3D GEOTECHNICAL MODEL FOR THE NORTH-WEST AREA OF BUCHAREST

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Abstract: The objective of this paper is to develop a ***3D geotechnical model*** with three components: stratigraphic, lithologic and parametric with the purpose of underground works planning.

The model could be useful for the designing in adequate geotechnical conditions of underground works, underground transport (underpasses, subways, town tunnels).

This model extends on a surface of approximately 95 km^2 and covers the Dâmbovița and Colentina meadows, the Dâmbovița - Colentina Interfluve, the high Field and the Colentina terraces.

The developped model goes as deep as 30 meters from the field surface and crosses several deposits of filling and Loess, Colentina and "intermediate deposits" Formations.

This model is based on data collected from ***71 boreholes*** located North-West of Bucharest, within the railway ring.

Methodologically, this model was achieved by means of topo-probabilistic models (***kriging***).
Keywords: 3D geotechnical model, stratigraphic model, lithological model, parametric model, kriging

1. Introduction

Safe underground works planning requires thorough geological knowledge of the formations affected by the future works. Besides the lithological, stratigraphic and structural data about the formations, detailed knowledge is needed also with regard to *physico-mechanical characteristics* of those formations.

The ***3D geotechnical model*** presented in this paper has three components that describe the formations deposited on the first 30 meters, in the North-West part of the city: a stratigraphic one, a lithological one and a parametric one. (***Fig. 1.1***).

The 3D models were built starting from data collected from *71 geotechnical boreholes located in the researched area*. Further, the 3D model was implemented according to topo-probabilistic models (***kriging***) that assess the level of uncertainty that describes the distribution of geotechnical parameters. The level of uncertainty is given by the observation points distribution and the parametric variability of formations.

2. General geomorphological framework of north-west Bucharest

Nowadays, the bedrock of the city of Bucharest and of the area inside the railway ring is the object of abundant geotechnical, hydrogeological, environmental and urban research. Thus, a synthesis of the ***lithostratigraphy and of the structure*** of the formations under research appears appropriate and necessary.

Bucharest is situated in the central part of the Vlasia Plain, which, in its turn is situated at the core of the Romanian Plain. The relief of the city is rather low and monotone, varying from 95 to 55 m high (***Fig. 1***). The rivers Colentina and Dambovita, with meadows as high as 85 m upstream and 55 m downstream and flowing NW-SE, divide the Bucharest Plain in three parts, relatively equal in terms of extent, but distinct in terms of age and lithological constitution (**Enciu et al., 2008**).

The ***Otopeni Field*** is situated on the left side of the river Colentina, within the forest Baneasa area and in its Western extent, towards the village of Straulesti. To the East, it continues up to the forests called Tunari, Boldu-Cretuleasa and Stefanesti. The ***Colentina Field*** lies between the rivers Colentina and Dambovita. The ***Cotroceni Field*** unfolds South of the meadow of the river Dambovita and, within the area of the municipality of Bucharest, has a high Field structure and three terraces formed by the river Argeş.

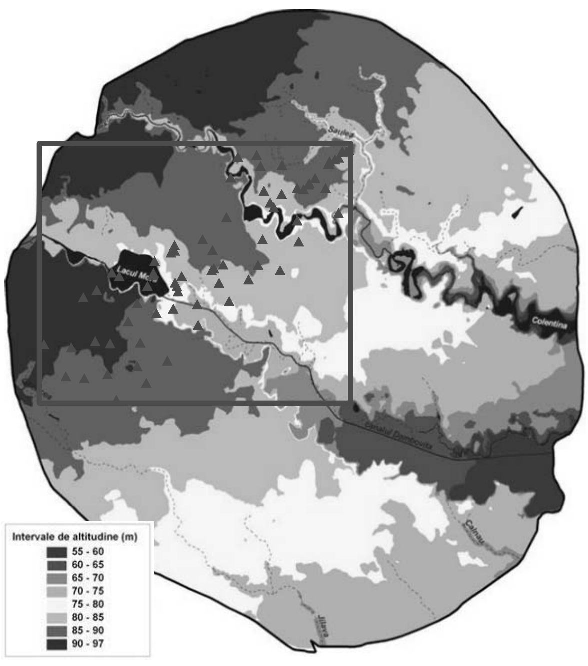

Fig. 1 *Developing area of the 3D geotechnical model*

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Geologically, the area of the municipality of Bucharest and the surface inside the railway ring overlap a part of the Northern limit of the ***Moesic platform***.

During the last evolution cycle, the Moesic platform (made up of a folded metamorphosed *base* and a *sedimentary cover*) was invaded by the waters of the Paratethys, which is known in Romanian literature as *The Dacian Basin*. During this last sedimentation cycle, formations belonging to the ***groups Olt-Vedea*** (Badenian-Sarmatian), ***Optaşi-Cartojani*** (Meotian-Pontian) and ***Bucharest*** (Pliocene-Quaternary) were accumulated (**Pauliuc et al., 1979**; **Marinescu et al., 1998**).

The Bucharest group contains nine formations : *Merisani* (lower Dacian), *Calinesti* (upper Dacian), *Izvoarele* (lower-middle Romanian), *Frãteşti* (upper Romanian – lower Pleistocene), *Coconi* (middle Pleistocene), *Mostiştea* (middle Pleistocene), *"intermediary deposits"*, *Colentina* and *Loess Formation.* The first three mentioned formations were defined by **Papaianopol** and **Marinescu (1994)**, while the last six mentioned formations were defined by **Liteanu (1952, 1953)**, **Liteanu** and **Ghenea (1966)**, **Alexeeva et al. (1983)**.

The geological formations intercepted in the 71 geotechnical boreholes of the data base are the following:

- the Loess Formation;
- the Colentina Formation;
- the "intermediary deposits" Formation.

The ***"Intermediary deposits" Formation*** develops between the *Mostiştea* and the *Colentina Formations* and are represented by a clayey-silty formation, interbedded with one or two fine sands intercalations.

Clay sediments are made up of bluish-purple or grey clays and marls and loessoid deposits with calcite canalicula and concretions. Some of them are more or less sandy or have sand lenses. In some areas of the Capital, deposits have to some extent a lenticular structure.

The fauna of these deposits contains species belonging to the *Viviparus*, *Melanopsis*, *Succinea* genera and fragments of other *gastropods*.

The upper part of the ***Colentina Formation*** is made up of fine rust-colored sand that gradually changes its color into red-orange, with numerous organic debris, in the deeper parts of the formation (**George Valsan, 1971**). The deeper we go the more the granulosity increases, resulting into gravel. The whole sandbar is characterized by lens-shaped sediments, enlarged towards the bed of the layer, regardless of whether the material is made up of fine sand with mica and gravel. All this evidence point to the fact that running water deposited the basic gravels in torrential regime. In a later period of maturity, they brought over small lens-shaped sands. Gravels are made up of *quartzite, micaschist, sandstone, gneiss* and *jasper* fragments.

Mammal fossil fauna includes *Elephas primigenius sibiricus, Elephas antiquus, Cervus euryceros, Cervus megaceros, Bos priscus, Bos primigenius, Rhinoceros tichorhinus, Canis lupus, Hyaena crocuta*.

The thickness of the Colentina Formation deposits varies according to the capability of the streams, which increases from Colentina (*3-5 m*), to Dâmboviţa *(3-7 m*) and Argeş (*5-7 m*).

The ***Loess Formation*** is made up of a sequence of 1-5 extended and continuous loess layers, separated by buried paleosoils (**Enciu et al., 2008**). The thickness of the layers varies from 1-2 m to almost 30 m. Loess clay deposits are lithologically specified by the granulometric variation of their components: *clays*, *silt* and *fine sands*.

These deposits are shaped as lenticular agglomerates, more or less clayish, with clacareous and mangano-ferruginous separations shaped as canalicula, concretions with frequent sand lenses.

The color of these deposits varies from yellow-reddish to blueish-purple and gray; the sequence of colors is extremely irregular. This means that the sedimentation conditions also vary: in *wind regime* and perhaps, locally, in swamps, abandoned stream branches, etc.

Literature data points to the fact that ***loess*** is a wind deposit specific to cold periods, with more active air circulation; the fossil soils were formed during rather temperate-warm periods, rich in precipitation.

As far as the ***structure*** of the formations is concerned, in **1989** (**Visarion et al.**) complete the synthesis of structural elements on the whole Moesic Platform, based on geophysical investigations that reveal the existence of ***two systems of faults*** in the Capital area, namely NW and ENE-WSW (***Fig. 2***).

The map shows that apart from the majority of W-E faults, there exists a newer generation of faults, namely the NNE-SSW ones. Among them, the one that crosses Bucharest from South to North, through the East, is noteworthy, as well as some intracrustal earthquake epicentres situated in the North, close to the Chitila flexure (names so by **Sãndulescu**, **1984**).

The explanation of faulting and of earthquake generation is provided by the platform being led into the subduction process towards the North, under the Carpathian Orogen.

3. The database for the 3D geotechnical model for north – west Bucharest

The 3D geotechnical model for North – West Bucharest was based on data collected from ***71 geotechnical boreholes*** (***Fig. 1***) from which were taken ***723 samples***, for which were made ***5400 determinations*** of physico-mechanical parameters.

The *stratigraphic*, *lithological* and *parametric* informations have been structured in a ***ROCKWORKS*** type of interactive ***database***. The application ***ROCKWORKS*** is based on an ***ACCESS*** type of application to which was added a powerful tool for ***3D zoning***.

The data stored in the ACCESS database, created with the manager files for boreholes, can be exported to ASCII, DBF and EXCEL files.

To select the necessary data for the creation of the 3D geotechnical model for North – West Bucharest was made an application in Visual Basic (***Fig. 3***); this application enables the following actions:

- first, it retrieves data from EXCEL files exported from the ACCESS base of ROCKWORKS package;
- second, it filters the data using selection criteria such as: spatial, stratigraphic, lithologic and parametric;
- third, it saves selected data in ASCII files compatible with software used for zoning physico-mechanical parameters.

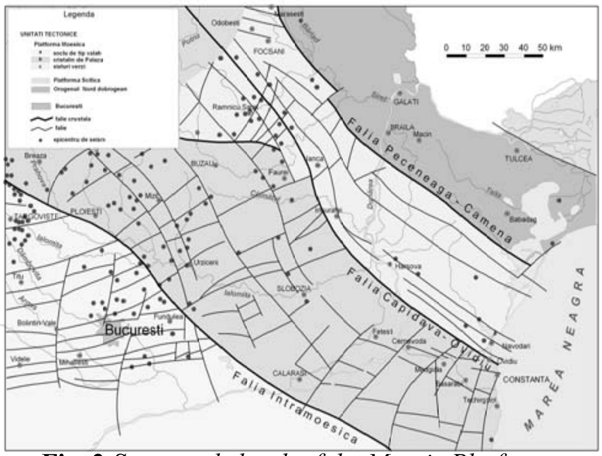

Fig. 2 *Structural sketch of the Moesic Platform (Visarion et al., 1989)*

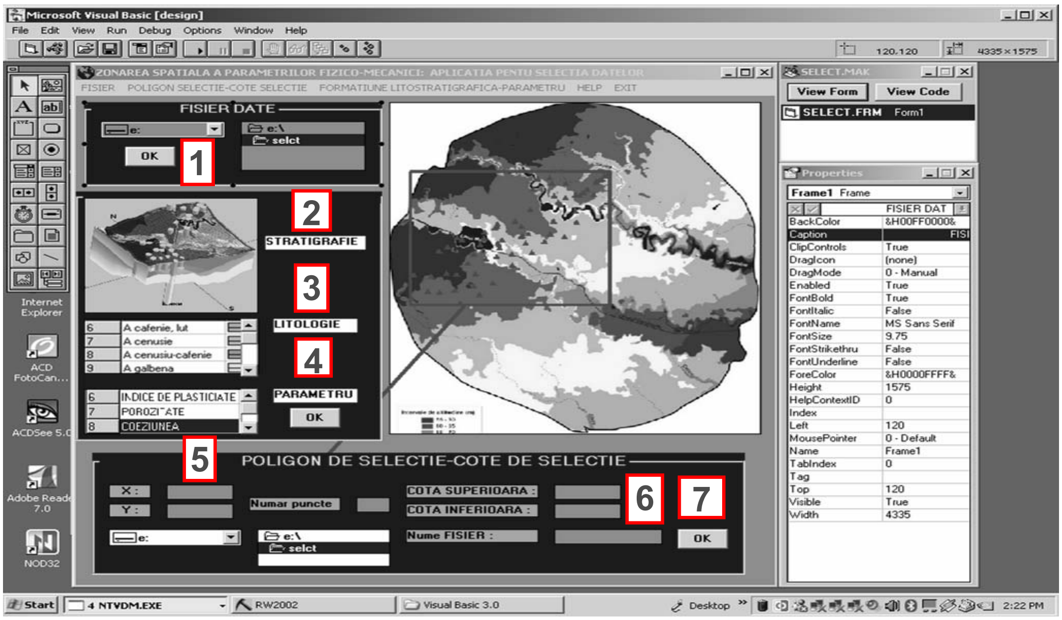

Fig. 3 *Application for data selection in view of creating the 3D geotechnical model*

4. The method of calculation used for carrying out the geotechnical model

The achievement of the 3D geotechnical model is based on ***topo-probabilistic methods*** of interpolation between *alphanumeric values* (lithology, stratigraphy) and *numeric values* (physico-mechanical parameters of rocks) obtained from a network of observation points with irregular distribution (the 71 boreholes located in the researched area). To this effect, I used two specific methods:

- *indicator kriging* for alphanumeric variables;
- *punctual kringing* (ordinary/universal) for numeric variables.

The application of kriging in the two variants was preceded by an analysis of primary data regarding the following:

- *the normality* of distribution for the numeric values;
- *the stationarity* of spatial distribution for the numeric values;
- *the anisotropy analysis* for the alphanumeric and numeric values.

It has been necessary to normalize and to eliminate regional trends of polynomial type (level two) for the oedometric modulus.

The ***anisotropy analysis*** was realized using as the main tool ***semivariogram***:

$$\gamma\left(\vec{d}\right)=\frac{1}{2\cdot N(\vec{d})}\sum_{(i,j)\mid d_{ij}=\vec{d}}^{N(\vec{d})}\left(v_i-v_j\right)^2$$

where:

$N\left(\vec{d}\right)$ – the number of values pairs situated at $\vec{d}$ distance;

$\vec{d}$ – the oriented distance between the points i and j where the v_i, v_j values are determined;

v_i, v_j – the values measured in the points i and j.

The estimation of values and errors of the geotechnical model is based on minimizing the variance of the estimation errors synthesized in kriging systems:

a) for ordinary kriging:

$$\begin{cases}\sum_{j=1}^{n} w_i\cdot\tilde{\gamma}_{ij}+\mu=\tilde{\gamma}_{i0}, \forall i=1,2,\ldots,n\\ \sum_{i=1}^{n} w_i=1\end{cases}$$

b) for universal kriging:

$$\begin{cases}\sum_{j=1}^{n} w_j\cdot\tilde{\gamma}_{ij}+\sum_{l=1}^{k}\mu_l\cdot f_l\left(p_i\right)=\gamma_{i_0}, i=1,2,\ldots,n\\ \sum_{i=1}^{n} w_i\cdot f_l\left(p_i\right)=f_l\left(p_0\right), l=1,2,\ldots,k\end{cases}$$

where:

$\tilde{\gamma}_{ij}$ - the value of variogram for the pair of values v_i, v_j situated at distance d_{ij};

w_i - the weight of v_i values;

μ - Lagrange's parameter;

f_l - the regional trend function in the p_i observation points; ($i=1,2,\ldots,n$);

n - the number of observation points.

The ***estimated value*** is calculated as follows:

$$v_{p_0}^{*}=\sum_{i=1}^{n} w_i\cdot v_i$$

The minimum variance of error estimation has two calculations:

a) for ordinary kriging:

$$\tilde{\sigma}_R^2=\sum_{i=1}^{n} w_i\cdot\tilde{\gamma}_{i0}+\mu$$

b) for universal kriging:

$$\tilde{\sigma}_R^2=\sum_{i=1}^{n} w_i\cdot\tilde{\gamma}_{i0}+\sum_{j=1}^{k}\mu_j\cdot f_j\left(p_0\right)$$

The ***error estimation*** of the 3D geotechnical model was realized for an *assumed risk* $\alpha=5\%$ using the relation: $\varepsilon\left(x_0, y_0, \alpha\right)=\pm 2\cdot\tilde{\sigma}_R$

The ***kriging*** allows to optimize the monitoring network by the *fictive point method* that uses the variogram model of the structure (model that incorporates the anisotropy parameters).

The calculation of ***anisotropy parameters*** (orientation for ellipsoid of anisotropy θ and anisotropy ratio $\eta=\frac{R}{r}$) is done using the *surface variogram* for each component of the 3D model (stratigraphic surfaces elevation, lithological type, plasticity index etc).

On the basis of the maximum permissible errors, the monitoring network is improved by filling it with additional investigation points. This ensures the accuracy requested by underground works planning.

5. 3D geotechnical model of the formations in the north-western area of Bucharest

The geotechnical model presented in this paper extends on a 95 km^2 area in the North-West part of Bucharest. It was built on the basis of 5,400 values of physical-mechanical parameters, determined on samples collected from the 71 boreholes (***Fig. 1***). The three components of the 3D geotechnical model are the following: *stratigraphic model*, *lithologic model* and *parametrical model*.

The geometrical characteristics (features) of the interpolation grid of the stratigraphic, lithological and parametric model (***Fig. 4***) are: $\Delta x=50m$, $\Delta y=50m$ and $\Delta z=1m$ where $\Delta x, \Delta y, \Delta z$ represent the distances between the interpolation grid nodes on Ox (West-East), Oy (North-South) and Oz (elevation) direction.

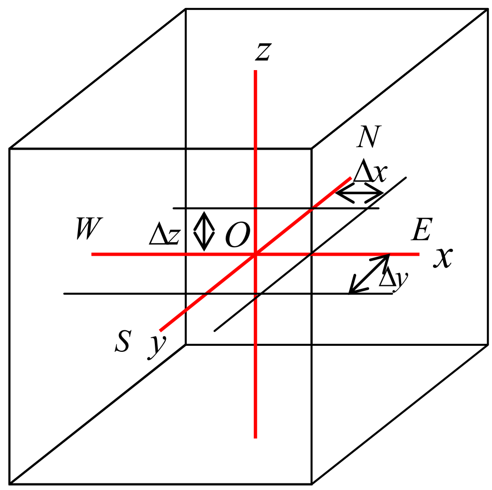

Fig. 4 *Geometrical characteristics of the interpolation grid*

5.1 The stratigraphic model

The stratigraphic units of the model (from the surface to depth) are: the *Loess Formation*, the *Colentina Formation* and the *"intermediary deposits" Formation*:

- the *Loess Formation* has maximum thickness in the high Field but is missing into the meadows of the two rivers;
- the *Colentina Formation* is present almost everywhere in the researched area, the thickness of the horizon being variable; it is missing in some drillings in the South-West and extreme North-West of the researched area;
- the "intermediary deposits" Formation has a relatively uniform disposition; there are some boreholes which did not detect this formation.

Aditionally to these three stratigraphic units, there is a horizon of filling material derived from building materials from demolations.

The average thicknesses of the four units belonging to the stratigraphic model (***Table 1***) indicate the presence of filling materials and loess deposits, which are less recomended for underground works, not exceeding 6 m deep. Deeper than 6m, the prevailing formation is the Colentina one, with better bearing capacity properties, providing stability to the foundation works or underground works, but only if the inflow of underground water is dealt with approapriately.

Table 1 *Average thickness and volume of stratigraphic units detected in the 71 boreholes*

Formation	Average thickness [m]	Volume $*10^7$ [m^3]
Filling material	0,95	9
Loess formation	5,00	48
Colentina formation	7,16	68
"Intermediary deposits" formation	17,90	170

Significant variations of these units limits, which appear at local scale, are emphasized by the detailed 3D models prepared on this purpose.

The ***3D stratigraphic model*** (***Fig. 5***) allows for a detailed description of the morphology of the separation surfaces between the identified stratigraphic units. The 3D stratigraphic model can be sectioned on any part of the work holding horizontal planes, at different elevations (e.g. map at +78 m – ***Fig. 6***) or vertical planes (e.g. SW-NW section – ***Fig. 7***). This allows to accurately determin the formations that are present at the base level and in the side walls of the excavations.

The stratigraphic model can be easily updated for already planned underground works by simply introducing the data derived from the supplementary boreholes into the general data base.

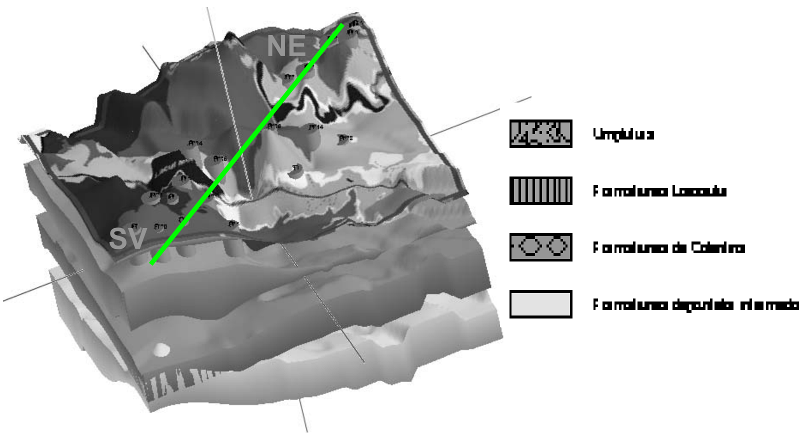

Fig. 5 *3D stratigraphic model*

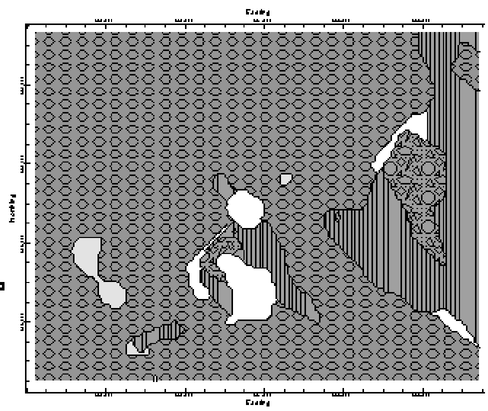

Fig. 6 *Stratigraphic map at the level +78m*

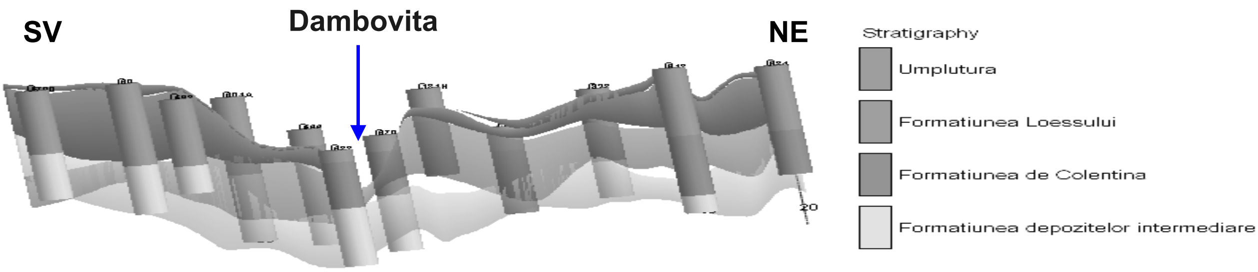

Fig. 7 *SW-NE section through the 3D stratigraphic model*

5.2. The lithological model

The ***3D lithological model*** was realized starting from the lithological analysis of all the geomorphological units existing in the researched area: the meadows of the rivers Dâmbovița and Colentina, the high Field, the Dâmbovița - Colentina Interfluve, the Colentina terraces.

The lithological variety of the researched area is represented by all lithological types in the ternary diagram together with four supplementary categories: clayey silty sand (NPA), sandy clayey silt (PAN), vegetal soil (PVEG), filling material (U).

The weights of lithological types for each geomorphological unit were evaluated on the basis of ***nominal histograms*** and ***ternary diagrams*** (e.g. the high Field; ***Fig. 8*** and ***Fig. 9***) as well as the comparative analysis within the researched geomorphological units (e.g. the Dâmbovița and Colentina river meadows - ***Fig.10***).

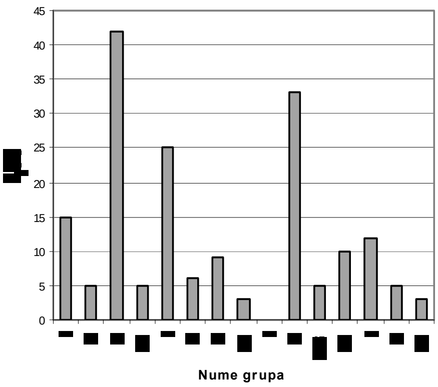

Fig. 8 *Nominal histogram for the lithology of formations in the high Field*

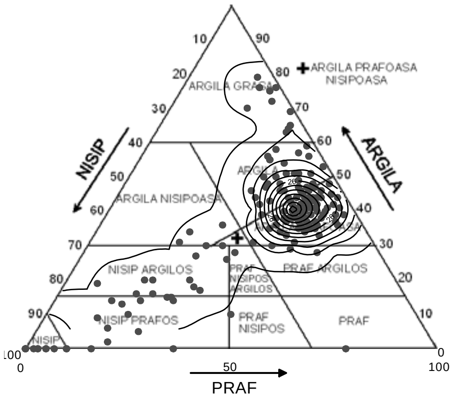

Fig. 9 *Ternary diagram of the deposits in the high Field, with the absolute frequency contur lines*

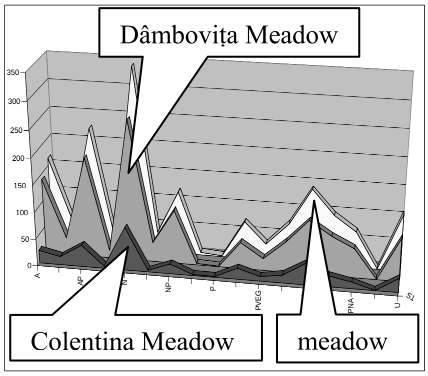

Fig. 10 *Frequency distribution diagram for the lithological types in the meadows of the rivers Dâmbovița and Colentina*

The main lithological features of the studied area are derived from the statistic analysis of the data (723 samples obtained from the 71 boreholes, for which 5400 determinations were carried out). They are the following:

- the lithological types in the meadows of the rivers *Dâmbovița* and *Colentina* are similarly distributed (***Fig.10***); this even distribution is characterized by the sands prevalence (the most prominent one), by the silty clays and the gravels, as well as by a minimum of the silty fraction;
- the lithological types in the *high Field*, the *Dâmbovița – Colentina Interfluve* and the *Colentina terraces* have a similar distribution, characterized by the prevalence of the silty clay and clayey silt.

The quantification of the similarity with respect to the lithological distribution in the meadows of the rivers *Dâmbovița and Colentina*, on one hand and in the *high Field*, the *Dâmbovița – Colentina Interfluve* and the *Colentina terraces*, on the other hand, was realized on the basis of some lithological correlation coefficients above 0,85 in both cases. All these results indicate the existence of *two domains of lithological homogeneity*: ***river meadow*** and ***terrace***.

The significance of the lithological variability in the studied area (13 distinct lithological types) has a complex spatial configuration marked by the characteristics of the stratigraphic model:

- distinct lithological variation at the limit between the Loess Formation and Colentina Formation;
- the continuous lithological variation at the limit between the Colentina Formation and the “intermediary deposits” Formation.

These general features are masked (hidden) in the model presented in this paper because of local variations and because of an uneven distribution of the investigation boreholes.

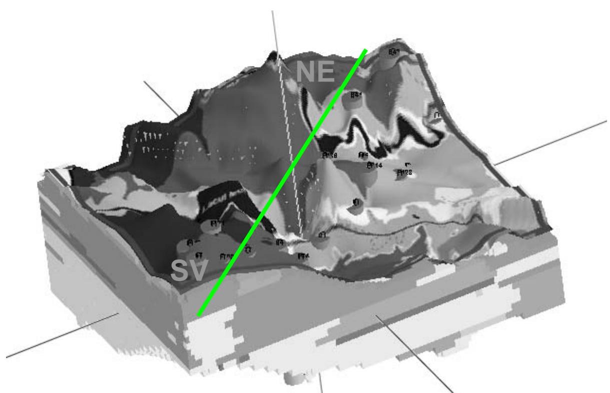

Fig. 11 *3D lithological model*

The above mentioned 3D lithological model (***Fig. 11***) permits the identification of some general lithological characteristics of the researched area:

- on the high Field, Interfluve and the Colentina terraces, the clayey and the silty fractions are prevailing in the upper part of the Quaternary formations, as part of the Loess Formation; the clayey fraction, which exists even at deeper levels, can be found in the structure of the Colentina Formation and also in the structure of "intermediary deposits" Formation;
- in the river meadow zones, the sandy fraction lies primarily at the surface, but it is present in the depth, too; the sand goes into the structure of the Colentina Formation and the "intermediary deposits" formation;
- on a general background of content less then 20% of clay, at +67 m elevation the distribution in horizontal plane highlights the expansion of the "clayey deposits" horizon;
- the distribution of the silty fraction maxima at +80 m on the high Field, Interfluve and the Colentina terraces points to the spatial expansion of the loess deposits in these geomorphological units;
- at +73 m elevation, one can find in the Colentina terraces non-cohesive terrace deposits; in the high Field unit, the non-cohesive deposits have a lens shape distribution.

Generally speaking, in the researched area there are lithological horizontal and vertical discontinuities, which are visible on a local scale. This variability can be detailed in ***vertical sections*** (***Fig. 12*** and ***Fig. 13***) and ***horizontal maps*** in the zones where underground works are being planned. The updating procedure of the lithological model is similar to the one applied to the stratigraphic model; this is due to the flexibility of the performed model, resulting from the topo-probabilistic models which I used.

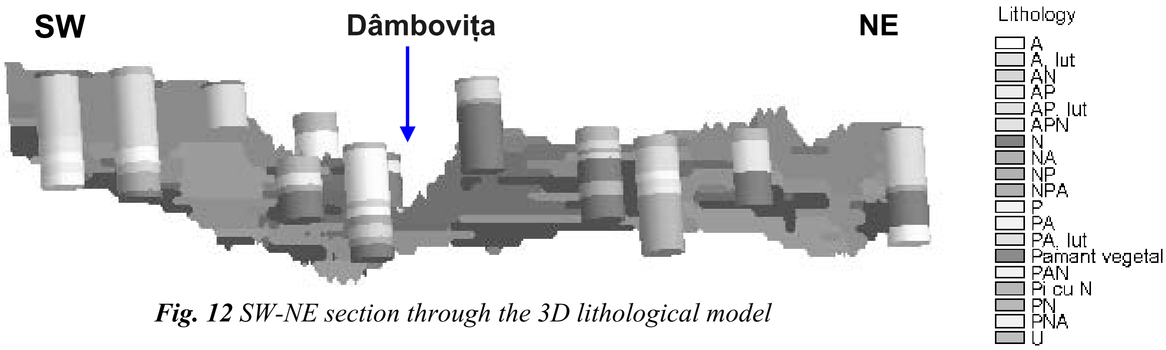

Fig. 12 *SW-NE section through the 3D lithological model*

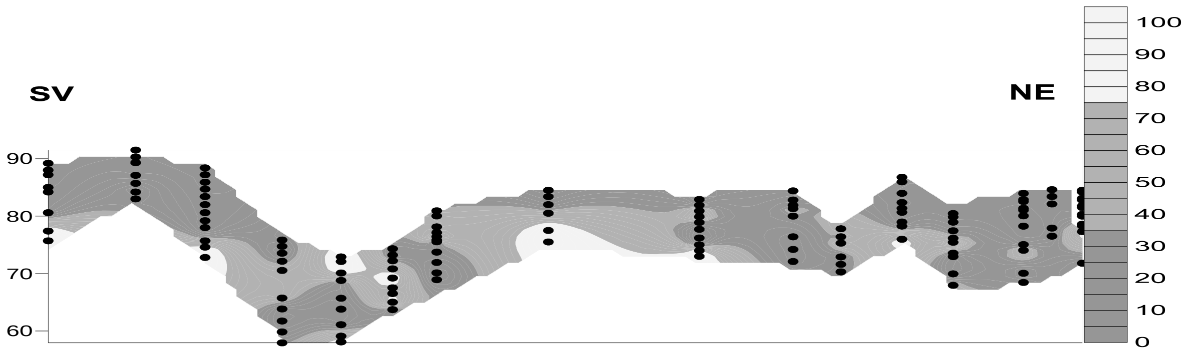

Fig. 13 *Variation of the sandy fraction in the vertical SW-NE section*

5.3. The parametric model

The aim of the ***3D parametric model***, based on the stratigraphic and the lithological model, is to provide the necessary parameters for underpasses, subways, bridges and hydrotechnical development in the North-Western part of Bucharest.

The main physico-mechanical parameters used to achieve the parametrical model are: plasticity index (I_P), apparent density (ρ), porosity (n), oedometric deformation modulus (E_{ed}), internal friction angle (ϕ), cohesion (c) and standard penetration test (SPT).

The achievement of the 3D parametric models for the seven physico-mechanical parameters (e.g. 3D parametrical model of plasticity index ***Fig. 14***) was based on the values determined in the 71 geotechnical boreholes.

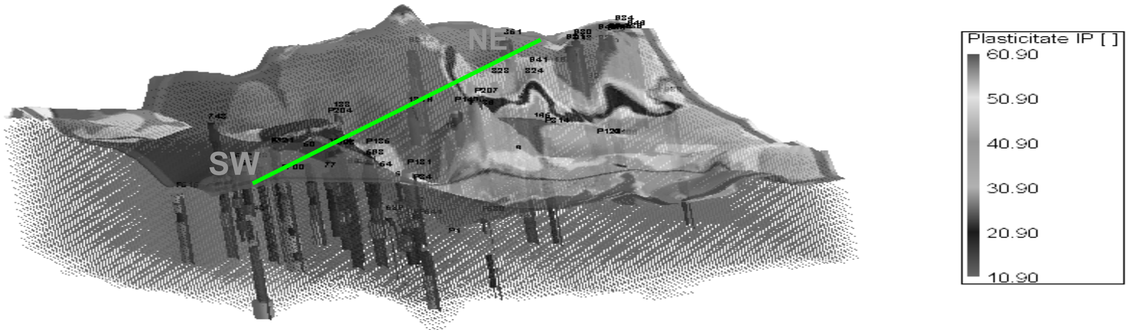

Fig. 14 *3D parametric model for the plasticity index*

The *seven 3D parametric models* achieved in the studied area allow the identification of the following characteristics of the distribution values for the physico-mechanical parameters:

- ***plasticity index*** is specific for clay layers (cohesive): its variation and especially the highest values overlap with the development areas of "intermediate clays". This information is extremely useful when designing retaining and dewatering work for civil objectives with one or more underground levels. This is so because the spatial extension of these deposits influence the choice of methods and technical processes.
- ***apparent density***: this parameter's extreme values highlights the areas where non-cohesive deposits have loose or medium state and the cohesive deposits have a low degree of consolidation, fundamentally influencing both the choice of the building foundation methods and the pumping system of the dewatering work.
- ***porosity***: the maximum values of this parameter in cohesive or low cohesive deposits are an indicator of the low degree of consolidation and consequently of an area with low resistance parameters;
- ***oedometric modulus***: its variation is in perfect inverse correlation with the porosity variation, so the very large compressibility distribution areas almost overlap with the areas of extreme porosity;
- ***friction angle:*** the variation of this parameter highlights the extreme areas – maximum ($\phi >$ 25°), minimum ($\phi <$20º) respectively;
- ***cohesion***: the distribution of cohesion values correlates with the friction angle distribution, so the extreme areas of ϕ correspond to the minimum areas of cohesion;
- ***standard penetration test***: the distribution of SPT values is very useful in terms of its practical application, because it clearly highlights the "vulnerable" areas, whose exact interpretation must be correlated with the granulometric analysis.

Local variability of parameters can be detailed by crossing the seven parametrical models with ***vertical planes*** (e.g. SW sections with plasticity index and porosity variation - ***Fig. 15*** and ***Fig. 16***) and ***horizontal planes*** at the level of the foundation or at the underground mining work for subway.

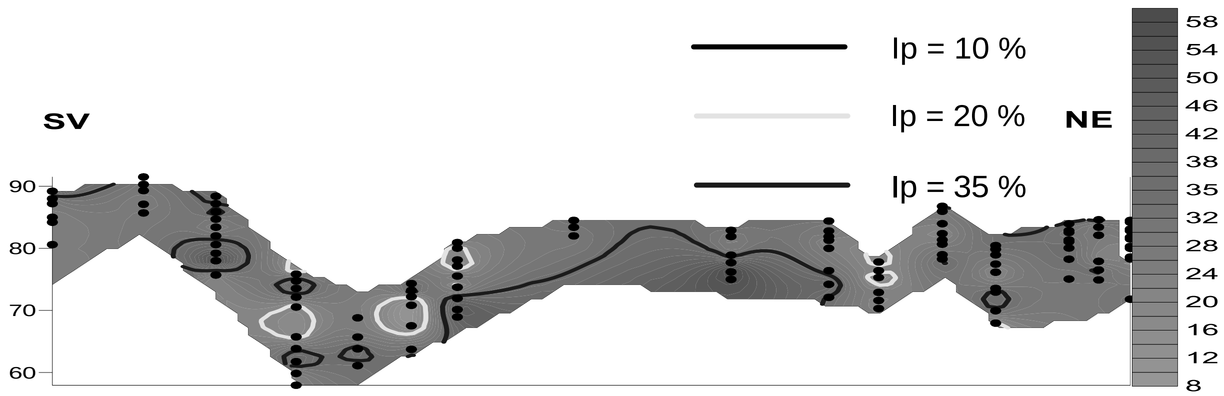

Fig. 15 *Variation of the plasticity index in the vertical SW-NE section*

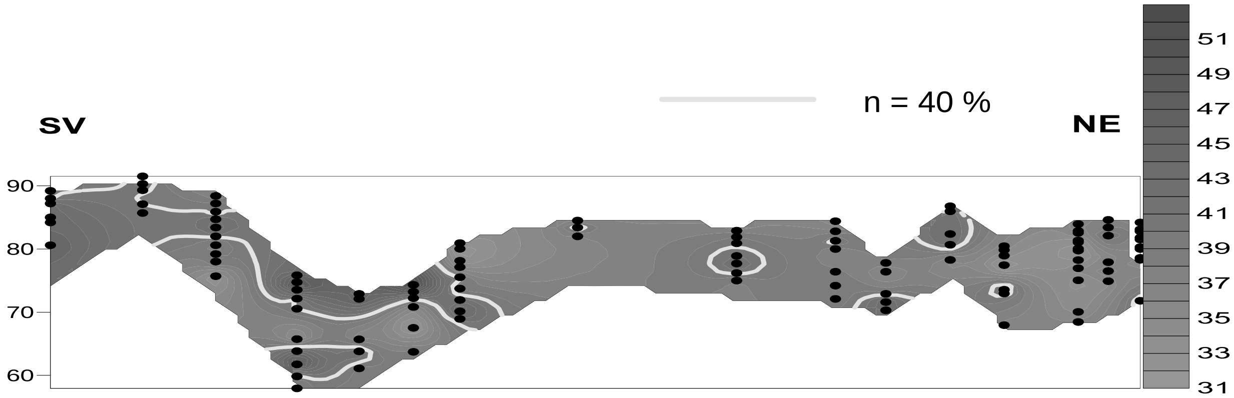

Fig. 16 *Variation of the porosity in the vertical SW-NE section*

6. Conclusions

The 3D geotechnical model achieved for the North-West area of Bucharest is a complex, multipurpose tool that provides, interactively, parametrical data required by underground mining work for the subway and hydrotechnical development.

The three components of the model presented in this paper – ***stratigraphic, lithological*** and ***parametric model*** – are based on the most flexible ***spatial interpolation methods*** (*indicator kriging*, ordinary and universal *punctual kriging*) and on a representative ***database*** (5400 values) for the Quaternary investigated formations.

The dominant feature of the spatial structures of the three models is the ***anisotropy***, which was synthesized into an ***unique model*** (***Fig. 17***) for the investigated formations. This unique model was used, with acceptable errors, to assess the spatial distribution of the stratigraphic and lithological units and of the physical-mechanical parameters.

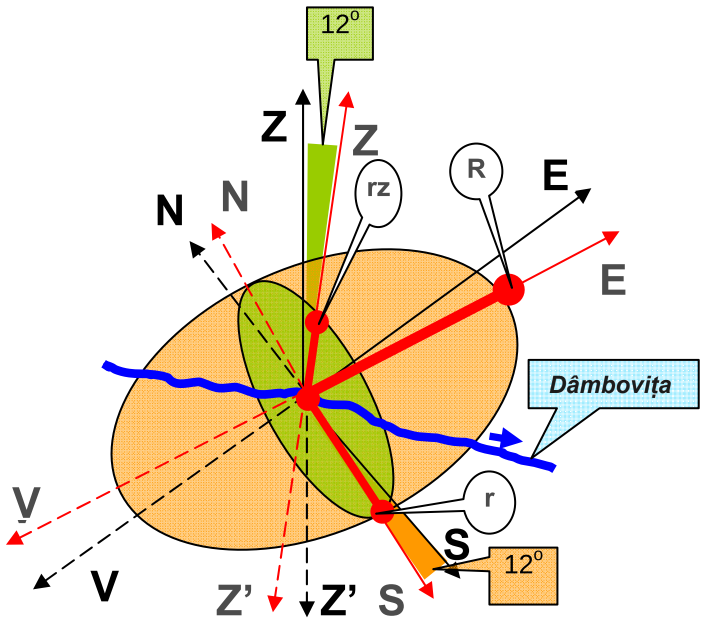

Fig. 17 *Anisotropy ellipsoid of Quaternary deposits from the North – West area of Bucharest*

The unique anisotropy features set for the North-West area of Bucharest city are the following:

- the direction of minimum continuity in ***"horizontal plan"*** N12°E;
- the direction of maximum continuity in ***"horizontal plan"*** N78°W;
- the ***"horizontal plan"*** of the anisotropy ellipsoid has the maximum slope direction N12°E and a 12° South slope;
- the direction of maximum continuity in the ***vertical plane*** is, as in all layered sedimentary structures, the "horizontal" one, that in the specific studied case has a 12° slope to the South;
- ***the anisotropy ratio*** in horizontal and vertical plane is 2.

The specific feature of the parametrical anisotropy ellipsoid for the cover formations in North-West area of Bucharest city is the ***low anisotropy ratio***. This feature is connected to the heterogeneity of the sedimentary environment at local scale.

If for small distances the spatial distribution laws change, as the distances increase, due to the low magnitude of these changes, the distribution laws tend to be very similar. This spatial feature of the structures recommended the ***kriging*** as optimal evaluation method of the spatial distribution for the parametrical spatial models from the North-West area of Bucharest.

The general characteristics of spatial variability for the parametric structures in the city area are the following:

- stationary variability for the extent of described model;
- local variability, specific to distances smaller than 300 m, for all the physico-mechanical parameters; this characteristic involves a high density of observation points for detailed spatial analysis specific to geotechnical studies.

The ***estimation errors*** of the spatial parametric distribution are influenced mainly by the distances between the investigation boreholes. The local heterogeneity allows for extrapolation only with the risk of uncontrolled errors; the interpolations introduce errors higher than 10% of the estimated value in the points placed at distances greater than 300 - 400 m from the points of direct investigation.

The 3D geotechnical model achieved for this research provides a software support that enables users to do the following:

- to realize an unlimited number of sections and horizontal planes in the areas where underground works are planned, in order to detail the geotechnical conditions;
- to be quickly updated with additional data that can be efficiently integrated in the database structure in order to reduce the estimation errors of the spatial distribution of the parameters.

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