sciendo Ovidius University Annals Series: Civil Engineering, Year 26, 2024
DOI: 10.2478/ouacsce-2024-0015

Punching settlement in loessoid soils. About the numerical modeling of this phenomenon

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***Abstract* – Loessoid soils are a special category amongst the continental sedimentary formations in the quaternary era. The term "loess" comes from the german word** *lose or los*, **used around the Rhine River region, and its meaning is *loose, porous, crumbly*. Loess has high porosity due to its macropores, which are visible to the naked eye and it is also very sensitive to humidity. This last characteristic has caused a lot of problems in the construction and operation process of buildings; it also made loessoid soils fit into the cathegory of very difficult terrains to build on.**

Punching settlement takes place when the foundation body pierces through the porous environment due to the breakage of its contracting macrostructure. This penetration effect leads to the creation of a plug of material that has reduced porosity, delimited by a contour that closes on the perimeter of the foundation surface.

Punching settlement has been studied in the past by I. Chercasov in 1967, A. Chirică after 1990 and C. Ciurea after 1999.

The purpose of this paper is to highlight the phenomenon of punching settlement through numerical modeling using the following calculation programs: COSMOS/M, which uses the finite element method in various linear and nonlinear, static and dynamic problems from various fields, and the FEM module in the GEO5 program, which is a modern calculation program specialized in solving geotechnical engineering problems.

Keywords* – *COSMOS/M, FEM, foundation, GEO5, loess, macropores, punching effect.

1. GENERAL DATA ABOUT LOESS AND LOESSOID DEPOSITS

Loess is a light yellow-gray sedimentary rock which have in composition calcium carbonates, it is unconsolidated or poorly consolidated with a high porosity (often 45-50%) and, related to this, relatively high permeability in its natural state – the filtration coefficient has a value of the order of 10-4 cm/s – and it is hundreds or thousands of times lower, if the material is disturbed. Loess is a cohesive, macroporous unsaturated soil, which upon contact with water undergoes sudden and irreversible changes in its internal structure, reflected by additional settlement with a crashing character (collapse) and decreases in the values of geomechanical parameters. Loess banks often appear as vertical walls, which can reach considerable heights, due to its characteristic property: forming vertical surfaces when the exposed wall collapses [1].

Loess is a specific formation of the quaternary (pleistocene) period, of eolian, fluvial, deluvial, glacial, fluvioglacial, pedogenetic, etc. origin.

From the perspective of granulometric composition and texture, it can be:

- Clayey loess, with a fine texture and a clay content of 25-30%;
- Sandy loess, with a coarse texture and a clay content of 10-15%;
- Typical loess, with a medium texture and a clay content of 15-25% [1].

From a mineralogical point of view, it consists of quartz, feldspars, micas, clay minerals, and heavy minerals. From a chemical point of view, it consists of calcite (dolls of loess), aluminum hydroxides, etc.

From the point of view of how it settles when moistened under the layer's own weight (geological load), loess is classified as follows:

group A: soils with additional settlements $I_{mg}<5$ cm;

group B: soils with additional settlements $I_{mg}\geq5$ cm.

Where: I_{mg} – additional settlement when moistened under the layer's own weight [1].

Fig. 1 Macroporous loess from Constanța's seafront [2]

Fig. 2 The detachment of loess in vertical planes

Loess covers approximately 17% of the entire territory of Romania. It constitutes the main surface rock over most of the Romanian Plain, in central and southern Dobrogea, as well as in the Moldavian Plateau. Exceptions are alluvial plains, divagation areas and dunes. On small areas, these formations are found in Banat and Crișana, the Subcarpathian area and northern Dobrogea, they appear very rarely in Transylvania.

2. BEHAVIOR OF LOESSS UNDER COMPRESSION STRESSES. SETTLEMENT BY PUNCHING

A suffering house located in the C.A. Rosetti street no. 5. Forgotten in other times and no longer finding its place in the eyes of people. Photographed, measured, with the building survey transferred to paper, but also as a result of the analysis of the facades and implicitly of the architecture, the identification of the materials and the work technique, it begins to reveal its secrets.

Punching settlement occurs when the body of a foundation penetrates the porous medium of the soil structure. This happens by breaking down the contracting macrostructure of the loess and leads to the creation of a plug of material with reduced porosity, which is delimited by the contour of the foundation surface.

The phenomenon of contractility consists in the reduction of pore volume under the simultaneous action of compression and shear stresses. This reduction is all the more pronounced as the intensity of the tangential unitary stresses acting on the soils increases.

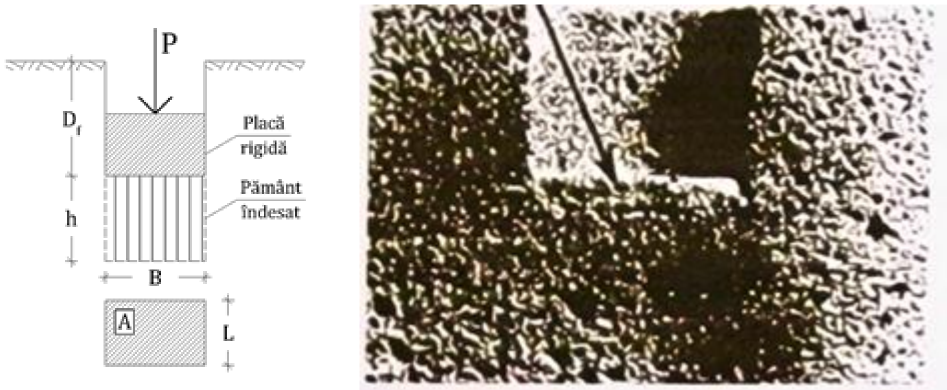
In the literature, punching is studied under the assumption of stress conditions that lead to plastic deformations in the ground, with its lateral thrust and the determination of the critical thrust pressure. In the case of loess, the phenomenon does not manifest itself according to the usual theoretical assumptions, namely through a load-settlement relationship.

I. I. Chercasov determined a way to evaluate the deformations resulting from the penetration of a rigid plate into a porous friable material. Settlement begins at a certain pressure, at which the structure collapses. For a given compressive stress, the punching process ends when the force applied by the rigid plate is in equilibrium with the forces acting on the contour of the compacted material plug. At higher values, the compacted plug will deform, crushing the soil structure by lateral thrust.

The process of punching settlement, according to the scheme proposed by Chercasov, takes place for values of the load P, in the range:

$$P_1 = A \cdot R \leq P < P_2 = A \cdot \frac{R}{k_0} \quad (1)[2]$$

Where: P_1, P_2 – the pressure range in which the punching process develops;
R – the compressive strength of the macrostructure at the initial porosity;
A – the area of the rigid plate base;
k_0 – the coefficient of lateral load at rest.



a. b.

Fig. 3 a. The scheme of the punching effect; b. The experiment conducted by Chercasov

3. NUMERICAL MODELING OF THE PUNCHING SETTLEMENT PHENOMENON. CALCULATION METHODS

This paper attempts to highlight the punching settlement phenomenon through numerical modeling using the following calculation programs: COSMOS/M and GEO5 – FEM.

COSMOS/M is a program that contains several theoretical calculation models, being a complete modular finite element calculation system, developed by *Structural Research* and *Analysis Corporation* for personal computers and workstations.

The system includes modules for solving linear and nonlinear, static and dynamic problems in various fields such as: structural mechanics, fluid mechanics, heat transfer, electromagnetics, and optimization.

GEO5 is a suite of software that provides solutions for most geotechnical engineering problems. The program includes modules for calculating the stability of slopes, shallow and deep foundations, retaining walls, tunnel analysis, settlement calculations, and finite element analysis.

For modeling the punching settlement phenomenon, the *FEM* finite element analysis module from this software suite was used. This module can also be used to evaluate displacements, internal forces, stresses, deformations, and plastic zones in the ground and structural elements, as well as other values correlated with the construction stages.

GEO5 is developed by *Fine Software*, *Czech Republic*, a software company for the fields of civil engineering: structural engineering and geotechnical engineering.

The numerical model chosen for the analysis in this article is the Drucker-Prager model, which is a nonlinear calculation model used in both *COSMOS/M* and *GEO5 – FEM*.

A similar application was made with the COSMOS/M program in the doctoral thesis *"Aspects of the interaction of hydrotechnical constructions with earthen foundations"* developed by Eng. Cornel CIUREA in 2005.

4. THE DRUCKER-PRAGER MODEL

The Drucker-Prager model (sometimes known as the extended von Mises model) modifies the Mohr-Coulomb yield function to avoid singularities associated with corners.

Unlike the Mohr-Coulomb model, the Drucker-Prager yield surface is smooth and is represented as a cylindrical cone in the principal stress space. Similarly to the Mohr-Coulomb model, the Drucker-Prager yield surface depends on the effective mean stress σ_m. [5]

The current version of the Drucker-Prager model implemented in *GEO5 – FEM* is based on the hypothesis of triaxial extension. In other words, the projection of the yield surface in the deviatoric plane reaches the inner corners of the Mohr-Coulomb hexagon (θ = -30°), where θ is the Lode angle.

Due to the fact that the form of the invariants I_1, J_2 şi J_3, which are used in the Coulomb yield criterion, is quite complicated and causes difficulties in treating plastic flow at the corners of the yield surface, Drucker and Prager refined this model, resulting in a perfectly plastic model that bears their name. The mathematical expression of this model is as follows:

$$f = \alpha \cdot I_1 + \sqrt{J_2} = k \qquad (2)[2]$$

The yield surface in the principal stress space describes a circular cone, with the hydrostatic axis as its axis of symmetry.

In point A, where the yield surfaces of the two yield criteria meet, the Lode angle θ has a value of π/3, and the material constants α and k are determined using the following expressions:

$$\alpha = \frac{2 \cdot \sin\phi}{\sqrt{3} \cdot (3 - \sin\phi)}\ ; \quad k = \frac{6 \cdot c \cdot \cos\phi}{\sqrt{3} \cdot (3 - \sin\phi)} \qquad (3)[2]$$

where:

- c - the cohesion of the material, determined in the laboratory through direct shear tests or triaxial compression tests,
- ϕ - the internal friction angle of the material, determined in the laboratory through direct shear tests or triaxial compression tests.

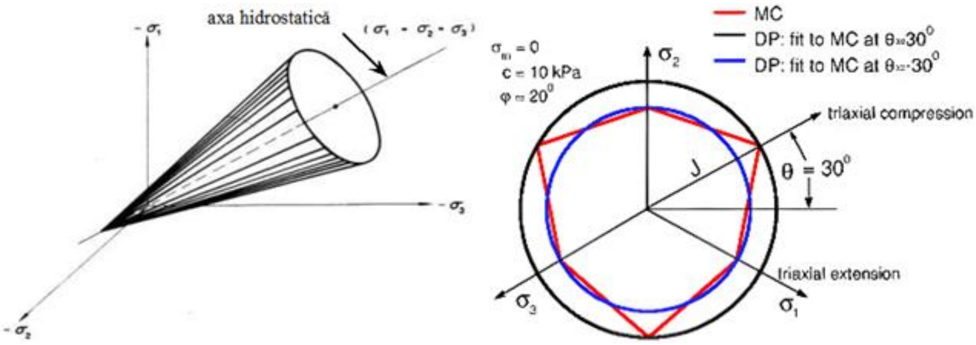


Fig. 4 Plane representation of the Drucker-Prager yield function for soils [2], [5]

In point B, where the two yield surfaces also meet, the Lode angle θ has a value of 0, and the expressions for the two parameters are as follows:

$$\alpha = \frac{2 \cdot \sin\phi}{\sqrt{3} \cdot (3 + \sin\phi)}\ ; \quad k = \frac{6 \cdot c \cdot \cos\phi}{\sqrt{3} \cdot (3 + \sin\phi)} \qquad (4)[2]$$

The main limitations of this model are evident when excessive plastic dilatancy occurs during flow:

- it cannot reproduce the hysteresis properties within the yield surface;

- it cannot estimate the increase in pore water pressure during undrained cyclic shear testing.

The model requires the input of the following parameters: the modulus of elasticity E, Poisson's ratio, the internal friction angle, the cohesion value, and the dilation angle. The last two parameters are used to define the yield condition. The formulation of the constitutive equations assumes the effective parameters: the effective internal friction angle φ_{ef} and the effective cohesion c_{ef}.

5. NUMERICAL MODELING

The analysis of the punching phenomenon was performed under the hypothesis of a constant width foundation of **0.80 m**, which transmits an increasing pressure to the foundation soil, ranging from **5,00÷180,00 kPa** in GEO5 – FEM and **5,00÷250,00 kPa** in COSMOS/M. The maximum values of the range are those at which the constitutive equation of the model has divergent solutions.

To simulate the behavior of a shallow foundation, we considered an area of foundation soil with a width equal to the depth of 40.00 m, subjected at the center of the span to an external pressure, which is actually the net pressure transmitted by the foundation to the foundation soil. This area of the foundation soil was discretized using finite elements.

In the numerical modeling performed with the *COSMOS/M* program, the foundation ground was discretized using quadrilateral finite elements with a side of **1,0 m**.

In the numerical modeling performed with the *GEO5 – FEM* program, the foundation ground was discretized using triangular finite elements with a side of **0,5 m**.

With both programs, the calculation was performed under the assumption of a plane strain condition. The boundary conditions were as follows:

– on the horizontal plane located 40 m below the foundation base, horizontal and vertical displacements were fixed;
– on the vertical planes located on either side of the foundation, horizontal displacements were fixed.

It should also be mentioned that in the *GEO5 – FEM* program, the vertical axis is the *z*-axis, while in the *COSMOS/M* program, the vertical axis is the *y*-axis.

The properties of the loess that makes up the foundation soil, used in the modeling of the application, are as follows:

– Bulk density: $\gamma = 15.00$ kN/m^3;
– Elastic modulus: $E = 6.15\ MPa$;
– Poisson's ratio: $\nu = 0.30$;
– Saturated bulk density: $\gamma_{sat} = 19.00\ kN/m^3$;
– Unload/reload modulus: $E_{ur} = 6.15\ MPa$;
– Internal friction angle: $\varphi_{ef} = 24.00°$;
– Cohesion of the soil: $c_{ef} = 8\ kPa$.

6. RESULTS OF THE NUMERICAL MODELING

The results obtained from simulating the behavior of the shallow foundation using the *GEO5 – FEM* and *COSMOS/M* programs with the Drucker-Prager model are presented below.

- Case 1: the pressure transmitted by the foundation is equal to 5 kPa

Table 1 – Results of the numerical analysis for the pressure transmitted by the foundation equal to 5 kPa (maximum values)

Calculation program	σ_x [kPa]	σ_y / σ_z [kPa]	ε_y / ε_z [%]	d_y / d_z [mm]
GEO5 – FEM	3,72	4,18	0,0392	1,90
COSMOS/M	0,0203	0,0243	0,02842 x 10^{-4}	3,233 x 10^{-4}

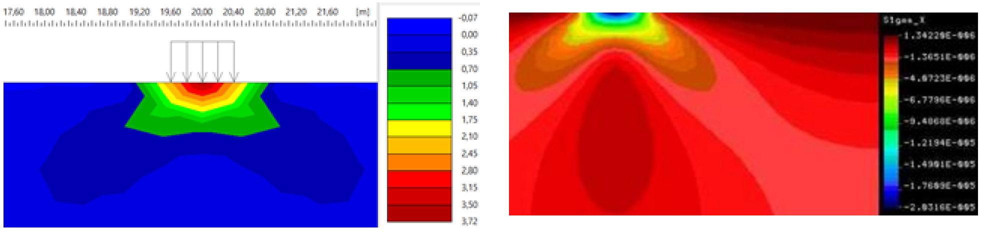


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Fig. 5 Stress diagrams $\boldsymbol{\sigma_x}$ [kPa] for a pressure of **5 kPa**: a. GEO5 – FEM, b. COSMOS/M

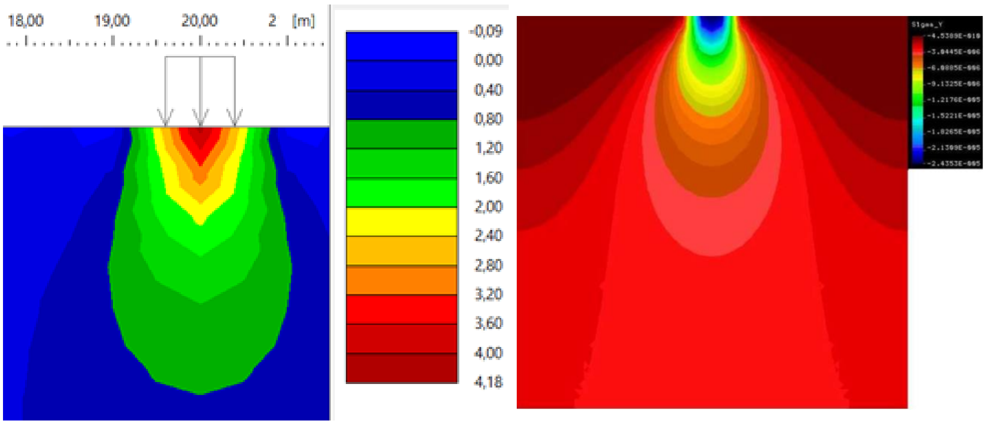

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Fig. 6 Stress diagrams $\boldsymbol{\sigma_z}/\boldsymbol{\sigma_y}$ $[\boldsymbol{kPa}]$ for a pressure of **5 kPa**: a. GEO5 – FEM, b. COSMOS/M

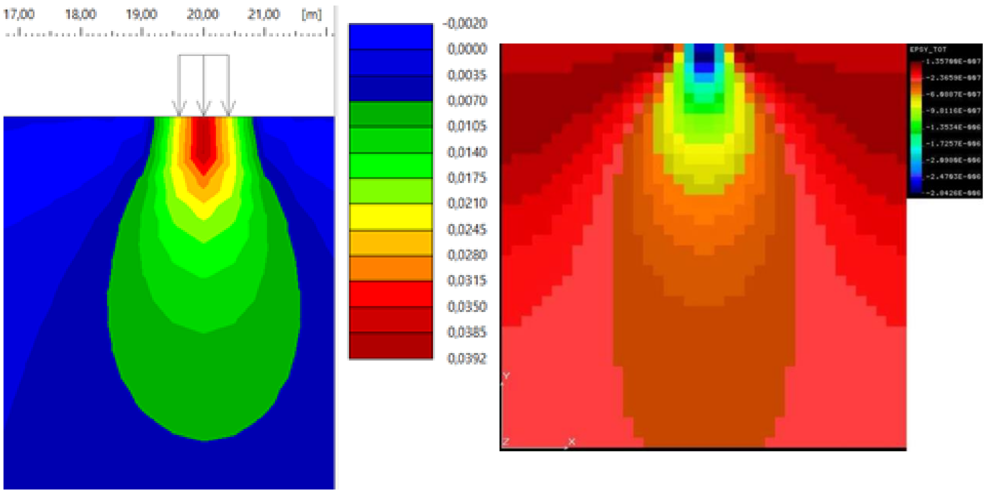

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Fig. 7 Specific strain diagrams $\boldsymbol{\varepsilon_z}/\boldsymbol{\varepsilon_y}$ [%] for a pressure of **5 kPa**: a. GEO5 – FEM, b. COSMOS/M

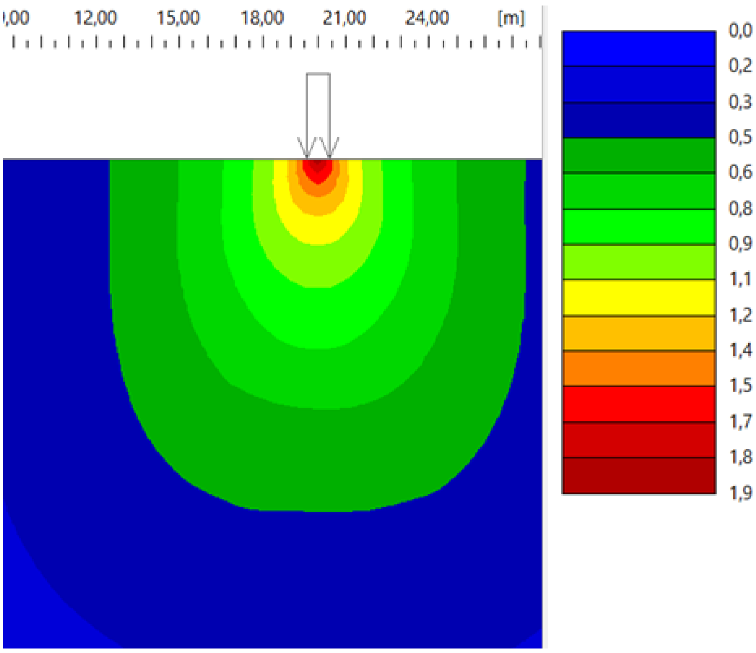

Fig. 8 Displacement diagram $\boldsymbol{d_z}$ $[\boldsymbol{mm}]$ obtained using GEO5-FEM for a pressure of **5 kPa**

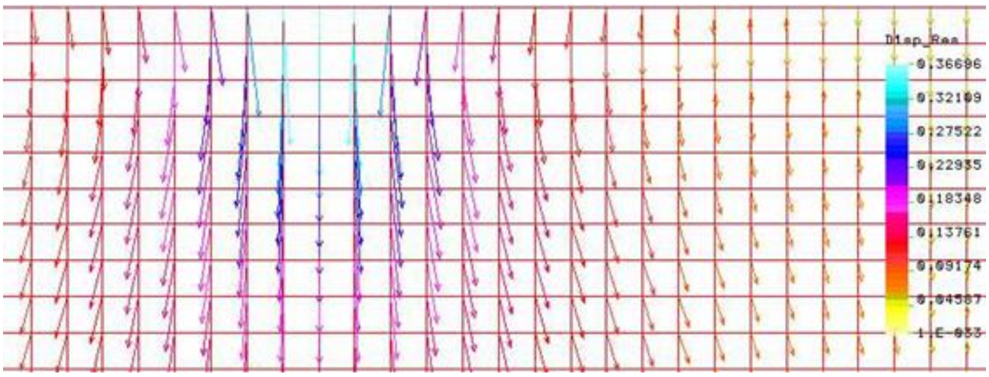

Fig. 9 Vector diagram of the resulting displacement obtained using the COSMOS/M program for a pressure of **5 kPa**

- Case 2: the pressure transmitted by the foundation is equal to **180 kPa** in the numerical modeling performed with the GEO5 – FEM program and **250 kPa** in the numerical modeling performed with the COSMOS/M program;

Table 2 – Results of the numerical analysis for a foundation pressure of 180 kPa in GEO5 – FEM and *250 kPa* in COSMOS/M – (maximum values)

Calculation program	$\boldsymbol{\sigma_x}$ $[\boldsymbol{kPa}]$	$\boldsymbol{\sigma_y} / \boldsymbol{\sigma_z}$ $[\boldsymbol{kPa}]$	$\boldsymbol{\varepsilon_x}$ [%]	$\boldsymbol{\varepsilon_y} / \boldsymbol{\varepsilon_z}$ [%]	$\boldsymbol{d_y} / \boldsymbol{d_z}$ **[mm]**
GEO5 – FEM	91,23	167,31	1,77	8,46	216,6
COSMOS/M	0,0371	0,161	2,37	2,65	1,60

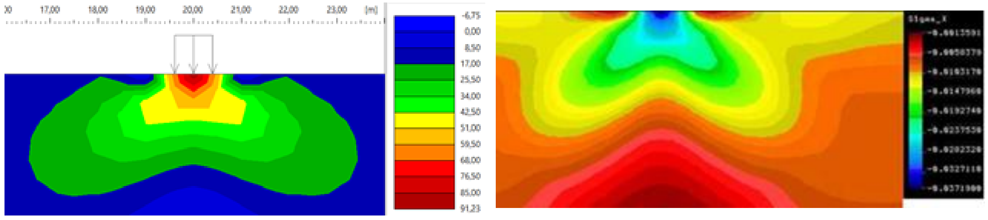

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Fig. 10 Stress diagrams $\boldsymbol{\sigma_x}$ [kPa]: a. GEO5 – FEM for a pressure of **180 kPa**, b. COSMOS/M for a pressure of **250 kPa**

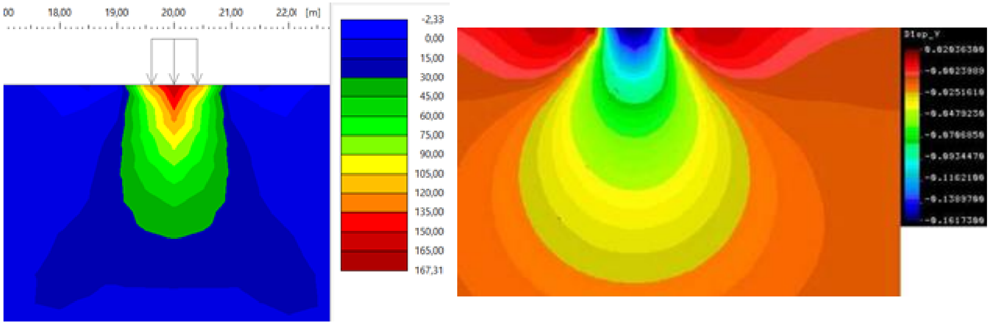

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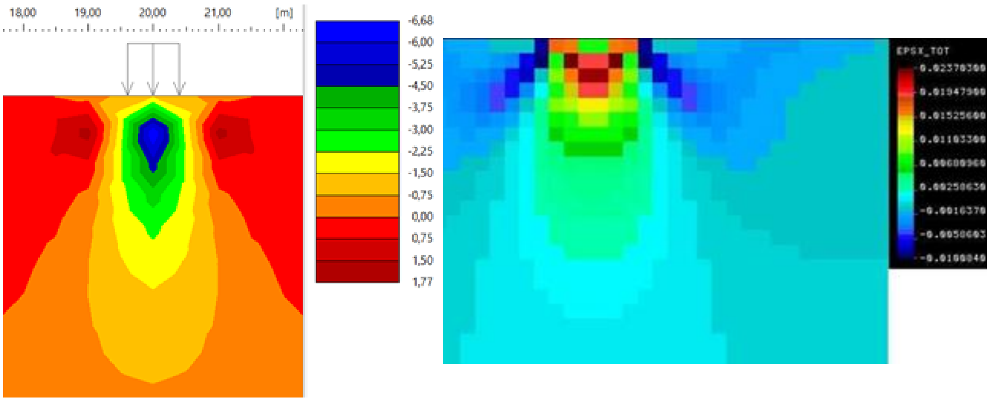
Fig. 11 Stress diagrams $\boldsymbol{\sigma_z}$ / $\boldsymbol{\sigma_y}$ [kPa]: a. GEO5 – FEM for a pressure of **180 kPa**, b. COSMOS/M for a pressure of **250 kPa**



a. b.

Fig. 12 Specific strain diagrams $\boldsymbol{\varepsilon_x}$ [%]: a. GEO5 – FEM for a pressure of **180 kPa**, b. COSMOS/M for a pressure of **250 kPa**

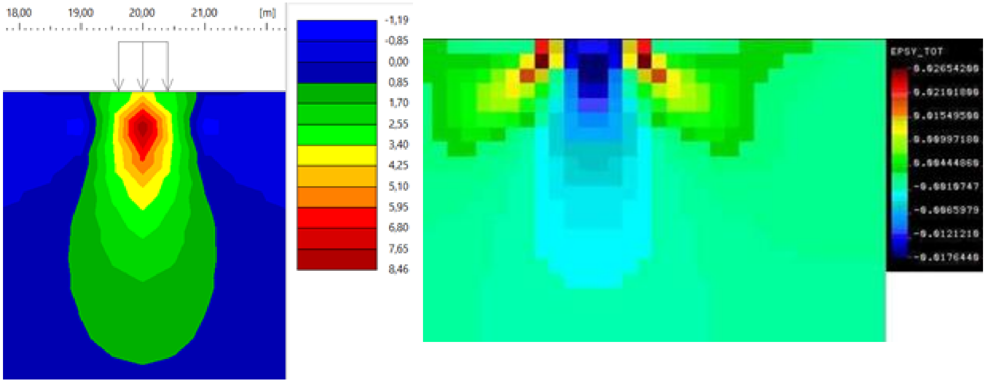


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Fig. 13 Specific strain diagrams $\boldsymbol{\varepsilon_z}$ / $\boldsymbol{\varepsilon_y}$ [%]: a. GEO5 – FEM for a pressure of **180 kPa**, b. COSMOS/M for a pressure of **250 kPa**

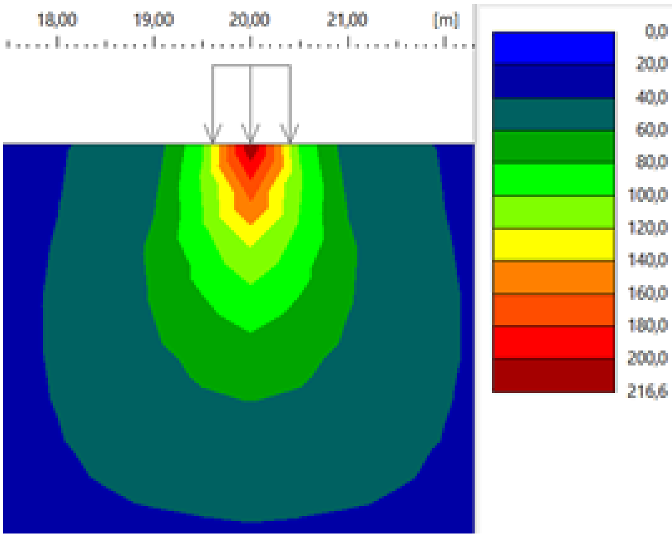

Fig. 14 Displacement diagram $\boldsymbol{d_z}$ $[\boldsymbol{mm}]$ obtained using GEO5-FEM for a pressure of **180 kPa**

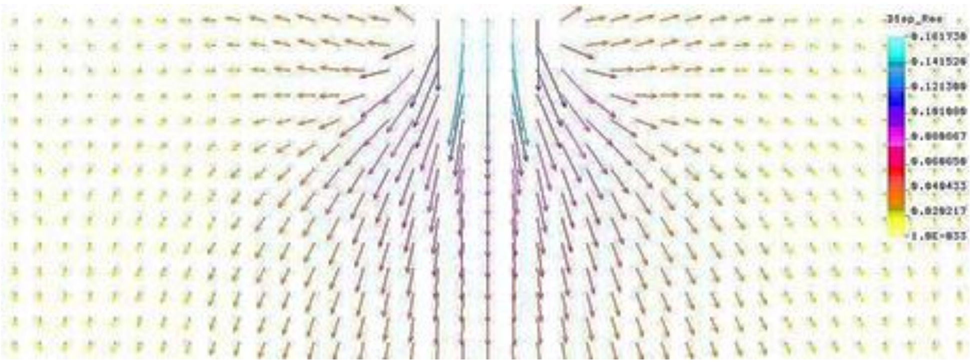

Fig. 15 Vector diagram of the resultant displacement obtained using COSMOS/M for a pressure of **250 kPa**

7. CONCLUSIONS

After performing numerical modeling of the phenomenon of settlement by punching of isolated foundations placed on unsaturated loess with the help of *GEO5 – FEM* and *COSMOS/M* programs using the Drucker-Prager model, we can draw the following conclusions:

- ✍ By performing numerical analyses, an attempt was made to find a calculation program that would provide results as close as possible to the behavior of loess.
- ✍ It was noticed that the results of the numerical analyses obtained with the *GEO5 – FEM* program are closer to the real behavior of loess than those obtained with the *COSMOS/M* program.
- ✍ It was found that if the magnitude of the external pressure exceeds 250 kPa in *COSMOS/M* and 180 kPa in *GEO5 – FEM*, the model becomes divergent, and no result can be obtained. If the magnitude of the external pressure drops below 250 kPa in *COSMOS/M* and 180 kPa in *GEO5 – FEM*, the model converges, and the results obtained are closer to the estimation made regarding the behavior of these types of soils.
- ✍ It was determined that the phenomenon of punching settlement is sufficiently well highlighted in *COSMOS/M* when the magnitude of the external pressure is equal to 5 kPa. At this value of the external pressure, it is observed that the values of all the calculated parameters are very small. The vectors of the resulting displacements, just below the foundation's base level, tend to "*move*" under the foundation. The orientation of the displacement vectors towards the area beneath the foundation's base indicates the development of a compacted material plug beneath the foundation, and the plug is a clear sign of the punching settlement phenomenon.
- ✍ The punching shear phenomenon is easy to see in *GEO5 – FEM* at all values of external pressure below 180 kPa. Through analyzing the results obtained with this calculation program, the following aspects can be observed:
  - the shape of volumetric deformation diagrams, ε_v, shows the development of the compacted material plug under the foundation and that it has the shape of a "*wedge*" [2];
  - the formation of the compacted material plug depends on the modification of the stress state in the foundation soil due to the increase of the pressure transmitted by the foundation;
  - the sharpness and lateral bulging of the compacted material plug become more pronounced as the pressure transmitted by the foundation increases.

Final conclusion:

Considering the results of numerical modeling performed with the two calculation programs, it can be concluded that to model the behavior of soils under mechanical loads, specialized calculation programs must be used that include constitutive laws with well-defined theoretical and experimental parameters, GEO5 – FEM being such a program.

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