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Industrial floors and analysis of the interaction between the floor slab and embankment

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ABSTRACT: Currently, the logistics warehouses market is in full development in Romania and Eastern Europe. The main elements in these warehouses are the floor slab and the storage systems (e.g., racks) which must take the loads and safely send them to the foundation soil. In general, the floor slabs are structures placed directly on ground, with large dimensions in X and Y directions generated by storage space requirements. The slabs-on-grade are realized through embankments formed of multiple compacted layers similar to those used in roads engineering. The proposed paper presents the analysis of the interaction between the embankment and the floor slab and also the effect on the concrete slab. As a common calculation methods are the reaction coefficient method and also, more advanced, the finite elements method. The paper presents the results of several numerical 3D modelling for different configurations.

KEYWORDS: industrial floors, subgrade, subgrade reaction, subbase, FEM analysis of industrial floors.

1 INTRODUCTION

Currently, the logistics warehouses market is in full development in Romania and Eastern Europe. The main elements in these warehouses are the floor slab and the storage systems (e.g., racks) which must take the loads and safely send them to the foundation soil. In general, the floor slabs are structures placed directly on ground, with large dimensions in X and Y directions generated by storage space requirements. The floor slab is constructed so that it must provide an adequate wearing surface with acceptable deformations and rotations, on which operations can be performed efficiently and safely. These large surface floors are expected to be built at the lowest possible costs and perform without issues year after year. Most of the warehouses use monolithic concrete floors. The selection criteria of which type of floor is required for a warehouse depends on a lot of factors such as various categories of goods to be stored, whether trucks are driven both inside and outside the warehouse, the storage height etc. The imposed loads and deformations together with foundation ground are the main elements that are designing the floor slab and its founding system. In the unlikely event that all requirements are not met, the floor can be suspended using piles which transfer the forces to a deeper resistant layer. Considering the similarities of the floor slabs embankments to the road embankments, most of the technical guides that are used in the design of floor slabs embankments are also used in roads design. The major difference between industrial floors and roads is given by loads, namely: floors take mostly static loads, while roads are mainly required to take dynamic loads. The choice of the foundation type depends both on the nature of the subgrade, but also on the size of the loads at the level of the floor slab and on the imposed limits in terms of allowable settlements. All these criteria lead to the correct choice of the floor slab foundation system. In situations where the loads are very high at the floor slab level and the settlement requirements are very restrictive, combined with the placement of the floor slab on a weak ground, the need for soil improvement or, as a last alternative, a deep foundation of the flooring appears - foundation on reinforced concrete piles.

2 SOIL SUPPORT SYSTEM OF FLOOR SLABS

The slabs-on-grade are realized through embankments formed of multiple compacted layers similar to those used in roads engineering. The main purpose of using multiple layers is to obtain a gradual transition of stiffness from the floor slab to the foundation ground (subgrade). The American Concrete Institute, ACI360R-10, divides the embankment into several layers similar to those of roads as follows:

- subgrade which is most often represented by the natural soil to be compacted or by soil improved by the adding binders or by backfill compacted in elementary layers of materials with or without addition of binders;
- subbase which generally consists of a granular material which, in addition to bringing a large contribution of load-bearing capacity and stiffness, also has the role of breaking capillarity;
- base layer on which the floor slab is actually made. This layer can be made of a granular material stabilized with cement in order to increase the bearing capacity and stiffness.

Analyzing the three horizons described above, it is to be noticed that there is a gradual transition of stiffness from the floor slab to the foundation ground (subgrade).

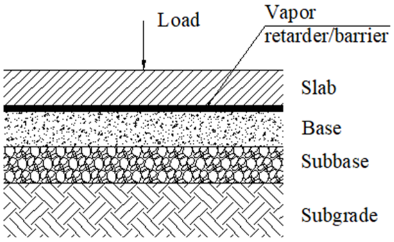

Figure 1. Slab support system terminology

Knapton (1999) introduced the hypothesis that for industrial floors the base layer no longer existed. In this situation, the floors can be assimilated with a rigid road system. According to Romanian norm NP 081 (2002) the rigid road structure consists of a concrete slab, followed by the subbase layer (which can be made of an upper subbase layer and a lower subbase layer).

By comparison, in the case of industrial floors, the rigid element is represented by the floor slab which is then followed by the upper subbase layer made of a stabilized granular material (e.g., ballast stabilized with cement) and the lower subbase layer which can be made of granular material (for example ballast). By analogy with slab support system terminology indicated in American Concrete Institute, ACI360R-10, if we consider the division of the subbase layer into upper and lower, we can assimilate the upper subbase layer with a base layer. The granular materials that can be used to make the subbase layer are sand with gravel, crushed stones, or a mixture of these materials. It is recommended to use the subbase layer under the floor slabs for several reasons, such as:

- from the technological point of view, it provides a good working platform for the use of machinery;
- it facilitates a uniform load-bearing surface under the floor slab;
- it reduces deformations in the joints area and therefore ensures the effectiveness of long-term load transfer between joints, by interlocking aggregates (if there is no other load transfer system, especially);
- it helps in controlling the excessive expansion and contraction of the subgrade layer, if it consists of soils with high expansion and contraction.

As a short conclusion, the typical support system (embankment) under an industrial floor slab consists in: subgrade layer followed by a subbase layer (which can be made of an upper subbase layer and also a lower subbase layer).

3 DESIGN OF SLAB ON GROUND SUPPORT SYSTEM

The design of slabs-on-ground to withstand moments and shear forces induced by applied loads is highly dependent on the interaction between the concrete slab and its supporting materials. Both the mechanical properties and the geometric configuration of the slab and subgrade layers play a critical role in ensuring structural performance.

For reliable behavior, the support system must provide adequate and uniform bearing capacity and remain stable under variable environmental conditions. Slab-on-ground failures can occur because a proper support system was not achieved.

There is no universal design method that applies to all cases. Instead, a range of construction strategies and design methodologies exist, and the appropriate combination should be selected based on the specific functional, structural, and geotechnical requirements of each project.

3.1 *Analytical method*

The methodologies used in the design of slabs-on-ground have their origins in analytical models initially developed for airports and highway pavements. A significant early contribution to this field was made by Westergaard (1926), who introduced the so-called "corner formula" for stress, representing one of the first rational attempts to quantify stress distribution in rigid pavement systems. Although early experimental results from pavement testing appeared to validate this theoretical model, its practical implementation in design practice has remained relatively limited due to its simplifying assumptions and idealized boundary conditions.

Westergaard developed one of the first rigorous theories of structural behavior of rigid pavement in the 1920s (Westergaard 1923, 1925, 1926). This theory considers a homogeneous, isotropic, and elastic slab resting on an ideal subgrade that exerts, at all points, a vertical reactive pressure proportional to the deflection of the slab. This is known as a Winkler subgrade (Winkler 1867). The subgrade acts as a linear spring, with a proportionality constant k with units of pressure (kPa) per unit deformation (m). The units are commonly abbreviated as kN/m^3. This is the constant now recognized as the coefficient (or modulus) of subgrade reaction. Extensive investigations of structural behavior of concrete pavement slabs performed in the 1930s at the Arlington Virginia Experimental Farm and at the Iowa State Engineering Experiment Station showed good agreement between observed stresses and those computed by the Westergaard theory, as long as the slab remained continuous with the supporting subgrade. Corrections were required only for the Westergaard corner formula to account for the effects of slab curling and loss of the contact with the subgrade.

Experimental investigations conducted in the 1930s provided compelling evidence that the mechanical behavior of many subgrade soils could be approximated by that of an elastic, isotropic medium. Within this framework, the modulus of deformation and Poisson's ratio emerged as key parameters for evaluating the soil's response to loading. These parameters allow for a simplified yet sufficiently accurate representation of subgrade deformation behavior in analytical models, particularly within the elastic range of soil response (Burmister, 1943; Terzaghi & Peck, 1948).

Based on the concept of the subgrade as an elastic and isotropic solid, and assuming that the slab is of infinite extent but of finite thickness, Burmister, in 1943, proposed the layered-solid theory of structural behavior for rigid pavements (Burmister 1943) and suggested that the design be based on a criterion of limited deformation under load. The design procedures for rigid pavements based on this theory, however, were not sufficiently developed for use in engineering practice.

All existing theories can be grouped according to models used to simulate the behavior of the subgrade. The two models used for the subgrade are: Elastic-isotropic solid and Winkler.

The Winkler subgrade models the soil as linear springs so that the reaction is taken proportionally to the slab deflection. Existing design theories are based on various combinations of these models. Design theories need not be limited to these combinations.

While the elastic-isotropic model provides closer prediction for the response of real soils, the use of the Winkler model is almost universally used for design, and a number of investigators have reported good agreement between observed responses to the Winkler-based predictions (ACI Committee 360, 2010).

3.1.1 *Modulus of subgrade reaction*

As is specified above, the Winkler model is almost universally used for design. The subgrade acts as a linear spring, with a proportionality constant *k* which is commonly called the coefficient (or modulus) of subgrade reaction. This modulus, is a spring constant that assumes a linear response between load and deformation from the subgrade.

Actually, there is no single *k* value for a subgrade because the relationship between load and deformation of a soil is nonlinear and is not a fundamental soil property. A typical nonlinear relationship between a normal compressive load and the resulting deformation for an area is shown in below picture.

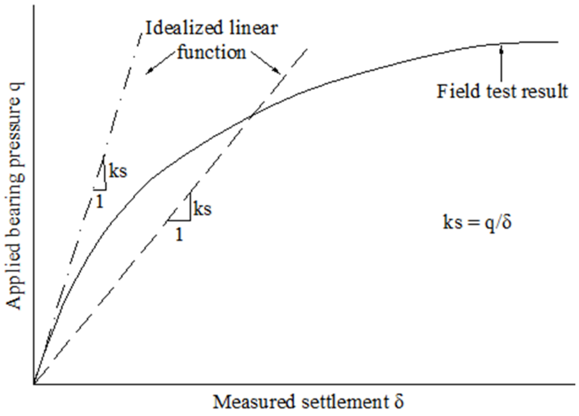

Figure 2. Plate load-deformation diagram (ACI Committee 360, 2010. American Concrete Institute - Guide to design of slabs on ground)

The type of soil structure, density, moisture content, and prior loading determine the load-deformation relationship. The relationship also depends on the width of the loaded area, shape of the loaded area, depth of the subgrade, and position under the slab. In addition, time may be a significant factor because any deeper compressible soils may settle due to consolidation, and near-surface soils may settle due to shrinkage from alternate wetting and drying (ACI Committee 360, 2010).

3.1.2 *Plate load field tests*

Determination of the modulus of subgrade reaction on representative subgrade, usually can be made with bearing plate of 760 mm diameter according to ASTM D 1196 or AND530 – 2012 (Appendix 3) which is a Romanian norm regarding to the quality control of embankments. Several tests over the project area are required to obtain representative k values, which generally result in a range of k values.

A correction is generally necessary to account for future saturation of cohesive soil subgrades, and this requires sampling and laboratory tests.

New Zealand Concrete Society - Seminar notes. Specification and design of commercial concrete slabs on grade include a conversion chart for the modulus of subgrade reaction k as a function of the plate diameter used.

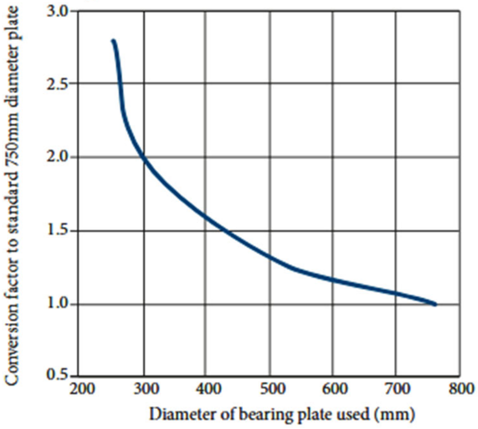

Figure 3. Conversion factors for different loading plate sizes. New Zealand Concrete Society, 2016. Specification and design of commercial concrete slabs on grade - Seminar notes.)

Analyzing the graph above, it can be observed that for a plate diameter of 300 mm, the conversion factor is approximately 2, and for a plate with a diameter of 600 mm, the factor is around 1.15–1.2.

3.2 *Finite element method*

The classical differential equation of a thin plate resting on an elastic subgrade is often used to represent the slab-on-ground. Solving the governing equations by conventional methods is feasible only for simplified models where the slab and subgrade are assumed to be continuous and homogeneous. In reality, however, a slab-on-ground usually contains discontinuities, such as joints and cracks, and the subgrade support may not be uniform. Thus, the use of this approach is quite limited.

The finite-element method can be used to analyze slabs-on-ground, particularly those with discontinuities. Various models have been proposed to represent the slab (Spears and Panarese 1983; Pichaumann 1973). Typically, these models use combinations of various elements, such as elastic blocks, rigid blocks, and torsion bars, to represent the slab. The subgrade is usually modeled by linear springs (the Winkler subgrade) placed under the nodal points. While the finite-element method offers good potential for complex problems, graphical solutions and simplified design equations have been traditionally used for design (ACI Committee 360, 2010).

4 DESIGN EXAMPLES

4.1 *Analytical method*

Below is a brief example of a calculation based on an elastic medium, in which the modulus of subgrade reaction k is obtained before design through static bearing plate load tests in the field, conducted on the subbase layer.

This value is then used in the analysis as the stiffness of the springs beneath the floor slab, allowing for the determination of internal forces within the slab.

The foundation soil consists of a upper clayey complex layer, composed of silty and/or sandy brownish-yellow clays, with a thickness of 9.00 m, followed by a sand layer with a thickness of 4.00 m and finally a clay layer with a thickness of 7.00 m till the end of the boreholes

Below is the composition of the embankment beneath the floor slab:

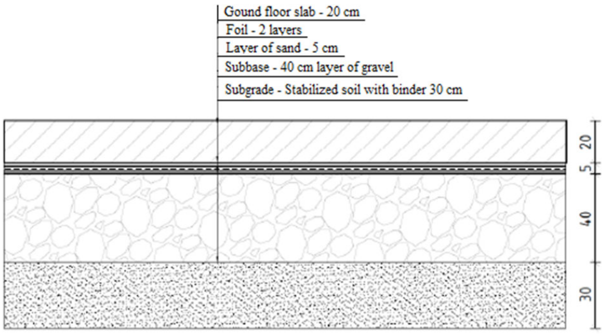

Figure 4. Embankment layers under the ground floor slab

For this example, it is considered a concrete slab with dimensions of 12.425 x 9.34 m slab to get a representative portion of the loaded areas. The slab is considered to be reinforced with steel fibers.

The selection also ensures adequate edge space of 0.5 m away from the points of extreme loading of the slab. The slab thickness is taken as 200 mm thick, concrete C25/30.

In the below picture it is present the SCIA design model.

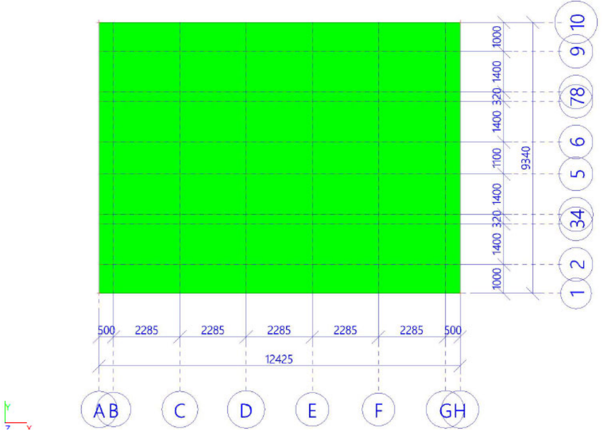

Figure 5. Design model

Forces are applied in the SCIA model over the base-plates, by converting the point loads applicable on points over an area of 200 mm x 95 mm of the base plate. The maximum load on each rack leg is 130 kN.

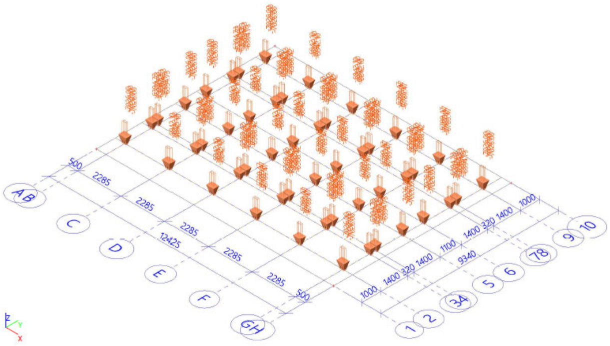

Figure 6. Loads application on the ground floor slab

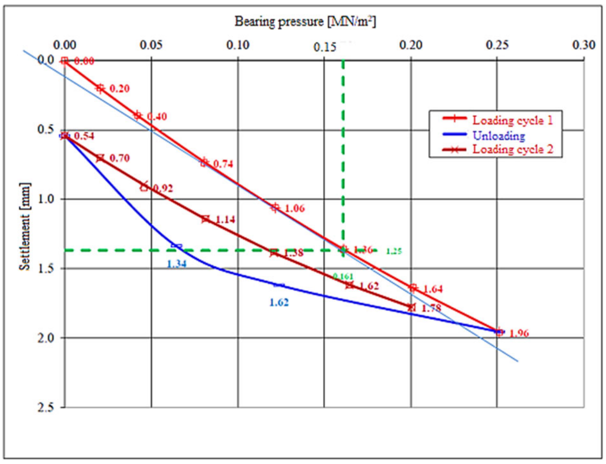

Figure 7. Pressure–settlement diagram used to determine both the static linear deformation moduli and the subgrade reaction modulus (*k*)

From above diagram, the results are as follows: E_{v1} = 58.10 MN/m^2; E_{v2} = 80.00 MN/m^2; E_{v2}/ E_{v1} = 1.38. Subgrade reaction modulus for diameter of bearing plate of 600 mm is $k_{(600)}$ = 128.80 MN/m^3.

Considering that the test was performed using a static bearing plate with a diameter of 600 mm, a diameter correction was applied.

The subgrade reaction modulus k was determined in accordance with AND530 – 2012 Appendix 3, based on the loading curve (Cycle 1), by selecting the pressure corresponding to a predefined settlement of 1.25 mm (see the green dashed line in the graph in Fig. 7).

Taking into account the correction the subgrade reaction modulus is $k_{(750)}$ = 112.10 MN/m^3. In the below picture is an example of the results in the floor slab.

As we can see in the below picture, the maximum settlement is 1.40 mm

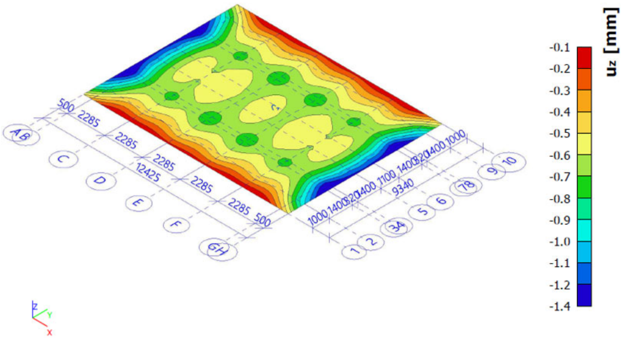

Figure 8. Vertical displacements diagram

4.2 *Finite element method*

Internationally, more advanced calculation methods are also used, such as FEM (Finite Element Method), where the foundation soil (subgrade), the subbase layer, and the floor slab can all be modeled. Additionally, the interaction between the concrete slab and the subgrade is considered by using an interface element.

The following presents a scenario similar to the previous one, where a floor slab subjected to point loads from racks is analyzed, examining the vertical deformation of varying subbase layer thicknesses and the stiffness of the layer. The analyze has made in Plaxis 3D software.

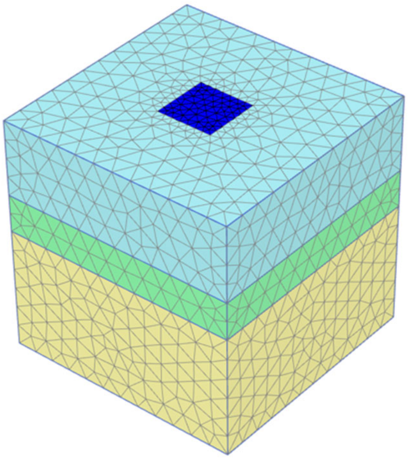

Figure 9. 3D Model for ground floor and soil

The foundation soil consists of a surface silty clay layer with a thickness of 7.00 m, followed by a sand layer with a thickness of 3.00 m and finally a clay layer with a thickness of 10.00 m till the end of the boreholes.

The constitutive law used for the soil is Hardening Soil.

Table 1. Soil parameters

Soil layer	$E_{50}{}^{ref}$ [MPa]	$E_{eod}{}^{ref}$ [MPa]	$E_{ur}{}^{ref}$ [MPa]	γ [kN/m^3]	C' [kPa]	Φ [°]
Silty clay	12	12	36	19	30	15
Sand	30	30	90	19	0	30
Clay	15	15	45	19	35	18

The thickness of the subbase layer varies from 0.40 m to 0.60 m, while its stiffness, expressed by the linear deformation modulus, ranges from 40 MPa to 120 MPa and the step is 10 MPa.

Table 2. Subbase layer parameters

Subbase layer	$E_{50}{}^{ref}$ [MPa]	$E_{eod}{}^{ref}$ [MPa]	$E_{ur}{}^{ref}$ [MPa]	γ [kN/m^3]	C' [kPa]	Φ [°]
Gravel	40÷120	40÷120	120÷360	19	0	30

The contact between the concrete slab and the foundation layer is modeled using an interface element in the calculation software, with the interface defined by common nodes.

The slab dimensions in plan are 6x6 m, with concrete class C25/30, a linear deformation modulus of 31,000 MPa, a Poisson's ratio of 0.2, and a concrete unit weight of 25 kN/m³. The slab is considered to be reinforced with steel fibers.

The concrete slab is loaded by pairs of racks placed at the center of the slab. Each rack transfers its load to the slab through four legs, resulting in a concentrated load over a small contact area.

The total load per rack is 12 tons, corresponding to approximately 3 tons (30 kN) per rack leg. The exact loads positioning is illustrated in the below picture.

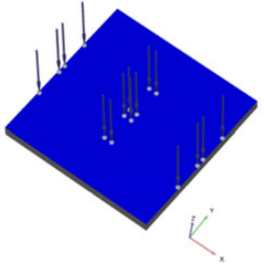

Figure 10. Position of load on the slab

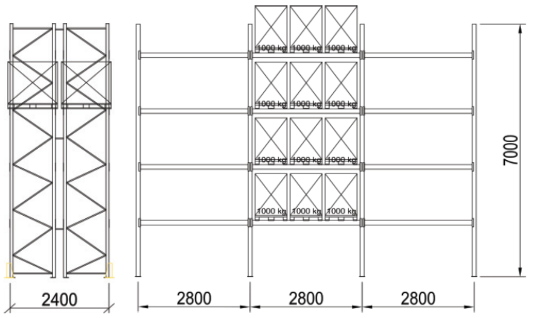

Figure 11. Sketch of shelve (Tomasovicova, D and Jendzelovsky, N. 2017)

Below figure represent the vertical displacements for the scenario with subbase layer thickness of 40 cm and stiffness of 40 MPa. The maximum displacement obtained is 7.30 mm.

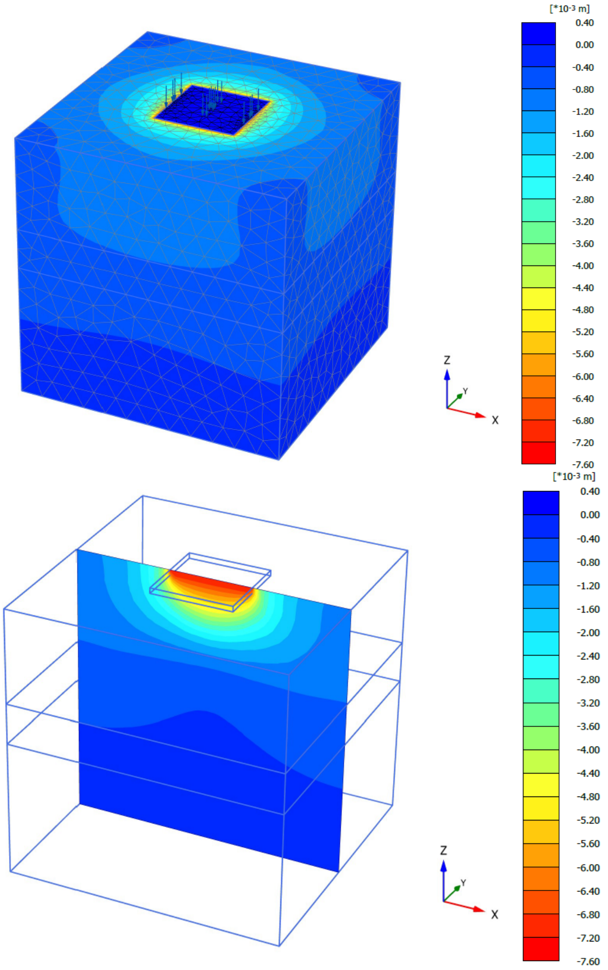

Figure 12. Vertical displacements

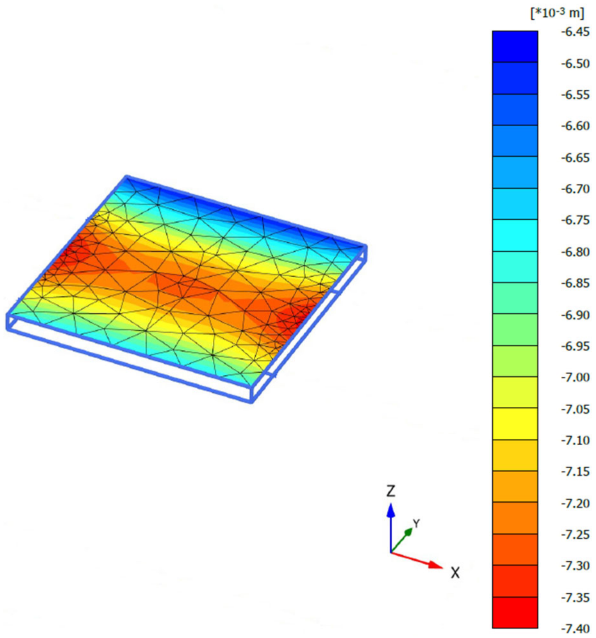

Figure 13. Vertical displacements on the slab level

From the Figure 12 it is noticed also that the effect of the point loads it spreads deep in the soil, in this case roughly till -5 m.

Thus, it can be concluded that an influence zone exists beneath the slab, where the effects of concentrated loads are distributed into the supporting layers.

A total of 27 cases were analyzed, using different foundation layer thicknesses: 0.40 m, 0.50 m, and 0.60 m. As is specified above, for the stiffness of the subbase layer was assigned 9 different values, ranging from 40 MPa to 120 MPa, with an increment of 10 MPa. The results are shown in the below graph.

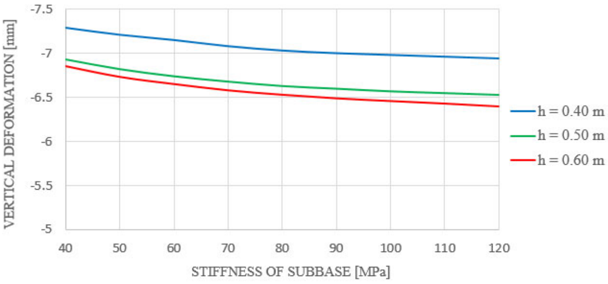

Figure 14. Diagram stiffness of subgrade – deformation

The graph above illustrates the variation of vertical deformation (in mm) as a function of the subbase stiffness (expressed as linear deformation modulus in MPa), for three different subbase layer thicknesses.

Vertical deformation decreases as the subbase stiffness increases, for all three subbase layer thicknesses. This confirms that a stiffer subbase distributes loads more effectively and reduces local settlements. For the same stiffness value, deformation is lower when the subbase layer is thicker.

The graph indicates that the flattening behavior beyond a stiffness of 80 MPa is more accentuated for the 0.40 m subbase thickness, whereas for the 0.50 m and 0.60 m layers, the curves continue to decline more gradually. This suggests that thinner subbase layers reach a stiffness efficiency limit faster, beyond which increasing stiffness does not significantly improve performance.

In contrast, thicker subbase layers continue to benefit from increased stiffness over a wider range, likely due to their greater ability to spread and dissipate stresses. Since the analysis is based on the Hardening Soil model, this trend further confirms the nonlinear stress-strain response of the system. The soil's plastic behavior becomes dominant sooner for thinner subbases, making their performance less sensitive to additional stiffness.

Moreover, the graph clearly shows a flattening trend of the deformation curves around a subbase stiffness of 80 MPa, particularly for the 0.40 m thickness. This behavior suggests that 80 MPa may represent a practical upper limit for achievable stiffness in real-world construction conditions. Although the numerical analysis extended up to 120 MPa, this was intentionally done to illustrate that beyond a certain threshold, further increases in stiffness result in only marginal reductions in vertical deformation. In reality, achieving stiffness values of 120 MPa is highly challenging and potentially unrealistic, due to inherent limitations in material compaction, moisture control, and soil properties.

This plateauing behavior can also be attributed to the nonlinear nature of soil response, especially since the Hardening Soil model was used in the simulation.

As a short conclusion, both stiffness and thickness of the subbase layer directly influence the deformation behavior of the floor slab. A higher subbase modulus leads to significantly reduced deformations, especially for thinner layers. Increasing the thickness of the subbase further improves performance, even if stiffness remains constant, as it helps dissipate concentrated loads more efficiently.

These trends support the design recommendation that, when it is not feasible to achieve a high deformation modulus (e.g., due to weak soils), increasing the subbase thickness can effectively compensate and improve slab performance.

5 CONCLUSIONS

Floor slabs are structures placed directly on ground, with large dimensions in X and Y directions generated by storage space requirements. Due to their size, the probability of defects, such as slab cracking increases proportionally with the area. Despite their critical role in the overall functionality of the facility, design and construction details for floor slabs often receive insufficient attention.

Analytical methods for design the support system beneath floor slabs are based on the Winkler elastic foundation model, in which the subgrade is idealized as a bed of springs capable of carrying loads along their longitudinal axis, assuming either linear or nonlinear elastic behavior. The springs are characterized by a stiffness coefficient k, known as the modulus of subgrade reaction or the Winkler coefficient.

The values of the modulus of subgrade reaction obtained from plate load tests may lead to an unconservative design, as the actual modulus can be lower in reality due to the deeper propagation of loading effects beyond the influence zone of the test plate. This thing is shown in the FEM analysis where we can notice that even the loads are applied in points, the effects extend deeper into the soil.

The reduction of vertical deformation is clearly influenced by both the stiffness and thickness of the subbase layer. While increased stiffness leads to improved slab performance, the results indicate that beyond approximately 80 MPa, the deformation curves begin to flatten, particularly for thinner layers, signaling a point beyond which further increases in stiffness provide minimal structural benefit.

The use of the Hardening Soil model highlights the nonlinear and stress-dependent behavior of the subgrade. The plastic response of the soil becomes dominant as stresses increase, especially for thinner subbase layers. This confirms that values as high as 120 MPa are not only difficult to achieve in practice, but also unnecessary, as they offer negligible improvement in slab deformation performance.

From the results of FEM analysis, it is noticed that if is not possible to achieve high values of the linear deformation modulus for the subbase layer, it is recommended to increase the thickness of the subbase layer and to assume a lower value for the deformation modulus.

The analytical approach based on Winkler theory offers a simplified and practical method for modeling the subgrade as a system of independent springs, making it suitable for preliminary design. However, it does not account for load interaction or subgrade continuity. In contrast, finite element methods (FEM) provide a more accurate representation of real soil behavior, especially under complex loading or layered soil conditions, by capturing stress distribution, discontinuities, and deformation patterns more realistically. Therefore, while Winkler-based models are effective for standard cases, FEM is recommended for detailed analysis and critical slab-on-grade design scenarios.

6 ACKNOWLEDGEMENTS

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