in Section 3.1. However, the measured flow rate must be prorated considering that Equations 5 and 6 are based on full radial flow (360 degree) towards the pumped well, whereas the model represents only one-quarter of the area of influence (90 degrees).

In the author's experience, the hydrogeologic model presented is very useful for the learner to visualize new concepts and terminology being introduced (e.g. datum, total hydraulic head, cone of depression, unconfined aquifer, etc.). The model also allows learners to actively participate in obtaining measurements that applied to theoretical formulae can provide hydrogeologic performance of the aquifer. Through visual observations and active participation the learner can experience all stages of the 5E model.

4 CONCLUSIONS

Geotechnical Engineering as a discipline is well-suited for applying experiential learning methodologies as a supplement to other traditional styles of academic education. This paper describes two portable physical models used in the classroom by the author for teaching geotechnical concepts to Algonquin College students enrolled in the Bachelors of Building Science degree program.

Since geotechnical materials are multi-phased (solid, liquid and gas), their behaviour is often less intuitive to the novice learner than other construction materials. These models can aid the learner to assimilate and apply geotechnical concepts through active participation, as well as visual and tactile sensing of soil behaviour.

The effective stress model offers the learner the opportunity to experience soil behaviour, to analyze and discuss various applications such as soil liquefaction, slope stability and bearing capacity. It also provides an interactive feature to compute geotechnical profiles in a real-time basis.

The hydrogeologic model presented aids the learner to visualize new concepts and terminology. The model also allows learners to take measurements and apply theoretical formulae to assess the hydrogeologic performance of an unconfined aquifer.

Both physical models presented can support all stages of the 5E instructional model (i.e. Engage, Explore, Explain, Elaborate and Evaluate) and the application of experiential learning methodologies to assimilate theory by active experimentation.

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