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Geotechnical centrifuge applications in the teaching of applied soil mechanics

Catalina Lozada [a], Lina Ximena Garzón [a] & Sandra Ximena Campagnoli[a]

[a] *Departamento de Ingeniería Civil, Escuela Colombiana de Ingeniería Julio Garavito, Bogotá, Colombia.*
catalina.lozada@escuelaing.edu.co

Abstract— This paper presents the characteristics of the new geotechnical centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito, including the installed capacities, future applications, and possibilities that offer the new centrifuge as an important tool for teaching and learning in geotechnics. This centrifuge has a radio of 610mm and a maximum acceleration of 200 gravities. A very complete acquisition system with a capacity of 12 sensors to measure different properties is installed. Also, the centrifuge has five oedometric consolidometers as a complementary tool to prepared fine soils in the construction boxes. The possibilities in teaching soil mechanics and applied soil mechanics using the new centrifuge are multiple and are based on the visualization of failure surfaces and deformations produced by different geotechnical structures.

Keywords— civil engineering, applied soil mechanics, geotechnical centrifuge, teaching in geotechnics.

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Aplicaciones de la centrífuga geotécnica en la enseñanza de la mecánica de suelos aplicada

Resumen— En este artículo se presentan las características de la nueva centrífuga geotécnica de la Escuela Colombiana de Ingeniería Julio Garavito. Se presentan las capacidades instaladas, aplicaciones futuras y posibilidades que ofrece la nueva centrifuga como herramienta de enseñanza y aprendizaje en geotecnia. Esta centrífuga tiene un radio de 610mm y puede alcanzar una aceleración de 200 gravedades. La centrifuga tiene instalado un completo sistema de adquisición de datos con una capacidad de 12 sensores que permiten medir diferentes propiedades. Adicionalmente, la centrifuga cuenta con cinco consolidómetros edometricos como herramientas complementarias para la preparación de suelos finos. Las múltiples posibilidades en enseñanza de la mecánica de suelos aplicada usando la nueva centrifuga se basan en la visualización de los mecanismos de falla y deformaciones producidas por diferentes estructuras geotécnicas.

Palabras Clave— ingeniería civil, mecánica de suelos aplicada, centrífuga geotecnia, enseñanza en geotecnia.

1 Introduction

For more than 60 decades, geotechnical modeling using the geotechnical centrifuge has been demonstrated to be a very important tool in the study of the behavior of geotechnical structures [1]. Currently, many centrifuges are in operation around the world; as stated by [2], in 2010 more than 110 geotechnical centrifuges existed in the world. The size of these centrifuges is wide, covering a range between few centimeters from the platform to the rotation axis to several meters. Some of these have been operating since 1972 as the centrifuge of the Schofield Center in Cambridge.

Physical modeling in centrifuge has been used around the world in four main applications: modeling of a prototype, investigation of new phenomena, parametric studies, and validation of the numerical methods [3]. In these applications, the stress history and the nonlinear properties in soil behavior are considered. These applications are multiple and have served to understand the deformation mechanisms and failure in the different geotechnical applications under similar stress conditions than in the field. Many problems involve strength, bearing capacity in different structures, settlement, compressibility, slope stability, retention structures, offshore structures, embankments, tunnels, mining, liquefaction, dynamic effect in soil-structure interaction, vegetation interaction, the behavior of soil with pipes, among others.

The research developed using geotechnical centrifuge has made it possible to probe and replicate in the reduced scale and to compare with the results in real scale different physical phenomena. This research becomes more complex each time and has served to develop and validate many scaling laws and similitude conditions [4].

The geotechnical modeling in a centrifuge is accomplished combined with mechanical and electronic developments to measure and quantify the physical variables during the tests; in many cases, the requirement of small instruments of measurement and accurate data imposes a very challenging task. Within the technological innovations used in the centrifuge, models have included the measurement devices of displacement such as laser displacement sensors, laser scanners, and fiber optic technology. Also, digital cameras have been used to analyze displacement and deformation fields [5]. Other physical variables such as water pressure, water content, suction, temperature, or acceleration have been measured through very sophisticated sensors.

The geotechnical centrifuge has been used also as a teaching and learning tool. This facility in the learning process has proven to be very useful in teaching mainly illustrating the theoretical failure mechanisms [6]–[11]. The new geotechnical centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito has been conceived mainly as a strong tool for teaching and learning soil mechanics and its applications. The geotechnical centrifuge has a radio of 610mm and can reach 200×g. Also, five oedometric consolidation apparatus have been constructed specially designed for the soil containers adapted to the centrifuge.

This paper describes the new geotechnical centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito including the new centrifuge as a powerful tool in teaching and learning soil mechanics, principles of modeling, characteristics of the centrifuge, soil sample preparation, possibilities, first experiences in teaching, and general perspectives.

2 The teaching of applied soil mechanics

The area of geotechnics in the curriculum of the Civil Engineering program at the Escuela Colombiana de Ingeniería Julio Garavito consists of the courses of basic soil mechanics and applied soil mechanics. The course of basic soil mechanics is complemented adequately with laboratory practices where the students characterize the soils and evaluate the index and mechanical properties. These practices allow the students to connect and associate the theoretical concepts through the experimental measurements in complex themes such as compressibility, stress-strain behavior, and shear strength. In the second course of applied soil mechanics, the content is related to shallow and deep foundations, slope stability, and retaining walls. In this course, the teaching methods have been based on the explanation of the analytical formulations and sometimes accompanied by numerical models, without any experimental tests. With the acquisition of the new centrifuge, it is expected a better connection in the learning of the theoretical concepts through experimental tests. This will be made by creating experimental practices about foundations, slopes, and retention walls in which the students can observe and analyze the failure mechanisms and apply the theoretical approaches seen in the course. With theoretical concepts and practice, it is expected that the students reflect, connect, and be engaged in the area o geotechnical engineering.

Different researchers have demonstrated the applicability of physical modeling in a geotechnical centrifuge for educational purposes [7]–[9], [11]–[15]. Conclusive evidence indicates that the students have a better understanding and more comprehension of the fundamental concepts if physical modeling is integrated adequately in the courses of applied soil mechanics. Also, other skills associated with interpretation, synthesis of data, communication, and teamwork are expected to develop.

According to [15], the benefits of physical modeling with geotechnical centrifuge applicable to the teaching of soil mechanics are: 1) through the physical models, it is possible to visualize complex non-linear geotechnical mechanisms, difficult to observe in another way, 2) directly analyzing the geotechnical systems in the model at a reduced scale, the students can develop intuition and physical sense about the fundamental mechanisms that govern the behavior of these systems, 3) the reduced scale models can be proven to collapse, allowing the students to observe failure mechanisms that are not observed in traditional experimental tests in soil mechanics, that are only focus on element tests, 4) through a back analysis of the physical models, the students can evaluate directly the differences between the predicted and the actual behavior of the geotechnical systems.

The small size of the new centrifuge facilitates the preparation of the tests at reasonable costs. However, a challenging task is found concerning the test design and the measurement of physical properties in the small size volume of soil samples. However, new developments of miniature equipment can be developed [16]–[19]. The space limitation in the inclusion of sensors has been compensated with the use of image analysis technics, images that are taken during the test with a camera integrated into the centrifuge.

3 Physical modeling using a geotechnical centrifuge.

Since the development of the idea in the mid-nineteenth century, physical modeling in a geotechnical centrifuge has become a valuable tool that makes it possible to advance in the knowledge of complex problems in geotechnical engineering [3].

A geotechnical centrifuge test resides of placing a soil sample on a reduced scale, known as a model, inside a centrifugal machine, in such a way that the inertial acceleration field produced by the rotation of the machine generates the same stress conditions in the model that the soil has in the real scale or what is known as a prototype [1].

There are two types of centrifuges: beam centrifuges and drum centrifuges. The beams are those that are composed of a beam that rotates around an axis and at the ends of which there are, either two tilting baskets or a tilting basket and a counterweight depending on the design. The model, which is prepared outside the centrifuge machine, is placed in the tilting basket. The drum ones are those made of a simple drum inside of it the model is prepared directly. The mini centrifuge of the Escuela Colombiana de Ingeniería is a beam type.

The basic principle of physical modeling in a geotechnical centrifuge resides in recreating the stress conditions that exist in the prototype in a 1 / N times reduced model, by the action of increasing the acceleration force of gravity in the centrifuge by N times. This force is provided by the centripetal acceleration force ($r\omega^2=Ng$) where r and ω are the radius and angular velocity of the centrifuge, respectively [20].

Scale laws are used to relate the behavior observed in the model in a centrifuge test with the behavior of the prototype. These laws are generally derived through dimensional analysis, the equations that govern a phenomenon, or the principles of mechanical similarity between a model and a prototype [20]. Some of the scale factors are presented in Table 1.

Table 1
Main scale factors for centrifuge tests.

Parameter	Scale factor (model / prototype)	Units
Acceleration	1	m/s^2
Length	1/N	m
Area	$1/N^2$	m^2
Volume	$1/N^3$	m^3
Mass	$1/N^3$	$Nm^{-1}s^2$
Stress	1	Nm^{-2}
Deformation	1	-
Force	$1/N^2$	N
Unit weight	N	$Nm^{-2}s^2$
Time(consolidation)	$1/N^2$	s

Source: Adapted from [21].

4 Characteristics of the new geotechnical centrifuge

The geotechnical centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito is a beam type centrifuge having a ratio to the platform of 610mm, at both sides of the beam are located two dumper baskets where the boxes that contain the soil are placed as shown in Fig. 1. The centrifuge has an acceleration range between 10×g and 200×g and at the maximum acceleration can support a maximum load of 12kg in each basket. The boxes for preparation of the soil models have 17cm length, 10cm width, and 15cm high.

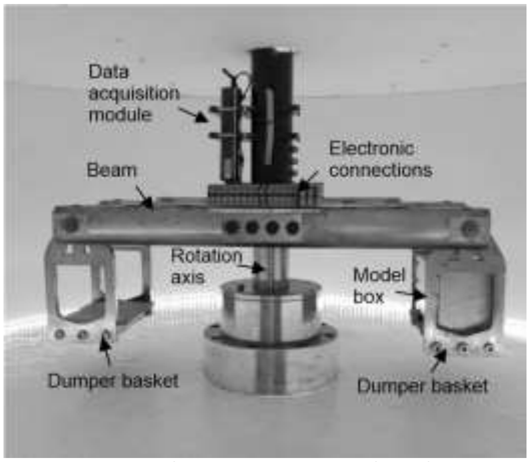

Figure 1. Components of the geotechnical centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito.
Source: The authors.

The geotechnical centrifuge has electronic connections having a wireless transmission signal of 12 sensors with an output voltage range between 500mV and 10V. The system also has internal connections for power suppliers, adaptors, motor drivers, and other external devices. The data of the installed sensors in the centrifuge are obtained through a data acquisition program developed in the software Labview. This program allows the user to capture, transform, visualize, and collect the signals of voltage received by the sensors. The multiple facilities of the installed system allow placed different sensors in the geotechnical models for measuring different variables such as pore water pressure, displacement, temperature, water content, acceleration, among others.

5 Soil preparation of the physical models

5.1 Preparation of coarse-grained soils

The preparation of the physical models in coarse-grained soils for modeling in the geotechnical centrifuge is made considering the scaling laws for the grain size. Therefore, fine sands are commonly used to not scale the size of the grains or create size effects in the interaction soil-structure, for example, foundation, anchors, tunnels, pipes, walls, or geogrids [4]. The preparation of soil models in sands is made with the soil raining or pluviation technique, which consists in fall down the dried soil from a specific height. The height of the fall down is associated with a specific density of the soil [22], [23].

5.2 Preparation of fine-graded soils

The preparation of physical models in fine-grained soils is usually made with high-water content, usually 1.5 times the liquidity limit [22]. At this water content, the liquidity consistency of soil allows a better mixture ensuring soil homogeneity. Afterward, the stress state of soil is created through a consolidation process simulating a normal consolidated or overconsolidated soil.

In a normally consolidated soil, the consolidation process occurred naturally owed to the self-weight of the soil, as a result, the unitary weight of soil varies linearly as depth increases. The simulation of stresses in this type of soil can be made using two technics, the first consists of placing the soil sample in the centrifuge at a specific gravity acceleration and time, and the second consists of consolidating using consolidation apparatus outside the centrifuge.

The simulation of stresses in the centrifuge is achieved by accelerating the centrifuge at a desired gravity and monitoring soil settlements to verify the process through consolidation curves. Even though the time in the centrifuge model is scaled with a factor N^2, this process could be very long. Therefore, generally, the state of stresses in the soil is simulated outside the centrifuge using a consolidation apparatus. The centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito has five consolidation apparatus for the preparation of soil samples as shown in Fig. 2.

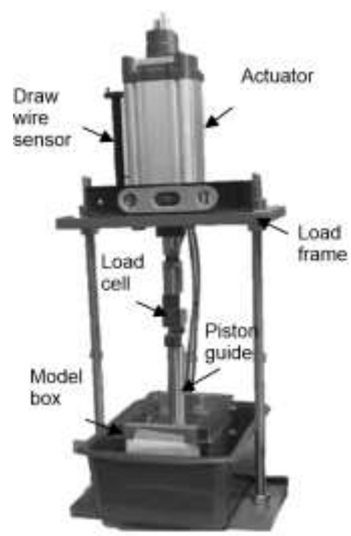

Figure 2. Components of the automatic consolidation apparatus of the Escuela Colombiana de Ingeniería Julio Garavito.
Source: The authors.

As illustrated in Fig. 2, each consolidometer has a mechanic actuator of double effect with a setback by spring, a steel frame, a sensor to measure the applied load, and a sensor for measuring piston displacement. The consolidometer allows the application of control loading steps from 3kg to 200kg with an accuracy of ±1.5kg. A program developed in the software Labview allows the user to collect the measurements of loads and displacements with a defined acquisition frequency.

The preparation of the normally consolidated samples in the pneumatic consolidometer consists of consolidating different layers with the same thickness increasing the applied stress with the increase of depth, a schematic procedure is shown in Fig. 3a. At the end of this process, the soil sample will have a soil profile as depicted in Fig. 3b. The shadow zones in this figure show the obtained error in each layer, the bottom shadow region represents an inexistent stress state, and the upper part the additional applied stress.

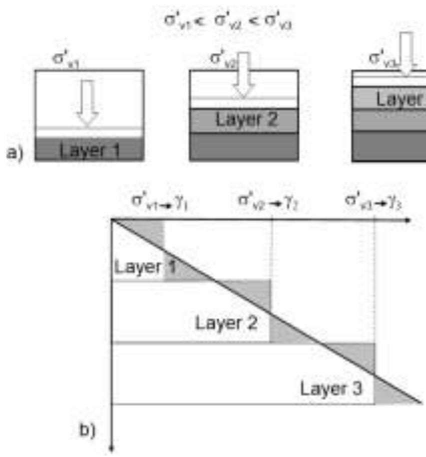

Figure 3. Preparation of fine-grained samples a) Schema of loads applications in layers using the consolidometer b) Consolidated soil profile.
Source: The authors.

6 Teaching approaches using the new geotechnical centrifuge

6.1 Learning interest of the students in the courses using physical modeling in geotechnics

Two surveys were applied, one for undergraduate students and the other for graduate students. The undergraduate students who responded to the survey were students who had already taken classes of soil mechanics and applied soil mechanics. The undergraduate survey had the purpose to measure the interest of the students in developing physical modeling practices with geotechnical centrifuge and to define the more interesting topics viewed in the courses to model in the centrifuge. The survey consisted of two questions that measure the interest in executing physical modeling practices and five questions that measure the more interesting topics for modeling (soil settlement, seepage in soil, stability of retaining walls and slopes, bearing capacity of shallow and deep foundations, among others). The possible responses were: strongly agree, agree, neutral, disagree, and strongly disagree.

Forty-nine students answered the survey obtaining the following results: the mean of the first two questions about the interest in including a laboratory experiment in the centrifuge and about the contribution of this practice in the learning process was between strongly agree and agree. Only one person has disagreed with one question. Concerning the topics for modeling in the centrifuge, the responses in order of more agreement to less agreement for basic soils mechanics were soil settlement, seepage in soil, and stress-strain behavior under applied loads, and for applied soil mechanics were bearing capacity of shallow and deep foundations, the stability of retaining walls and slopes.

In the case of the graduate students, the survey was answered for students who had already taken a course called Methods of Analysis in Geotechnics, MAGE. In this course a physical modeling work was carried out in the mini geotechnical centrifuge, this modeling is explained next in this article. The survey had the purpose to evaluate this first experience of physical modeling in a geotechnical centrifuge.

The questions measured the benefits of laboratory practice in the learning process of the course, the effectiveness of connecting traditional theory and numerical analysis with physical modeling, and specific questions about the test results such as visualization of the slope failure mechanism, among others. It was also asked about whether participation in the practice of physical modeling motivated them to continue with doctoral studies. As for the undergraduate survey, the possible responses were: strongly agree, agree, neutral, disagree, and strongly disagree. Six students answered the survey, and the results of all questions vary between strongly agree and agree. In general, the students agreed that laboratory practice helped their learning process for the course and that this helped them to better understand the theory explained in the class. Regarding the question asking if the laboratory practice had made them think about starting doctoral studies, the answers were strongly agree, agree, and neutral in equal percentages.

6.2 Firsts experiences using the geotechnical centrifuge

The first experience in physical modeling in a geotechnical centrifuge was given in the second academic period of 2019, in the course of the master's program in civil engineering with an emphasis in Geotechnics called Methods of Analysis in Geotechnics, MAGE. In this course, the different analysis methods used in the design of geotechnical structures are studied: shallow foundations, retaining walls, and slopes. Likewise, an introduction to reliability-based design is given and the effect of spatial variability of soil properties on the behavior of geotechnical structures is studied.

Specifically, on the effect of the heterogeneity of soil properties on the behavior of soil structures, a field still to be investigated, a physical modeling work was carried out in the mini geotechnical centrifuge, which consisted of the simulation of two slopes with a 45° slope, one from a homogeneous soil and the other from a heterogeneous soil. The slopes were subjected to flights in the geotechnical centrifuge until they failed. The failure mechanism and the effect of spatial variability of soil properties on slope stability were studied. For the manufacture of the homogeneous models, the fine soil preparation technique described earlier in this article was used, to manufacture the heterogeneous models, three mixtures of kaolin and bentonite soils were used and the construction technique proposed by [24]. Fig. 4 shows the models of the homogeneous and heterogeneous slope.

Figure 4. Laboratory models of the MAGE graduate course: a) Homogeneous soil slope; b) Heterogeneous soil slope.
Source: The authors.

Another experience using the geotechnical centrifuge was made in a group of undergraduate students named Semillero de Geotenia, this group is organized for the students that are interested in geotechnical engineering and want to get deeper knowledge in the field. Through participation in this group, the students develop small research projects on different topics of geotechnics. The first experience in this group, developed in the second semester of 2019, using the geotechnical centrifuge and the oedometric consolidation apparatus was made in the study of different slope stability reinforcement methods. Fig. 8 shows the physical and numerical results of the compared methods: micro-piles and nails. The gravity level achieved during this test was 200×g.

Figures 5a and 5b show the results of the physical models with the failure surface and figures 5c and 5d show the results using a limit equilibrium method in the software slide 2D. Fig. 5b shows an example of image analysis using ink as a tracer to analyze displacements in the slope. The activities of comparison of the theoretical results and the physical models give very interesting results, motivating and encouraging the students in geotechnical engineering. These experiences have permitted the students, now engineers, to have an additional framework in their studies.

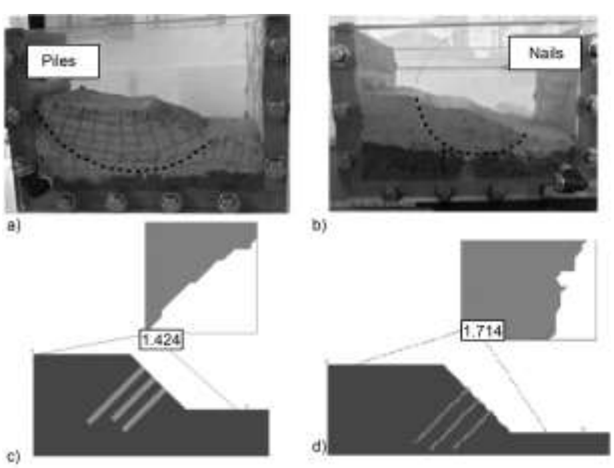

Figure 5. Physical modeling using geotechnical centrifuge Semillero de Geotecnia a) Physical model with micro-piles, b) Physical model with nails, c) Numerical model with micro-piles, and d) Numerical model with nails.
Source: The authors.

6.3 *Possibilities in teaching soil mechanics*

The geotechnical centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito offers multiple possibilities in physical modeling, mainly focused on the teaching of geotechnics, within the future experimental applications are shallow foundations, deep foundations, slopes, retaining walls, tunnels, among others.
The physical modeling of these structures requires to simulate the loads that act over the soil, to characterize the soil for analysis and interpretation of results, and to visualize the displacement and deformation fields. The application of loads in the centrifuge will be achieved through the construction of mechanical systems designed specially to apply loads during the tests at a high acceleration field. The analysis of the results obtained in the physical models and the comparison with theoretical and numerical results is made together with the characterization of the strength of the soil prepared in the laboratory. This will be achieved with the construction of mini-systems to characterize this soil such as cone penetration tests CPT, T-bar, dilatometer, among others [16]. The analysis and interpretation of the results of the physical models also require the visualization of displacement and deformation fields [5]. This can be achieved with the installation of adequate lights inside the centrifuge and the design and construction of camera support. All mentioned devices and developments for modeling require a safe mechanical design that supports a maximum acceleration of 200g.

7 Conclusions

The construction and operation of the geotechnical centrifuge of the Escuela Colombiana de Ingeniería Julio Garavito have the main purpose to offer to the students a better understanding of mechanisms of soil behavior associated with the different geotechnical systems.

This new geotechnical centrifuge is capable to reach high acceleration allowing to model great scales of the prototype; as well it has a high load capacity. The geotechnical centrifuge is complemented with automatic oedometric consolidometers for preparing fine-grained soils and an acquisition system to measure different soil properties.

The geotechnical centrifuge is proven to be a very strong tool for improving the teaching and learning process in the program of civil engineering as well as in the program of master in geotechnical engineering. A survey implemented to the students confirms their interest in developing experimental practices in the centrifuge, also the experiences presented in this paper demonstrate better connection and association with theoretical concepts. With this machine, it is expected that the students increase their interest in the field of geotechnical engineering motivating them to continue their academic formation in the area. Also, the new geotechnical centrifuge will be appreciated for its usefulness in research works.

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References

[1] R. E. Taylor, *Geotechnical centrifuge technology*, CRC Press. 2003.

[2] D. S. Kim, N. R. Kim, Y. W. Choo, and G. C. Cho, "A newly developed state-of-the-art geotechnical centrifuge in Korea," *KSCE J. Civ. Eng.*, vol. 17, no. 1, pp. 77–84, 2013, doi: 10.1007/s12205-013-1350-5.

[3] C. W. W. Ng, "The state-of-the-art centrifuge modelling of geotechnical problems at HKUST," *J. Zhejiang Univ. Sci. A*, vol. 15, no. 1, pp. 1–21, Jan. 2014, doi: 10.1631/jzus.A1300217.

[4] J. Garnier *et al.*, "Catalogue of Scaling Laws and Similitude Questions in Geotechnical Centrifuge Modelling," *Int. J. Phys. Model. Geotech.*, vol. 7, pp. 1-1-23–23, 2007, doi: 10.1680/ijpmg.2007.7.3.01.

[5] D. White and W. Take, "GeoPIV : Particle Image Velocimetry (PIV) software for use in geotechnical testing," 2002.

[6] J. A. Black and C. S. D, "The development of a small scale geotechnical teaching centrifuge," in *Enhancing Engineering Higher Education*, 2012, vol. 1, no. January, pp. 37–41, doi: 10.1201/b16200-19.

[7] M. M. Dewoolkar, T. Goddery, and D. Znidarcic, "Centrifuge modeling for undergraduate geotechnical engineering instruction," *Geotech. Test. J.*, vol. 26, no. 2, pp. 201–209, 2003, doi: 10.1520/gtj11327j.

[8] T. A. Newson, M. F. Bransby, and G. Kainourgiaki, "The use of small centrifuges for geotechnical education," *Proc., 4th Int. Conf. Phys. Model. Geomech.*, pp. 215–220, 2002.

[9] U. El Shamy, T. Abdoun, F. McMartin, and M. A. Pando, "Integration of centrifuge testing in undergraduate geotechnical engineering education at remote campuses," *Eur. J. Eng. Educ.*, vol. 38, no. 3, pp. 268–280, 2013, doi: 10.1080/03043797.2013.794199.

[10] A. F. Tessari and J. A. Black, "Development of a teaching centrifuge learning environment using mechanically stabilized earth walls," in *Physical Modelling in Geotechnics ICPMG 2018*, 2018, vol. 1, no. July, pp. 545–550.

[11] I. U. Khan and S. M. Bayton, "Learning through physical modelling observations in the Undergraduate Curriculum," in *Proceedings of the XVII ECSMGE-2019*, 2019, pp. 1–7, doi: 10.32075/17ECSMGE-2019-0778.

[12] J. A. Black and S. D. Clarke, "The development of a small-scale geotechnical teaching centrifuge," in *Enhancing Engineering Higher Education.*, 2012, pp. 37–41.

[13] B. Caicedo, "Geotechnical centrifuge applications to foundations engineering teaching," in *Proc., 1st Int. Conf. on Geotechnical Engineering Education and Training*, 2000, pp. 271–274.

[14] V. Drnevich and W. Craig, "The Use of a Centrifuge in Geotechnical Engineering Education," *Geotech. Test. J.*, vol. 12, no. 4, p. 288, 1989, doi: 10.1520/GTJ10986J.

[15] J. Wartman, "Geotechnical physical modeling for education: Learning theory approach," *J. Prof. Issues Eng. Educ. Pract.*, vol. 132, no. 4, pp. 288–296, 2006, doi: 10.1061/(ASCE)1052-3928(2006)132:4(288).

[16] H. G. Allersma, "Development of Miniature Equipment for a Small Geotechnical Centrifuge," *Transp. Res. Rec.*, vol. 1432, p. 99, 1994.

[17] M. S. S. Almeida, J. R. M. S. Oliveira, H. P. G. Motta, M. C. F. Almeida, and R. G. Borges, "CPT and T-bar penetrometers for site investigation in centrifuge tests," *Soils and Rocks*, vol. 34, pp. 79-88., 2011.

[18] M. S. S. Almeida *et al.*, "The geotechnical beam centrifuge at COPPE centrifuge laboratory," in *Physical Modelling in Geotechnics ICPMG 2014*, 2015, vol. 1, pp. 271–277.

[19] T. Carey, "A new shared miniature cone penetrometer for centrifuge testing," in *Physical Modelling in Geotechnics*, vol. 1, CRC Press, 2018, pp. 293–298.

[20] G. Madabhushi, *Centrifuge Modelling for Civil Engineers*. 2015.

[21] G. Madabhushi, *Centrifuge Modelling for Civil Engineers*. CRC Press, 2017.

[22] J. Garnier, "Modèles physiques en géotechnique Physical models in geotechnics Similitude en mécanique," in *Conférence Caquot*, 2001, no. 1, p. 29.

[23] M. Khari, K. A. Kassim, and A. Adnan, "Sand Samples' Preparation Using Mobile Pluviator," *Arab. J. Sci. Eng.*, vol. 39, no. 10, pp. 6825–6834, 2014, doi: 10.1007/s13369-014-1247-8.

[24] L. X. Garzón, B. Caicedo, M. Sánchez-Silva, and K. K. Phoon, "Physical modelling of soil uncertainty," *Int. J. Phys. Model. Geotech.*, vol. 15, no. 1, pp. 19–34, Mar. 2015, doi: 10.1680/ijpmg.14.00012.

C. Lozada, recibió el título de Ingeniera Civil en 2010, el título de Magister en Ingeniería civil en 2012 y el título de Doctora en Ingeniería en 2016, todos ellos de la Universidad de los Andes, Colombia, y el doctorado en doble titulación con el École Centrale de Nantes, Francia. Tiene experiencia en enseñanza de la modelación física de estructuras geotécnicas a través de máquina centrífuga geotecnia. Sus intereses investigativos incluyen: modelación física en geotecnia, suelos parcialmente saturados y estudio de interacción clima-suelo. Se vinculó a la Escuela Colombiana de Ingeniería Julio Garavito en el año 2016 en donde es profesora Asistente.
ORCID: 0000-0002-7630-1710

L. X. Garzón, Ingeniera civil de la Universidad Industrial de Santander (UIS), Magíster y Doctora en Ingeniería de la Universidad de los Andes. Su tesis doctoral titulada "Physical modelling of soil spatial variability: application of shallow foundation" estudió, haciendo uso de la centrifuga geotécnica, el efecto de la variabilidad espacial de las propiedades del suelo en una estructura superficial simple. Sus intereses en investigación son: Caracterización estadística de geomateriales; Análisis y diseño de estructuras basadas en confiabilidad y Modelación física en centrífuga geotécnica. Ha publicado en revistas internacionales y ha sido ponente en encuentros académicos nacionales e internacionales. En 2014 obtuvo el ICPMG2014 Best Paper Award, University of Western Australia y en 2008 M.Sc Scholarship Award de University el Business Program M.Sc, Uniandes. Está vinculada a la Escuela Colombiana de Ingeniería Julio Garavito desde 2016, como profesora asistente, dictando cursos de diseño geotécnico en pregrado y posgrado; actualmente es la directora de la Especialización en Fundaciones.
ORCID: 0000-0002-2365-5881

S. X. Campagnoli, Ingeniera Civil de la Escuela Colombiana de Ingeniería Julio Garavito. Especialista en Geotecnia de la Universidad Politécnica de Madrid y Nacional de Colombia. En su ejercicio profesional se ha dedicado a la docencia universitaria en los cursos teóricos y de laboratorio de mecánica de suelos, pavimentos y materiales para carreteras, al desarrollo de investigación aplicada y a la consultoría principalmente en Ingeniería de Pavimentos para Colciencias, PNUD, CAF, INVIAS, ECOPETROL-ICP y otras. Promotora de la red de programas de Ingeniería Civil - REPIC y par académico del CNA. Fue Decana del programa de Ingeniería Civil. Coautora del libro *Pavimentos Asfálticos de carreteras, Guía práctica para los estudios y diseños* y autora de numerosos artículos relacionados con materiales para carreteras. Está vinculada a la Escuela Colombiana de Ingeniería Julio Garavito desde 1983.
ORCID: 0000-0002-5793-8046