An interactive computational strategy for teaching the analysis of silo structures in civil engineering

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Abstract

In this article, a Matlab-based software environment called Guide Silo Design (GSD) is proposed to help undergraduate students to better understand the complex phenomena involved in the analysis process of silo structures. The software is integrated with two commercial finite element softwares. These are the Open Application Programming Interface (OAPI) code in SAP2000 and the ANSYS Parametric Design Language (APDL) code in ANSYS. GSD allows civil engineering students to create a virtual simulation environment in which an effective and appropriate teaching-learning process can be experienced. The GSD environment is programmed in Matlab using a finite element-based mathematical framework. Furthermore, as the analysis of silo structures is highly relevant in real engineering projects, students can acquire fundamental knowledge for their future works as engineers. The present interactive virtual environment has great potential to improve the learning process of the analysis of silo structures.

Keywords: Active learning environment, simulation software, finite element method, silo structure

1. INTRODUCTION

By simulating a physical system, students can visualize and connect abstract mathematical concepts with reality. Simulations allow students to face the dynamics of a process and develop the skills they will need for success in the future as structural engineers. Furthermore, computational simulations can represent an active, and sometimes, an interactive learning-centered technique in which students can engage in the learning process by recreating complex physical phenomena in a virtual environment. However, there are educational institutions where skeptical faculty members are not either familiarized themselves with these techniques or there is a perception of radical changes in the curricula [1].

In engineering, typical teaching strategies are based on the study of problem-orientated cases. Historically, structural engineering courses exhibit high failure rates, which represent a strong argument in favor of the exploration of new forms of teaching [2]. It is here where active learning emerges as an effective technique to develop the future engineer competences by resembling professional practice inside the classroom [3]. Active learning is often contrasted to the traditional lecture where students passively receive information from the instructor [1]. However, not every active learning technique is adequate to be applied in a certain undergraduate course. In this paper, the Problem-Based Learning (PBL) method is chosen due to its ability to introduce specific problems at the beginning of the semester and put the student in context with a professional situation. This technique is always active and usually collaborative or cooperative, and it involves significant amounts of self-directed learning activities from the part on students [1].

Research on active learning experience and PBL was originally implemented in medical institutions. Most of it suggests certain degree of improvement on the student learning capacity. For example, Prince [1] concludes that PBL does improve other learning outcomes such as problem solving and critical thinking skills, long-term retention of knowledge, and study habits. The author also concludes that PBL better prepares engineering students for life-long learning when compared to traditional teaching methods [4–6]. Vernon and Blake [7] studied 35 cases where PBL produced a significant improvement on student attitudes and opinions about their programs. Albanese and Mitchell

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[8] found that, in general, students and faculty members prefer a PBL approach. Norman and Schmidt [9] conclude that PBL does provide a more challenging, motivating and enjoyable approach to education.

In the civil engineering context, educational institutions have seen an increasing interest on this method over the last few years. Dutson et al. [10] reviewed literature on capstone courses using project-oriented teaching methods and discussed many of the principles of PBL. Johnson [11] applied PBL in a semester-length, junior/senior level course in hydraulic engineering. The study probed that PBL increases the learning, interpersonal, and writing skills of students, as well as their awareness of the benefits of teamwork. Steinemann [12] used PBL to develop a new graduate-level course in sustainable engineering. Here, PBL was used to provide hands-on experiences to improve communication and teamwork. Ribeiro and Mizukami [13] experimented with PBL in a course for fifth-year civil engineering students. The course focused on professional practice topics. Chinowsky et al. [14] reported on their experiences learned from four implementations of PBL within special course offerings. The authors concluded that the introduction of PBL in the civil engineering curricula provides the opportunity to expand beyond a knowledge point concentration, and students have the opportunity to explore problems that encourage skills beyond traditional analytic intelligence. Solis et al. [15] mixed PBL with traditional course objectives or assessment tools. Other authors have reported some general hands-on strategies to structural engineering courses. For example, Fernández-Sánchez and Millán [16] presented experiences in a structural analysis course of a civil engineering degree to motivate students to learn structural analysis and design by using classical theory, performing calculations by hand, using a computer program, and using a plastic toy for model trusses to measure strain and stresses. Mosalam et al. [17] applied PBL in earthquake engineering using activities involving theoretical and hands-on-experience components.

Structural courses in civil engineering usually require the study of practical cases where expensive experimental laboratories may become a considerable budget for universities. In addition, regardless of the financial resources, lab-based teaching strategies are, in many cases, limited to time constraints and a possible large number of students sharing the same experience. To overcome these problems, special team-building exercises between the instructor and student may be needed. Open discussions become critical for the students to share what is being learned and for the instructor to facilitate additional learning and promote problem solving skills [18]. In this context, computational simulations and PBL represent a faster, cheaper and effective alternative to simulate large experiments (those who can not be experimented in a university laboratory), playing an important role in the student learning process.

In order to generate a simulation, several computational tools are available nowadays. Probably, one of the most frequently used techniques to simulate physical problems in civil engineering is the Finite Element Method (FEM) [19–21]. FEM is a numerical approach to solve a set of partial differential equations that describe a physical phenomenon. The possibility of applying numerical methods (like FEM) to obtain approximate solutions to very complex problems has opened new opportunities to change traditional teaching-learning methods. Simulations allow students to learn more efficiently by using an student-centered active learning technique, rather than using a conventional teaching process focused on the lecturer [1, 2, 18, 22]. This type of technologies also helps to improve group sharing of resources and group collaboration [23]. Even more, this technique can also help to understand complex phenomena of difficult visualization by means of conventional analytical approaches, promoting hands-on learning.

The main relevance of FEM in the context of this paper is its versatility to analyze the physical response of a wide range of civil engineering structures. Two popular commercial finite element (FE) softwares are SAP2000 [24] and ANSYS [25]. In order to adapt a FE software for the specific purpose of assisting teaching in the analysis of civil structures, a programming code is needed. In particular, SAP2000 uses the OAPI programing language, and ANSYS uses the APDL code, which allow users to create a friendly Graphical User Interface (GUI). By using this software environment, students can select relevant information related to the structure and then, once the numerical solution is finished, analyze the simulated structural behavior, e.g., observe motion and displacements in the structure, visualize stresses and strains in the material and detect where the structure might fail.

Silos are important civil engineering structures widely employed by all kind of industries to bulk storage of different products and goods. Also, this structure serves as a temporary storage to compensate for industrial fluctuations between production and delivery. Refer to Figure 1 for a typical silo structure.

Figure 1: Typical structure of a metallic silo.

Due to its wide and frequent use in the industrial sector, it was found convenient to choose this structure as a typical case study in an engineering course. This is of particular interest in the Chilean mining and agricultural industries where silos are of great relevance to ensure high levels of productivity. Moreover, given the complex behavior of these structures, the understanding of the mechanics of silos is a challenge for civil engineering students. Unfortunately, the traditional teaching-learning strategies to analyze these structures are mainly based on the delivery of theoretical concepts and mathematical background. Therefore, the use of computational simulations to teach the structural behavior of silos can represent an effective active learning strategy. In fact, simulations of real world exercises have become very relevant in engineering studies, with positive reactions from the students [26–29].

In this work, GSD is proposed to teach students the analysis of complex metallic silos. Within the proposed simulated environment, all the mathematical computations are carried out in a hidden mode (batch mode), so that students are not required to have a deep knowledge on FEM and its theory. It is intended that the students focus on the visualization of the theoretical concepts associated with the mechanics of silo structures instead of focusing purely on mathematical equations. Furthermore, it is important to mention that GSD has been implemented with educational purposes. The main target groups are undergraduate students pursuing a civil engineering degree, but not civil engineers with extensive professional experience in structural engineering. Senior engineers can use directly commercial FE softwares without the use of the proposed interface. GSD is presented here as an educational strategy to complement the civil engineering curricula, emphasizing on the visualization of the physical phenomena, such as contour plots of stress and strain fields, localization of stress concentration areas (typically associated with crack initiation), comparison between deformed and undeformed shapes, visual assessment of choosing different pressure laws and their impact on the structure, etc. We note that the mathematical equations related to these physical phenomena are very difficult to understand without the assistance of a simulated environment. Importantly, the main steps involved in the structural analysis of silos are emphasized by GSD at all times.

This paper is organized as follows. Section 2 describes the GSD environment. Section 3 presents a practical case of application of the developed software. Section 4 reports the educational application of the developed environment and, finally, Section 5 summarizes the main conclusions of the present article.

2. GSD SIMULATION ENVIRONMENT

2.1. System architecture and interaction with the finite element method

The proposed simulation environment for the design of silo structures is organized into four main modules: (1) Geometry definition, (2) Material properties in SAP2000, (3) Load cases, and (4) Post-processing results. It was noted that the first 3 modules represent the pre-processing stage of the analysis. The fact that this organization is broken down into four modules allows the students to understand the main steps involved in the structural analysis of silos and in general, any type of structure.

The algorithm was developed in Matlab environment and several GUI windows were defined to allow the students to learn interactively. The code structure is outlined in Figure 2. The structure is mainly developed in SAP2000 because

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of its wide use among civil engineering students and designers. With the OAPI language it is possible to provide access during run-time between the third-party application (i.e., Matlab in this case) and the simulation software itself. The OAPI language is activated within the Matlab script, making it feasible to gain access to an extensive collection of objects and functions and control the operation of SAP2000 entirely in the background, completely overriding the standard point-and-click procedure. As a consequence, this feature represents a possibility for students to have access to both pre- and post-processing stages in the virtual environment, which is very useful from the learning point of view. Importantly, ANSYS is only called in case the student chooses to compute the pressure distribution from the material contained in the silo by means of its explicit FE modeling. Here, ANSYS is called from the Matlab script by generating a .txt input file in APDL language. Then, the input code also implements parametric post-processing which is exported to a .txt result file so that Matlab can transfer it to SAP2000.

After the FE problem is solved, lecturers can explain how the simulated physical phenomenon behaved in pseudo-time, allowing students (guided by their lecturer) to interpret results in the post-processing stage.
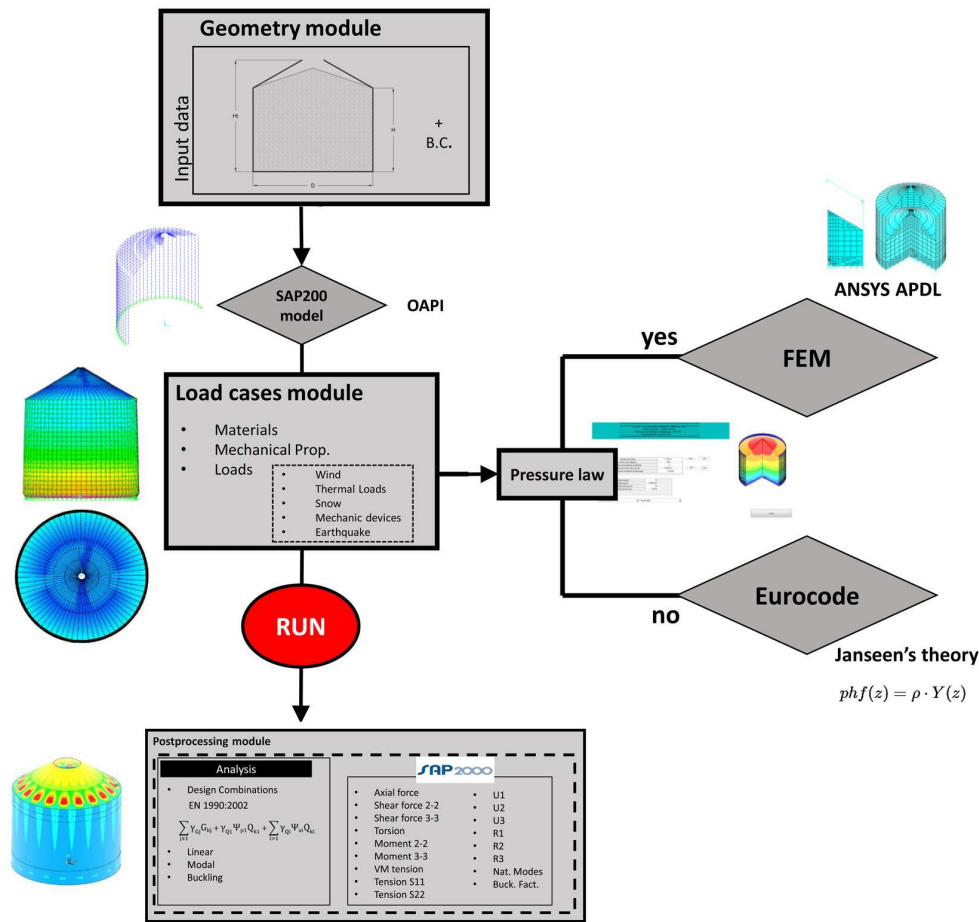

Figure 2: Schematic software representation.

2.2. Modeling with a graphical user interface

In order to facilitate the learning process among students, a user friendly GUI was developed. As commented earlier, the GUI consists of four main components. These are the definition of (i) the geometry, (ii) the material properties, (iii) the load cases, and the (iv) the post-processing. In the following, each of these modules is described.

(i) *Definition of geometry*

Figure 3 shows the geometry window. Here the students can define the general geometry of the silo with parameters like height, width, diameter, angle of the conical roof, etc., as well as the reinforcements of the roof

and the dimensions of the body shells and the boundary conditions at the base. By clicking on the "Generate Geometry" button, GSD calls SAP2000 via OAPI where the main FE model is generated. The model is defined with shell and beam elements as shown in Fig. 4. The body is reinforced by vertical beams which continue on the roof as radial reinforcements. The students can also define ring reinforcements to simulate a typical silo roof. The surfaces, cylindrical body, and inclined roof, are connected at the end of the beams by linking their rotational degrees of freedom, simulating a pin connection. The thickness of the body shells can be introduced in the tab entitled "Shells" as shown in Figure 5 (which can be variable along the height of the silo if required by the student), and the roof structure definition in the tab "Roof structure" shown in Figure 6. Importantly, for the sake of simplicity, the authors have avoided throughout the paper a detailed description of the input information required to fill in each cell of a window, focusing only on the most important inputs.

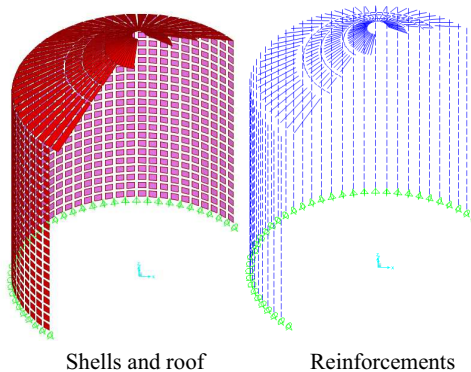
Figure 3: Geometry module.

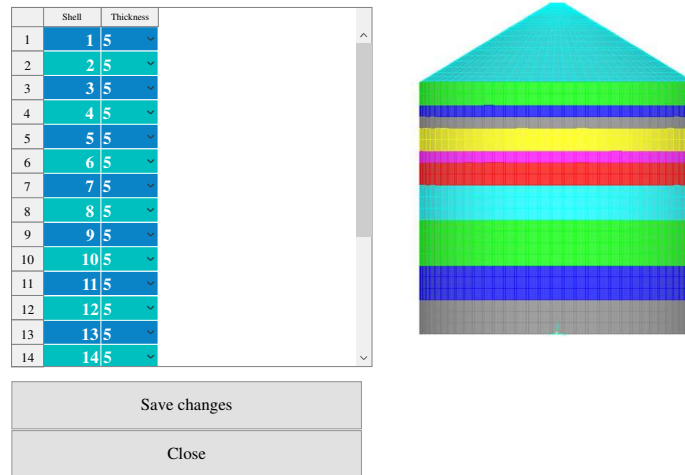Figure 4: Detail view of body shells and linear reinforcements.

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Figure 5: Body shell GUI.
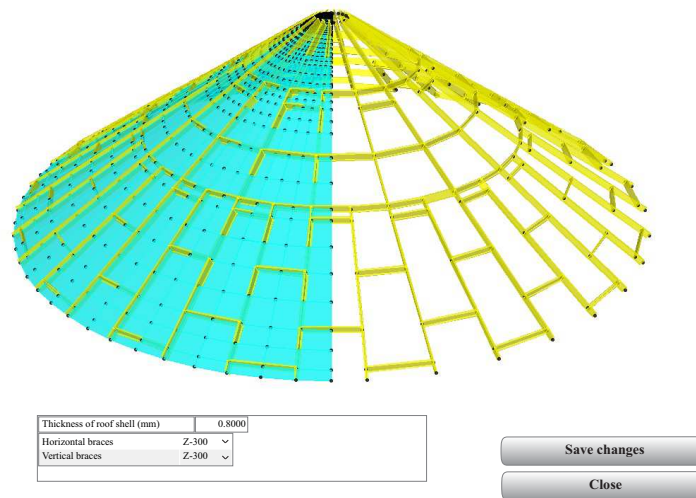
Figure 6: Roof structure definition GUI.

(ii) *Material and Mechanical Properties Module*

Once the blank geometry of the model has been generated in the previous module, the material GUI shown in Figure 7 is automatically opened. Here the student can choose between different predefined materials (wheat, barley or corn) or introduce a new material by defining its physical properties (friction angle, density, cohesion, and dilatancy). From this window, students can access other different tabs to define the rest of the model.

All the input data is saved in the workspace, and introduced later into the SAP2000 model as general sections for linear elements and thin shells. The walls' cross sections are defined as sinusoidal (refer, for instance, to the corrugated surface of the walls shown in Figure 1). Because of the cross section geometry, the panels will respond orthotropically to the loading conditions. To take this behavior into consideration, GSD considers orthotropic shells by means of a mechanical homogenization procedure, and by introducing modifiers to the bending and membrane stiffness components.

Real engineering problems can be frequently challenging when young engineers have not developed a rational procedure to interpret initial constrains. This modeling procedure facilitates the frequently blurred transition from applying constrains to analyzing and evaluating engineering problems. Using this proposed technique,

the instructor can explain to the students the implicit assumptions included in the computational analysis to recognize the effect on the mechanical response. As a consequence, the instructor and the students can explore different geometrical or mechanical properties to debate the expected results of the analysis. Finally, the student can obtain the needed background of the problem in order to move forward to the following modules.

SOFTWARE TO CALCULATE PRESSURES IN CYLINDRICAL METAL SILOS
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Job name | jobname | Bulk material | Wheat

Bulk material parameters

	Value	Unit
Weight	9.00	kN/m³
Lateral pressure coefficient (k)	0.54	-
Friction coefficient (μ)	0.38	-
Angle of frction (Φ)	30.00	grad
Angle of repose (Φ_b)	34.00	grad

Characteristic value conversion (EN 1991-4)

	Value	Unit
Conversion factor a_k	1.11	-
Conversion factor a_μ	1.16	-
Conversion factor $a\Phi$	1.12	-

Geometry parameters

	Value	Unit
Height of the equivalent material (h_c)	17.737	m
Height of the cylindrical body (H_b)	13.728	m
Total height (H)	20.300	m
Height of the body shells (h_V)	1.144	m
Diameter (D)	22.929	m
a_w (EN 1994-1)	0.2	-

Steel

	Value	Unit
Thermal expansion coefficient	1.17E-5	grad⁻¹
Young's modulus (E)	210000	MPa
Poisson's ratio (v)	0.3	-
Mass density	7850	kg/m³
Yield strength (f_Y)	350	MPa

O FEM pressures

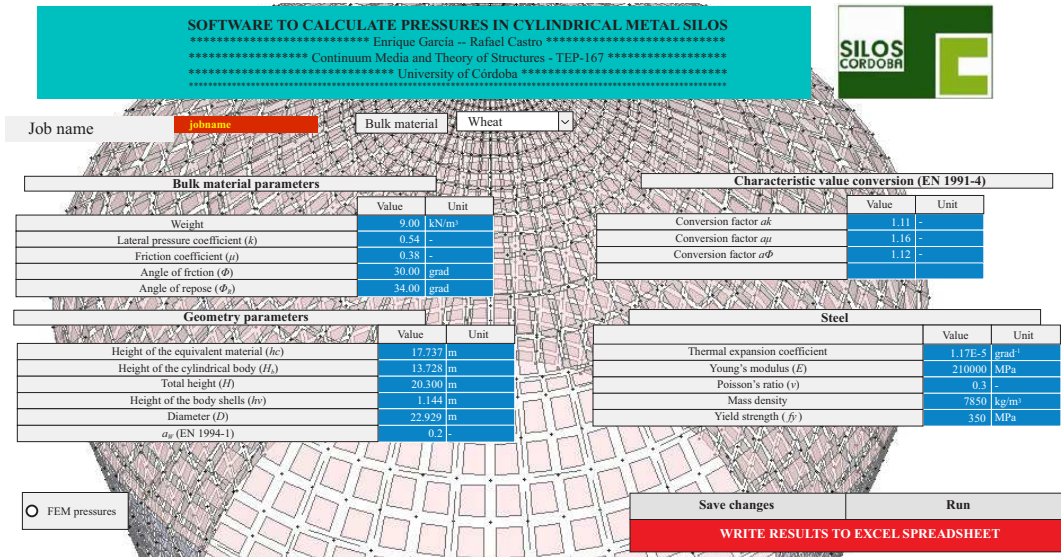Save changes | Run

WRITE RESULTS TO EXCEL SPREADSHEET

Figure 7: Material GUI.

(iii) *Load cases definition module*

Loads and load cases can be defined in the window shown in Figure 8. The load cases are taken from Eurocode 1 [30] as well as their combinations factors. The students can modify their default values for wind loads (BS EN 1991-1-4:2005), snow (BS EN 1991-1-3:2003), earthquakes (NCSR-02), and thermal actions (BS EN 1991-1-5:2003), among other loads.

Snow

	Value	Unit
S_k	1.2000	kN/m³
μ_i	0.8000	-
C_e	1	-
C_t	1	-

Thermal load

	Value	Unit
C_T	1.2000	-
T_{min}	-8	°
T_{max}	44	°
T_3	2	°
T_{in}	20	°
ΔT_{fixed}	5	°

Earthquake accel. coeff. | 0.040

	Value	Unit
Basic velocity	10	m/s
C_{dir}	1	-
C_{season}	1	-
Air density	1.2900	kg/m³

Number of mode shapes | 3

Wind

	Value	Unit
z_z	1.2000	kN/m³
z_{min}	0.8000	-
C_o	1	-

Differential settlement

	Node	Displacement (mm)
1	1	0

Roof's loads

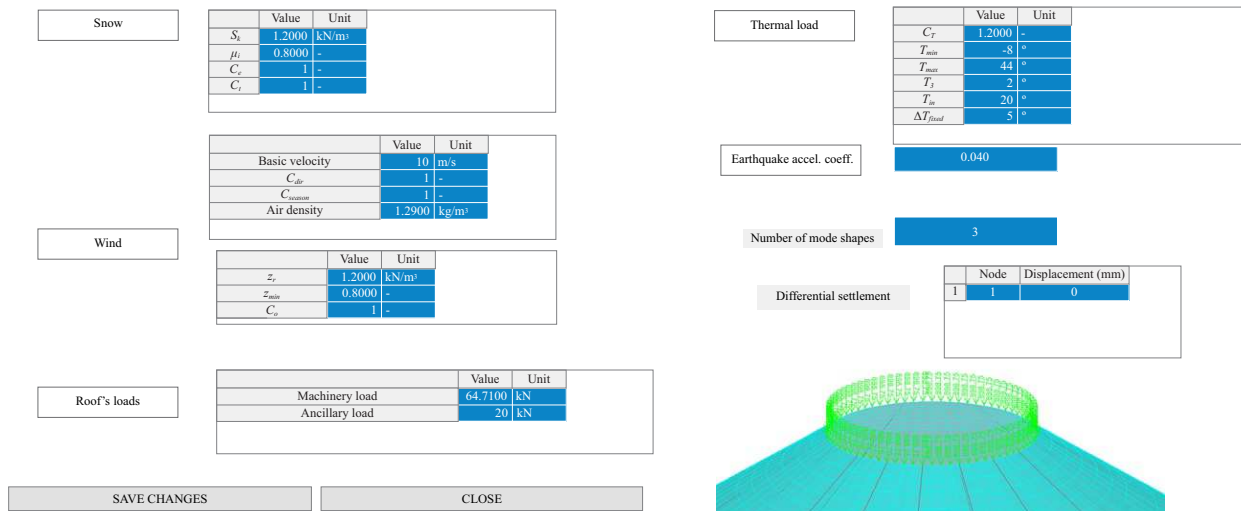|	Value	Unit
Machinery load	64.7100	kN
Ancillary load	20	kN

SAVE CHANGES | CLOSE

Figure 8: Loads definition GUI.

For the modeling of pressures coming from the stored material acting on the silo's walls, students can choose two alternatives. The first option is an analytical expression given by Eurocode 1 [30], and the second alternative

is a pressure distribution computed by means of FEM. For each case, the pressure is defined for three different states: static, discharge, and filling.

For the first alternative, the bulk material stored inside the silo is not explicitly modeled. What the student models here is the interaction between the bulk material and the silo's walls by means of compressive springs as shown in Figure 9. For a cylindrical silo with radius R, the flexibility $C(z)$ of the bulk material with Young's modulus E_m and Poisson's ratio v can be expressed by the relation
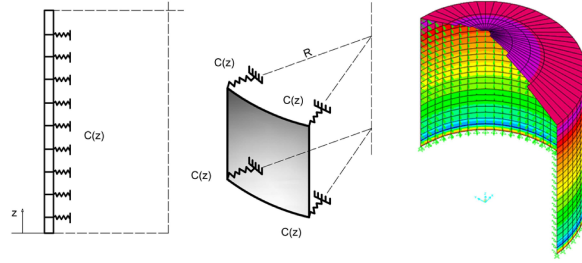
$$C(z) = \frac{E_m}{R \cdot (1 - v)}, \tag{1}$$

Figure 9: Modeling of the interaction between the silo's walls and the bulk material contained within the silo.

which is assumed to be constant for a given wall depth. Thus, GSD calls SAP2000 to build a FE model which takes into account the stiffness of the material contained inside the silo structure.

The pressure distribution law $p_h(z)$ coming from the material on the silo's walls is defined in accordance with the Janssen's theory [31]. This theory gives the analytical expression

$$p_h(z) = \rho \cdot Y(z), \tag{2}$$

where ρ is the bulk material's density, and

$$Y(z) = 1 - e^{\left(-\frac{z}{z_0}\right)}, \tag{3}$$

with $z_0 = \frac{A}{U \cdot k \cdot \mu}$, A the area of the silo's base, U its perimeter, k the Janssen ratio of horizontal to vertical pressure, and μ the coefficient of sliding friction between the bulk solid and the wall surface. For those readers interested in further details on this subject, the authors refer, for instance, to [31].

If the student chooses the second alternative, GSD adopts FEM to compute the pressure distribution. Here, three new axisymmetric models are now generated in ANSYS, called via batch mode. GSD automatically generates three *.txt* input files with the same name as the project and a suffix with the state. Once the FEM ratio button is clicked, a new GUI emerges as shown in Figure 10. This step allows students to select the corresponding state of analysis. For instance, if the student chooses to define the discharging process, a conical or cylindrical model (funnel and mass flow, respectively) must be selected to investigate the effect of the nozzle geometry (refer to Figures 11(a) and 11(b)). Here, the student must introduced the type of wall behavior (rigid or flexible), the angle of the discharge cone, the radius of the discharge tunnel, as well as some numerical parameters such as mesh size, contact stiffness, tolerances, and hopper dimensions, among others. The wall is defined with the element type SHELL208 and the bulk with element type PLANE42. The steel is defined as an isotropic elastic material and the bulk is modeled with an elastic-plastic model with a Drucker-Prager yield surface. These assumptions allow students to capture the grain behavior realistically rather than using a merely elastic behavior. Consequently, the student must input the corresponding material properties of bulk, such as cohesion, internal friction angle, and dilatancy angle. The interaction between wall and bulk is modeled with contact elements (surface-surface) implemented in ANSYS. The behavior of the contact is defined as no-separation type because the bulk and the wall are supposed to be permanently in contact during the deformation. The discharging method is defined

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using sliding surfaces modeled with frictional contact elements as shown in Figures 11(a) and 11(b). Refer, for instance, to [32] for the same modeling approach.

The static state assumes no motion of grain within the silos structure. Figure 11(c) shows the model for this condition. The filling process is simulated with a quasi-stationary non-linear analysis using the so-called *Birth and Death* elements in ANSYS. During this technique, GSD deletes some elements by applying a quasi-zero factor to their stiffness components and masses, allowing the filling process to be simulated by an accumulative deformation activated progressively. The introduction of all of these parameters obliges students to be aware of the input data and main assumptions made during the analysis of a silo structure. This will ensure the success of the learning process among students.

In the final stage, GSD calls ANSYS and executes the axisymmetric model chosen by the student. Once the convergence is reached, the pressures and friction on the wall are written in two separate *.txt* files. GSD reads these two files and implements an interpolation curve (minimum square method and spline interpolation) to define the pressure in the SAP2000 model as a load pattern for each node. In regard to the computing time involved in processing each computational simulation was 90 s, approximately, in a HP Z440 workstation, four physical cores, 2.6 GHz, 128 GB RAM, 500 GB internal storage.

FINITE ELEMENT MODELLING OF PRESSURES AND FLOW IN SILOS
**************************** Enrique García -- Rafael Castro ****************************
****************** Continuum Media and Theory of Structures - TEP-167 ******************
**************************** University of Córdoba ****************************

Mesh size	1.1440	m
Number of substeps	200	-
Layers of filling	4	-
Radius of discharge (R_i)	3.4375	m
Angle of discharge (β)	34	grad

h_v/n — 1

R/n — 8

FKN wall/wall	10
tol. wall/wall	1.00E-03
FKN friction surface	40
tol. friction surface	0.0100

Funnel flow model ∨ Rigid wall ∨

Close
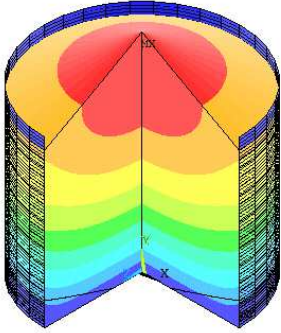
Figure 10: Pressure laws by finite element GUI.

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Figure 11: Axisymmetric solids in ANSYS: (a) conical discharging model; (b) cylindrical discharging model; and (c) static model. The authors noted that the filling model has been omitted (here, the simulation was obtained by activating the grain progressively using an element *Birth and Death* technique).

3. PRACTICAL HANDS-ON APPLICATION EXAMPLE

During the teaching process of GSD, the student is able to enhance his/her ability to apply engineering criteria, integrate concepts, and assess the suitability of possible engineering solutions. In order to illustrate the potential of the developed simulation environment, a practical case of seated steel silo is presented. This case is aimed to be a helpful example for students to understand the differences in the design of silos under pressure laws defined by Eurocode 1 and by the FE approach. The structure of the silo is composed of a cylindrical body of 25 m height and a diameter of 27.5 m, with a conical roof inclined 30 degrees (Figure 12). The cylindrical body is reinforced with cold-formed beams and the thickness of the body shells decreases with height. The grain stored is wheat with material properties shown in Table 1.

Figure 12: Schematic representation of the application example.

Table 1: Material properties of wheat.

Parameter	Value
Density (kN/m^3)	9
Lat. Press. coeff.	0.54
Friction coeff.	0.38
Angle of friction (deg)	30
Angle of repose (deg)	34

Figure 13 shows the contour plot of the Von Mises stresses in the deformed structure. Here, it is relevant to remark that the visual inspection of the output solution is crucial to detect possible errors made by the student. In fact, the visual assessment of the solution is mandatory in engineering problems. The visual inspection constitutes a powerful tool for the student to better understand the complex physical phenomena involved in the discharging and filling processes of silos.
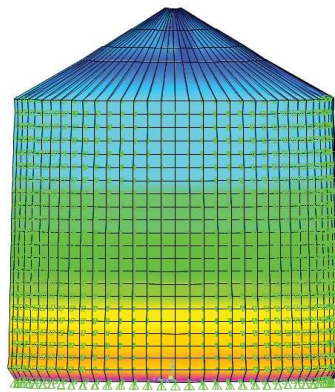
Figure 13: Contour plot of the Von Mises stresses in the deformed structure.

To obtain the corresponding pressure laws, GSD allows the learners to choose between Eurocode 1 and FEM. As previously commented, the instructor teaches the theoretical pressure laws based on a modified Janseen's theory. In Figure 14(a), a comparison between the pressure laws obtained from both methodologies is illustrated for the static condition. It can be inferred that, in this case, Eurocode 1 leads to oversized designs. For pressures ranging between 30000 N/m^2 and 70000 N/m^2, the FE approach gives a mean reduction of 20 %.

(a) Pressure in static condition

(b) Pressure in discharge condition
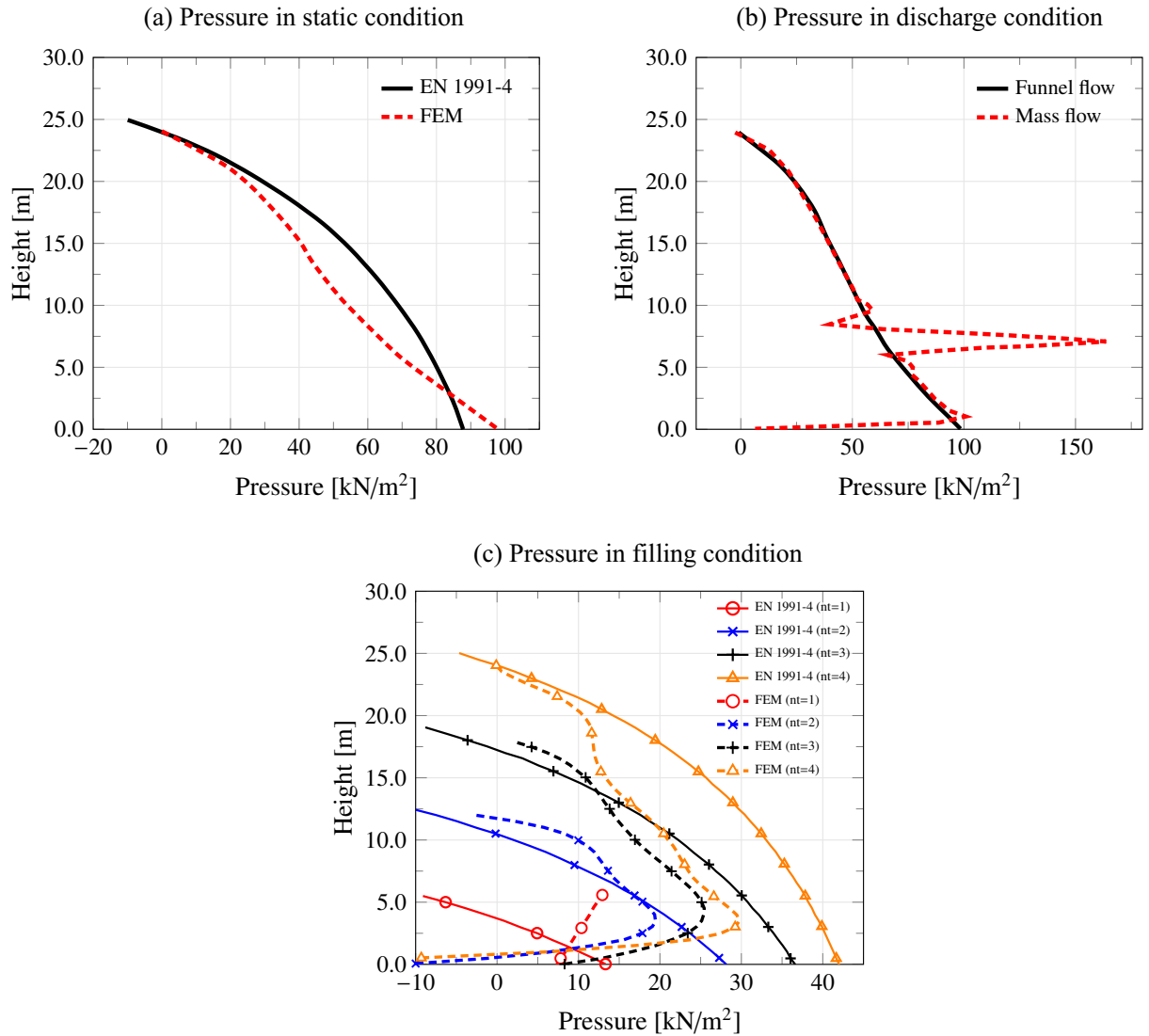
(c) Pressure in filling condition

Figure 14: Pressure distributions at different stages.

The discharge process is only defined in Eurocode 1 with two magnification factors in terms of the slenderness of the silo. As indicated in the previous section, the students can distinguish between funnel and mass flow. In Figure 14(b), the pressure at discharge stage is represented for each flow type. Note that the values are quite close except at about 7 m height. This is due to the singularity in the intersection between the sliding discharge surface and the silo's wall for the case of conical discharge flow. This effect is a typical behavior found in low slenderness silos in which a great moving mass flows through a surrounding volume of material at rest. Analytical models hardly can describe this phenomenon and usually provide uncertain results. GSD also provides information about pressure in the stage defined along the filling process. In Figure 14(c), the filling process is plotted for four different heights of material. As observed, the numerical and analytical pressure distributions show similar trends.

By analyzing these results, students can compare the predictions made by both approaches and gain insight into the pressure distribution at different stages. Thus, students can integrate spacial and temporal datasets, and test multiple scenarios to get an idea of possible outcomes while considering diverse assumptions and model inputs.

Once the pressure distribution is computed, GSD features the structural analysis of the silo considering the load case combinations prescribed by Eurocode 1. In particular, fourteen load combinations are defined on the basis of the previously indicated load cases and labeled with LC-i, i=1,...,14. As a result, GSD delivers the corresponding axial force, bending moment, and shear force diagrams (refer to Figures 15(a), Figure 15(b), and Figure 15(c),

respectively).
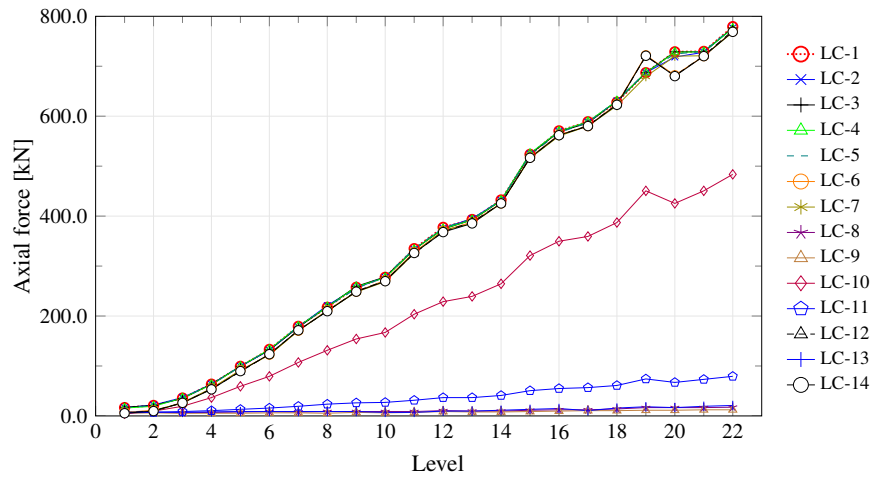
(a) Axial efforts
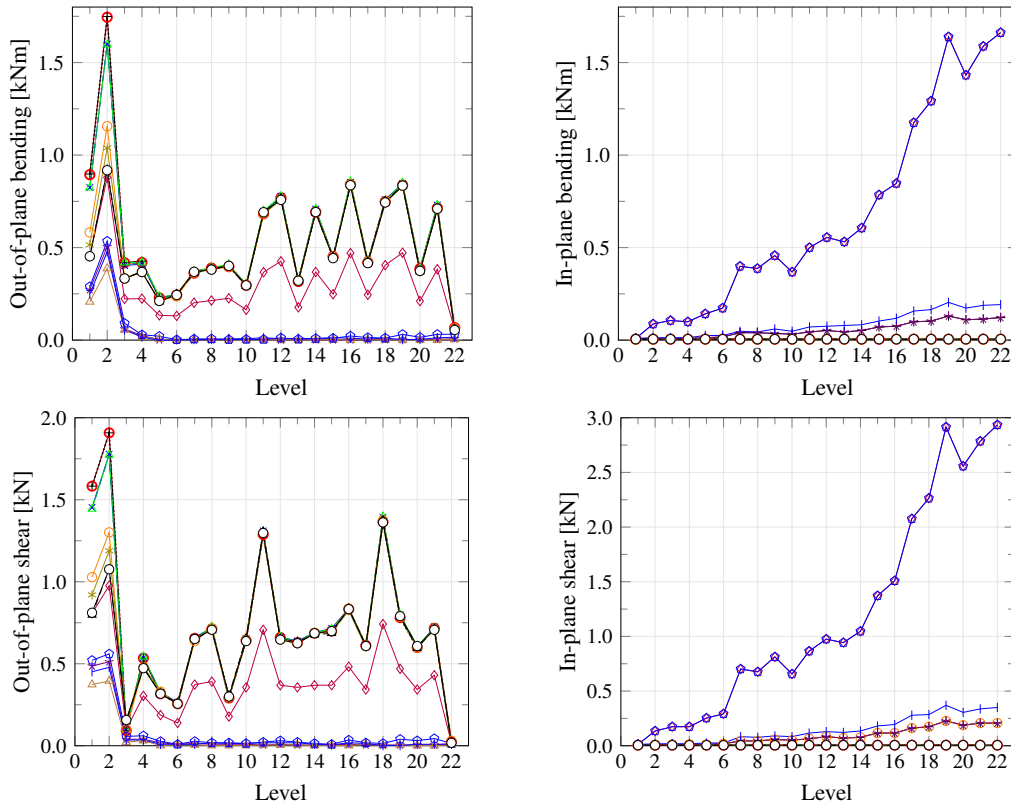
(b) Bending and shear efforts

Figure 15: Reinforcements forces for design load combinations.

In addition, students can verify stresses by means of GSD, which provides graphical representation of the Von Mises stresses for either a given load combination, or load combination envelope (Figure 16).
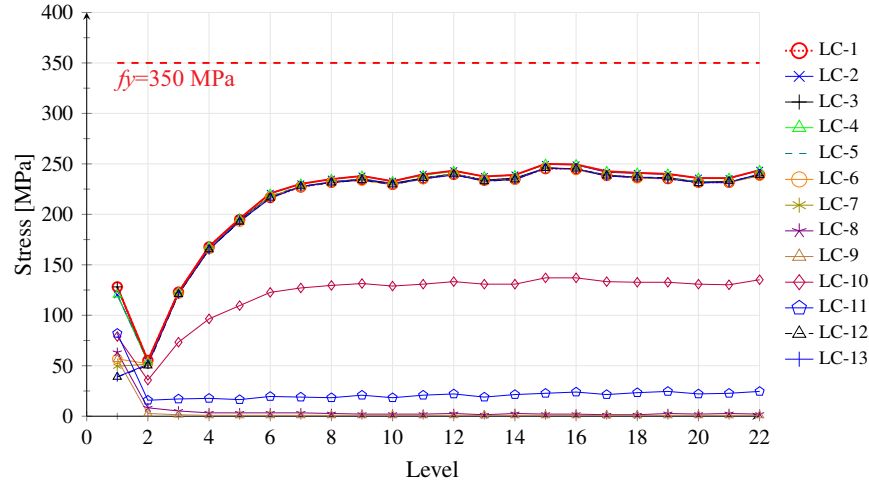
Figure 16: Von Mises stresses in shell elements.

Several silos with different types of material and geometric configurations can be analyzed by the students. However, regardless of the particular silo, the students can develop the ability to apply knowledge, integrate concepts, analyze and interpret data.

4. EDUCATIONAL EXPERIENCE

As silo structures are of great relevance for the agricultural and mining industries in Chile, the Civil Engineering Department at the University of Santiago, Chile, introduced a specific seminar in the last semester of the curricular trajectory to analyze and design this type of structure. Originally, this seminar was taught using traditional teaching methods based on conventional lectures and examinations. After a formal assessment of this seminar, several limitations were found. For instance, lack of connection between mathematical concepts and physical phenomena, abuse of spreadsheets to predict failure of silos without a deep understanding of the physical problem, failure of the instructor to promote the study of the subject among students, etc.

In order to overcome the above drawbacks, we incorporated GSD in this seminar to support the teaching activities. Here, final-year-students attended a two-week module in the computer lab to analyze a silo structure by means of GSD. At this level, the knowledge managed by these students and required to solve this exercise is mainly structural mechanics and steel design. During each week, the student worked for 6 hours, distributed into 3 two-hour-sessions, under the guidance of an instructor. The total number of students enrolled in this module was 18.

During these lectures, several real cases, similar to the one discussed above, were solved in order to illustrate the following main concepts.

- The fact that Janssen's theory does not take into account neither the flexibility and the boundary conditions of the silo.

- The importance of using a computational FE model to capture realistically the above effects, in order to obtain more accurate solutions and therefore, cost-saving designs.

- The relevance of the discharge process in the silo design, making emphasis on the fact that different flow patterns (mass or funnel) depend mainly on the silo's slenderness.

- The need of more accurate modeling strategies to capture accurately the filling process. By using GSD, a conventional static analysis is avoided. Instead, a quasi-static analysis is carried out by dividing the filling process into several loading steps in order to capture the progressive and cumulative loading sequence.

The use of GSD was intended to reach several levels of understanding among students. A first level consists of understanding the main logical steps involved in the structural analysis of silos. By defining sequentially the geometry,

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material properties and loading conditions of the model and then, accessing the results in the postprocessing module, the instructor was able to explain the main stages associated to the analysis of a silo.

A second and deeper level of understanding was obtained by strengthening the mathematical and physical concepts involved in the analysis of silos. Special attention was paid to the understanding of stress contour plots, deformed shapes and the mechanics of grain-wall interaction. In addition, by repeating the use of GSD, students were able to test several models and assess the influence of any initial input value on the overall structural response. Furthermore, mathematical solutions and computational predictions were compared by students.

A third and much deeper level of understanding was developed by predicting the structural behavior of silos for a specific set of initial conditions. After solving several examples, skilled students were able to anticipate the solution of a given case study. This type of exercise was motivated by the instructor in order to support the active learning process. The guidance during the sessions is one of the key characteristics for improving conceptual learning through interactive engagement and help to develop the students skills [33–35].

It is important to note that other FE commercial softwares can be used to analyze silo structures but users must spend considerable time to build the model. During these lectures, however, it was found that students spent more time on relevant aspects of the analysis, rather than wasting too much time on the manual generation of a complex model (including variable pressure distributions, structure-grain interaction, non-linear effects, modeling of discharge and filling processes, complex material models, among others).

At the end of this two-week-module, a questionnaire was given to students to measure the learning experience and to evaluate their opinions and attitudes. The module assessment consisted of a series of questions whose results were measured in a Likert-type scale: totally agree, agree, undecided, disagree or strongly disagree. Most students were either agree or totally agree that the proposed module enhances the learning of engineering concepts, as shown in Table 2. Also from the assessment, the authors found that students enjoyed the experience, highlighting the fruitful discussions on the analysis of postprocessing results (i.e., deformed shapes, stress contour plots, discharging and filling processes, etc.). In fact, 15 out of 18 students declared they preferred to attend a lecture supported by computational simulations (like GSD). When asked about the technical concepts taught by the instructor, 16 students considered that the mathematical and physical concepts were highly strengthened by the use of GSD. Furthermore, 13 students declared they felt very confident to predict accurately the overall structural behavior of a silo for an initial set of conditions. Moreover, 17 students responded they would recommend the implementation of this methodology in other courses.

Table 2: Part of the questionnaire developed at Santiago University and the Likert scaled responses obtained at the end of the two-week module.

Question	Survey scale
This type of learning experience enhances the learning of engineering concepts	Totally agree
The use of a simulated environment helps to visualize better the physical phenomena	Totally agree
The visual postprocessing interface in GSD allows the discussion of the numerical results	Totally agree
Were the mathematical and physical concepts strengthened by the use of GSD	Totally agree
Would you like to have more modules supported by computational simulations	Totally agree
After taking this module, are you confident in predicting the overall structural behavior of a silo	Agree
The module was intellectually stimulating and challenging	Totally agree

For instructors, it is possible to give this module within 2 or 3 weeks, in parallel to advanced structural design modules. Lecturers are advised to exploit the visual components of GSD, without forgetting the importance of explaining the corresponding theoretical concepts. A user's manual can be provided by the instructor during the first lecture in order to give detailed theoretical information and technical guidance of GSD.

Finally, the present teaching-learning methodology can be easily implemented into the analysis of other civil engineering structures. For instance: (i) bridges, in which a teaching-learning platform may help students to skip the time consuming definition of a detailed 3D geometry and its corresponding FE model, and focus on the complex calculation of prestressed cable forces; or (ii) steel-concrete composite slabs, where a virtual platform may allow students to understand the complex non-linear behavior of shear stud anchors subject to push out loads.

5. CONCLUSIONS

In this article, a software environment for the analysis of steel silo structures was presented, called GSD. SAP2000 and ANSYS were used in conjunction with Matlab to create this computational simulation platform. This work was aimed to provide civil engineering students a helpful tool to understand the complex structural behavior of silos. Special attention was given to the calculation of internal pressures resulting from the interaction between the silo and the stored bulk material. In addition, several input and output graphical interfaces were incorporated to GSD in order to make it friendly and easy use, favoring the learning process among students. Several case studies were analyzed in a civil engineering module in order to assess the impact of using GSD and PBL among students. A survey showed that the proposed simulation environment enhanced significantly the active learning experience.

The present teaching-learning strategy can represent a robust platform to help lecturers to explain complex theoretical concepts in class, and prepare students to give solutions to real engineering problems.

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