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DOCTORAL THESIS

- *SUMMARY* -

Contributions regarding the calculation and construction of metal grain silos

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2. KEYWORDS

Silos, silo cells, silo calculation, seismic calculation of silos, buckling, finite element analysis, FEM, silo composition, seismic compliance of silos, silo calculation under wind action, soil-structure interaction, floating piles, pile foundations, FEM modeling of silo cells, advanced FEM modeling, earthquake effects evaluation.

3. INTRODUCTION TO THE THESIS TOPIC

The doctoral thesis addresses a topic of paramount importance in the current stage, contributing to the digital development of Civil Engineering, particularly in the design, execution, and operation of constructions. Through the adopted research plan, the aim was for the findings to enable possible implementation of modifications or additions to technical construction regulations. The research results highlighted the need for developing standardized data management support tools. The research plan targeted the implementation of change through digital transformation in architecture and engineering, yielding significant advancements through modern technologies:

- Information modeling;
- Simulation of actions in construction;
- Permissiveness of modeling in construction;
- Real quantification of spatial connections between elements;

The research conducted highlighted the possibility of reducing risks, identifying critical areas and design errors. It also emphasized the strengthening of teamwork and the importance of generating models with complete data that the executor can leverage in real time. Particularly important in addressing the topic is the fact that the method applied in analyzing construction systems enables the optimization of energy consumption performance, the management of carbon emissions, and identifies solutions that support net-zero objectives and eco-certifications.

The Romanian Government has approved the methodology for implementing BIM (Building Information Modeling) at the national level for public projects funded from public resources. As part of the conducted research, the main implementation stages have been outlined, which will enhance the efficiency of documentation, design, execution, operation, and post-use processes. This lays the groundwork for a simplified and updated regulatory framework to support investments in the transition toward green, resilient buildings.

Starting in 2022, methodologies for implementing BIM (Building Information Modeling) at the national level began to be promoted. The following period was defined by the preparation of the implementation framework through the development of communication elements and technical regulatory structures. At this stage, such research is especially important as it contributes to launching the nationwide adoption of BIM by applying it to public sector projects. This phase will certainly continue through process analyses, updates to specific technical regulations and standards. Based on the results obtained, norms and administrative procedures will be revised, and training programs will be implemented for construction specialists in both the public and private sectors.

In the coming period, the categories of projects to which BIM (Building Information Modeling) will be applied will be expanded, and the evaluation framework and monitoring of performance indicators achieved through the implementation of pilot projects will be improved.

In recent years, concerns have highlighted the importance of developing framework methods and procedures for adapting these types of structures, along with construction and installation solutions tailored to the specific conditions of our country. These concerns have largely been driven by global climate change and the presence of seismic activity—an especially significant factor, as the behavior of the construction types examined in the case study depends directly on proportionality between cause (action) and effect (structural response).

The chosen research model addresses metal silo cells as well as reinforced concrete silo cells, which fall into the category of special constructions and exhibit distinct behavior depending on their location, seismic parameters, and geographical characteristics specific to the site. These structures also feature particularities in terms of adapting to the site-specific foundation conditions, with each adopted structural system being significantly affected from a geotechnical behavior perspective under long-term effects. Broadly speaking, in selecting foundation systems for metal silos, the design phase must consider cyclical loading-unloading demands. In this respect, the doctoral thesis topic is of considerable interest, especially since current legislation lacks sufficient provisions for design based on performance criteria that consider the influence of soil-structure interaction.

The experience of the past 20 years has revealed that such structures exhibit significant vulnerabilities to wind and seismic action, as well as geotechnical behavior. The current Romanian regulations in this field do not provide sufficient pre-design and design provisions to adequately address the requirements and demands of this category of structures.

In this context, the research conducted supported the development of calculation procedures based on mathematical models described in the Structural Eurocodes, with direct applicability in modern software suitable for finite element analysis—capable of meeting the demands imposed by operation and usage. Additionally, the research aimed to contribute to the harmonization of Romania's design standards and regulations with those of the European Union.

The paper presents a set of new approaches for the structural analysis of prefabricated metal silos using finite element calculation software, while also accounting for nearly all requirements and demands set by European design standards. The thesis is equally valuable for offering a schematic, synthetic, and logical organization of the design and verification stages for thin-walled steel elements that make up silo cells.

Validating the behavior of metal silos and identifying their vulnerabilities is extremely complex, primarily due to the lack of consolidation of the data components within the analytical model. Currently, simplified models are used—both in terms of geometry, analytical modeling, and the interpretation of results—which often involve significant deviations, distancing the mathematically interpreted behavior from the actual physical response.

Through the results of the conducted research, the thesis proposes a new approach to the seismic action effect applied to the superstructure of prefabricated steel silo cells. The study includes a series of numerical iterations and comparisons between input parameters and outcomes for metal silos, using both spectral-type seismic analysis and effect-based seismic analysis—specifically through pseudo-static modeling—to quantify the impact of seismic action on the stored material.

4. SUMMARY OF THE CONTENT OF THE DOCTORAL THESIS

4.1. PART – I -: BACKGROUND TO THE TOPIC. NATIONAL STANDARDS AND STRUCTURAL EUROCODES FOR THE CALCULATION OF SILOS

Certainly, within the national context of standardization and the structural design principles for silos, it can be stated that harmonizing design norms was no longer considered necessary, precisely because the Structural Eurocodes—addressing in detail and with complexity the behavior of silos and tanks—were assimilated into Romanian law through the series of standards SR EN 1990, SR EN 1991-4, SR EN 1993-4, and SR EN 1998-4. While the paradigm for analytical evaluation of silos is clearly outlined in the Eurocodes, the lack of gradual, annual harmonization of national standards has led to challenges in understanding and applying current modeling techniques. This is especially relevant given that European standards only gained legal status in Romania via Ministerial Order No. 630 in 2010. Until that point, the gap in rigor between the numerical modeling methods used in Romania and those employed across Europe was significant, often impacting the quality of designed structures.

As of 2025, designing a metal silo structure based on these European standards remains a challenge, even though— as previously mentioned— they are officially recognized under Romanian law. The paper reveals that the process from the input data regarding the silo structure to the interpretation of cell behavior and the identification of vulnerabilities is lengthy and interwoven with numerous cross-references among paragraphs in the mentioned Eurocode frameworks. In addition to this series of codes focused on load evaluation for silos, a separate set of standards addresses the behavior of thin-walled sheet metal profiles—whether flat, corrugated, circular, or plate-shaped—which make up the silo shell.

These standards are partial provisions from SR EN 1993, specifically SR EN 1993-1-1, SR EN 1993-1-3, SR EN 1993-1-5, and SR EN 1993-1-7. Proper validation of stress and failure mechanisms in thin-walled steel profiles can only be achieved through cross-referencing between chapters of these codes. The complexity is inherent to the geometric composition of silos arranged in silo banks. To reinforce this point—even the slightest eccentricity introduced into the geometry can lead the structural engineer outside the boundaries of the Eurocode, beyond the possibility of following a deterministic path for numerical validation of the structural dimensions that form part of the silo's framework. This overview of the standard series may help assess the level of risk assumed by the engineer when it comes to sizing and validating outcomes for such industrial structures. If we continuously shift from one simplified model to another, we lose sight of actual behavior, and the general tendency becomes one of overdesign—i.e., inferring the dimensions of load-bearing elements based on upper-bound assumptions.

We benefit from complex standards; however, they rely on sectional calculations using methods that incorporate multiple simplifications regarding stiffness and strength. Therefore, even though these standards exist, the results obtained are penalized and often differ by a factor of three to six compared to the actual behavior observed in service. These estimates stem from both the research undertaken and the design experience accumulated by the author over 20 years of professional practice. Through various projects, the author identified deficiencies in the numerical algorithms—not in terms of correctness, but in their deviation from real-world behavior due to simple modifications of response factors or coefficients. A valuable addition to discussions on international standards and design norms might be a heightened attention to the fundamental principles behind the composition of numerical models, as described in SR EN 1990. This standard presents an approach using a set of probabilistic gamma factors, while on the opposite end, sigma representative coefficients are employed for calibrating and quantifying the contribution of operational loads within the structural numerical model under analysis.

4.2. PART – II - : PERSONAL CONTRIBUTIONS MADE TO THE SEISMIC ANALYSIS OF SILOS WITH THE HELP OF AUTOMATIC CALCULATION PROGRAMS

Finite element models are developed—regardless of the type of engineering structures—based on the set of rules and principles outlined in the Structural Eurocodes. To define mathematical models correctly, all principles of stiffness, strength, safety, durability, and sustainability presented in Eurocode 0—also known in specialized literature as the Fundamental Code—must be properly understood and numerically interpreted.

To define a mathematical model specific to a silo cell-type construction, one must carefully follow the steps outlined in the relevant regulatory or standards framework.

All the decisions that a structural design engineer must take depend on:

- the composition, type, and geometry of the foundation system;
- the type of material from which the silo structure is to be built;
- if the silo is metallic, an important factor in determining the complexity of the calculation model is the type of sheet metal used (smooth sheet, corrugated sheet, etc.);

- regardless of the material from which the silo will be built, an extremely important aspect is the value of the ratio between radius (r) and height (H) (or, alternatively, the ratio between the footprint size in plan and the elevation);
- for metal silos, it is important to consider the slenderness category of the shell, as this determines the selection of shape equations that will describe the movement of the stored material based on loading–unloading hypotheses;
- the conformation mode, meaning the way in which the sheet plates are arranged around the circumference of the silo cell. Also included here, as defining elements in selecting optimal FEM geometrization solutions for silo structures, are the contact between the plates and the foundation system, or the contact between the metal plates and the vertical stiffening elements (where applicable);
- perhaps among the final defining elements in the geometric creation of silos within finite element analysis programs is the contact zone between the roof and the shell.

Regardless of the complexity of the mathematical model used as the basis for decisions regarding the structural configuration of silo cells, in addition to evaluating the static and seismic dynamic behavior of the stored material, the effects of wind and seismic action must be carefully assessed. Introducing these actions into the proposed numerical model for decision-making has an impact, as it imposes geometric and contact constraints on the calculation elements—whether surface elements or linear elements.

Wind action for construction is evaluated in accordance with the provisions of SR EN 1991-1-4; however, for this type of structure, the standard method of calculating wind action is often restrictive—the results obtained are only semi-accurate.

For storage structures (silos, tanks), the methods proposed in EN 1991-1-4 may be applied, but with reservations, as they do not support drawing relevant conclusions regarding deformation behavior or identifying stability failure modes. Stability loss must be analyzed and treated as a limit state (LS) when dealing with metal silos—most of which are classified as structures with intermediate or high slenderness.

In EN 1991-1-4, the method for calculating wind action is primarily presented for buildings; therefore, insufficient information is provided regarding the evaluation of this action and its application to silos or circular-shaped tanks.

By analyzing a series of results extracted from projects studied by the author, alternative methods have been identified in the specialized literature for determining the distribution of wind pressure on the external generator of the shell—specifically the method described in SR EN 1993-4-1, Annex C. For the calculation model developed in this way to deliver high performance in terms of results, the geometry of the silos must be defined by considering the variation of pressure values along the cylindrical surface. This aspect is crucial, as the geometry must provide the software user with a sufficiently large number of discrete nodes directly on the silo's cylinder—nodes that assist in defining pressure loading planes. What further complicates the modeling stage is the pattern of wind pressure variation on this structure, which evolves both horizontally and vertically.

In this section of the Eurocode, the following two relationships are presented:

- circumferential variation of pressure distribution (positive towards the interior) / isolated silo with closed roof.

$$C_p = -0{,}54 + 0{,}16\left({}^{d_c}/_{H}\right) + \left[0{,}28 + 0{,}04\left({}^{d_c}/_{H}\right)\right]\cos\theta + \left[1{,}04 - 0{,}20\left({}^{d_c}/_{H}\right)\right]\cos 2\theta + \left[0{,}36 - 0{,}05\left({}^{d_c}/_{H}\right)\right]\cos 3\theta - \left[0{,}14 - 0{,}05\left({}^{d_c}/_{H}\right)\right]\cos 4\theta$$

where:

d_c – the diameter of the silo;

H – the total height of the silo tower;

${}^{d_c}/_{H}$ – the size ratio between the considered diameter and the total height.

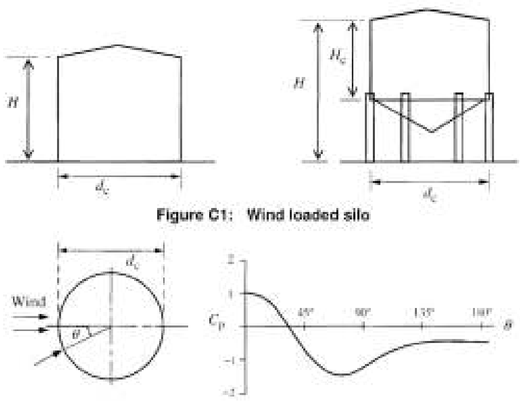

Fig. 27 – Wind pressure variation around the circumference of a fixed-base silo according to EN 1993-4-1, Annex C [47]

- circumferential variation of pressure distribution (positive towards the interior) / silo with closed roof within a group:

$$C_p = 0,20 + 0,60\cos\theta + 0,27\cos 2\theta - 0,05\cos 3\theta - 0,13\cos 4\theta + 0,13\cos 6\theta - 0,09\cos 8\theta + 0,07\cos 10\theta$$

where:

d_c – the diameter of the silo;

H – the total height of the silo tower;

d_c/H – the overall size ratio between the considered diameter and the total height.

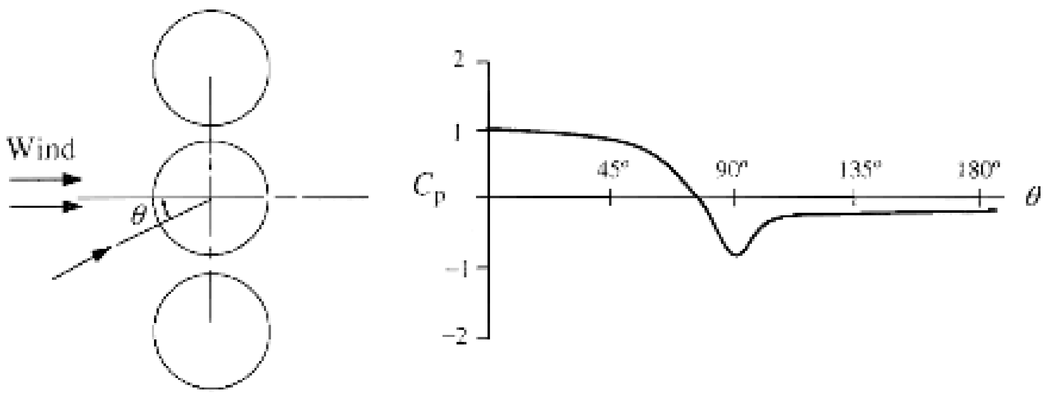

Fig. 28 – Wind pressure variation on half the circumference of the group of cells EN 1993-4-1, Annex C [47]

Even though they are less common in practice, the Eurocode also addresses the issue of uncovered silos (without a closed roof). In this case, a decrement ΔC_p is added to the values obtained using the previously presented relationships, thereby ensuring the mathematical modeling of internal pressure effects.

Returning to the input data and modeling principles of the proposed silo, in order to generate the discrete shape of the structure, a value must be introduced for the angle ϴ as described in the pressure variation distribution equation Cp. In this case, the value of angle ϴ corresponds to the arc angle of the metal sheet, which is 10.29 degrees. By defining this angle ϴ, all positive and negative Cp values and wind pressures acting on the silo body will be determined. Based on this discretization principle, the vertical structure of the silo will be divided into calculation sections, each with a height of 2.20 m.

The distribution of wind pressure variations along the circumference of the silo shell, as a function of ϴ and the relative calculation height, is presented in the series of tables below:

θ [deg]	***0.00***	***10.29***	***20.58***	***30.87***	***41.16***	***45.00***	***51.45***	***61.74***	***72.03***	***82.32***	***90.00***
Cp	1.00	0.93	0.73	0.43	0.08	-0.05	-0.26	-0.54	-0.73	-0.79	-0.77
We = Cp*qp(z) [kN/m2]	1.29	1.19	0.93	0.55	0.10	-0.07	-0.34	-0.70	-0.93	-1.02	-0.99

92.61	***102.90***	***113.19***	***123.48***	***133.77***	***135.00***	***144.06***	***154.35***	***164.64***	***174.93***	***180.00***
-0.75	-0.63	-0.48	-0.34	-0.24	-0.24	-0.20	-0.19	-0.21	-0.23	-0.23
-0.97	-0.81	-0.62	-0.44	-0.31	-0.30	-0.25	-0.25	-0.28	-0.30	-0.30
185.22	***195.51***	***205.80***	***216.09***	***225.00***	***226.38***	***236.67***	***246.96***	***257.25***	***267.54***	***270.00***
-0.23	-0.21	-0.19	-0.20	-0.24	-0.25	-0.35	-0.49	-0.64	-0.75	-0.77
-0.30	-0.27	-0.25	-0.25	-0.30	-0.32	-0.44	-0.62	-0.82	-0.97	-0.99

277.83	***288.12***	***298.41***	***308.70***	***315.00***	***318.99***	***329.28***	***339.57***	***349.86***	***360.15***
-0.79	-0.72	-0.54	-0.26	-0.05	0.08	0.43	0.73	0.93	1.00
-1.02	-0.93	-0.70	-0.33	-0.07	0.11	0.55	0.94	1.20	1.29

Considering the simplifying assumption, by correctly defining the silo geometry in SCIA Engineer and having the complete set of reference pressure values ($w_e(z)$), the following distribution will be obtained through continuous medium modeling:

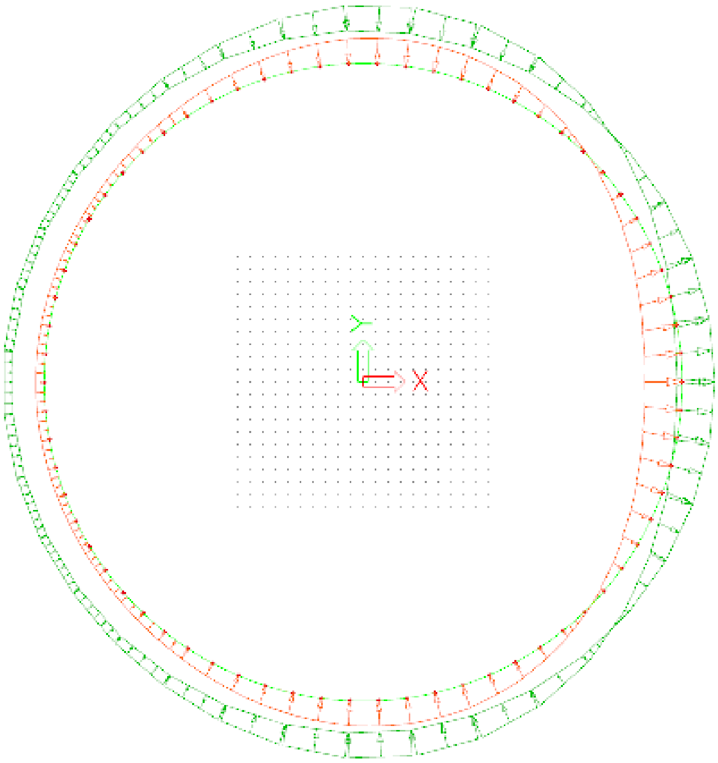

Fig. 28 - SCIA Engineer, wind pressure distribution

From the experience of creating finite element models for the analysis of this type of structure, only through such a distribution can higher accuracy be achieved in terms of stresses and bending demands developed in the calculation plane of the steel sheets that make up the silo body. A clearer picture of the stress values and their distribution across the steel sheet structure will lead to a more judicious and realistic interpretation of the local stability failure modes, specifically meridional and circumferential buckling.

For illustration, several gradient charts for stresses and deformations are presented below:

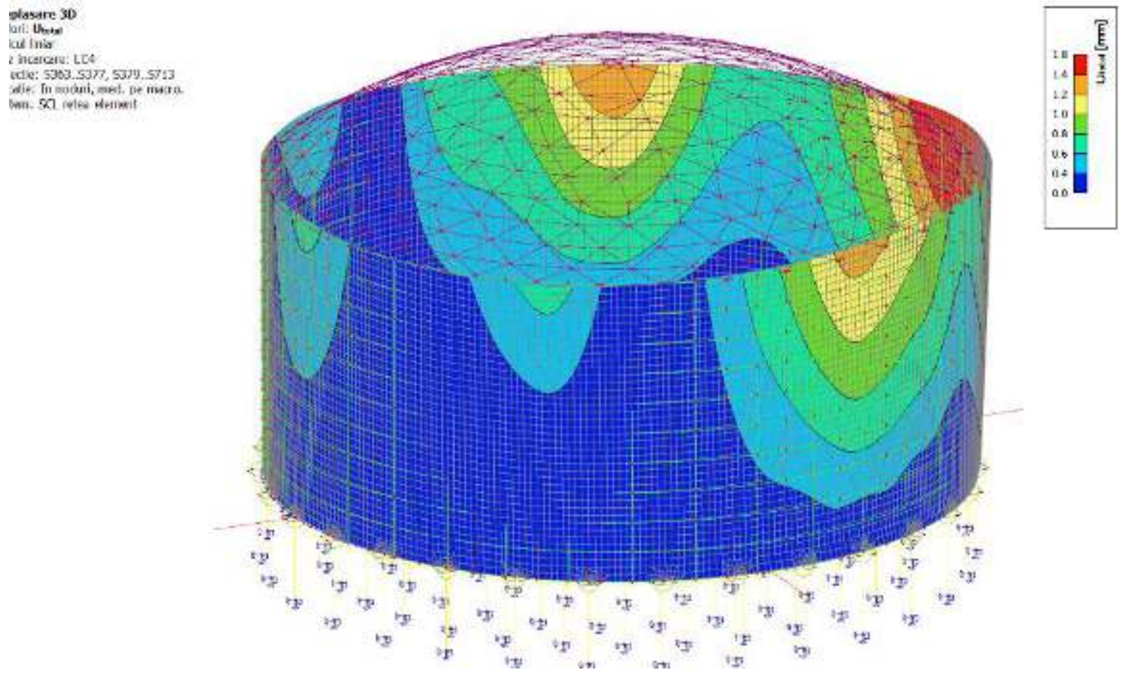

Fig. 28 - SCIA Engineer, 3D displacements of smooth thin sheets forming the silo shell

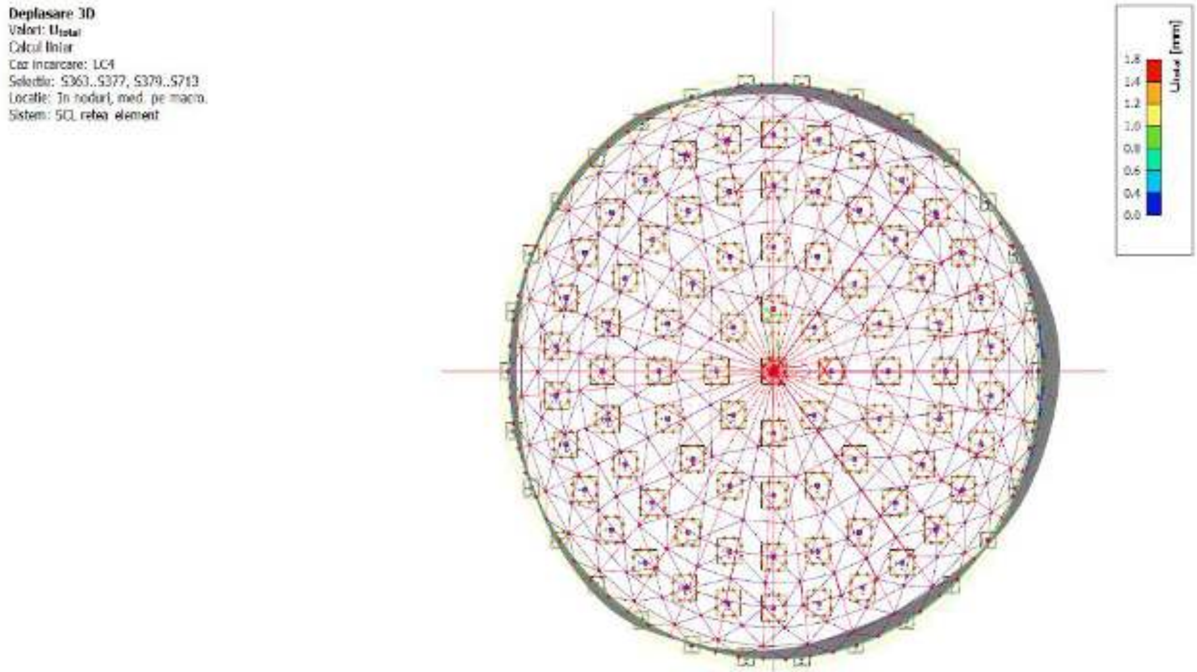

Fig. 29 - SCIA Engineer, 3D displacements of smooth thin sheets forming the silo shell – top view

The paper highlights how important it is to identify alternative seismic design methods for the category of special structures, which includes silos and tanks. The need is all the more pressing considering that, in Romania, ever since the first part of the national seismic design code was introduced in 2013, Part IV—dedicated to the seismic design of silos and tanks—has yet to be published.

For this reason, in design practice for silos, it becomes extremely difficult to establish the theoretical foundations that can be used to develop an efficient seismic calculation method. The problem becomes even more complex as the overall stiffness of silos decreases, meaning that the slenderness of the structural system has a significant influence on the overall behavior.

Slenderness plays a decisive role in the behavior of silo structures and also a key role in choosing the type of analytical model to be used in order to achieve a representative structural response—yielding accurate forces and displacements without peaks in the measurements.

According to SR EN 1991-4 – "Actions on structures. Silos and tanks," slenderness is presented as a decisive factor in assessing the loads on the vertical walls of silos. Therefore, the loads on the vertical walls of silos will be evaluated based on the silo's slenderness, aiming to classify it into the following categories:

- slender silos:

$$2.0 \leq {}^{h_c}/_{d_c}$$

- silos with intermediate slenderness:

$$1.0 < {}^{h_c}/_{d_c} < 2.0$$

- flat silos:

$$0.4 < {}^{h_c}/_{d_c} < 1.0$$

- retention silos:

$${}^{h_c}/_{d_c} \leq 0.4$$

When the design of a rigid silo (made of reinforced concrete) is required, the seismic calculation can be performed using the modal method through response spectra, similar to buildings, with the effect of slenderness being negligible in the context of the structural response.

When the design of a slender silo or one with intermediate slenderness is required, it is recommended that the seismic analysis be carried out using dynamic pressures determined according to SR EN 1998-4, with the effect of slenderness being an essential component in interpreting the structural response.

The modal method using response spectra applied to silos involves, similar to buildings, converting the action of the granular material into a mass, which, in a subsequent stage, will be associated with the wall through springs with stiffness Kc, determined based on material constants (see Figure 3).

Although the method appears accessible and allows easy modeling with calculation programs (F.E.M.), it presents the major disadvantage that the application of masses is done pointwise on the silo wall, at the point of application of the resultant of the dynamic pressure diagram. In other words, when the situation requires the design of a slender silo or one with intermediate slenderness, the mass being applied pointwise on the wall surface will result in erroneous maximum values for stresses, strains, and displacements at the application points—values that cannot lead to a proper assessment of the structural system's strength and stability.

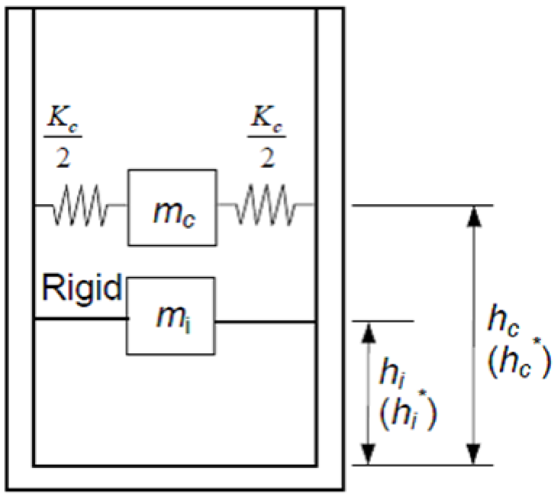

Fig. 3 - Model composition diagram using the modal method [47]

The seismic calculation method that involves using the normal pressure exerted by the stored material is presented in SR EN 1998-4, Section 3.3, as an alternative to the previously mentioned spectral method. Indeed, the method can be considered semi-accurate because it does not explicitly account for the mechanical properties and dynamic response of the granular material—that is, it does not use finite elements to model the mechanical properties and dynamic behavior of the stored material. In this way, the method aims to directly model the effect on the silo wall caused by the response of the granular material to the horizontal component of seismic action. The response of the stored material will be represented by an additional normal pressure (overpressure) with the following expressions:

- ***for circular silo:***

$$\Delta_{ph,s} = \Delta_{ph,so} \cos(\theta)$$

where:

$\Delta_{ph,s}$ = reference pressure;

θ = angle between the radial direction of a point analyzed on the wall and the direction of the horizontal component of seismic action.

- ***for rectangular silo:***
  - <u>wall „under wind”:</u>

$$\Delta_{ph,s} = \Delta_{ph,so}$$

  - <u>wall „in wind":</u>

$$\Delta_{ph,s} = -\Delta_{ph,so}$$

  - <u>wall parallel to the horizontal component of seismic action:</u>

$$\Delta_{ph,s} = 0$$

At the points on the silo wall located at a vertical distance x from the flat bottom or from the apex of a conical or pyramidal hopper, the reference pressure Δ_(ph,so) has the following expression:

$$\Delta_{ph,so} = \alpha_{(z)}\gamma\, min(r_s; 3x)$$

where:

$\alpha_{(z)}$ = the ratio between the response acceleration of a silo, at a vertical distance z from the equivalent surface of the stored material, and the gravitational acceleration;

$$r_s = min\left(h_b; {}^{d_c}/_2\right) \qquad \text{in which:}$$

h_b = total height of the silo, measured from the flat bottom or from the discharge outlet of the hopper to the equivalent surface of the stored material;

d_c = internal dimension of the silo parallel to the horizontal component of seismic action (internal diameter for circular silos or horizontal internal dimension parallel to the horizontal component of seismic action for rectangular ones).

For silos where material discharge is done through a hopper, the reference pressure between the skirt and the discharge outlet is calculated using the following relation:

$$\Delta_{ph,so} = \alpha_{(z)}\gamma\, min(r_s; 3x)/\cos(\beta)$$

in which:

β = inclination angle of a silo hopper wall, measured relative to the vertical, or the angle of the steepest slope line relative to the vertical of a pyramidal hopper wall.

To calibrate the alternative analytical model, SR EN 1998-4 specifies, through paragraphs (11) and (12), two sine qua non rules:

(i) at no point on the silo wall shall the sum of the static pressure of the granular material and the seismic action effect Δph, s be less than zero;

(ii) If, at any point on the silo wall, the sum of Δ(ph,s) and the static pressure of the granular material on the wall is negative (clearly implying suction), then the previously mentioned relations cannot be applied. In this situation, the additional normal pressures on the wall Δ(ph,s) are redistributed to ensure that their sum with the static pressure of the granular material on the wall remains positive, while maintaining the same resultant force on the same horizontal plane as the original Δ_(ph,s) values.

Through the deepening of the alternative seismic calculation method specific to silos and from the design experience accumulated with this type of structure, significant difficulties were encountered in determining the parameter α(z), an issue largely due to the lack of content in the Eurocode. [162]

Therefore, within the research program, I proposed my own interpretation regarding the method for determining α(z), starting from the very definition of the term extracted from SR EN 1998-4, Section 3.3, Article 8, Relation (3.5).

Therefore, the equation that can define the term α(z) takes the following expression:

$$\alpha_{(z)} = \frac{K_z a_g}{g}$$

where:

$K_z =$ coefficient representing the amplification of ground seismic acceleration along the height of the structure;

$a_g =$ design ground acceleration (for the horizontal component of ground motion), for which two relations are established:

Thus, the design equation for the seismic ultimate limit state has the following expression:

$$\sum_{j>1} G_{k,j}" + "(P_h + \Delta_{ph,s})" + "\sum_{i>1} \psi_{2,1} Q_{k,i}$$

where:

$\sum_{j>1} G_{k,j} =$ group of all permanent loads;

$\sum_{i>1} \psi_{2,1} Q_{k,i} =$ group of all variable loads of the same nature;

$\psi_{2,1} Q_k =$ quasi-permanent value of a variable action determined such that the total time period during which it will be exceeded represents a significant portion of the reference period.

$(P_h + \Delta_{ph,s}) =$ response of the granular material to the horizontal component of seismic action superimposed on the normal pressure applied to the vertical walls of the silo..

To highlight the contributions made in assessing the effects of earthquakes on metallic silo cells, the thesis presents comprehensive numerical examples carried out using the SCIA Engineer software.

The steel silo proposed as an analytical model for validating theoretical concepts and methods is located within the new COMVEX grain terminal at DANELE 79-81, Port Constanța. The studied steel silo cell is part of the terminal's structure, alongside 15 other silo cells with similar capacity. The storage capacity of the numerically analyzed cell is 10,000 tons.

From a geometric point of view, the analyzed silo is described by:

- silo diameter (d_c): 27,50 m
- tower height (h_c): 19,43 m
- roof height (h_roof): 7,65m
- roof angle: 18 deg
- steel plate thickness (t_t): 3mm

The material used for the steel sheets forming the body of the silo cell is structural steel with a strength grade of S235. This steel has a longitudinal deformation modulus (E) of 210,000 MPa, and a characteristic yield strength of 235 N/mm².

In the numerical modeling presented in this chapter, the metallic silo shell was constructed from a series of steel sheets with a relative height of 1022 mm. These sheets were arranged circumferentially, with a polar distribution angle of 22.5 degrees.

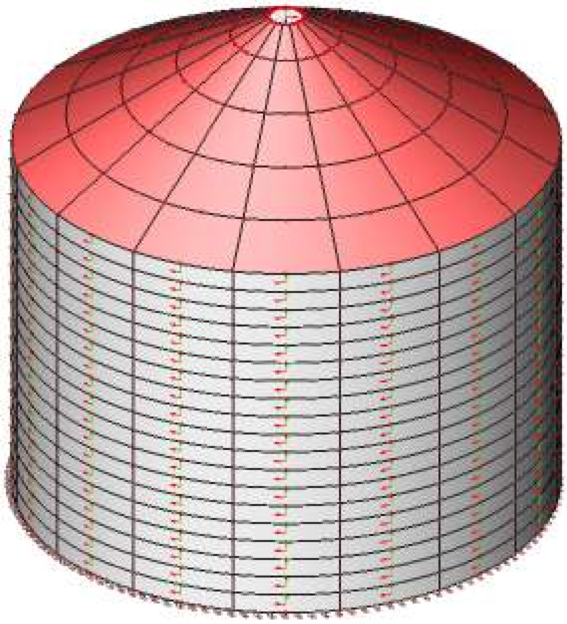

Fig. 6 – Silo geometry extracted from the SCIA Engineer analysis program

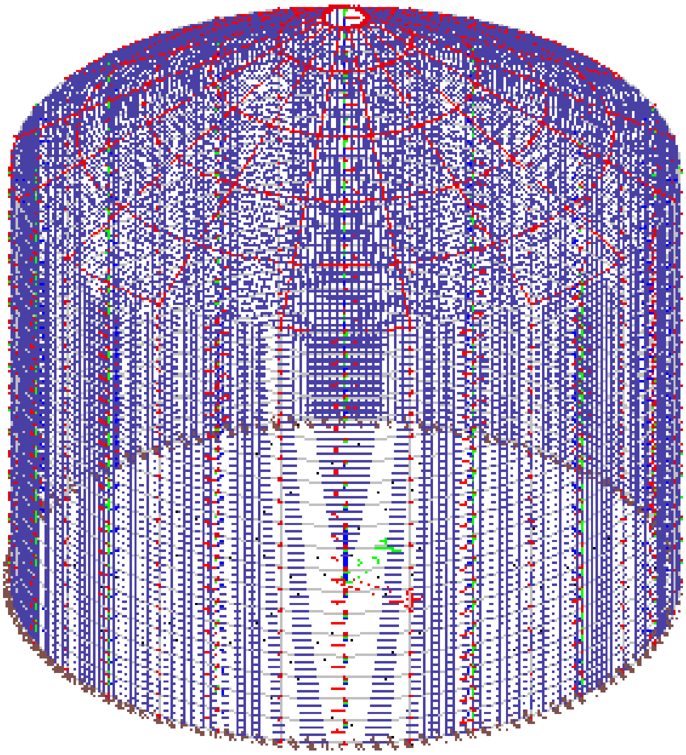

Fig. 7 – Graphical representation of the FE (Finite Element) discretization mesh, extracted from the SCIA Engineer analysis program

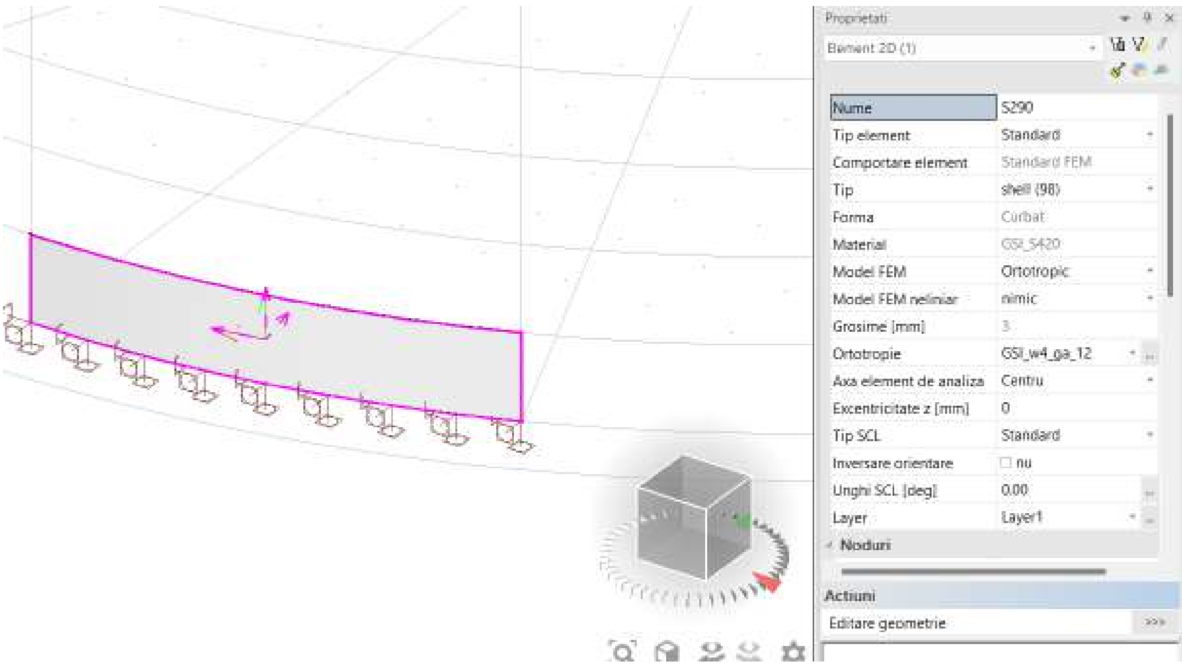

Fig. 8 – Extrusion of the S235 steel sheet geometry from the metallic silo shell assembly, extracted from the SCIA Engineer analysis program

In the calculation and design methodology described by SR EN 1991-4, the silo must be evaluated for the following specific operational hypotheses:

- normal pressure acting on the vertical wall of the silo;
- maximum tensile stress due to friction along the wall;
- maximum normal pressure at the bottom of the silo;
- discharge pressure both at the vertical wall level and, where applicable, at the base level;
- the seismic pressure component exerts on the silo wall, but also on the base.

Among these hypotheses, this research report will illustrate the normal loading pressure acting on the silo wall, the discharge pressure, and the seismic pressure component exerted by the movement of the stored material on the wall.

Regardless of the hypothesis considered, when transitioning to finite element modeling in SCIA Engineer, the estimated spatial distribution of the pressures acting on the steel sheets forming the silo shell must be evaluated. The calculation obtained solely based on the provisions of SR EN 1991-4 yields only the analytical values of the design normal pressures; however, it does not provide their variation or distribution in a triaxial Cartesian coordinate system as required by the analysis software.

Precisely because the best way to validate input data in finite element analysis programs is through pressure diagrams presented in standards or specialized literature, relevant comparative images will be presented.

The resulting dataset must be processed and completed through extrapolation in order to generate, for each circumferential sector of the horizontal cross-section, the spatial distribution of pressures.

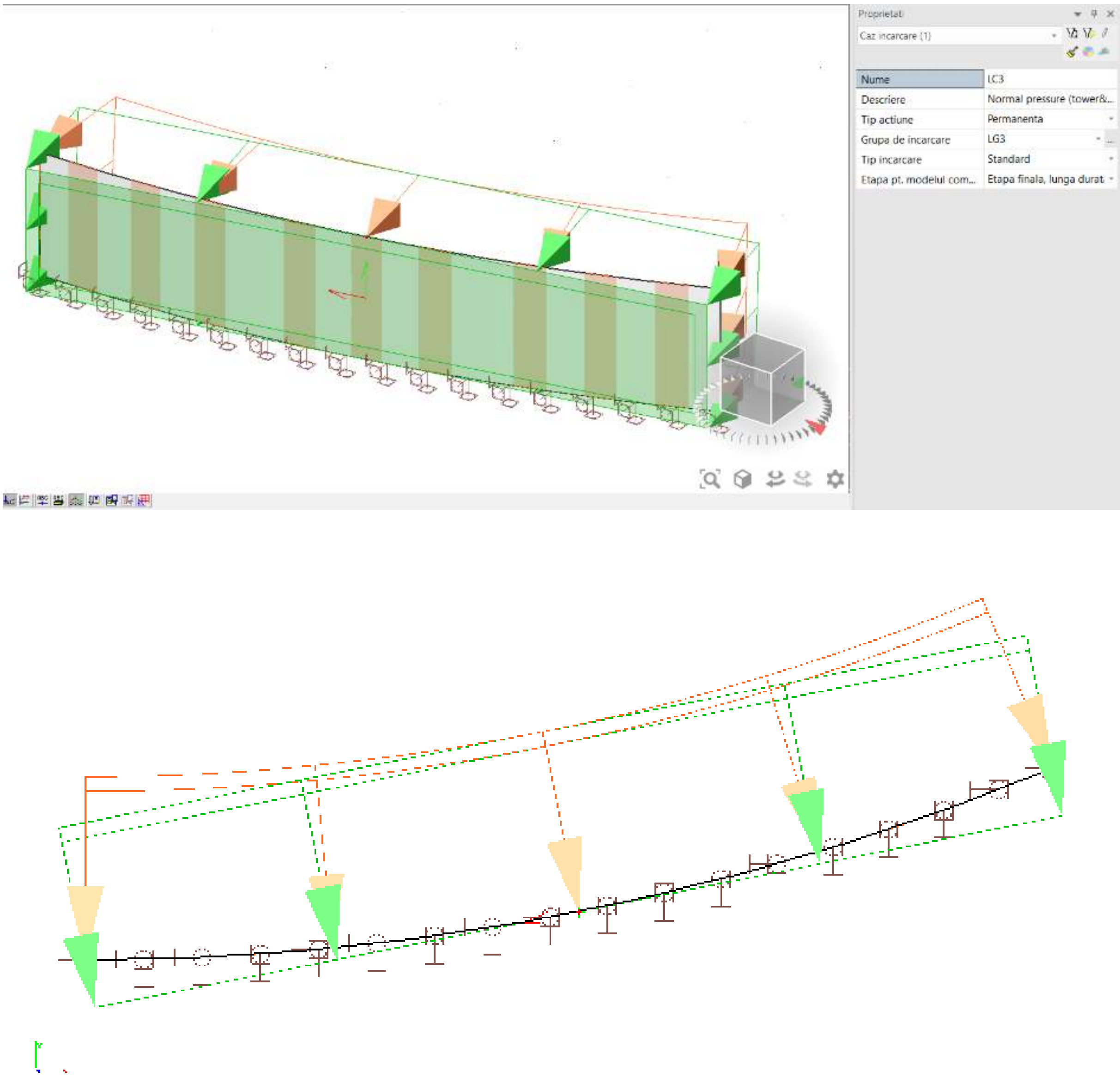

Fig. 9 – Transfer of the planar pressure associated with a steel sheet to its curved surface, extracted from the SCIA Engineer analysis program

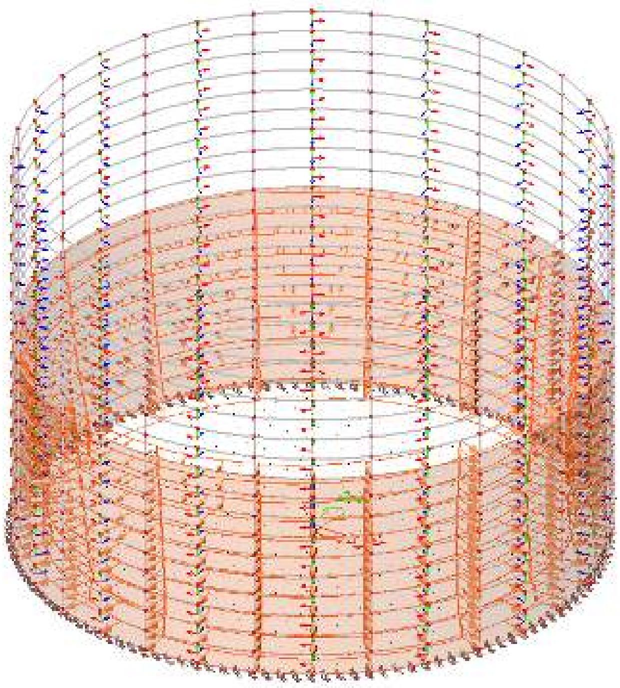

Fig. 20 – Distribution of pressure caused by the seismic effect on the material (isometric view), extracted from SCIA Engineer

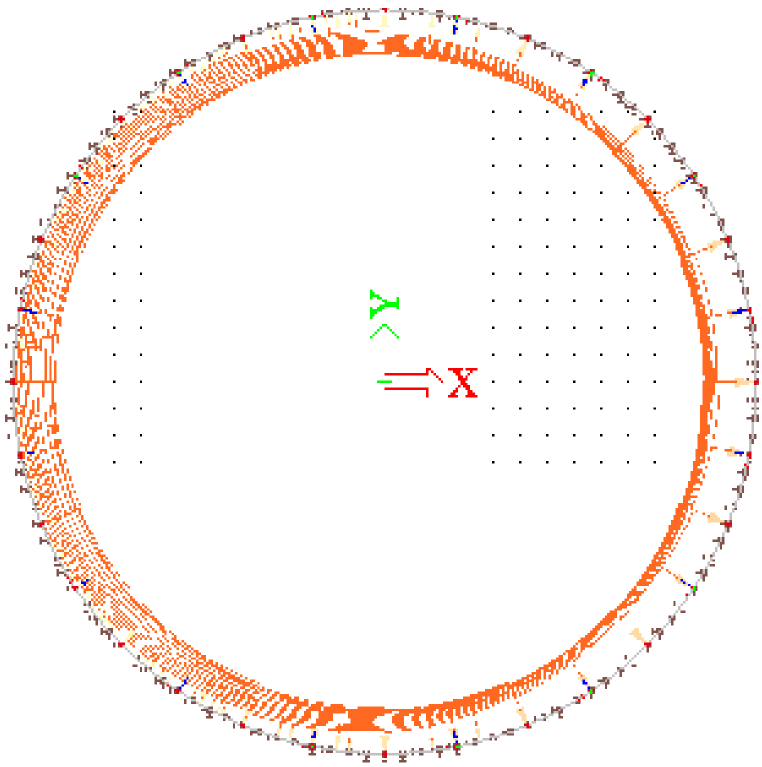

Fig. 21 – Distribution of pressure caused by the seismic effect on the material (horizontal view), extracted from SCIA Engineer

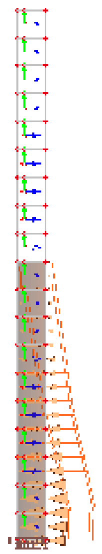

Fig. 22 – Distribution of pressure caused by the seismic effect on the material (vertical view), extracted from SCIA Engineer

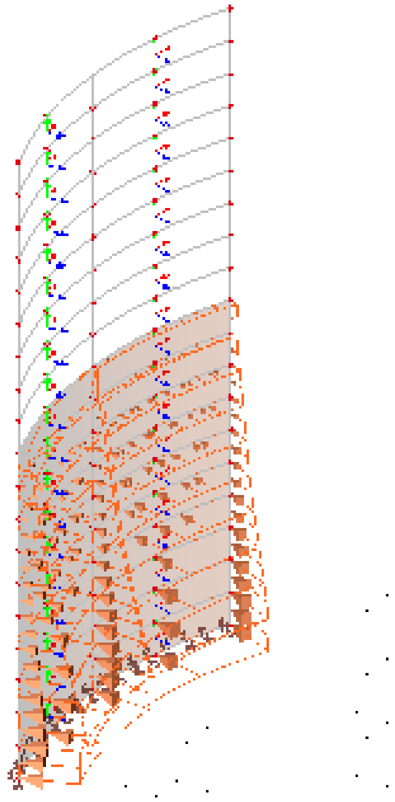

Fig. 23 – Distribution of pressure caused by the seismic effect on the material (horizontal and vertical), extracted from SCIA Engineer

5. FINAL CONCLUSIONS AND RECOMMENDATIONS

The chosen research model addresses metal silo cells, as well as reinforced concrete silo cells, which are included in the category of special constructions with different behavior depending on the location, the seismic and, respectively, geographical parameters characteristic of the location area. These constructions also present particularities from the perspective of adapting to the foundation conditions on the site, each structural system adopted being sensitively affected in terms of geotechnical behavior under long-term effects. In a broad sense, when choosing the foundation systems of metal silos, consideration must be given to the consideration, at the design stage, of a cyclic load of the "loading - unloading" type. And from this aspect, the topic of the doctoral thesis is of interest because in the legislative context there are not enough provisions indicated regarding the design based on performance criteria considering the influence of the terrain - structure interaction. (chap.6 and chap.7, subchap.7.1/7.2)

The research carried out supported the development of calculation procedures using the mathematical models described in the Structural Eurocodes with direct applicability in modern software suitable for finite element analysis, capable of meeting the requirements imposed by exploitation and operation. At the same time, the research activity aimed to support the harmonization of Romanian design standards and regulations with those of the European Union. (chap.7, subchap.7.1)

During the research program, two research reports were prepared in which the research results were presented, reports that had the following areas of analysis:

1. methodology for quantifying the effects of seismic action for silo design, FEM analysis and numerical applications;
2. identification of risks in the behavior of silos. Calculation evaluation of the loss of stability of the silo cell shells. Within these reports, the research results were presented and disseminated, the objectives being successfully met.

In addition to the analytical field, the research work also aimed at aspects related to equipping calculation models with specific BIM (Building Information Modelling) data sets, an increasingly present requirement at international level, but since 2022 also at national level. In accordance with the ISO SR EN 19650 standard, all calculation models made with finite element analysis programs have proven to allow export to openBIM formats, regardless of their complexity.

In the doctoral research project, the applied methodology was based on the calculation methods taken as input data because in their knowledge, rules and principles extracted from the Structural Eurocodes SR EN 1998-4 and SR EN 1991-4 are offered, both dealing with the issue of silo tanks and horizontal pipes. These were harmonized with mathematical rules for calibrating some coefficients and factors that participate in the calculation relationships of the overstrength factors and were also combined with new elements regarding the determination of the overloads given by the stored material by consolidating it during the exercise of dynamic seismic movements - an approach that meets the objectives proposed by the doctoral research project.

The paper manages to provide solutions for identifying a professional numerical modeling based on geometry, the state of stress from both a static and a dynamic point of view of seismic type, the numerical validation of the scenarios and a judicious interpretation of the results obtained from the calculation. (chap.6 and chap.7)

The doctoral thesis presents numerous original approaches, new approaches by inducing concrete aspects and real tools for numerically solving vulnerabilities, most often contact vulnerabilities; these being the ones that cause the collapse of silos made of thin steel walls, of their related elements, such as trestles or metal towers. (chap.6, subchap.6.3)

The geometrization of silos in automatic calculation programs, as originally presented in the paper, highlights the major impact of these characteristics on the veracity of the results. The results of the research conducted have shown that by composing the geometric model, a certain level of deviation from the real physical model can be imposed, to all which aspects regarding the plastic and non-isotropic behavior of materials are added. In this way, both the structural concept in the design and the monitoring of the objective in operation can be controlled.

An element of originality is also the fact that in the 3D modeling within the research project, the author also proposes another approach that aims at the effect of loads on the silo walls that highlighted the influence of the cargo flow profile in the cell tower. (chap.7, subchap.7.4)

A high degree of originality is also represented by the modern approach with punctual solutions to problems regarding the numerical modeling of silos using automatic calculation programs, the program used by the author being SCIA Engineer for the numerical validation of the elements in the superstructure for the numerical validation of those in the composition of the special foundation infrastructure. (chap.7, subchap.7.4.1./7.4.2.).

In addition to the models proposed in the thesis to increase the performance of numerical analysis models for silo design, the importance of the original presentation of easy-to-interpret flow diagrams for the Eurocode-based dimensioning of silo shells is also noteworthy..

Along with all these specific and abstract notions of theory applied to silos, the thesis also has an innovative, original character, because it proposes to future researchers a variant of "analysis" of SAF (Structural Analysis Format) calculation models - according to BIM (Building Information Modeling) ISO 19650 standards. The future in the construction industry internationally but also in Romania will belong to digitalization, which will allow us to introduce a large and relevant volume of data into automatic calculation programs in order to model the physical behavior of the analyzed construction, it would be interesting to continue the evolution of data through their digital mapping. Thus, the 3D models created manually by us today will in the future be created with the help of AI (Artificial Intelligence) engines which can then offer us a holistic perspective on multi-criteria analysis of Hazard (climatic, seismic, geotechnical, etc.). We can consider that the originality, novelty and topicality of the research work is the very activity of synthesis and coagulation of the rules and principles of calculation of silos from national and European regulations. In this way, traceability of the stages that must be followed to evaluate the actions applicable to the structural elements of silos as well as of the stages of design and verification of the thin sheets that make up the body of these structures can be ensured.

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