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Complex Thinking in Civil Engineering Education: A Case Study on Consolidation Settlements in the Geotechnical Context of Mexico City

Eduardo Reyes de Luna, Rubén Fuentes-Álvarez, Iván García-Kerdan, Marco Cruz-Sandoval, Jorge Membrillo-Hernández

Author for correspondence:
Jorge Membrillo-Hernández
jmembrillo@tec.mx

Abstract

Background/purpose. Teaching complex concepts in STEM areas has led education researchers to innovate in teaching models. In this report, we present a study of engineering teaching on the geotechnical structure of Mexico City, which is characterized by highly compressible clayey soils and significant seismic activity, which, for the discipline, presents unique challenges for civil engineering. Complex thinking competencies, precisely four sub-competencies, systemic, scientific, critical, and innovative thinking, were examined among engineering students through an experimental exercise on soil consolidation settlements conducted in a Soil Mechanics course.

Materials/methods. Seventy-six students participated in the experience, combining traditional laboratory methods with MATLAB computational analysis. The study assessed students' perceptions of the development of these sub-competencies.

Results. The results revealed compliance in all sub-competencies, particularly in systemic and critical thinking, which underlines the importance of combining theoretical knowledge with practical application to address complex geotechnical problems.

Conclusion. We conclude that it is appropriate to integrate practical experiences and technological tools in engineering education to develop complex thinking sub-competencies. Therefore, we propose to adopt similar pedagogical strategies to prepare future engineers with the transversal competencies necessary to face real-world challenges, especially in regions with high geotechnical and seismic activity.

1. Introduction

Complex thinking is increasingly recognized as a vital skill for students in higher education, enabling them to analyze, evaluate, and synthesize diverse information to solve multifaceted problems. Higher education institutions play a crucial role in fostering this skill by creating interdisciplinary learning environments that challenge students to consider multiple perspectives. Students are encouraged to connect theoretical concepts with real-world applications through pedagogical approaches such as problem-based learning, challenge-based learning, and systems thinking (Membrillo-Hernández et al., 2023). These methods push students to critically assess the broader implications of their decisions, whether in science, society, or ethics, and approach challenges with innovation and adaptability.

Moreover, complex thinking thrives in environments where collaboration, creativity, and reflection are integral to learning. Universities must design curricula emphasizing interconnectivity between disciplines, enabling students to see how different fields influence and shape one another. This could involve integrating case studies, simulations, and real-world projects that require students to think critically and act decisively. By fostering skills like critical thinking, decision-making, and adaptability, higher education institutions can prepare students to navigate the uncertainties and complexities of the modern world, equipping them to become leaders and innovators in their respective fields.

Developing **disciplinary competencies** is essential in civil engineering to ensure students master the technical skills required to design, construct, and maintain infrastructure. Competencies such as structural analysis, geotechnical engineering, and fluid mechanics are core to the field and form the foundation of professional expertise. Through hands-on laboratory work, internships, and project-based courses, students gain practical experience and apply theoretical knowledge to solve engineering problems. Accreditation bodies like ABET emphasize these competencies to ensure that civil engineering graduates are equipped with the technical rigor to meet industry standards. Simultaneously, cultivating **transversal competencies** is crucial to preparing civil engineers for the broader demands of the profession. Skills such as teamwork, communication, leadership, and ethical decision-making are indispensable in interdisciplinary projects that involve collaboration with architects, urban planners, and policymakers. Additionally, sustainability and environmental awareness have become central to modern engineering practice, requiring students to think beyond technical solutions and consider social and ecological impacts. Incorporating challenge-based learning and real-world case studies into civil engineering programs allows students to address complex, open-ended problems that mirror industry challenges, ensuring they graduate as well-rounded professionals ready to tackle global issues (Membrillo-Hernández et al., 2023).

2. Literature Review

2.1. The context of the didactic experience

Mexico City faces significant geotechnical challenges due to natural conditions and human activities. Built on the former bed of Lake Texcoco, the city rests primarily on highly compressible clay soils. This, combined with the overexploitation of underground aquifers to meet the water demands of approximately 22 million people in the Valley of Mexico, results in differential ground settlements. These settlements, which can reach up to 45 centimeters per year in some areas, are irregular surface subsidence events that can cause cracks and structural damage to various structures (Paredes et al., 2022; Tena-Colunga et al., 2021). Additionally, Mexico City is located in an active seismic region due to the interaction of several tectonic plates, including the Cocos Plate and the North American Plate (Toscana-Aparicio, 2017; Suárez-Ramos et al., 2022). Historically, the city has experienced significant earthquakes, such as those in 1957, 1985, and 2017, with magnitudes of 7.8, 8.1, and 8.2 on the Richter scale, respectively, which caused extensive damage and loss of life, highlighting the

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vulnerability of the city's infrastructure (Tena-Colunga et al., 2021). This situation creates a complex environment in which infrastructures are constantly under threat. These factors generate a unique territorial context in which the prevention and mitigation of geotechnical risks are essential for urban safety and resilience (Toscana-Aparicio, 2017; Suárez-Ramos et al., 2022).

In this context, consolidation settlements become highly relevant. This phenomenon occurs when the soil is compacted under an applied load, expelling water from its pores and reducing its volume, which results in progressive ground subsidence (Kim et al., 2022). Mexico City is particularly susceptible to this process due to the presence of clay soils and the intense extraction of groundwater (Paredes et al., 2022). According to figures from the National Water Commission, in 2018, approximately 61% of the water for consumptive use came from surface sources, while the rest came from groundwater (https://www.gob.mx/conagua/acciones-y-programas/usos-del-agua). According to a study by Khorrami (Khorrami et al., 2023), since 2014, Mexico City has been extracting between 1 and 13 cubic kilometers of groundwater annually. Understanding settlement due to consolidation in civil engineering is significant because it directly impacts structural design and infrastructure construction. A deep and adequate knowledge of this phenomenon allows engineers to predict and mitigate settlements, design appropriate foundations, and ensure the safety of structures. Moreover, the interaction between earthquakes and settlements requires a comprehensive approach to ensure that infrastructures can withstand both events (Paredes et al., 2022).

Through well-designed laboratory practices, civil engineering students must acquire disciplinary and transversal competencies in this field (Abelha et al., 2020). The goal is for students to graduate with theoretical knowledge and transversal competencies, such as complex thinking, and how these competencies are acquired through observable and measurable evidence that allows professors to gauge the student's mastery (Sigahi et al., 2023). Performing consolidation settlement tests in the laboratory provides students with a theoretical and practical understanding of how different types of soils behave under varying loading conditions. These practices enrich technical knowledge and promote the development of complex thinking, a key competency for addressing the complexities of the modern world (Sotelo et al., 2023).

Developing Complex Thinking is crucial in the context of civil engineering in Mexico. Future engineers must be able to integrate technical knowledge with a deep understanding of the geotechnical and socio-environmental context to formulate innovative and sustainable solutions. This study analyzes university students' perception regarding developing complex thinking competencies during the soil mechanics course, where students perform consolidation settlement tests in the civil engineering laboratory.

3. Methodology

A sample of 76 students, 29 women and 47 men (see Table 1), was selected for this study. The participants were enrolled in the seventh semester of the civil engineering program at a Mexican university, taking the soil mechanics course in the Spring semester of 2024. The study was conducted following the university's ethical guidelines, ensuring respect for the privacy and well-being of the participants.

Table 1. Participant data by gender

Male		Female		Total	
n	%	n	%	n	%
47	38.16	29	61.84	76	100.00

The eComplexity instrument was used to assess the perception of complex thinking development and was explicitly designed to measure the four sub-competencies. The instrument has undergone a rigorous process of theoretical and statistical validation. The internal consistency of the instrument, measured using Cronbach's alpha coefficient, yielded a value of 0.966, reflecting excellent reliability in the instrument's items (Cruz-Sandoval et al., 2023; Castillo-Martínez et al., 2024; Vázquez-Parra et al., 2024).

The applied instrument comprises 25 items distributed across four sub-competencies: Systemic, Scientific, Critical, and Innovative Thinking (see Table 2). The students completed the questionnaire voluntarily and self-administered, rating each item using a Likert scale from 1 to 5, ranging from "strongly disagree" (1) to "strongly agree" (5).

The instrument described in Table 2 was administered at two key moments. First, it was applied at the beginning of the course as a diagnostic assessment to measure the students' initial perception of complex thinking and its sub-competencies. Later, a second evaluation was conducted at the end of the course to analyze the evolution in the students' perception of their development in complex thinking and its sub-competencies.

The data obtained at the beginning and end of the course were processed using the statistical analysis environments R (https://www.r-project.org/) and Rstudio (http://www.rstudio.com/). The data treatment included an exploratory, descriptive statistical analysis, calculating the means and standard deviations for the complex thinking macro-competency and each sub-competency. Additionally, a visual analysis using violin plots was employed, which provides a combined view of the data distribution. This type of graph combines a kernel density plot with a boxplot, offering a clear understanding of data dispersion and distribution (https://www.simplypsychology.org/boxplots.html#:~:text=In%20descriptive%20statistics%2C) (Hintze & Nelson, 1998).

Furthermore, a principal component analysis (PCA) was performed, complemented by a non-correlational biplot with a form parameter of $\alpha=1$, to facilitate the interpretation of student behavior throughout the course (https://www.geeksforgeeks.org/principal-component-analysis-pca/). This methodology identified patterns in students' perceptions of developing complex thinking competencies.

Table 2. Complex thinking items by sub-competency.

Sub-competency	#	Item
Systemic Thinking	1	I can find associations between a project's variables, conditions, and constraints.
	2	I identify data from my discipline and other areas contributing to solving problems.
	3	I participate in projects that have to be solved using inter/multidisciplinary perspectives.
	4	I organize information to solve problems.
	5	I enjoy learning different perspectives on a problem.
	6	I am inclined to use strategies to understand the parts and whole of a problem.

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Scientific Thinking	7	I can identify the essential components of a problem to formulate a research question.
	8	I know the structure and formats for research reports used in my area or discipline.
	9	I identify the structure of a research article used in my area or discipline.
	10	I apply the appropriate analysis methodology to solve a research problem.
	11	I design research instruments consistent with the research method used.
	12	I formulate and test research hypotheses.
	13	I am inclined to use scientific data to analyze research problems.
Critical Thinking	14	I can critically analyze problems from different perspectives.
	15	I identify the rationale for my and others' judgments to recognize false arguments.
	16	I self-evaluate the progress and achievement of my goals to make the necessary adjustments.
	17	I use reasoning based on scientific knowledge to make judgments about a problem.
	18	I make sure to review the ethical guidelines of the projects in which I participate.
	19	I appreciate criticism in the development of projects in order to improve them.
Innovative Thinking	20	I know the criteria to determine a problem.
	21	I can identify variables from various disciplines that can help answer questions.
	22	I apply innovative solutions to diverse problems.
	23	I solve problems by interpreting data from different disciplines.
	24	I analyze research problems, contemplating the context to create solutions.
	25	I tend to evaluate solutions derived from a problem in a critical and innovative sense.

4. Results

4.1. Theoretical Framework and Experimental Settings. Challenges of the Valley of Mexico

The subsoil of the Valley of Mexico is characterized by the high presence of lacustrine clays, which are highly compressible and low in strength. These soil characteristics increase its susceptibility to subsidence and cracking phenomena. Subsidence refers to the gradual sinking of the Earth's surface, exacerbated by the intensive extraction of groundwater. As water is withdrawn, the clays compact, causing the ground to sink (González-Morán et al., 1999; Cabral-Cano et al., 2024; Figueroa-Miranda et al., 2018).

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Furthermore, as clayey soils compact, they tend to form cracks that propagate to the surface, compromising the structural integrity of various infrastructures. Additionally, the soil in the Valley of Mexico tends to amplify seismic movement, prolonging the duration of tremors and increasing the risk of structural damage to buildings during earthquakes (Tena-Colunga et al., 2021).

4.2. Soil Consolidation and Differential Settlements

Soil consolidation is a geotechnical process that involves the reduction of soil volume under an applied load due to the expulsion of water from its pores. Terzaghi developed the consolidation theory, establishing a model that defines the relationship between the applied load, time, and soil volume reduction (Towhata, 2008). Terzaghi's one-dimensional consolidation equation is fundamental for predicting soil behavior under different loads. The equation considers the consolidation coefficient, soil permeability, and soil compressibility factors. Consolidation is particularly relevant in clayey soils, such as those in the Valley of Mexico, where the process can be slow due to the low permeability of the clays. As a load is applied, the excess pore pressure dissipates gradually through water expulsion, decreasing soil volume and subsequent settlement.

Differential settlements refer to the difference in the amount of settlement that occurs in various parts of a structure or ground under a load. These settlements induce stresses in structures, leading to cracks or structural failures. Such differences can be caused by load variations, soil heterogeneity, or non-uniform drainage conditions (Paredes et al., 2022).

4.3. Seismic Vulnerability and Mitigation Strategies

Mexico City serves as a vast living seismological laboratory. According to data from the National Seismological System, from 2023 to 2024, a total of 137 micro-earthquakes have been recorded in Mexico City—85 in 2023 and 52 as of September 26, 2024, averaging about one micro-earthquake every 4.6 days (https://www.gaceta.unam.mx/en-2024-en-la-cdmx-se-ha-registrado-en-promedio-un-sismo-de-baja-intensidad-cada-24-dias). Furthermore, Mexico is one of the most seismically active countries in the world. Statistics show that more than 90 earthquakes greater than four on the Richter scale are recorded annually, representing about 60% of all seismic events worldwide (http://www2.ssn.unam.mx:8080/catalogo/). The clay soils of the Valley of Mexico, characterized by their high plasticity and compressibility, cause seismic waves to amplify, resulting in more vigorous ground motions at the surface. This phenomenon, known as seismic amplification, is particularly pronounced in the Valley of Mexico due to the geological structure of the subsoil (Seed & Idriss, 1969). The interaction of seismic waves with soils, such as those found in the Valley of Mexico, can lead to severe structural damage.

A series of mitigation strategies and technologies have been implemented to reduce the vulnerability of various infrastructures to earthquakes. One of the key measures is strengthening construction codes in Mexico City, which now include stricter seismic design requirements. The development of technologies such as seismic isolation, which allows buildings to move independently from the ground, has also been highlighted, thereby reducing the impact of seismic motion (Lin & Williams, 1995). Early warning and monitoring systems have also been deployed, which can detect earthquakes in their initial stages and alert the population to evacuate and save lives (Allen & Kanamori, 2003).

4.4. Analysis of Settlements by Consolidation

Based on Terzaghi's differential equation, which describes the behavior of one-dimensional consolidation, the students applied the Casagrande graphical method to determine the time t50 corresponding to 50% of primary consolidation and the derived equations to calculate the consolidation coefficient (Towhata, 2008). A precise estimation of consolidation is achieved using the dimensionless time T50 and the t50 value obtained experimentally. The void ratio values are calculated from the load increments, and compressibility curves are constructed, allowing for a detailed approximation of settlements.

Terzaghi's differential equation was used to describe the behavior of one-dimensional consolidation:

$$\frac{\partial U}{\partial t} = C_V = \frac{\partial^2 U}{az^2} \qquad \text{(Eq1)}$$

Where:

$C_v = \frac{kz(1+e)}{\rho gav}$ (is the consolidation coefficient)

$m_V = \frac{a_V}{1+e}$ (is the volumetric variation coefficient)

The boundary conditions are:

Initial: For time $t = 0, U_e = U_{0e} = 0, \text{ for } 0 \leq Z \leq H$

Final: For $t = \infty, U_e = 0, \text{ for } 0 \leq Z \leq H$

For any time t: $\frac{\partial U_e}{\partial Z} = 0 \text{ in } Z = 0;\ U_e = 0 \text{ in } Z = H$

The solution is expressed as:

$$\frac{U_e}{U_{0e}} = \sum_{m=0}^{m=\infty} \frac{2}{M} \text{sen}\left[M\left(1\text{-}\frac{Z}{H}\right)\right] \exp(\text{-}M^2\ T_V) \qquad \text{(Eq2)}$$

Where

Use excess pore pressure.

U_{0e}- excess pore pressure at $t = 0$

$M = \frac{\pi}{2}(2m+1),, m = 1,2,3, \dots, \infty$

H– maximum distance for water flow

TV– dimensionless vertical time factor, where: $T_V = \frac{C_V t}{H^2}$

The degree of consolidation is equal to:

$$U_V = \frac{\sigma' \text{-} \sigma'_0}{\sigma'_f \text{-} \sigma'_0} \qquad \text{(Eq3)}$$

From the stresses in the soil $\sigma = \sigma' + U$:

For $= 0$ and $q = 0,\ \gamma s(H\text{-}Z) = \sigma'_0 + U_h$

With load increment:

For $t = 0,\ q + \gamma s(H\text{-}Z) = \sigma'_0 + U_h + U_{0e}$

For $t = t,\ q + \gamma s(H\text{-}Z) = \sigma' + U_h + U_e$

For $t = \infty,\ q + \gamma s(H\text{-}Z) = \sigma'_f + U_h$

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Substituting results in:

$$U_V = \frac{U_{0e}\text{-}U_e}{U_{0e}} = 1\text{-}\frac{U_e}{U_{0e}} \qquad \text{(Eq4)}$$

Substituting Eq4 into Eq2:

$$U_V = 1\text{-}\sum_{m=0}^{m=\infty} \frac{2}{M} \operatorname{sen}\left[M\left(1\text{-}\frac{Z}{H}\right)\right] \exp(\text{-}M^2\, T_V) \qquad \text{(Eq5)}$$

To determine the average:

$$\overline{U_V} = 1\text{-}\frac{\overline{U_e}}{U_{0e}} = 1\text{-}\frac{1}{H}\int_0^H \frac{U_e}{U_{0e}}\, dz \qquad \text{(Eq6)}$$

Therefore:

$$\overline{U_V} = 1\text{-}\frac{1}{H}\int_0^H \sum_{m=0}^{m=\infty} \frac{2}{M} \operatorname{sen}\left[M\left(1\text{-}\frac{Z}{H}\right)\right] \exp(\text{-}M^2\, T_V) = \text{-}\sum_{m=0}^{m=\infty} \frac{2}{M^2} \exp(\text{-}M^2\, T_V) \qquad \text{(Eq7)}$$

Equation 7 is used to obtain the value of T50, representing the dimensionless time corresponding to 50% consolidation. Casagrande's graphical method, which gives the value of t50, indicates that 50% of the primary consolidation is reached in the analyzed sample. Both values are used to determine the consolidation coefficient Cv using the equation:

$$C_V = \frac{T_{50}\, {H_e}^2}{t_{50}} \qquad \text{(Eq8)}$$

Where He is the maximum distance traveled by the water, the height of the sample confined in the metal ring divided by 2 $(H_e = H_{Sample}/2)$.

Subsequently, the Casagrande method allows for the graphical determination of t50 through the intersection of the deformation and time curves. Initially, the time t1 is identified on the consolidation curve. This value is multiplied by 4, generating an increase on the deformation axis, which is extrapolated onto the time axis, facilitating the identification of the point corresponding to 0% deformation (d0%). To estimate the 100% deformation, two lines are drawn: one tangent to the parabola at the inflection point and another tangent to the last points of the curve.

The point of intersection between these two lines defines the 100% deformation (d100%). From the d0% and d100%values, d50% is calculated, representing the midpoint. Finally, a line is drawn from this point to the consolidation curve, allowing the determination of the time corresponding to 50% consolidation (t50). This is shown in Figure 1.

The test obtained not only the t50 values but also the void ratio values corresponding to each load increment, which are based on the d_(100%) value of each curve. With this data, the compressibility curve is constructed, allowing for the determination of settlements.

4.5. On the Laboratory Practice

In the unidimensional consolidation test, the behavior of clayey soil under incremental loading is evaluated by measuring the deformations of the soil confined in a metal ring. The purpose of this confinement is to prevent lateral deformations, ensuring that the deformations occur solely in the vertical direction. To facilitate simultaneous drainage in both directions, porous stones are placed on the top and bottom of the sample. This assembly, consisting of the ring, the soil sample, and the porous stones, is submerged in a container filled with water, thus ensuring complete saturation of the sample, which is essential for adequately analyzing the consolidation behavior of the soil.

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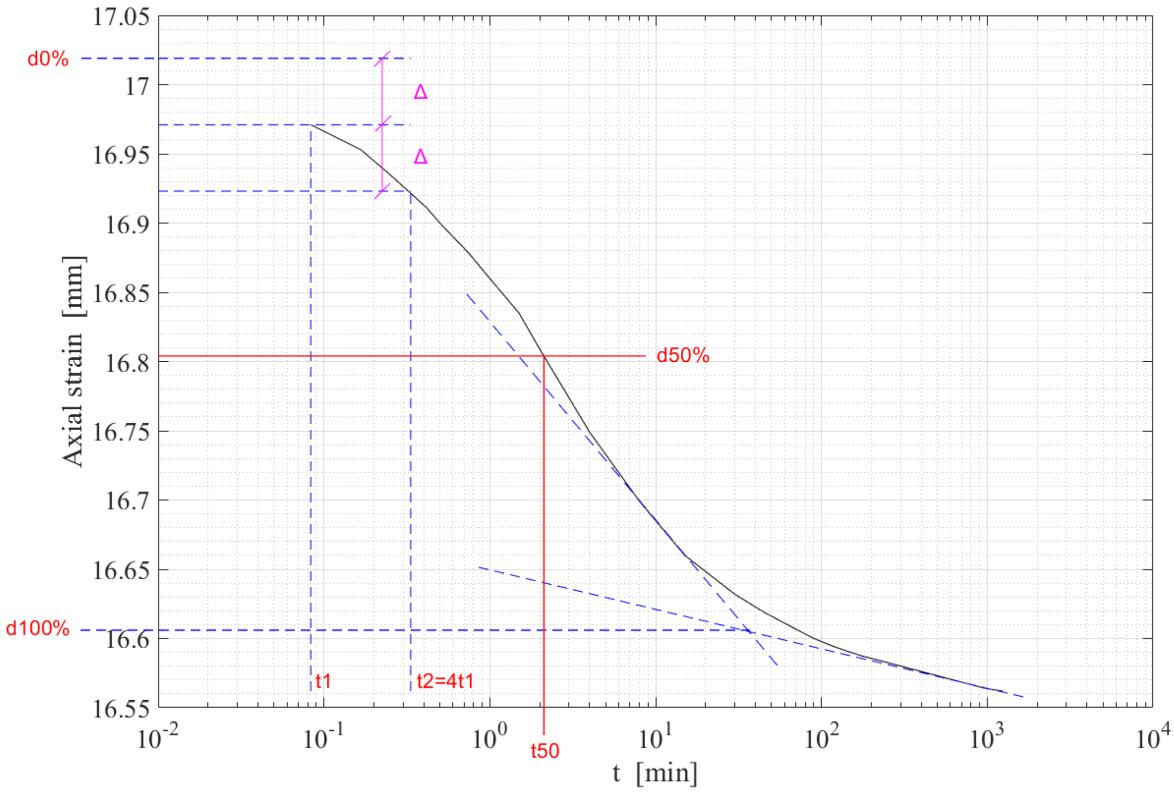

Figure 1. Graphical determination of t50 using the Casagrande method.

Figure 2 shows the equipment used to carry out the one-dimensional consolidation test. Figure 2A displays the clay soil confined in a metal ring. Figure 2B presents the consolidometer used to measure the soil's response under various applied loads. Figure 2C illustrates the devices used to simulate the consolidation of saturated soil, allowing drainage in both directions. Finally, Figure 2D shows the assembled components of the equipment for the one-dimensional consolidation test.

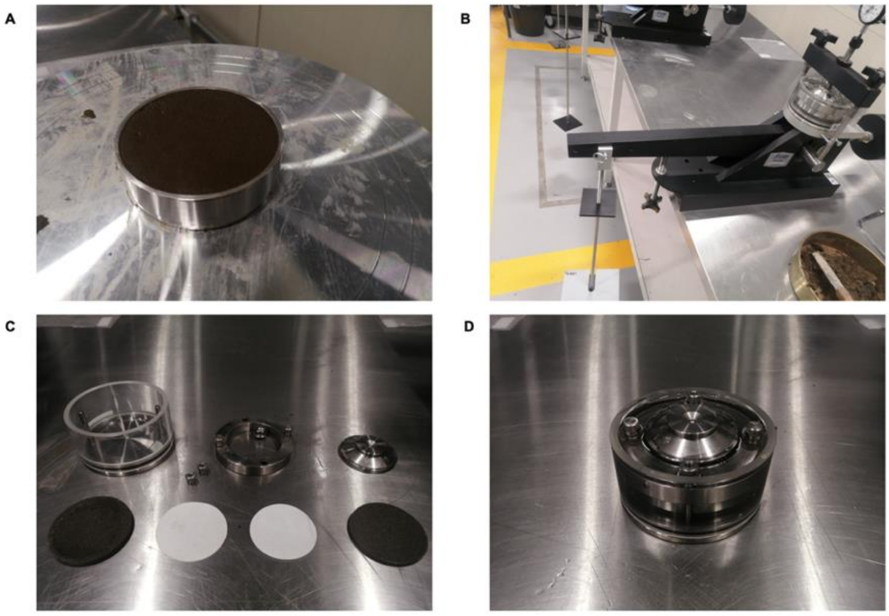

Figure 2. Equipment and components used in the one-dimensional consolidation test. See Text for details.

The initial properties of the sample include the following: specific weight of the sample $(\gamma_m)\ of\ 1.1511\frac{g}{cm^3}$, specific weight of solids $(Ss)\ of\ 2.60$, solid mass $(Ws)\ of\ 35.41\ g$, water content $(\omega)\ of\ 276.53\%$, and a void ratio $(e)\ of\ 7.5051$. A progressive load increase was applied to the sample using a consolidometer, starting with 1 kg (**Figure 3A**), followed by 2 kg (**Figure 3B**), 4 kg (**Figure 3C**), 8 kg (**Figure 3D**), and finally 16 kg (**Figure 3E**). The leverage ratio of the consolidometer arm allowed for the application of equivalent stresses of $0.2009\,kg/cm^2$, $0.4019\ kg/cm^2$, $0.8038\ kg/cm^2$, $1.6076\ kg/cm^2$ and $3.2152\ kg/cm^2$ corresponding to each applied load. From the consolidation curves obtained, the t50 value can be determined, corresponding to when the sample reaches 50% of primary consolidation. **Figure 3** shows the consolidation curves from the experiment under different loads.

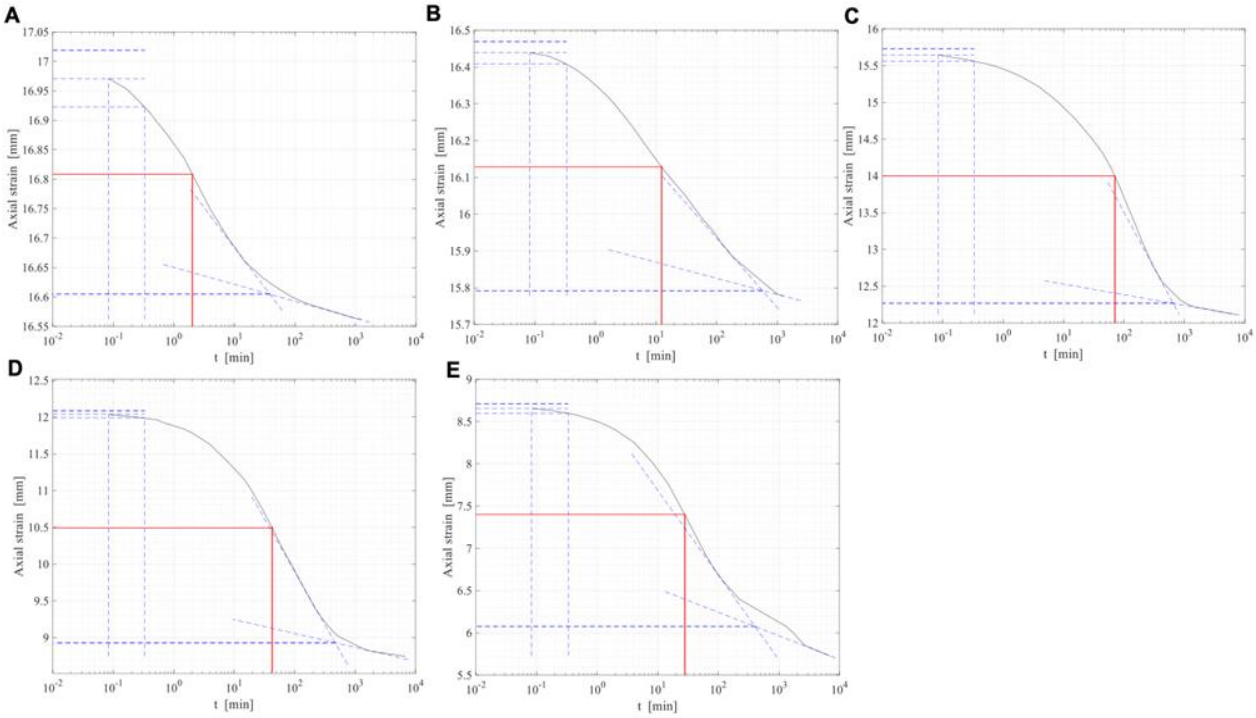

Figure 3. Consolidation curves: (A) t50=2 min, (B) t50=12 min, (C) t50=70 min, (D) t50=41 min, (E) t50=29 min.

4.6. Comparative Validation

The Casagrande graphical method is the standard procedure for students to analyze soil consolidation. This method enables the determination of key parameters, such as the consolidation time t50, the coefficient of consolidation Cv, axial deformation, and the void ratio. However, to further strengthen students' complex thinking skills, they are also trained to use computational tools like MATLAB for numerical analysis. Using the experimental data obtained in the laboratory, students are tasked with programming and running MATLAB scripts that allow them to compare experimental results with theoretical predictions.

The results indicate a high linear correlation between the two approaches, validating the accuracy of the MATLAB code developed by students to estimate parameters such as axial deformation, time to reach 50% primary consolidation, the coefficient of consolidation, and the void ratio. This consistency between theoretical and experimental data confirms that both methods are equally effective in interpreting and analyzing soil behavior under consolidation conditions, providing students with a comprehensive understanding of the phenomenon.

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4.7. Challenges of the Valley of Mexico

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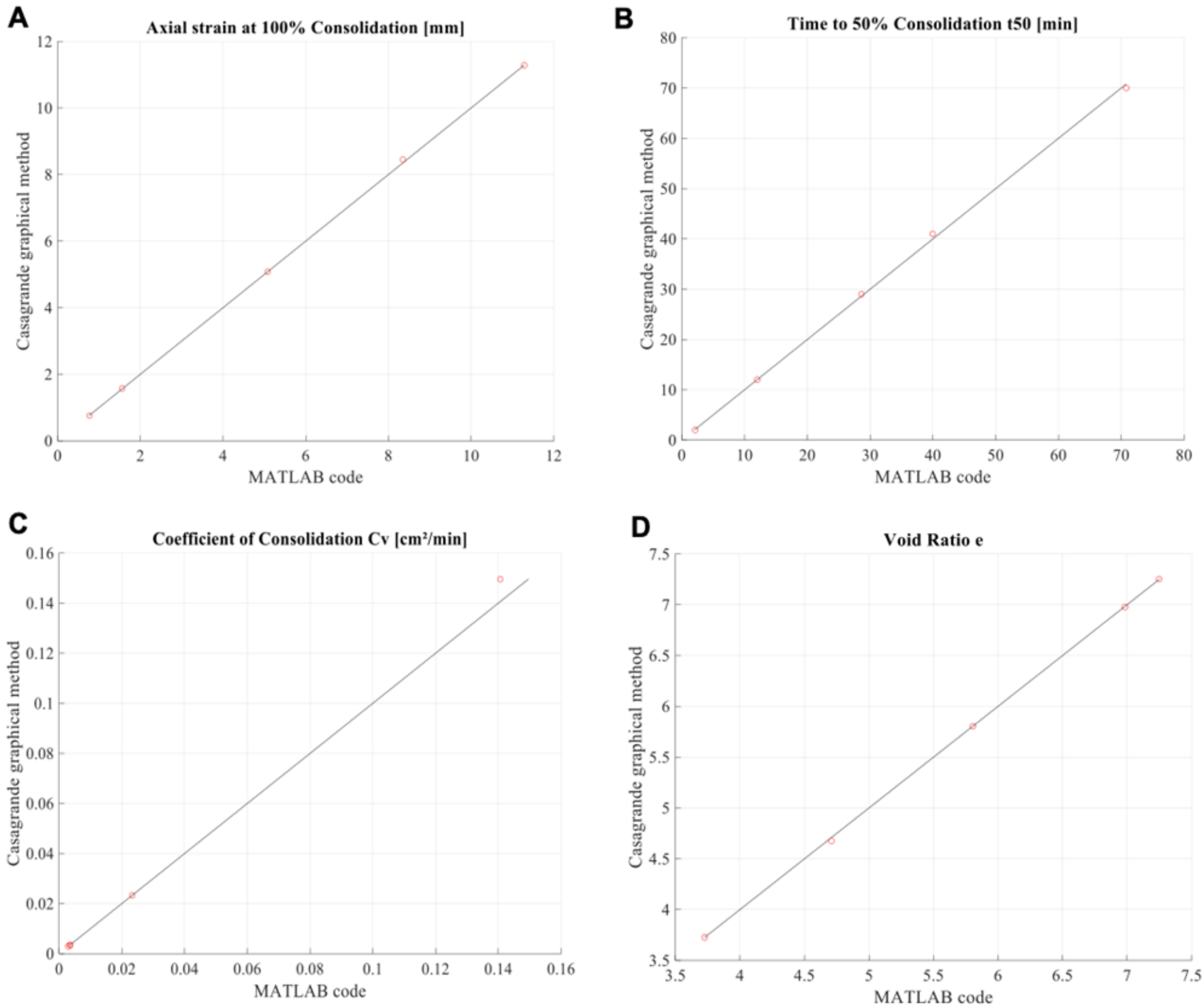

Figure 4. Comparative Analysis of Experimental vs. Theoretical Results. (A) Axial deformation at 100% consolidation. (B) Time to reach 50% consolidation. (C) Consolidation coefficient Cv. (D) Void ratio e.

Furthermore, as clayey soils compact, they tend to form cracks that propagate to the surface, compromising the structural integrity of various infrastructures. Additionally, the soil in the Valley of Mexico tends to amplify seismic movement, prolonging the duration of tremors and increasing the risk of structural damage to buildings during earthquakes (Tena-Colunga et al., 2021).

4.8. Soil Consolidation and Differential Settlements

Soil consolidation is a geotechnical process that involves the reduction of soil volume under an applied load due to the expulsion of water from its pores. Terzaghi developed the consolidation theory, establishing a model that defines the relationship between the applied load, time, and soil volume reduction (Towhata, 2008). Terzaghi's one-dimensional consolidation equation is fundamental for predicting soil behavior under different loads. The equation considers the

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consolidation coefficient, soil permeability, and soil compressibility factors. Consolidation is particularly relevant in clayey soils, such as those in the Valley of Mexico, where the process can be slow due to the low permeability of the clays. As a load is applied, the excess pore pressure dissipates gradually through water expulsion, decreasing soil volume and subsequent settlement.

Differential settlements refer to the difference in the amount of settlement that occurs in various parts of a structure or ground under a load. These settlements induce stresses in structures, leading to cracks or structural failures. Such differences can be caused by load variations, soil heterogeneity, or non-uniform drainage conditions (Paredes et al., 2022).

The results show a general increase in the perception of the development of complex thinking competencies and their sub-competencies among the students following the soil mechanics course, particularly the laboratory practice on consolidation settlements (see Table 3). Regarding systemic thinking, the initial mean was 3.89 (Sd = 0.39), while the final mean rose to 4.16 (Sd = 0.39). Similarly, scientific thinking increased from an initial mean of 3.53 (Sd = 0.57) to 4.10 (Sd = 0.60). Critical thinking also improved, with the mean rising from 3.77 (Sd = 0.45) to 4.14 (Sd = 0.52). As for innovative thinking, the initial mean was 3.66 (Sd = 0.57) and increased to 4.16 (Sd = 0.50) in the final assessment. Finally, the overall perception of complex thinking development showed a notable increase, with the initial mean of 3.71 (Sd = 0.42) rising to a final mean of 4.15 (Sd = 0.44). These results suggest a substantial improvement in students' perception of their development in each of the sub-competencies of complex thinking after completing the course (see Table 3). Figure 5 illustrates the perception of the complex thinking competency and its sub-competencies in the initial and final diagnoses.

Table 3. Perceived achievement of the complex thinking competency and its sub-competencies among students.

	Initial		Final	
	Mean	Sd	Mean	Sd
Systemic thinking	3.89	0.39	4.16	0.39
Scientific thinking	3.53	0.57	4.10	0.60
Critical thinking	3.77	0.45	4.14	0.52
Innovative thinking	3.66	0.57	4.16	0.50
Complex thinking	3.71	0.42	4.15	0.44

Figure 6 presents a comparative analysis of the student's perception regarding the development of complex thinking sub-competencies, evaluated at the beginning and end of the soil mechanics course, following the laboratory test on soil consolidation settlements. The violin plots visually represent the distribution of responses in both the initial and final evaluations, covering the sub-competencies of systemic thinking, scientific thinking, critical thinking, and innovative thinking.

In each sub-competency, there is a shift towards higher values in the final evaluation, indicating an improvement in the perception of the development of these skills. This change is particularly evident in the sub-competencies of systemic and critical thinking, where a higher concentration of responses in the upper levels is observed following the formative intervention. Additionally, the shape of the density curves reflects a reduction in data dispersion in the final evaluation, suggesting greater consistency in students' perception of their development.

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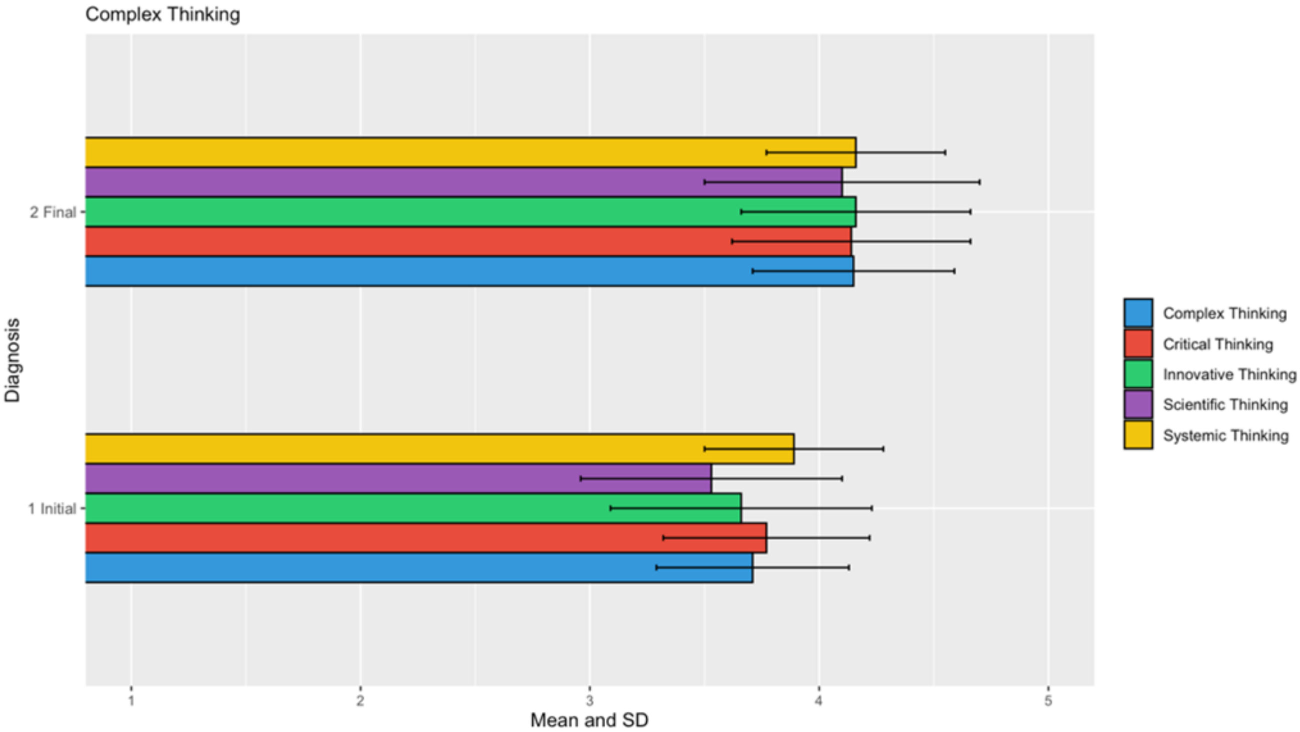

Figure 5. Comparative bar chart of students' perceived development of complex thinking and sub-competencies before and after the soil consolidation lab.

Figure 6. Violin plots. Comparative analysis of students' perception of complex thinking sub-competencies before and after the soil consolidation lab test.

Table 4 shows that the first two principal components (PC1 and PC2) account for a cumulative proportion of 85.3% of the total variance, indicating that these components capture most of the information in the original variables. PC1, which explains 76% of the variance, is highly positively correlated with all sub-competencies: systemic thinking, scientific thinking, critical thinking, and innovative thinking, with loadings of 0.50, 0.50, 0.49, and 0.49, respectively. This component

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represents a common factor for general complex thinking development. PC2 explains 8% of the variance and is mainly associated with scientific thinking (0.58), suggesting that this sub-competency varies independently from the others, particularly innovative thinking, which shows a negative loading (-0.79) on this component.

Table 4. Complex thinking sub-competencies: principal component analysis matrix

Concept	PC1	PC2	PC3	PC4
Systemic thinking	0.50	0.12	0.47	0.70
Scientific thinking	0.50	0.58	0.20	-0.60
Critical thinking	0.49	0.07	-0.84	0.19
Innovative thinking	0.49	-0.79	0.15	-0.30
Standard deviation	1.75	0.58	0.56	0.51
Proportion of variance	0.76	0.08	0.07	0.06
Cumulative Proportion	0.76	0.853	0.932	1.00

The biplot shown in Figure 7 represents the relationships between the complex thinking sub-competencies and their distribution among students at the beginning and end of the course. The axes represent the first two principal components: PC1, which explains 76.6% of the total variance, and PC2, which accounts for 8.6%. Together, these two components capture more than 85% of the variability in the data.

The arrows indicate the contribution of each sub-competency to the space of the principal components. Systemic thinking and critical thinking sub-competencies contribute more to PC1, suggesting that these competencies experienced more significant development throughout the course. This is reflected in the orientation and size of the arrows, which are more aligned with PC1, indicating that the development of these competencies is strongly associated with the variability captured by this component.

The points on the graph represent students grouped into two stages: the beginning (purple) and the end (blue) of the course. After the educational intervention, the separation of the groups along the PC1 axis reflects a notable improvement in the development of competencies, particularly in critical thinking and systemic thinking.

Table 5 shows the results of the student's t-test applied to assess the significant differences between the initial and final measurements of the perception of complex thinking competency development and its sub-competencies. The results demonstrate highly significant differences across all the evaluated sub-competencies and the overall complex thinking competency. These p-values, all below 0.001, confirm that the intervention conducted during the course had a statistically significant impact on the perceived development of the complex thinking sub-competencies.

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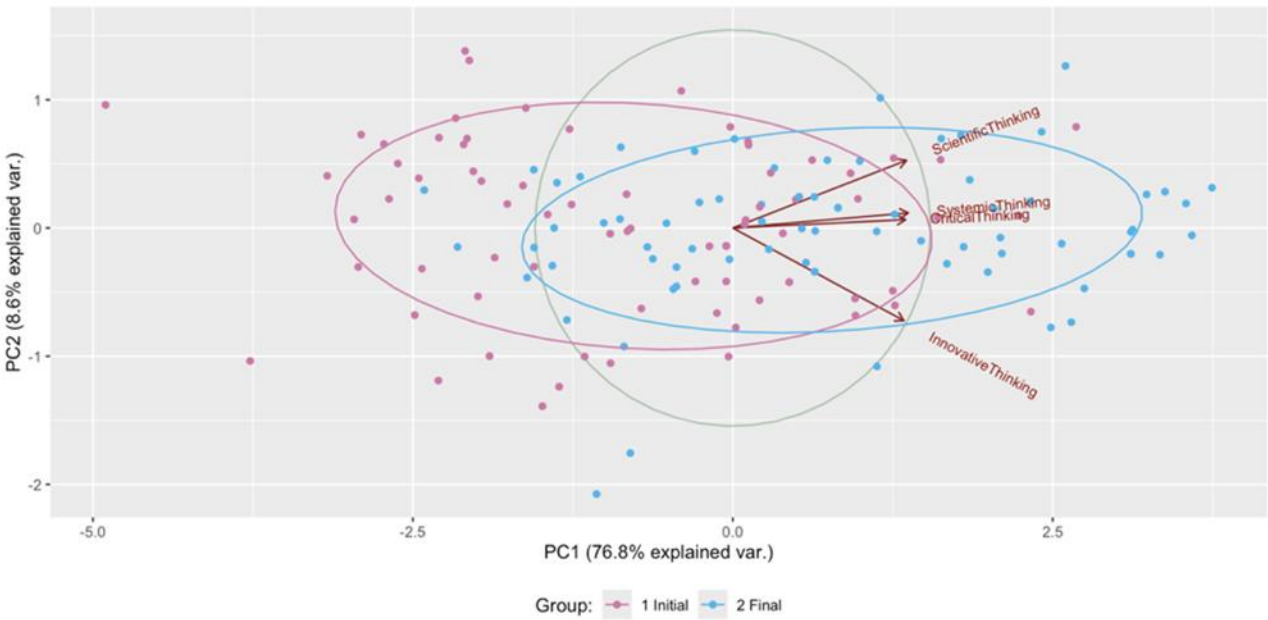

Figure 7. Complex thinking sub-competencies. Biplot of form (α=1).

Table 5. Results of the significant differences between the initial and final diagnosis in the perception of achievement of complex thinking competency (student's t-test).

	t	*df*	*p-value*
Complex thinking (Initial vs final diagnosis)	-6.27	149.75	3.56e-09
Systemic thinking (Initial vs final diagnosis)	-4.46	149.99	1.537e-05
Scientific thinking (Initial vs final diagnosis)	-5.94	149.57	1.84e-08
Critical thinking (Initial vs final diagnosis)	-4.58	146.83	9.632e-06
Innovative thinking (Initial vs final diagnosis)	-5.78	147.54	4.266e-08

5. Discussion

5.1. Development of Competencies in Civil Engineering

In higher education, civil engineering students must develop disciplinary and transversal competencies to mitigate geotechnical and seismic risks. The consolidation settlement tests conducted in the soil mechanics laboratory are essential. Through these tests and models, such as

Terzaghi's, students can observe the consolidation process and analyze the results in real time. In addition to disciplinary competencies, transversal competencies are of utmost importance, as they significantly impact the quality of professional practice (Tobón & Luna-Nemecio, 2021; Pham et al., 2025). Several universities focus on developing transversal competencies such as self-awareness and management, innovative entrepreneurship, social intelligence, ethics and citizenship, complexity reasoning, communication, and digital transformation (Ruè, 2008; Cruz-Sandoval et al., 2023).

Consolidation settlement laboratory tests provide a practical platform for students to develop and apply complex thinking. By performing these tests, students must observe and analyze how soils behave under different load conditions, consider the long-term effects of consolidation, evaluate how these processes may affect the stability of structures in the real world, and create innovative solutions to mitigate the effects. These pedagogical experiences are vital for consolidating the knowledge acquired and understanding how theories are applied in real-life situations (Sotelo et al., 2023; Hofstein & Lunetta, 2004).

The results of this study highlight the positive impact of integrating laboratory practices into the perceived development of complex thinking competencies among civil engineering students, as noted by other studies (Sotelo et al., 2023; Hofstein & Lunetta, 2004). After completing the soil mechanics course, which included a laboratory practice on soil consolidation settlements, significant improvements were observed in the four evaluated sub-competencies: systemic, scientific, critical, and innovative thinking. These practices provide students with an ideal environment to develop key cognitive skills, suggesting that experiential and experimental activities strengthen transversal competencies essential for professional development (Azofeifa et al., 2024).

The original contribution of this study lies in its combined approach of laboratory work and technology. Using computational tools such as MATLAB allowed students to perform comparative analyses between theoretical and experimental data. This deepened their understanding of soil behavior under different loads and enhanced their critical problem-solving and data-analysis skills. Combining traditional graphical methods with technological tools demonstrates that both approaches are equally effective and complementary for civil engineering education, underscoring the importance of integrating advanced technologies into the engineering curriculum.

The findings align with previous research suggesting that practical activities foster meaningful learning and the acquisition of complex competencies when complemented by technological tools (Hofstein & Lunetta, 2004; Cruz-Sandoval et al., 2023). The notable development in the sub-competencies of systemic and critical thinking reflects the student's ability to approach geotechnical problems comprehensively, considering the technical aspects and broader implications, such as the risks associated with soil consolidation and its relationship to seismic vulnerability.

The significant improvement in systemic and critical thinking competencies is particularly relevant in Mexico City, a geotechnically complex area characterized by highly compressible soils and exposure to intense seismic activity. Civil engineers graduating from these institutions face the challenge of designing resilient solutions to differential settlements and seismic amplification, recurrent problems in the Valley of Mexico. In this sense, training based on practical laboratories, such as consolidation settlement experiments, provides students with technical understanding and the ability to think critically about risks and apply innovative solutions to mitigate their effects.

This research underscores the need for Mexican universities to adopt pedagogical practices integrating technology and experimental work as part of a comprehensive approach to competency development. The importance of these competencies in the Mexican context cannot be overstated: designing resilient and sustainable infrastructure in a seismically active and geotechnically challenging region requires engineers who can integrate critical, systemic, and innovative thinking into their proposals. By preparing students to face these challenges, the study contributes to forming engineers who will play a key role in urban infrastructure's future sustainability and safety. Despite the promising results, this study has certain limitations. The sample was based on a single institution and limited to 76 students, which may constrain the generalizability of the findings. Additionally, the absence of a control group prevents direct comparison with other pedagogical approaches. Future research could address these aspects by employing more robust experimental designs, including control groups and larger samples.

Furthermore, longitudinal studies would be valuable in analyzing how the development of these competencies in an academic setting impacts the professional practice of civil engineers. Expanding the study to other engineering disciplines could provide a more comprehensive view of laboratory practices' role in developing transversal competencies. Incorporating other advanced technological tools and comparing results between national and international institutions would also offer new perspectives on the evolution of these competencies.

6. Conclusion

This study provides compelling evidence that laboratory practices and computational tools effectively develop complex thinking skills in civil engineering students. These competencies become even more critical in the geotechnically challenging context of Mexico City, where clay soils and seismic activity present unique problems. The study prepares students to tackle complex issues and formulate resilient and sustainable solutions in their professional careers by equipping them with advanced technical and cognitive skills. The pedagogical implications underscore the importance of integrating practical and technological methods in engineering education, ensuring that graduates are well-prepared to face real-world challenges in environments as demanding as the Valley of Mexico.

Declarations

Author Contributions. ERL, RFA, and IGK: A literature review. Conceptualization: JMH, MCS, IGK. Methodology, data analysis: ERL, RFA, IGK, JMH. Review-editing and writing: IGK, JMH, RFA, ERL, MCS. All authors have read and approved the published version of the article.

Conflicts of Interest. The authors declare no conflict of interest.

Funding. none

Ethics Statement. The study followed the guidelines approved by the Institute for the Future of Education of the Instituto Tecnológico de Monterrey, Mexico. Informed consent was not applicable since the study did not involve human subjects and only used anonymized student data.

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About the Contributor(s)

Eduardo Reyes de Luna, Ph.D., is the Head of the Civil Engineering Academic Program at the Santa Fe Campus of the School of Engineering and Sciences at Tecnológico de Monterrey. His research interests include structural engineering, seismic engineering, mathematical simulation, and mechanics of materials.
Email: eduardoreyes.de@tec.mx
ORCID: https://orcig.org/0000-0002-9788-8936

Rubén Fuentes Alvarez, Ph.D., is the Associate Director of the Department of Mechatronics and former Director of the Biomedical Engineering Program at the School of Engineering and Sciences at Tecnológico in the Mexico City region. His research interests include artificial intelligence, assistive robotics, intelligent bio-instrumentation, and biomechanics.
Email: joru.fua@tec.mx

ORCID: https://orcid.org/0000-0003-3170-9381

Iván García Kerdan, Ph.D. is Associate Professor and Head of the School of Engineering and Sciences (Santa Fe Campus) at Tecnológico de Monterrey. He is also a visiting researcher at Imperial College London's Department of Chemical Engineering. He holds a Ph.D. in Energy Engineering from UCL and a degree in Mechatronic and Energy Engineering from the National University of Mexico, UNAM. His research explores techno-economic aspects of energy systems and decarbonization strategies.
Email: i.garciakerdan@tec.mx
ORCID: https://orcid.org/0000-0002-0566-555X

Marco Cruz-Sandoval, Ph.D., is the Head of the Department of Sustainable and Civil Technologies at the Tecnológico de Monterrey for the Mexico City Region, based at the Santa Fe Campus. His research has focused on resilient and sustainable cities, mainly on social, environmental, and spatial justice. Additionally, he has developed strategies for compositional data analysis (CoDa) methods for the specialized literature on multivariate statistical analysis of urban phenomena. His statistical and geostatistical analyses aim to support policies aligned with sustainable development goals.
E-mail: cruzsandovalmarco@tec.mx
ORCID: https://orcid.org/0000-0001-5703-4023

Jorge Membrillo-Hernández, Ph. D., is a Full Researcher at the Institute for the Future of Education and the School of Engineering and Sciences at the Tecnológico de Monterrey. His research interests include Challenge-based Learning, Sustainable Education, Artificial Intelligence, and STEM education.
Email: jmembrillo@tec.mx
ORCID: https://orcid.org/0000-0001-7650-8116