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FINITE ELEMENT MODELING CONSIDERATIONS OF DEEP FOUNDATIONS. THE CONTROL INSTRUMENTS IN THE DISCRETIZATION MESH GENERATION AT THE PILOT-RAFT INTERACTION POINT

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Abstract: *The article aims to give a less theoretical and more practical definition to the tool called Subregion, from which the advantage of directly controlling the stiffness of the scraper slab without bringing an additional load of its own weight to the pilot's head can be concretely demonstrated. Deep foundations will therefore be analyzed. The Subregion is extremely useful in finite element modeling because it helps define caps without breaking the continuous surface of tile elements. This aspect will be covered in detail in the article, such modeling with Subregions leads to high-performance computational models, optimal from the point of view of file sizes. From practice, the author will present two case studies, concluding on the optimal ratio between the precision of the calculations and the volume of probable errors at the level of the results.*

Key words: *F.E.M., Subregions, silos, soil – structure interaction, SCIA Engineer.*

1. Finite element analysis. Problem classification, modeling and discretization

Finite element analysis (F.E.A.), also called the finite element method (F.E.M.), is a method for solving field problems numerically. A field problem requires us to determine the spatial distribution of one or more dependent variables. Thus, we can look for the temperature distribution in the piston of an engine, or we can look for the distribution of displacements and stresses in a paving slab.

Mathematically, a field problem is described by differential equations or an integral expression. Either description can be used to formulate finite elements. Finite element (F.E.) formulations, in ready-to-use form, are contained in general-purpose F.E.A. programs. It is possible to use the programs F.E.A. while having little knowledge of the analysis method or the problem to which it is applied, causing consequences that can range from embarrassing to disastrous.

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The specific literature gives multiple definitions to the method, however, it is considered relevant for this article to define the "discretization network – MESH" as the arrangement of the elements.

Numerically, an F.E. mesh is represented by a system of algebraic equations that must be solved for unknown nodes. The nodal unknowns are values of the field magnitude and, depending on the element type, perhaps its first derivatives. The solution for the nodal quantities, when combined with the assumed field in any given element, completely determines the spatial variation of the field in that element.

Although a F.E.A. solution is not exact, the solution can be improved by using mode elements to represent the structure.

From the vast specific literature, finite element modeling, regardless of the complexity of the analyzed problem, involves going through three sine-qua-non stages: classification, modeling, and discretization.

Classification is essential to any type of numerical analysis because it involves identifying the problem and finding possible solutions - in common terms, we say that the first step in solving a problem is identifying it. In the preliminary stages of defining the calculation model related to an engineering construction, a lot of questions arise that lead to a calibration of the data to be entered into the calculation programs. The most frequently encountered questions at this stage in the evolution of the project are: what are the geometric and topological data of the construction? What are the assumptions / physical phenomena that I need to include in the computational dimension of the model? What types of links / contacts do I need to consider for the correct modeling of the interaction between the building's component elements? What types of interactions between environments do I need to consider in my analysis? Should I run a linear or non-linear analysis? What is the target level of accuracy for the defined problem?

From the multiple analyzes run, I can conclude by saying that modeling a problem in an automatic calculation program does not answer only one of the above questions. It is difficult, almost impossible, to fit the problem into a single category. Probably, the most difficult answer is the one related to the question related to the type of interaction, e.g.: land - structure, liquid - tank jacket, granular material - silo jacket, etc. Consider, for example, the interaction between the silage material and the thin metal sheet wall of a silo under the impact of seismic action: the movement of the bulk material causes the silo wall to undergo deformations, deformations that will subsequently modify the movement of the material. From this example it follows that the displacements of the resistance structure and the movement of the silage material cannot be considered separately in the calculation, but always together.

Modelling should be seen as an essential stage, the key stage in the flow of numerical processes of the analysis because here the focus is on understanding the physical phenomenon. Numerical modeling can proceed if and only if the physical phenomenon has been fully understood. Numerical modeling forces the interpretation, decoding of the mechanics of the physical phenomenon to be able to produce a derived mathematical model, built from discrete elements (mathematical tools), which can generate precise results regarding the stress and deformation behavior of the analyzed elements. Thus, a geometric model becomes a mathematical model when its behavior is accurately described or approximated, through differential equations and the application of boundary conditions. Equations can have restrictions such as: homogeneity, isotropy, material type, rotations, and minimum deformations.

Finite Element Analysis (F.E.A.) is a simulation, not reality. The analysis is applied to a mathematical model, a model that represents the idealization of the physical phenomenon that involves the consideration in the calculation of the geometry, the material properties, the boundary conditions, the loads in a simplified way established by the engineer.

Discretization. The mathematical model created in the Modeling stage enters the discretization sequence, which involves the division of continuous linear and surface elements into solidarized finite elements in a calculation network. Discretization, through its paradigm, introduces another approximation. The goal being to build a mathematical model starting from a real physical phenomenon, we accept the following two sources of error: the modeling error and the discretization error. The modeling error can be eliminated by improving the proposed model, and the discretization error can be eliminated by increasing the finite elements in the computational mesh. Regardless of the type and accuracy of the modeling, it must be recognized that there will always be a balance relationship between these two errors, i.e. even if the discretization error is reduced to 0 the phenomenon in reality cannot be reproduced with absolute accuracy due to limitations, modeling errors.

Starting from all these introductory descriptions about the finite element analysis we will discuss in the following chapters the most important steps to be taken in the definition of calculation models for the dimensioning of deep foundations. For these types of constructions, the emphasis will have to be placed: in the modeling stage, on the appropriate definition of the interactions of grader - foundation soil / pile - grader - foundation soil, and in the discretization stage, on the composition and density of the finite elements in the networks, such as and on the transfer of results between elements with different thicknesses and stiffnesses.

2. Modeling interactions between environments specific to deep foundations. Mathematical Modelling of deep foundations

Finite element modeling is recognized today by design engineers as the modus operandi, with many newly designed constructions being run, dimensioned, and statically or dynamically checked using an automated calculation program. Among the calculation models made by structural design engineers, the largest volume of work is distributed in the field of superstructures and, unfortunately, an exponentially reduced number is distributed to special infrastructure works, that is, geotechnical and foundation works.

According to the directions in modeling presented in the previous chapter, in F.E.M.

modeling problems from the geotechnics and foundations group, it is required that the level of knowledge for the use of automatic calculation programs to be medium to advanced. The reason is given by the mathematical interpretation of a wide spectrum of interactions between the elements that share the indirect foundations and the foundation ground. In essence, the most difficulties in creating the mathematical model are encountered in the Classification stage of the problem because here we must establish and have a good geotechnical database through which we can mathematically model the ground under the foundation. Most of the time the modeling contains errors precisely because of the lack of geotechnical data; what is known well to very well being the geometry and way of making up the foundation.

From the perspective of the calculation of dimensioning and verification of deep foundations, it is mandatory to consider the interactions, because a separation in the calculation between the foundation, regardless of its type, and the ground will lead to important errors.

For the calculation of special foundations, two major types of interactions are to be evaluated: the pile - leveler interaction and the foundation - ground interaction. In this sense, the article will deal with the two interactions in turn and, to make the exposition much more practical, concrete ways and tools will be illustrated for the creation of mathematical models.

The complexity of these two interactions in practice forces the design engineer to choose, as an automatic calculation tool for dimensioning, analytical calculation, or finite element calculation programs in the plane state of stresses specific to technical geology and foundations. The decision is not necessarily wrong, but it must be recognized that it is a restrictive one because in such programs the superstructures that unload the loads on the infrastructure in contact with analytically modeled foundation ground cannot be geometrically modeled. From here we draw the conclusion that in these modeling fields, the precision of the definition and discretization of the terrain interfaces is high, but the model contains 0 information about the behavior in efforts and deformations of the elements that make up the superstructure of the construction. In the specialized literature in the field studied, which underpins the analytical models for direct calculation of foundations, the importance of considering the stiffness of the superstructure in the calculation of limit or service deformations of foundations is presented. Thus, it must be recognized that the analytical modeling in these programs should be done only to obtain the expression in stresses and strains of the ground under the foundation in the area limited by the active depth of the foundation because the "foundation" element is introduced only by thickness, type of material and boundary condition - the working hypothesis is much simplifying, therefore semi-precise.

Thus, in design practice, it is good to make calculation models both with programs dedicated to geotechnics and foundations, as well as with finite element calculation programs dedicated to the dimensioning analysis of superstructures.

Moreover, to emphasize this aspect, in chapters 3 and 4 of the paper, models and results will be presented in SCIA Engineer.

Returning to the types of interaction stated at the beginning of the chapter, it must be clarified that to have a qualitative picture of the results obtained with the help of structural calculation programs, the tools for defining mathematical models must be used carefully, otherwise modeling and discretization errors may occur which can substantially jeopardize the analysis.

For the “pile – raft” interaction, the tools of the programs must be chosen and used, which help: in the fine, detailed discretization of the network of infinitesimal elements local to the contact point, in the averaging of bending and shear stresses in the proximity of the contact point, and in the management of local stiffness of the raft in the area of the contact point. All these tools are necessary in the modeling and discretization stage, precisely because the piles are recognized by the program as "beam" type linear elements (1D) and with a behavior to sectional stresses and deformations specific to “columns” (1D vertical elements). To change the behavior of the "column" into a "pile", the interaction with the raft must be managed, and then the interaction with the ground must be managed or, even more, defined.

Only through the simple comparison between the two modeling paradigms (geotechnical analytical modeling - foundations vs. modeling with automatic calculation of structures) we identify, in the field of soil - structure interaction, the presence of many simplifying assumptions that must be applied. In structural calculation programs, the foundation ground cannot be modeled planarly or spatially with the help of interfaces, so models that assume inter-links between the elementary layers cannot be processed under the conditions of the defined finite element analysis half-space. Thus, the engineer designing the structures, the operator, must equate the friction, interaction, adhesion of the pile and the leveling slab with the foundation ground by using spring constants or, as they are also called in the specialized literature, proportionality factors (Ks).

The geotechnical design regulations, even in our country through NP 112-2014, indicate values for proportionality factors depending on the type of land. For correctness, the bed coefficients (Ks) require numerical calibration with the constituent model of the elastic interaction model chosen in the calculation program - here we have mezzo and macro two models: Winkler and Winkler - Pasternak.

3. Rules and principles for modeling F.E.M. of deep foundations. Description of the Subregion concept

If in the case of the pile - raft interaction the definition of the contact has a major impact on the level of discretization of the calculation surface of the 2D flat element, in the case of the soil - foundation interaction the definition is much more complex because it requires the establishment of boundary conditions between the raft and the ground under its base , between the pilot and the terrain traversed (adhesion) and, last but not least, between the base of the pilot and the terrain where it stops. I have avoided using the terms “fixed” and “hinged” for the last boundary condition presented previously precisely because in almost all situations in the field the pilot, on the end or lower part, presents a semi-continuity, that is, the contact point has an intrinsic rigidity - it is neither perfect fit nor perfect articulation.

In the context of this chapter, as will be demonstrated in the content of the article, we make it clear that deep foundation piles must be modeled in automatic structure calculation programs by considering the actual depth resulting from prescriptive dimensioning relation, often the pile sheet stopping in the models calculation somewhere at an equivalent depth of 4*ø (ø - represents the nominal diameter of the pile), and the limit condition on the lower end of the pile being the perfect embedment.

Greater attention must be paid to the modeling of the elements that describe the geometry of the system defined in the automatic calculation programs, because by obtaining an increased precision at the level of the mathematical model, we can then focus our attention on the EN 1990 prescriptions that refer to the possibility of reducing the values of the factors of gamma probability entering structural and geotechnical design equations.

Computer programs today offer a wide range of tools for modeling and discretization, but for fear of making mistakes, many design engineers do not use the latest, more advanced ones, making the decision to solve the numerical system directly from the data geometry entered. It should be emphasized that by simplifying the geometric input, the developed mathematical model will be greatly penalized and will give the designer less accurate results. The current trend in the matter of defining mathematical models is for the modeling to be as complex as possible, and the use of discretization tools such as the Subregion to be widely used because only in this way can qualitative results be obtained that will lead to decisions to optimize the elements that they compose the resistance infrastructure.

We often find in practice the modeling situation where, locally, only a part of a surface element needs to be assigned specific computational properties. For these in the SCIA Engineer software you can use the tool called Subregion.

Subregion allows the introduction of different material and stiffness properties on a specific area of a calculation surface. The subregion presents multiple advantages in the modeling of the variable sections of general erasures, but it also finds its applicability in the modeling of foundations on an elastic medium when it is desired to consider in the calculation the stiffness contribution brought by the vertical elements of resistance, a component of “rigid box” type infrastructures” (basement diaphragms). This aspect will be revealed in the two case studies presented in chapter 4.

This modeling tool, together with the functions of local discretization and those of averaging the maximum values of the stresses obtained from the analyses, provides precision and control for the engineer designing structures when solutions to complex problems of behavior of foundations through interaction must be found.

The following attributes can be indicated for a Subregion: material, thickness, position in front of the calculation plane of the element and eccentricity on the elevation.

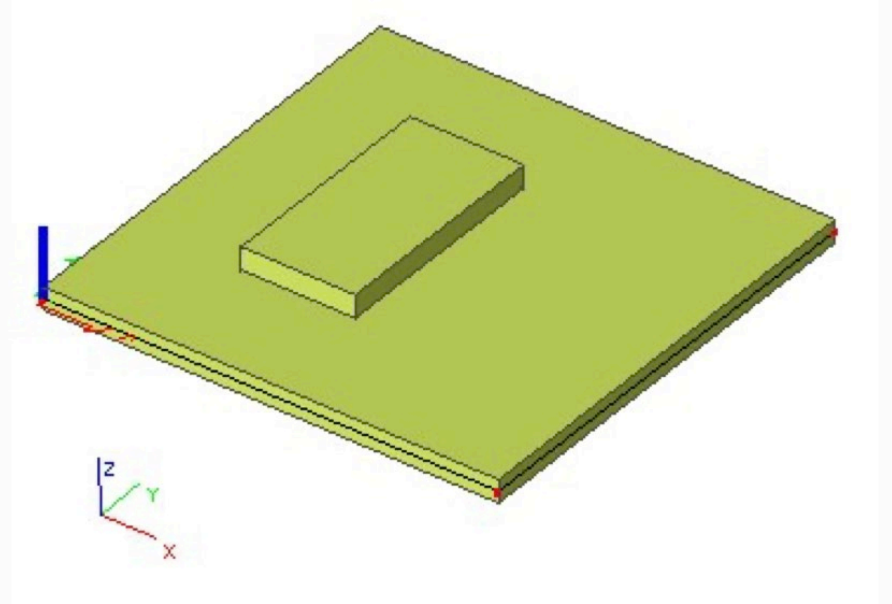


Fig. 1. *Subregion. Geometry and Eccentricity Representation (SCIA Engineer)*

4. Contributions regarding the Computation of Calculation Models with Subregions. Sizing Foundations with SCIA Engineer

In the content of this chapter, two examples of mathematical models made with the finite element calculation program SCIA Engineer will be presented that will highlight the advantage of using Subregions in defining the structural system of deep foundations.

In the first example, the modeling situation of a piled screed is presented, the focus being on the interaction area between the upper end of the pile and the slab of the screed. From the design conditions, in the given mathematical model, it was necessary to consider an increase in the thickness of the wiper on the contact area with the pilot. The introduction of the flaring geometry can be attributed to the model in two variants: the first being the one that involves cutting the eraser with the initial section by respecting the planar shape of the flared surface and the subsequent addition of a new surface element with the new thickness, and the second variant being the one that involves keeping the continuity of the eraser with the initial thickness and completing it on the surface indicated for flaring with a Subregion having the newly indicated thickness.

At a first comparison between the two proposals for solving the modeling problem raised in the calculation, the second method is much more accurate. The accuracy is given by the very fact that the computing environment remains continuous, and the thickness is indicated by a simple geometric and stiffness attribute. By choosing, in the given situation, to use the Subregion, the parasitic geometric elements are eliminated (gap, edges of the gap, 2D element inserted on account of a gap applied to another 2D element, etc.) which, beyond a certain numerical limit, can hinder the speed of processing in the calculation model and can even qualitatively affect the results obtained.

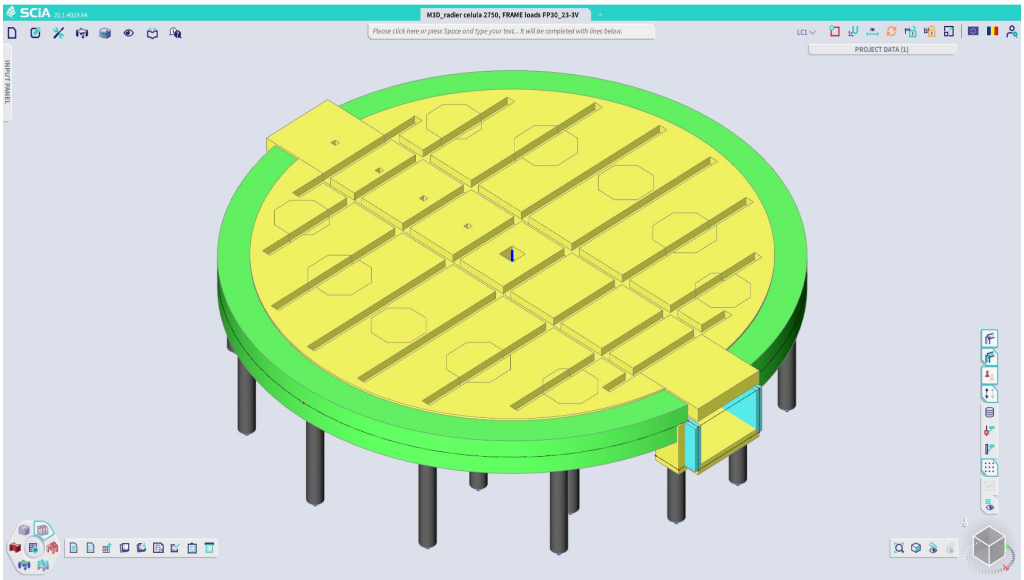


Fig. 2. *Perspective view of the raft mathematical model, SCIA Engineer*

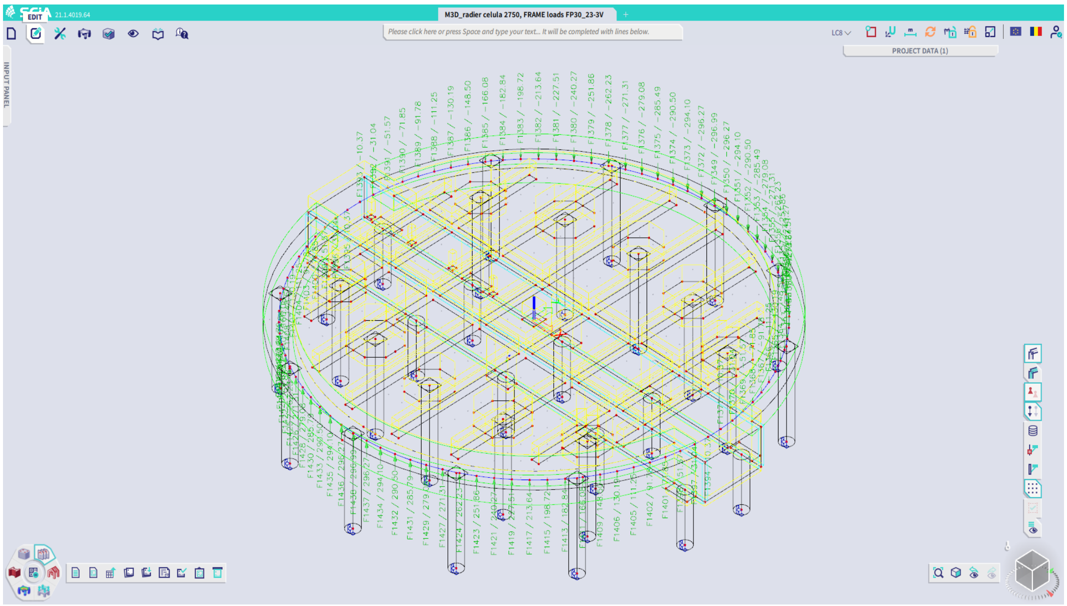


Fig. 3. *Circumferential load distribution on silo raft ring, SCIA Engineer*

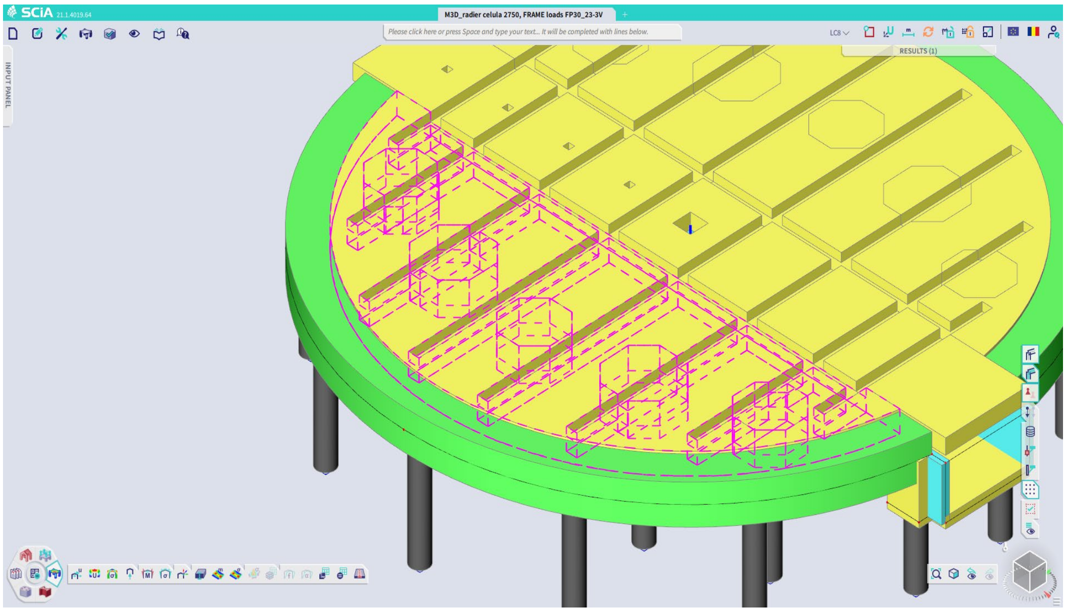
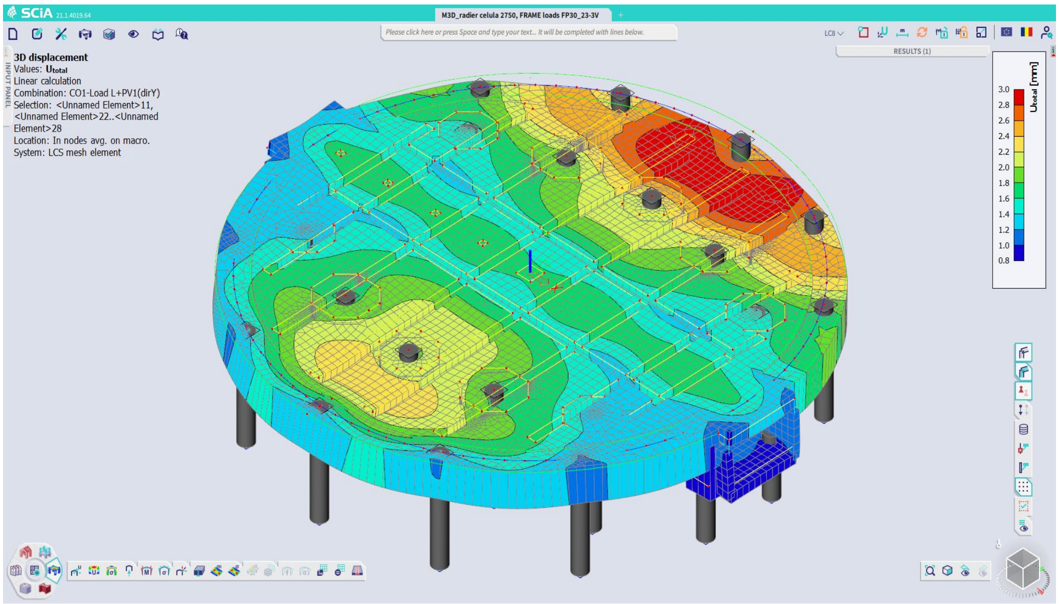


Fig. 4. *Subregions distribution over the main slab system plane, SCIA Engineer*



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3D displacement
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Linear calculation
Combination: CO1-Load L+PV1(dirY)
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<Unnamed Element>22..<Unnamed
Element>28
Location: In nodes avg. on macro.
System: LCS mesh element
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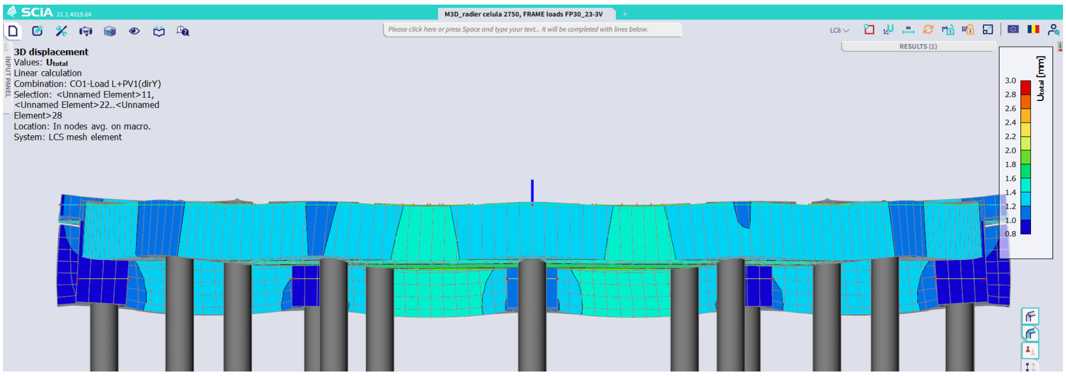
Fig. 5. *General view of the 3D model, displacements considering the add Subregions rigidity, SCIA Engineer*



3D displacement
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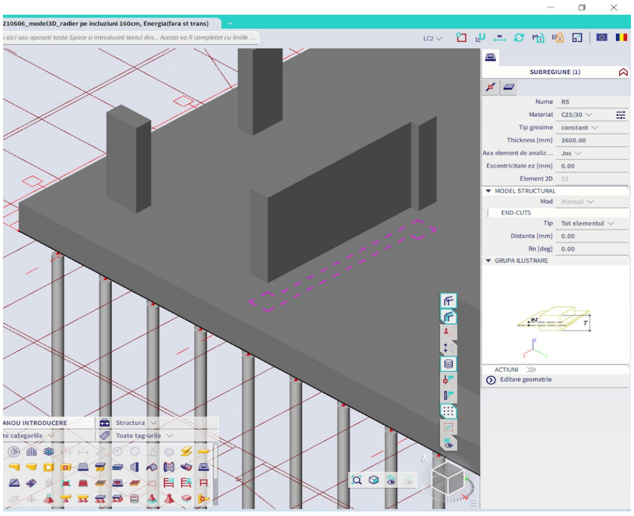
Linear calculation
Combination: CO1-Load L+PV1(dirY)
Selection: <Unnamed Element>11, <Unnamed Element>22..<Unnamed Element>28
Location: In nodes avg. on macro.
System: LCS mesh element

Fig. 6. *Lateral view of the 3D model, displacements considering the add Subregions rigidity, SCIA Engineer*

In the second example, the modeling situation of a general embankment that transfers loads to a transfer layer composed of compacted crushed stone and a group of rigid plain concrete inclusions is presented. The purpose of the analysis, which also led to the practical use of the Subregions, was to calculate based on known reactions (fundamental grouping and special grouping) exclusively the behavior of the eraser and the group of inclusions. Here, the use of Subregions was imposed because, as it is easy to appreciate, the self-weight of the superstructure was considered in the value of the known set of reactions, which required only the stiffness contribution of the basement walls to be considered in the evaluation of the behavior of the raft.

Like the first case study presented here, at least two approaches are possible in the definition of the calculation model: the first modeling of the slab and the basement walls with (2D) horizontal and vertical surface elements, respectively, and a second one involving the modeling only of the surface element (2D) and the introduction of walls with Subregion.



Nume R5
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Tip grosime constant
Thickness [mm] 3600.00
Axa element de analiz... Jos
Excentricitate ez [mm] 0.00
Element 2D S1
Mod Manual
Tip Tot elementul
Distanta [mm] 0.00
Rn [deg] 0.00

Fig. 7. *Subregions geometry into wall definition and its properties, SCIA Engineer*

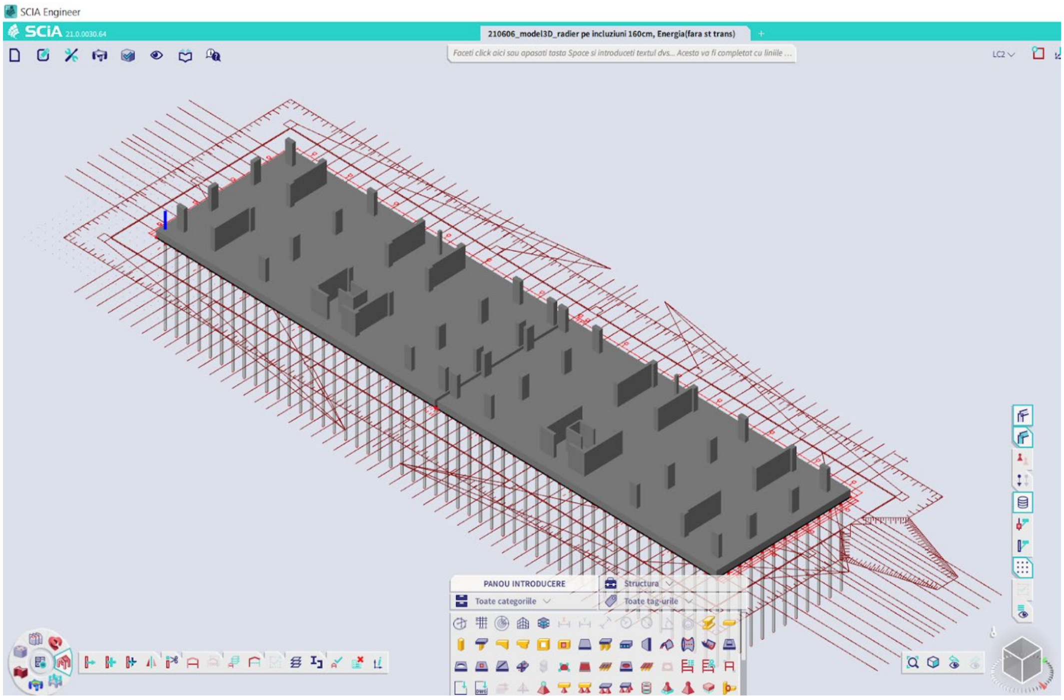


Fig. 8. *Overall view of the 3D mathematical model, SCIA Engineer*

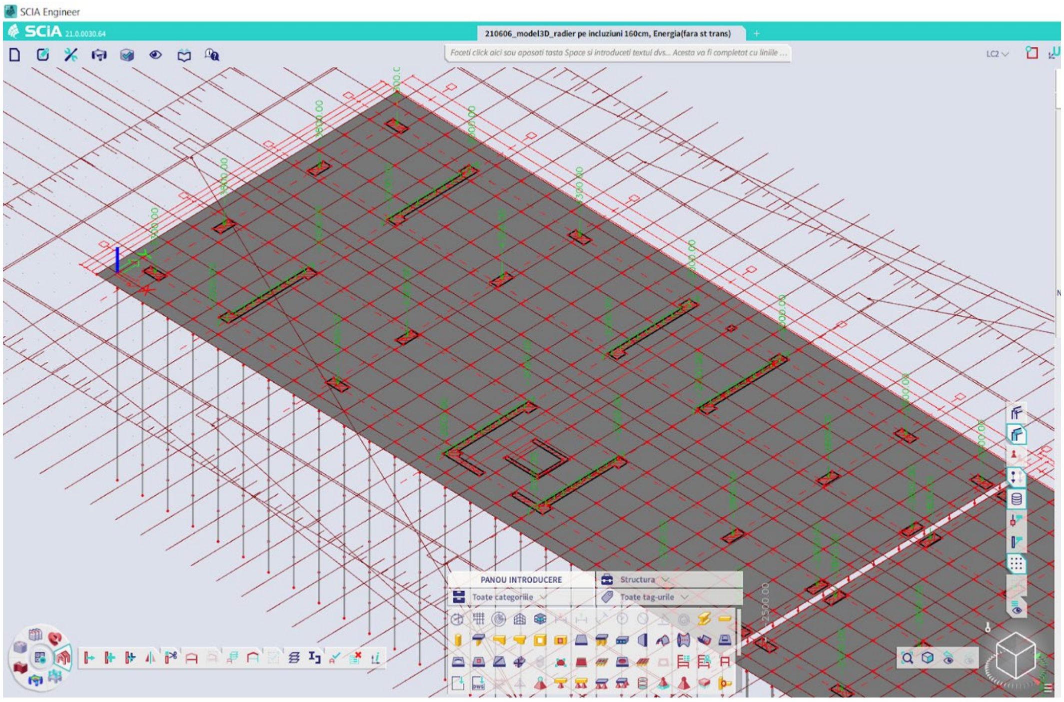
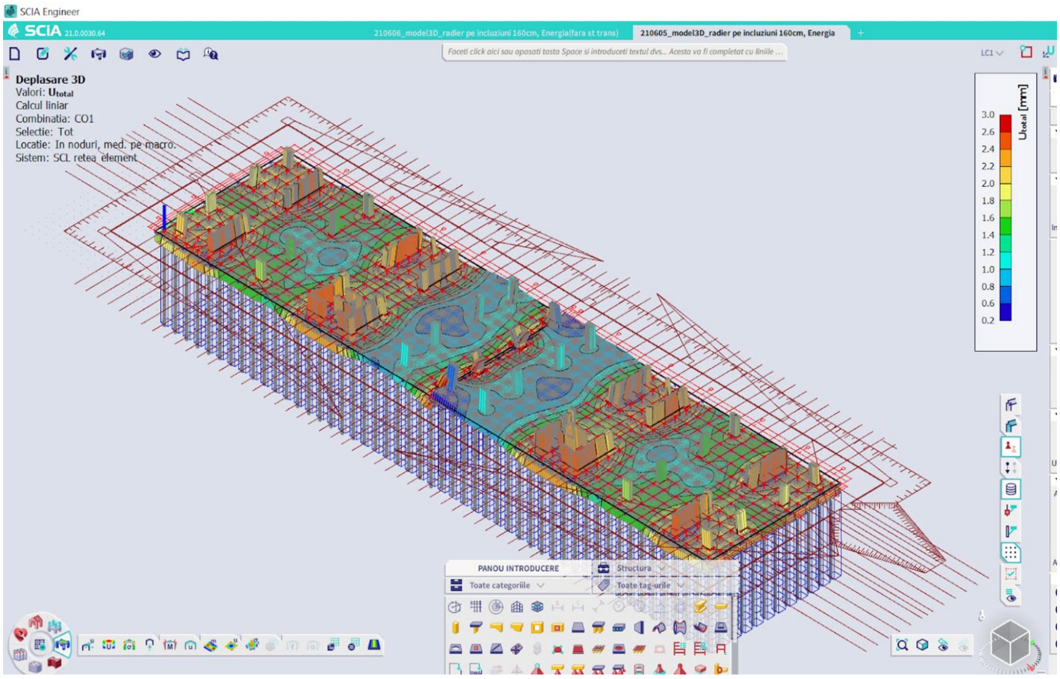


Fig. 9. *Line loads and point loads distribution on the raft surface, SCIA Engineer*



Deplasare 3D
Valori: U_{total}
Calcul liniar
Combinatia: CO1
Selectie: Tot
Locatie: In noduri, med. pe macro.
Sistem: SCL retea element

Fig. 10. *3D displacements raft considering the effect of the Subregions, SCIA Engineer*

Deplasare 3D
Valori: U_{total}
Calcul liniar
Combinatia: CO1
Selectie: Tot
Locatie: In noduri, med. pe macro.
Sistem: SCL retea element

Fig. 11. *3D displacements of the raft in lateral view, SCIA Engineer*

5. Conclusions

As we presented in the previous chapters, but also as it emerges from the examples presented in the form of these two case studies, the creation of mathematical models for the resistance structures of foundations presents multiple challenges. All these challenges lead to obtaining an advanced level of knowledge both design software and to an advanced level of knowledge of the physical phenomenon proposed for discretization and analysis.

A first conclusion that can be drawn is that the definition of mathematical models must necessarily go through the three fundamental stages described in the first chapter, that is: classification, modeling and discretization. The data level must have a constant linear distribution, that is, the engineer must establish a satisfactory to good level for the data for each of the three stages of the calculation.

Another conclusion that emerges from the presentations given by the author is that the highest density of calculation errors canton, that is, they are located, in the stages of modeling and discretization. To reduce errors in mathematical models solved with the finite element method, it is important that the continuous calculation environments are not frequently interrupted by geometries or transitional elements (incident voids, 2D elements - in - 2D elements, parasitic internal sides, parasitic internal nodes, etc.). All these general interruptions are gross errors, especially in the calculation of 2D surface elements, e.g.: floors, general level foundations, structural walls. When variable actions or areas with different thicknesses and stiffnesses must be introduced into the model, it is recommended to use the Subregion tools, as defined in Chapters 3 and 4 of the paper.

A conclusion that can be drawn at the end of this article, at the same time representing a direction for future research activities, is that in the case of mathematical models related to foundations on piles or in the case of soil consolidation with rigid inclusions, it is imperative to model the piles with their real depth. Based on the results, the derived modeling of the piles on an equivalent depth equal to 4*ø is not validated - the results contain significant errors both at the level of the sectional stress diagrams and at the level of their values.

For the validation of the mathematical model with a real depth pile, in the Classification stage, relevant data must be collected from the geotechnical studies carried out on-site for the appropriate choice of the soil-structure interaction model and, implicitly, of the appropriate values for the bed coefficients.

As a future research direction, such approaches, and tools for modeling F.E.M. can help in the analysis of deep foundations related to silage cells under low-frequency loading-unloading cyclic loads, providing a data calibration and a corresponding quality of the results to obtain the time evolution of foundation land settlements, column deformations. At the same time, only based on such models, it is possible to establish the correct depth of fixing the piles in multi-layered lands or in those with a complex geological morphology.

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