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Laboratory Experiments in Soil Mechanics by Means of Digital Twins and Low-Cost Equipment

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ABSTRACT: The Soil Mechanics Laboratory has been traditionally an important component in most courses on Soil Mechanics and Geotechnical Engineering. Nowadays, the available technology allows to build low cost systems that bring the experiment to the student in a simple manner. The paper describes two examples including a physical model of a falling head permeameter and a simple device to perform direct shear tests. Students can be directly involved in the development of these pieces of equipment, so they become familiar with a technology that is simple and available at low cost. Simplifying and decreasing the cost of educational experiments puts at the grasp of students concepts of monitoring, automation, digitalisation and real applications and eventually unites theory and practice. This integration of knowledge is a fundamental aspect in the future development of Internet of Things and Construction 4.0.

Keywords: Laboratory, digital twins, low-cost equipment

1 Introduction

To some extent Soil Mechanics and Geotechnical Engineering is a subject with two souls. One is based on rigorous scientific postulates, developing concepts by means of theoretical assumptions. The other one is based on empiricism and practical applications to real construction problems. Both approaches coexist and an important effort is required by University lecturers and professors to maintain a link between these two souls. Although this difficulty may be present in many subjects within the Civil Engineering Curriculum, it is in Geotechnical Engineering where this duality becomes more evident. This is probably because Soil Mechanics is a relatively young subject and theories are less developed than in Structural Engineering or Hydraulics. Also, the nature of soil complicates any rational analysis based on simple mathematical descriptions. As a consequence of that, the gap between theory and practice seems to be more important than in other disciplines.

Apart from this difficulty, local tradition plays an important role when weighting the percentage of theory and practice in the curriculum. This is a well-documented fact within all branches of Engineering. In some countries, engineering colleges are strongly "science-oriented" shifting away from practice in a process sometimes referred as "academic drift" (Harwood, 2006). This is particularly evident in continental Europe as an outcome of the rationalist tradition. However, in other countries (i.e., Britain, USA), empiricism has been an important point when defining the engineering curriculum. In that case experimentation plays an important role and many concepts are first introduced to students by performing a simple experiment in the classroom (Feisel and Rosa, 2005).

When teaching Soil Mechanics and Geotechnical Engineering it is possible to adopt either one framework (scientific or practice oriented), but in all cases laboratory experiments are carried out or at least described (Jaksa, 2008). The importance assigned to the laboratory work depends not only on the local tradition, but also on the resources available, number of students, etc., as maintaining a laboratory is always expensive even for teaching purposes. The development of virtual labs (e.g. Jaksa et al., 2016) has contributed to the reduction of operational costs, but still classical, real (not virtual) experiments are useful when introducing new concepts to students. Now the technology available has considerably reduced the cost of producing laboratory equipment and a new opportunity for teaching a subject based on experimentation arises.

The paper presents two experiments developed in this context. The first example refers to a falling head permeameter to measure permeability of sandy soils. A simple device was used to perform the experiment using low-cost sensors. From measurements of the level of water at the inlet and the time, it is possible to estimate soil permeability. Using visual digital tools it is possible to represent the experiment in a digital model, so a view of the test including the falling level of water and a real-time analysis of measurements can be presented. This is called a digital twin, that is, a digital replica of a physical model whose behaviour can be observed simultaneously (digitally and physically) in real time. The second example refers to the construction of a direct shear test apparatus using low-cost sensors and a 3D printer. In this case the objective was to replicate a conventional direct shear equipment, appropriate for teaching purposes. The technology available is also useful when developing research-oriented equipment (Pierce, 2012). The quality of the sensors and of the elements manufactured with a 3D printer has improved significantly and these techniques are already being used in research laboratories. This paper points out the new paradigm that this technology provides to Geotechnical Engineering students.

2 Open-source laboratory

The term “open-source” refers usually to a software that is both free and available in source code. “Free” in this context refers to freedom to manipulate, redistribute or modify the code, but does not necessarily mean free of charge. This term has been now extended to hardware (Pierce, 2014), and refers to a hardware whose design is made publicly available and anyone can modify and improve.

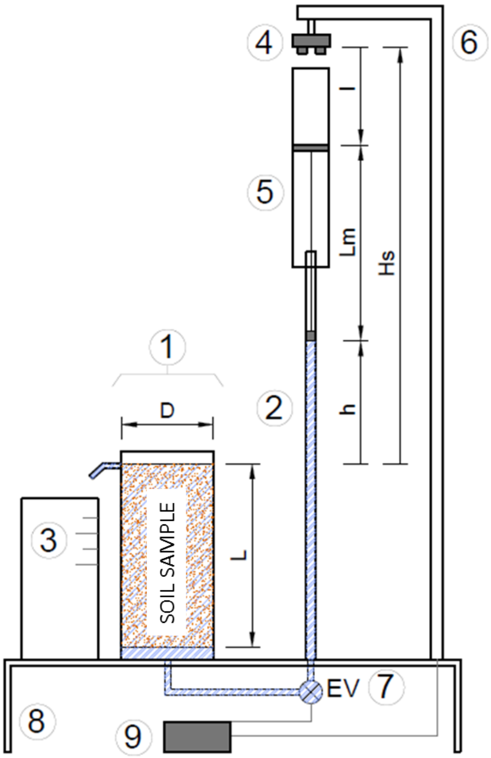
There are a few ingredients involved in this concept. On the one hand, 3D printer technology allows materialising parts of devices by additive manufacturing from a variety of materials. On the other hand, an Arduino microcontroller constitutes the brain of the system. This microcontroller is powerful and easy-to-use open hardware-prototyping platform for students with little to none prior knowledge in electronics. In addition to that, low-cost sensors are used to measure the physical variables in the experiment. Finally, to replicate the model in a digital manner, a graphical user interface can also be developed as part of the system.

There are several examples of application of this technique to Civil Engineering Education (Chacón et al., 2018) including models that are totally developed by students from scratch. The experience of the authors suggests that digital twins can be very useful for the understanding of physical phenomena either in a portable form at the classroom or in the laboratory. In addition to that, students become familiar with sensors and microcontrollers, which is a positive side effect, as most civil engineering students do not know these techniques. Thus, measuring physical variables and interpreting real problems becomes affordable not only in the laboratory, but also when working in practical applications in their future careers.

3 A falling-head permeameter

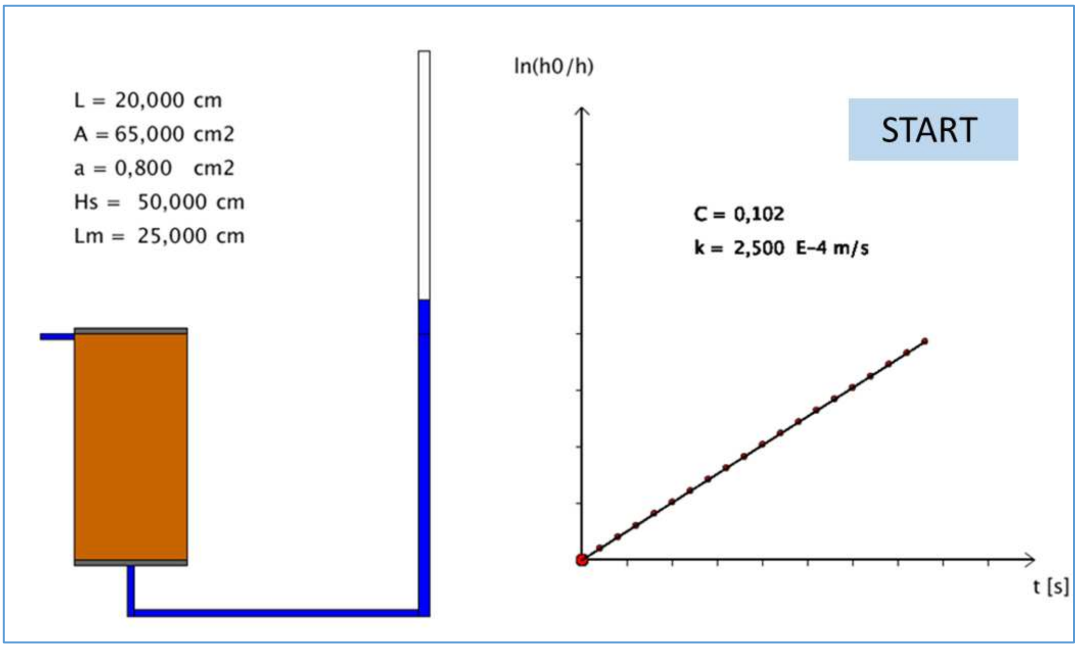
The methodology outlined above was adopted to build a piece of equipment to measure permeability in sandy and silty soils. This test requires the design of a soil column through which water flows for a period of time. The liquid stored in a tank percolates and its height is continuously measured with distance sensors and subsequently shown in real time digitally. The solid parts (supports, etc.) have been designed with impervious 3D printed materials.

Figure 1 presents a sketch of the physical model and Figure 2 shows the digital model fed with the data provided by the Arduino microcontroller UNO board, i.e. a basic board. The digital model developed using a graphical user interface allows to interpret the experiment directly in real time conditions. In this case, the combination of the physical and the digital models helps the student to understand concepts.



1	Soil sample
2	Burette
3	Beaker for water exit
4	Ultrasonic sensor to measure distance
5	Reflection plate floating on the burette water
6	Solid support
7	Solenoid valve, connected to microcontroller
8	Supporting base
9	Arduino microcontroller

Figure 1. Physical model of a falling head permeameter, controlled by an Arduino UNO board (L = sample height, D = sample diameter, Hs = distance sensor - top of sample, Lm = Length of bar connecting the reflection plate and the floating device in the burette, h = distance between burette water level and outlet water level, l = distance from the sensor to the reflection plate)



L = 20,000 cm
A = 65,000 cm2
a = 0,800 cm2
Hs = 50,000 cm
Lm = 25,000 cm

C = 0,102
k = 2,500 E-4 m/s

Figure 2. Digital twin model of the falling head permeameter as shown in the monitor. Left: sketch of the experiment. Right: measured heights and times, interpreted according to equation (1). (A = $\pi D^2/4$ = 65 cm^2, a = burette cross section = 0.8 cm^2, h0 = initial height of water level in the burette from top of the sample, k = soil permeability, C = gradient of the straight line, t = time, refer to Figure 1 for other symbols)

The estimation of soil permeability can be carried out from expression (1) linking water height in the burette and time (Terzaghi et al., 1996):

$$\ln\left(\frac{h_o}{h}\right) = \frac{k\,A}{a\,L}\ t \tag{1}$$

where h_o is the initial height of water level in the burette from the water outlet height (which is the top of the sample), h is that current height of water at time t, k is soil permeability, L is the sample height, A is the sample cross section area and a is the burette cross section area. The plot “natural logarithm of height ratio” versus “time” should be a straight line with gradient C,

$$\mathrm{C} = \frac{k\,A}{a\,L} \tag{2}$$

and from that gradient it becomes straightforward to estimate soil permeability, k. This estimation is carried out in real time, while the experiment is being performed, thanks to the duality physical model – digital model.

Regarding the electronic devices involved, only an ultrasonic sensor and an Arduino microcontroller are required. Figure 3a shows the ultrasonic 40kHz sensor: a sound is emitted and the reflection on a plate produces an echo that is received. Measuring time allows determining the distance from the sensor to the reflecting plate, l, and that value is used to compute the height of water, h:

$$h = Hs - Lm - l \tag{3}$$

where Hs is the distance from the sensor to the top of the sample and Lm is the length of bar connecting the reflection plate and the floating device in the burette.

Figure 3b shows the Arduino microcontroller and the cables connecting the sensor. Programming the Arduino is quite simple and civil engineering students have the opportunity to learn some basic concepts on instrumentation and microcontrollers. What requires more skills is the development of the digital twin. In this case, the picture and the graph shown in real time in Figure 2 were produced using Java programming language by means of a user-friendly software “Processing” (version 3.3.6).

Typically, sandy soils are used for the experiments, because clayey soils have low permeabilities and the flow becomes too slow for teaching purposes. Section 5 describes the experience of implementing this type of activities in the Civil Engineering curriculum at UPC-BarcelonaTech.

The cost of the materials used in the construction of this falling head permeameter is about 100 euros, associated to the cost of the ultrasonic sensor, the solenoid valve and the Arduino microcontroller (excluding the solid plastic parts).

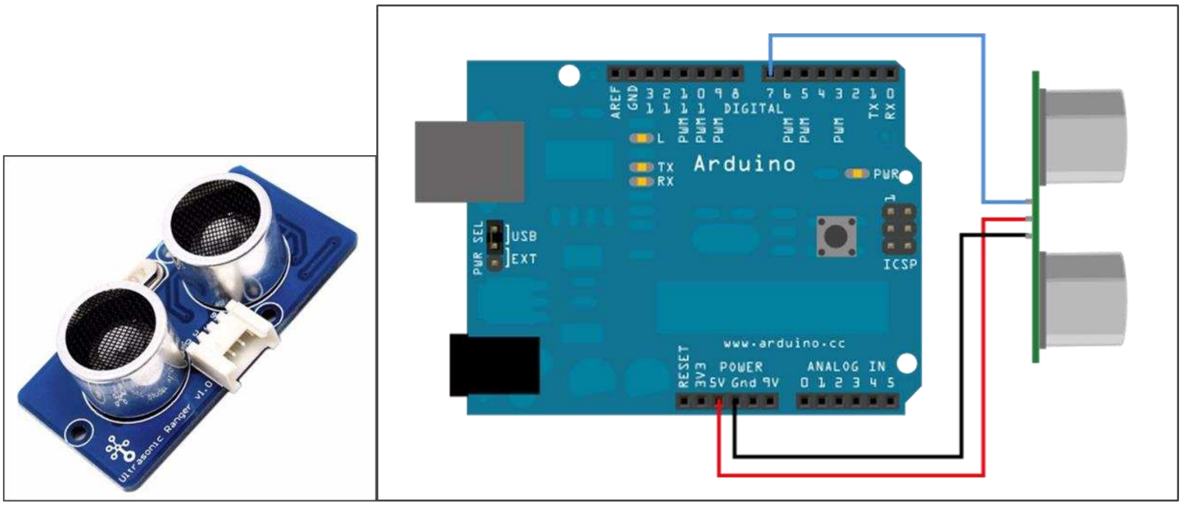


Figure 3. Left: a) ultrasonic sensor. Right: b) Arduino microcontroller and sensor connected

4 A direct shear test apparatus

Another example of the methodology presented above involving low-cost devices in the laboratory is the development of a direct shear test apparatus. This classical test illustrates the important concept of dilatancy in soils, that is, the generation of volume change when a shear stress/strain is applied. Soft soils tend to decrease volume when shearing (negative dilatancy), whereas dense soils tend to increase volume when sheared (positive dilatancy). The coupling between volume and shear distinguishes the behaviour of soils from elasticity and this constitutes a new concept for civil engineering students.

Figure 4 shows the apparatus designed and built by means of a 3D printer. Apart from the solid parts, the other components of the device are:

- An Arduino MEGA microcontroller (with more capabilities than a UNO board, Figure 5)
- Linear guide actuator and stepper motor, to apply an increasing horizontal displacement step by step (Figure 6). Vertical force is constant and applied by means of weights.
- Load cell to measure the horizontal force applied (Figure 7).
- Sensor for vertical displacements based on the Hall effect, that is, the variation of a magnetic field depending on the distance between two magnets (Figure 8).

The device is designed for teaching purposes in a classroom and for the sake of simplicity no water is used. Typically, a dry sandy sample of dimensions 5 cm x 5 cm x 2 cm inside the red box (Figure 4) can be tested. Constant vertical load should be less than 10 Kg to handle the setup (corresponding to a maximum normal stress of about 40 kPa). Horizontal relative displacement is obtained from the stepper motor controlled by the Arduino device. Shear force is obtained from the load cell (Figure 7). Measuring vertical displacement with accuracy constitutes a challenge and the Hall effect transducers have been found to be accurate (Clayton et al., 1989).

This simple configuration is adequate to show the students the concept of dilatancy. If dry sand particles are poured into the box and a low dense sample is "created", a settlement is expected when shearing the soil. However, when dry sand particles are poured carefully and manually compacted with a simple rod to obtain a dense sample, an uplift of the upper part is observed when shearing the soil.

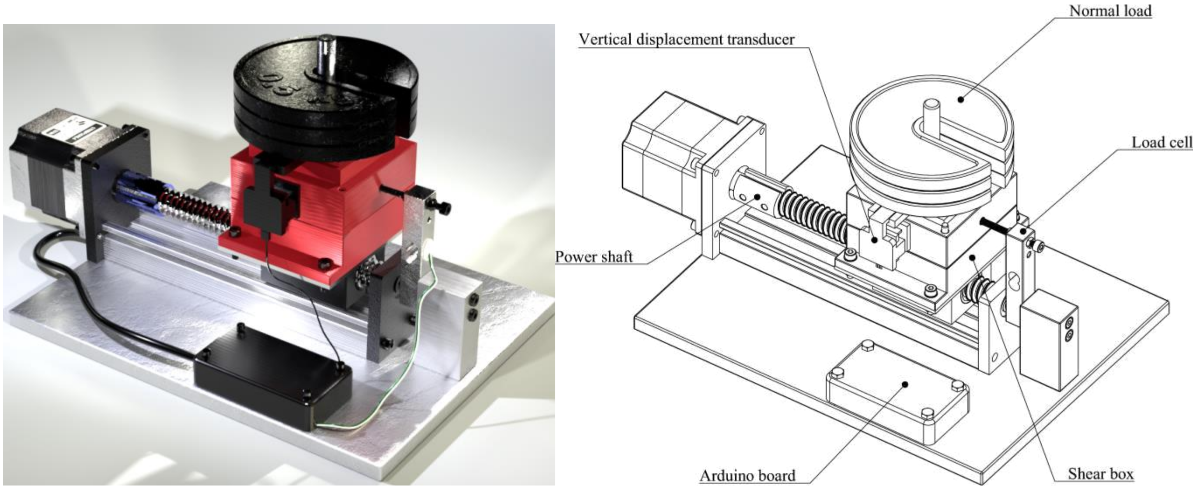


Figure 4. Direct shear test apparatus

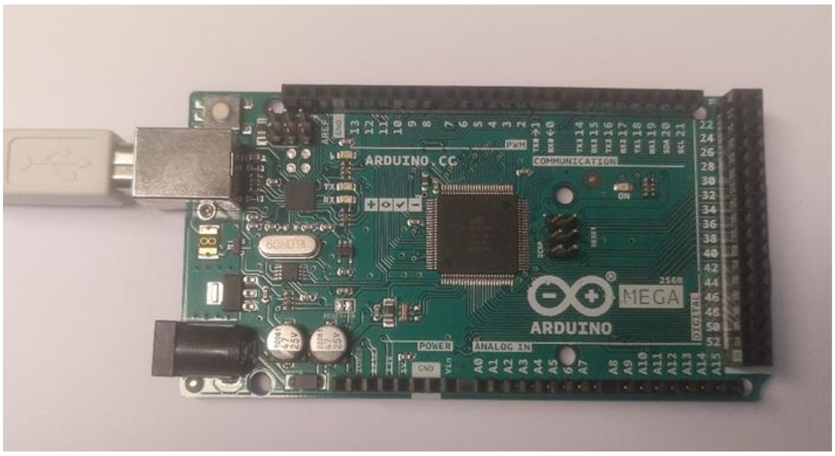


Figure 5. View of the Arduino MEGA board

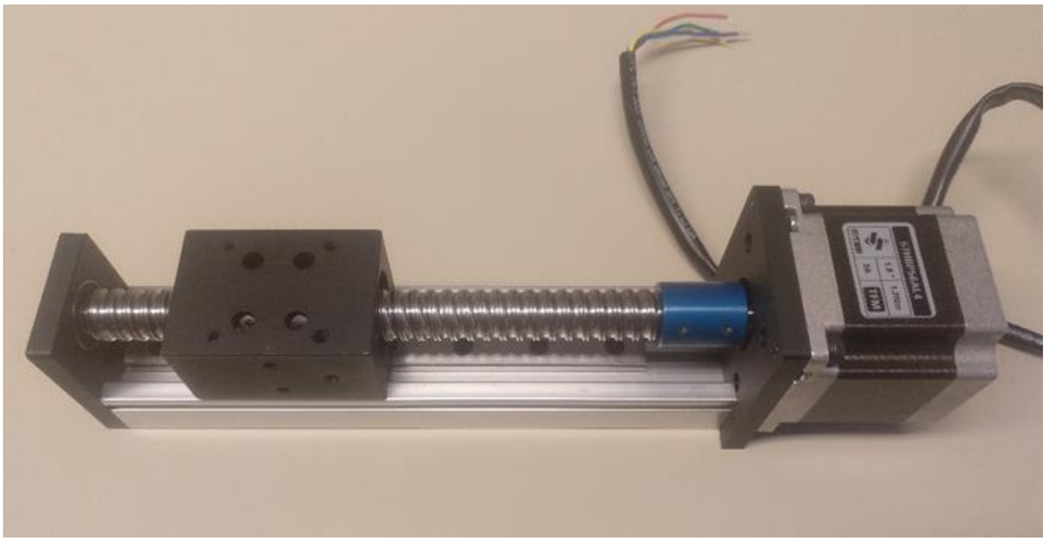


Figure 6. Linear guide actuator and stepper motor

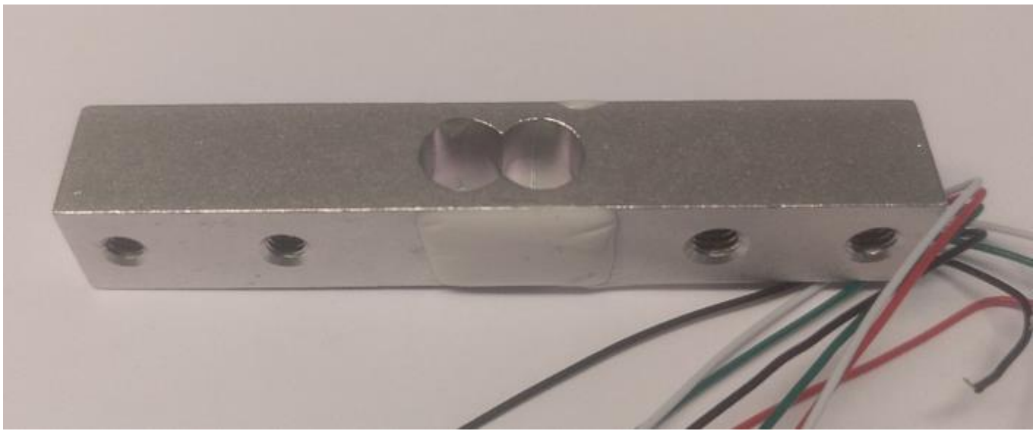


Figure 7. Load cell

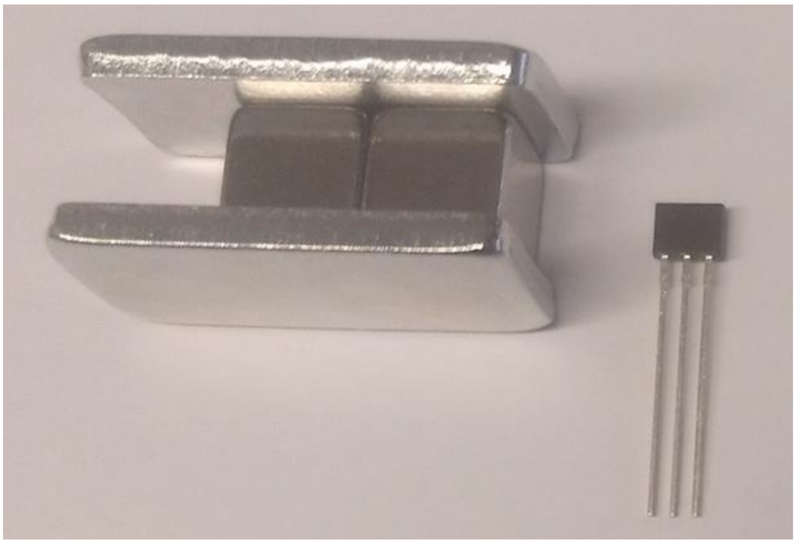


Figure 8. Magnets and Hall effect sensor

Table 1. Cost of the devices used in the direct shear apparatus (euros), excluding the 3D printed items

Device	Model	Function	Cost (€)
Microcontroller	Arduino Mega	Data acquisition and automation	35
Linear guide actuator+ stepper motor	CBX1605-300A +57HBP56AL4	Apply and control linear displacement	114
Load cell + signal conditioner	20 kg load cell +Bluelover Hx711	Measurement of shear force	12
Vertical displacement sensor	Hall sensor 49 E + magnet	Measurement of vertical displacement	3

This direct shear equipment has been developed as a physical model. In this case, a digital twin model has not been developed yet, although it is straightforward from the measurements provided by the sensors and the stepper motor. Normal force is constant and the normal stress is computed dividing the normal force by the contact failure area which is reduced during the experiment. Shear stress is obtained from the load cell measuring horizontal force and computing the value horizontal force over contact area. Horizontal displacement is obtained from the linear guide actuator so the curve shear stress – relative horizontal displacement can be plotted. The vertical displacement sensor (hall sensor) is required to show the coupling between shear deformation and volume change, that is, dilatancy (an effect that cannot be reproduced by the theory of elasticity). Vertical displacements are expected to be small (about tenths of millimetre, depending on the soil density).

The apparatus described cannot be used in general for research or professional purposes. The main drawback is the lack of water (only dry samples are considered) and the low level of stresses applied due to the plastic components used and the “portable” nature of the setup. This is to simplify the design and keep the cost under low values. Table 1 presents that cost and it can be seen that all components cost below 165 euros, excluding the solid parts made with a 3D printer. This is well below the typical cost of a conventional direct shear test apparatus.

Another factor that constitutes a drawback when designing a laboratory low-cost equipment is accuracy, i.e. when measuring displacements of about 0.1 mm. However, in this case, the use of a hall sensor has shown to be convenient for this purpose. In the context of Geotechnical Engineering Education, accuracy when performing experiments is generally not a key issue, as the main objective is to show fundamental concepts. Despite those apparent drawbacks, an improved version of the equipment for standard tests in the laboratory could be built, still at a reasonable low cost if compared with typical prices from industry.

5 Implementation in the Civil Engineering Curriculum

The classical Civil Engineering curriculum has traditionally included some laboratory experiments in several subjects. As a matter of fact, Soil Mechanics BEng students at UPC estimate the permeability of a sandy soil using a classical falling head permeameter, measuring heights with a ruler and time with a chronometer. This is one of the compulsory laboratory works carried out by groups of 3 to 4 students. They spend 3 hours including the preparation of the sample and the setup, performing the experiment and finally observing liquefaction when the hydraulic gradient is too high. They are supervised by a technician and an academic.

The direct shear test is taught to students but they do not perform a test at BEng level. They do that experiment at Master Level (only Geotechnical Engineering students) in teams of 3-4 students, using a fully instrumented device as in professional laboratories. They spend about 3 hours preparing the sample and performing the test, supervised by a technician and an academic. Despite the logic of this approach, there is still room for improvement. By using the open source hardware and software and low-cost equipment, it is possible to facilitate the implementation of laboratory works at undergraduate level and, simultaneously, to show the students several concepts related to the Internet of Things.

With this objective, during the last two academic years, the School of Civil Engineering at UPC-BarcelonaTech has promoted the development of an academic project on Engineering Education aimed at studying the potential of low-cost physical models and digital twins as a pedagogical vehicle for Civil Engineering classrooms. The School has provided some grants ("learning enhancement scholarships") with which students from the 4th year of the BEng degree develop weekly tasks (about 5 hours per week during 3 months), intended to improve teaching within School supervised by academic staff (Chacón et al., 2018). The applications involve several fields, as Steel Structural Engineering, Environmental Engineering, Coastal Engineering and Geotechnical Engineering as well. Some of the developments have been implemented already in normal classrooms.

The initiative of this academic project came from the previous experience of an optional subject on Structural Dynamics at Master Level, which included the development of digital twins as collaborative coursework. Despite the apparent complexity of these devices, the materialisation of these digital artifacts in their simplest form implies the use of a technology, available at low cost under open source conditions: sensors, data acquisition systems and graphical user interfaces. Senior Civil Engineering students can cope with that if they are guided properly.

The School is developing a new Civil Engineering curriculum starting in academic year 2020-21 and, thanks to this experience, a new optional subject on "Digital twins and augmented reality" offered to 4th year BEng students has been proposed. That will require an effort from Civil Engineering students, who are often acquainted with fabrication and programming but not necessarily with electronics. One of the greatest challenges of this type of projects is to assess and, if necessary, remedy the students' lack of background in electronics.

As a consequence of all these initiatives, the popularisation of these techniques among Civil Engineering students is expected to increase, even at Bachelor level. On the one hand, some of the devices developed will be used in normal or laboratory classrooms (i.e. Soil Mechanics). On the other hand, the optional subject on "Digital twins and augmented reality" will provide students with the basic knowledge to develop new devices in the future.

The new falling head permeameter will substitute the conventional device used so far. Three additional devices must be made, as 4 teams work simultaneously in the laboratory. The direct shear test apparatus will be shown in classrooms at BEng level next academic year. Depending on the experience, another compulsory practical work based on this device could be defined in the future.

6 Conclusions

The cases presented, falling head permeameter and direct shear test apparatus, constitute two examples of application of "open-source hardware" as described previously, an extension of the wellknown concept of “open-source software”. Apart from that, the concept of “digital twin” adds an extra value to the experiment, as the interpretation of the test is carried out in real time by the user. These tools define a new paradigm in the teaching of practical subjects. They are simple and not expensive so that it is possible to include them in a classroom or in any laboratory environment. Even if the local tradition of the Faculty is more academic and rationalist, or if the budget available is limited, the simplicity of these setups allows to incorporate them in a natural manner when teaching Soil Mechanics. Involving the students in the development of these artefacts is also a useful aspect, as Civil Engineering students are not familiar with these techniques. The future of the Internet of Things relies partly on reducing the gap between monitoring, automation, digitalisation and real applications, and this type of teaching activities contribute to that direction.

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Alberto Ledesma is a Professor on Soil Mechanics and Geotechnical Engineering at the Technical University of Catalonia (UPC-BarcelonaTech) in Barcelona, Spain. He obtained his PhD at UPC in 1987, with an extraordinary award for Civil Engineering theses. He was visiting Scholar at Swansea University (UK), during 1988-89, working on finite elements applied to coupled soil dynamic problems. He became a full professor in 2002 and has been involved in research projects including backanalysis, landslides, unsaturated soils, desiccating cracking and numerical methods in geotechnical problems as tunneling in urban areas. He has participated also as Geotechnical advisor in this type of large construction problems. His teaching interests include Soil Mechanics, Numerical Methods and Geotechnical Construction. In recent years, he has participated in local teaching improvement projects in order to change the classical methodologies traditionally used in Soil Mechanics Lectures. He is member of the TC306 Committee on Geotechnical Engineering Education.

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Antonio Lloret obtained a PhD degree on Unsaturated Soil Mechanics, graduating in 1982 in the UPC. He is Professor at that University since 2002. He has taught different subjects including Soil Mechanics, Soil Mechanics Laboratory, Unsaturated Soil Mechanics, Instrumentation in Civil Engineering and Geotechnical design. He was selected Assistant Dean of this academic center since 1988 to 1991 and since 1993 to 1994 for Teaching and Learning in Civil Engineering. Since 1983 and for 16 years he was Head of Laboratory of Geotechnical Engineering. During this period, a large number of innovative techniques and test equipment were developed. His main research interests continue to be in unsaturated soil mechanics and laboratory testing and their application to Civil and Geoenvironmental Engineering. A co-author, he has received the 1994 Telford Medal and 2010 Geotechnical Research Medal, both from the Institution of Civil Engineers of London.

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Mercedes Sondon graduated as a Civil Engineer in 2011 from the Universitat Politécnica de Catalunya (UPC). In 2016 she obtained a MSc degree in Geotechnical Engineering from UPC. She is currently the head of the Design Area of specialized testing equipment of the Geotechnical Laboratory of the Civil Engineering School of Barcelona. In this position, she designs and coordinates the construction of prototypes for testing soil and rock specimens under thermal, hydraulic and stress changes. She has extended her expertise to the design of complex medium-size testing devices, which are a mock-up of prototype installations. Outside academia, she worked in the period 2009-2013 in the Department of Hydraulic Engineering of ENDESA. She was involved in the design and calculation of several hydro-electric developments in Spain and Portugal. More recently (2013-present) she was involved in Geotechnical consultant work in a variety of aspects: landslides, dams, foundations and harbours.