Pre-Quaternary basement of Bratislava (part 1): genetic vs. geotechnical characteristics of the Neogene foundation soils

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Predkvartérne podložie Bratislavy (1. časť): genetické vs. geotechnické charakteristiky neogénnych zemín

Abstract: The foundation soils of the majority of complicated buildings (or high-rise structures) in the Bratislava urban area are formed by the Neogene sediments, situated below the Quaternary cover. These are prevailingly high-rise buildings founded in the deep foundation pits. This contribution is focused on the analysis of the possible relations between the sediments origin and their geotechnical parameters (properties). The introductory part of the analysis was carried out on the model profile situated at the left bank of the Danube River, where the construction of high-rise buildings containing underground part was concentrated recently. The analysis was oriented on the characteristic of the pre-Quaternary basement surface morphology, geologic structure up to the reach of the exploration works and substantial geotechnical characteristics of the foundation soils. The analysis comprised comparison of geotechnical properties of the Neogene cohesive subsoils of the pre-Quaternary basement on the localities with predicted occurrence of genetically different lithostratigraphic formations. The sedimentological and geotechnical characteristics of foundation soils of the Neogene complex formed the baseline data of the analysis. The geotechnical data were taken from the engineering geological tasks realized by the authors of this study. The results of the analysis point out on the mutual affinity of the foundation soil properties, belonging to the Beladice Fm. (deltaic sequence) and Volkovce Fm. (alluvial sequence). The geostatic pressure (pressure of the superposed layers) existing during the entire period of their burial in the profile have had the dominant influence on the actual geotechnical parameters (geological pre-consolidation). This effect overwhelms the differences in the subsoils properties, which could be determined by the facies character related to their origin. Studied sedimentary formations differ in lateral stability: the Volkovce Fm. exhibits much higher lateral lithological heterogeneity than Beladice Fm., what could affect a construction site conditions. Due to the relatively massive input data files, the results of the analysis can serve beside a clearer orientation in the local Neogene lithostratigraphy also for the primary orientation in local geotechnical parameters values of the subsoils. An analogous study will be elaborated in the further continuation on an area of the wider city centre.
Key words: Danube Basin, Bratislava, Neogene, Volkovce Fm., Beladice Fm., geotechnical characteristics of subsoils

1. INTRODUCTION

The area of Bratislava is characterized by a quite varied geologic structure involving a wide range of rocks from the Malé Karpaty Mts. Crystalline of the Palaeozoic age up to subrecent sediments of the Danube River. The bulk of the territory is covered by the Quaternary sediments of various genetic types, whose basement is formed by the Neogene sediments at most of the urban area. Due to its position in the geological profile, the Neogene sediments of the pre-Quaternary basement are foundation soils (subsoils) of the major part of high-rise buildings, which are in terms of the geotechnical construction design ranked in the 2nd or 3rd geotechnical category (according to Slovak Technical Standard STN 73 1001). The mechanical properties of the foundation soils determine the long-term behaviour and operational safety of the buildings after their completion. A detailed knowledge of the strength and deformation characteristics affects the reliability of the calculations results not only at the ultimate limit state, but also at the serviceability limit state. At the same time it is necessary to know the factors affecting a possible variance of the geotechnical characteristics, possibly their dependences on the formation conditions of the individual facial types of the sediments. The knowledge of these factors can have simultaneously a significant consequence on the efficiency and reliability of the engineering geological and geotechnical exploration results of the prospective construction sites.

By implementing the Eurocode 7 standard in 2010 into the projection practise in the Slovak Republic, a part of the previous STN 73 1001 standard *"Foundation of structures. Subsoil under shallow foundations"*, which contained an annex of normative characteristics of foundation soils, was removed. The provisions of the new STN and EC-7 system assume the design of the geotechnical constructions ranked in the 2nd and 3rd geotechnical category preferably on the basis of the subsoil-mechanical tests

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results. The characteristic properties of the rock environment, the Neogene foundation soils of the pre-Quaternary basement in this case, are considered as random variables. Their determination methods assume the use of recommended statistical procedures, where are, as a rule, the sets with a relatively small number of samples. Similar sets can be very sensitive on the position of the outliers, which are affected mainly by directional (space) variability of the examined characteristic in the studied ground massif. The standard deterministic approach of the evaluating the geotechnical characteristics and the design of the geotechnical model of the subsoil can be considerably affected (even damaged) by the occurrence of outliers and vice versa it can be little sensitive on the occurrence of critical values.

The model profile for the sedimentary development analysis was selected to take into account the course of the expected lithostratigraphic boundaries in the pre-Quaternary basement unit of the Neogene sediments of Bratislava. The profile runs from the buried elevation of the crystalline in the vicinity of the Malé Karpaty Mts. (area of the Račianska street) towards south-east into the environment of the north-western margin of the Gabčíkovo depression (the Slovnaft refinery area), i.e. approximately perpendicularly to the edge of the morphostructure. The construction sites, selected for the analysis, complied with their location in the profile, quality of the documentation and mutual comparability (reliably documented geological profile with sufficient reach of the exploration works into the pre-Quaternary basement, sufficient extent of the subsoil-mechanical tests carried out in the same laboratories by the standardized methodology). Simultaneously the basic research results comprising the biostratigraphical data, which were considered as reference points of the profile in the analysis, were taken into consideration, as well. The course of the chosen profile with indication of the location of realized exploration works within the selected construction sites is shown on Fig. 1.

The direct basement of the Quaternary sediments in the studied profile is represented by the sediments of the Late Miocene and Pliocene age. Significant changes in the view of the Late Miocene evolution of the Danube Basin were published recently, principally in the sources Kováč et al. (2006, 2010, 2011), Magyar et al. (2013), and Šujan et al. (2016). Gradual migration of the sedimentary environments, caused by the progradation of shelf slopes and delta bodies prevailingly from the north-west into the basin of Lake Pannon was identified in the last decade by use of the seismostratigraphy and sequence stratigraphy. Migration of the environments and first of all slow refilling of the deep water depocentre of Lake Pannon caused the heterochronous nature of individual formations across the basin. This heterochronous nature of sedimentation was confirmed biostratigraphically, magnetostratigraphically (Magyar et al., 2007) and by authigenic $^{10}Be/^{9}Be$ dating method (Šujan et al., 2016). Change in the sedimentation regime is documented by the occurrence of several lithostratigraphic units, where different depositional processes resulted in the different lithological composition of the Neogene sediments at the studied localities. The actual analysis is based on the definition of lithostratigraphic units *sensu* Kováč et al. (2010, 2011) and Šujan et al. (2016), therefore the references to previous conceptions *sensu* Vass (2002) etc. are not mentioned.

2. SEDIMENTOLOGICAL CHARACTERISTIC OF THE STUDIED FORMATIONS

A sedimentation in the brackish lacustrine environment was taking place in the studied territory during the early Pannonian (approximately 11.6~10.5 Ma), which appeared by gradual transgression after the regressive Sarmatian (Magyar et al., 2013). An oscillation of Lake Pannon water level caused the alternation of a more dynamic coastal environment with more distinct input of the sandy fraction and an offshore environment with dominance of clay and silt deposition (Fordinál & Tuba, 1992; Nagy et al., 1995). The lacustrine sediments classified into the Ivanka Fm. (*sensu* Kováč et al., 2011) transgressively overlay directly the Tatricum crystalline of the Malé Karpaty Mts. in the studied territory (Fordinál & Tuba, 1992; Fordinál, 1993; Nagy et al., 1995). The Malé Karpaty Mts. formed a very moderate subaerial elevation or flooded swell during the sedimentation, because they did not constitute as a more significant source of the coarse-clastic material.

The shelf edge, dividing the offshore environment from the deep basin floor environment, was situated approximately in the central part of the Danube Basin in the period before 10.0 Ma (Magyar et al., 2013). A transitional environment of the lacustrine coast and lagoons dominated in the studied area at the same time (Fordinál & Tuba, 1992; Nagy et al., 1995; Šujan et al., 2016). Sediments deposited in that environment are considered to be the equivalent of the Beladice Fm. (*sensu* Kováč et al., 2011), which was originally classified to the Pontian (Vass, 2002). The overlying alluvial sequence of the Volkovce Fm. (*sensu* Kováč et al., 2011) was documented in the depth interval of approximately 15~100 m of the Ma-1 borehole (Fig. 1; Nagy et al., 1995), based on the lithological character of the sediments, absence of brackish mollusc fauna and very limited occurrence of freshwater mollusc fauna. Alluvial sedimentation dominated at the Malé Karpaty Mts. – Danube Basin transition area in the period approximately after 9.7 Ma (Šujan et al., 2016). This alluvial sequence was documented in the basement of the Quaternary sediments in the JRD-207 and VD-2 boreholes (Fig. 1; Fordinál & Tuba, 1992). Onset of the alluvial sedimentation on the underlying deposits of the Beladice Fm. (which is typical by common presence of coal layers) is very well documented by the oil-prospecting (counter-flush) boreholes of the Svätý Jur series hydrocarbon prospection (Cílek, 1957, 1960). Younger Neogene sequences were not documented in the studied territory; however, the sediments of the Pliocene Kolárovo Fm. are foreseen southwards at the Žitný ostrov area (ca. 2.6~4.1? Ma; Kováč et al. 2011). Note: the terms fluvial and alluvial are differentiated in accordance with the international sedimentological standards *sensu* Miall (2006) and Nichols (2009).

The evaluated localities are arranged in an around 11 km long strip of approximately northwest-southeast orientation, i.e. approximately perpendicular to the margin of the Malé Karpaty Mts. morphostructure, which form the northwestern margin of the Danube Basin (Fig. 1). Geological section on Fig. 2a documents schematically the geological settings of the studied area. The Neogene sediments are secondarily aslope in consequence of the Malé Karpaty Mts. horst uplift, which was connected with the Plio-Pleistocene inversion of the basin (e.g. Horváth, 1995). The Quaternary fluvial gravels and sands of the palaeo-Danube overlay discordantly and erosively the Neogene formations. Stratigraphical division in the geological section relies partially on the JRD-205 and JRD-206 boreholes (lithology and interpretation relies on data published by Fordinál & Tuba, 1992; Fordinál, 1993). In these boreholes were biostratigraphically identified shallow-water brackish sediments of the early Pannonian age, deposited on the granitoid rocks of the Palaeozoic basement. The lower Pannonian beds, which represent the Ivanka Fm., were not recorded at the studied localities. However, the results of the JRD-205 and JRD-206 boreholes indicate their presence in the basal part of the Neogene succession (Fig. 2a; Fordinál & Tuba 1992; Fordinál 1993).

The Beladice Fm. (which overlies the Ivanka Fm.) was described from the boreholes at the Slovany and Nové Slovany localities (Račianska street, Fig. 2b), situated closest to the north-eastern basin margin. The basin margin is formed here by the crystalline complexes of the Malé Karpaty Mts. Sediments are of typical fine-grained composition with strong dominance of silts and clays and with minor presence of fine-grained and clayey sands. Pelites are blue, blue-grey, and grey, with abundant occurrence of lignites and coal clays. Presence of shell beds of lacustrine molluscs classified as *Melanopsis* sp. and *Congeria* sp. at the Slovany locality are indicative for variable salinity. Described sequence can be correlated with the Beladice Fm. and represents a coastal environment with very flat morphology (*sensu* Reading, 1986). The beds are relatively stable in

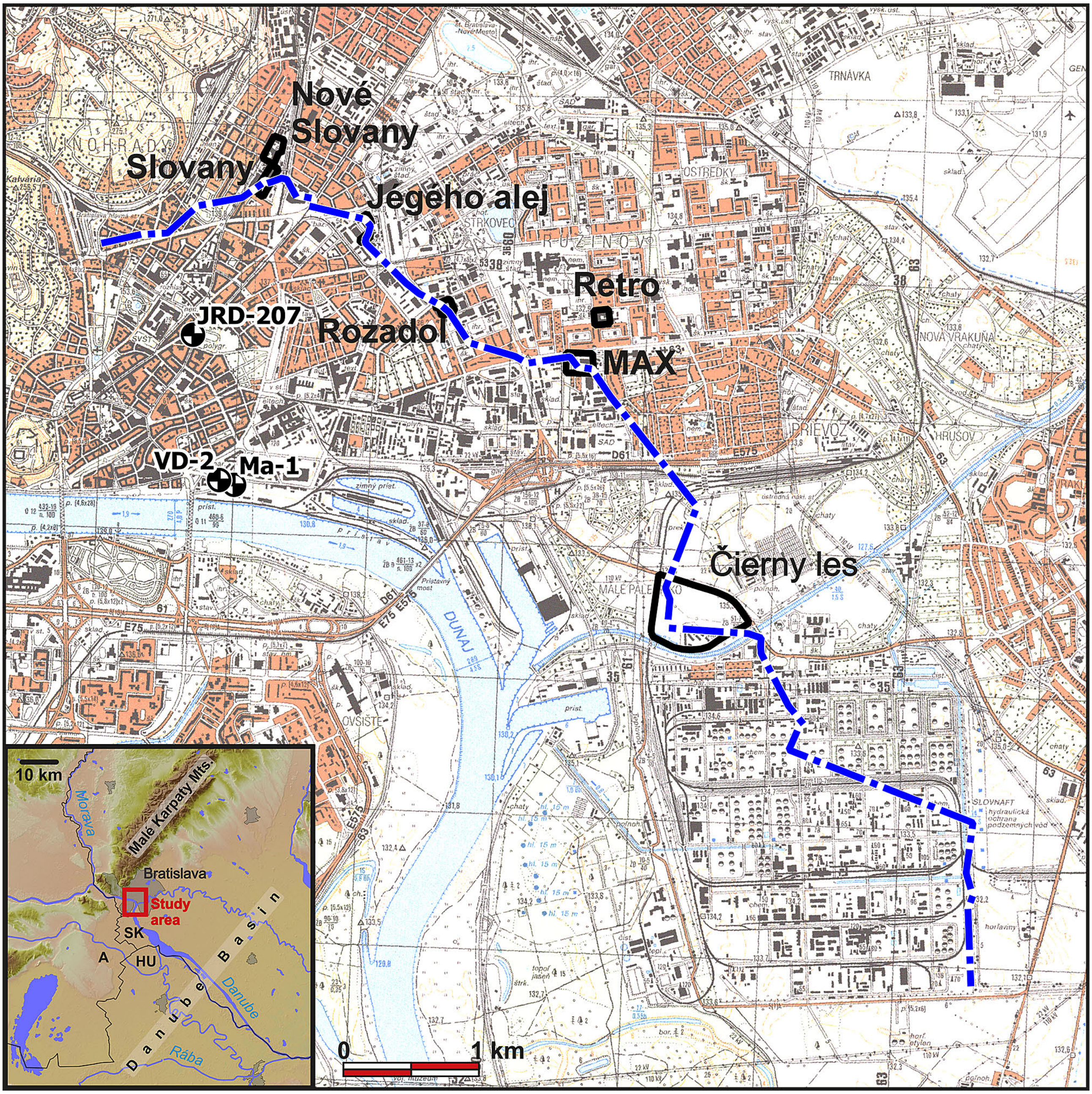

Fig. 1. The course of the model profile with the location indication of the selected localities.

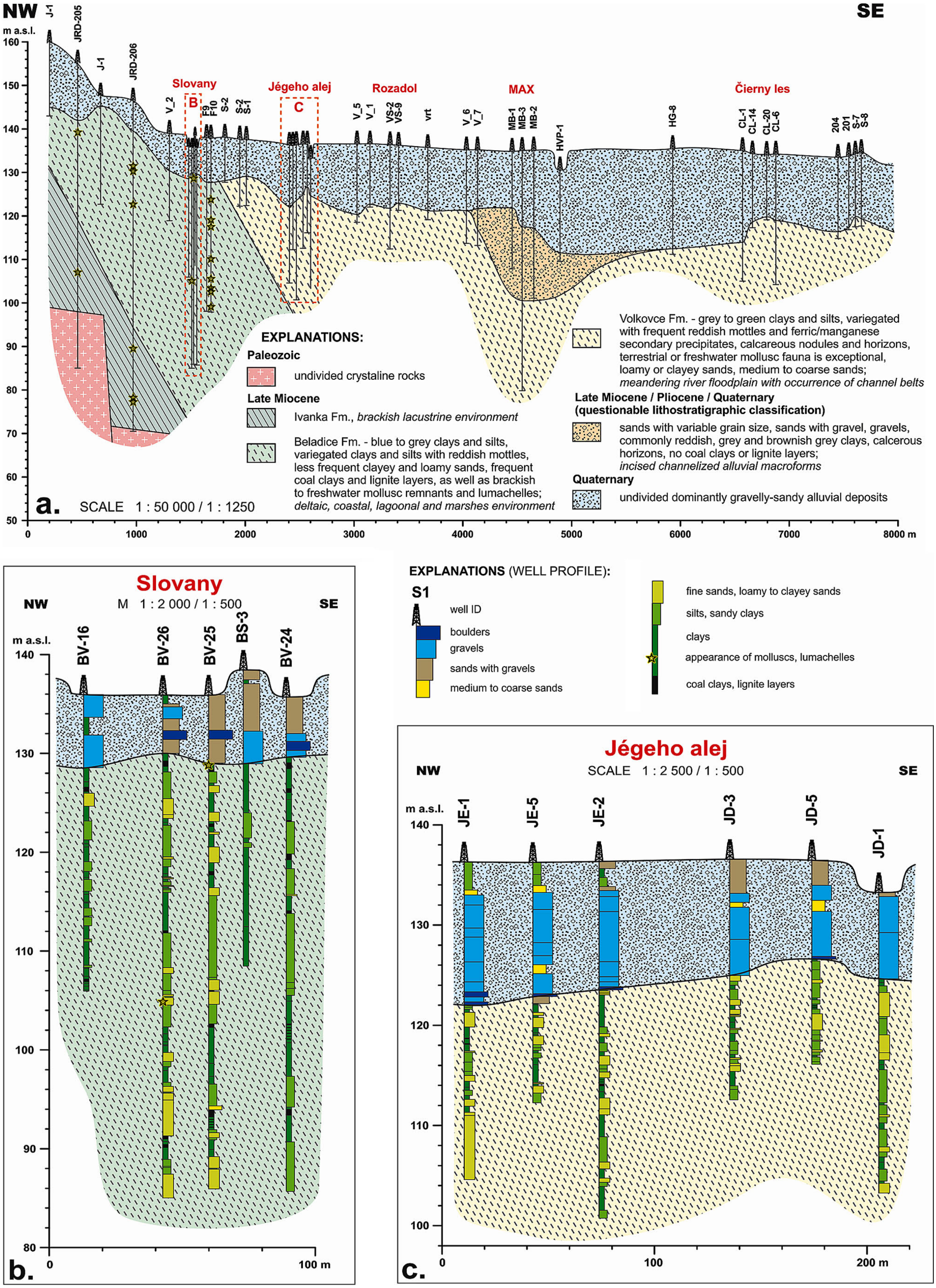

Fig. 2. a) Geological section in the line of the model profile; b) detail of the Slovany locality; c) detail of the Jégého alej locality.

the vertical sequence, with smooth lithological transitions, which mirror cyclical changes of the water level, affecting the environment's dynamics. The higher content of the sandy fraction is bound to sediments of the coastal zone, while the clayey sediments were deposited in an environment of marshes (in case of the occurrence of coal layers) or they were deposited in a deeper water column below a wave base, what is indicated by the findings of autochtonous molluscs. The input of the coarser fraction was probably influenced also by the vicinity of delta bodies, which positions migrated along the basin margin by their avulsion. A significant lateral stability of the layers with similar lithological characteristics can be expected in described genetic type of the sediment.

The Late Miocene alluvial sequence of the Volkovce Fm., shown in the detail from the Jégého alej locality at the Jégého street (Fig. 2c), was recorded in the basement of the Quaternary deposits at the further localities. The sediments of the formation are represented by grey, brown-grey, grey-green and grey-blue clays and silts (loams), sandy clays and silts. The clayey and silty (loamy) sands occur substantially more often compared to the Beladice Fm. The beds are vertically less stable, the lithology changes more often, the lithological changes are more abrupt. The content of the coal layers is less and mollusc macrofauna was not described at the study localities. The horizons with occurrence of the calcareous concretions and coatings are frequent, the iron rust coatings were described, as well. These secondary lithological features point to the influence of the groundwater level after sedimentation and pedogenetic processes following the deposition. The sediments of the Volkovce Fm. were deposited at the study localities in the river environment with low dynamics. Considering the low content of the sandy sediments, most of the localities were probably situated in an alluvial plain with variable distance from channel belts of the meandering stream (*sensu* Bridge & Diemer, 1983).

The sediments of the Volkovce Fm. at the Retro locality (the Trávniky housing estate) are represented predominantly by clayey sand (with sporadic appearance of the gravel layer) and minor content of pelites, what indicates the vicinity of the sedimentation to the channel of the river. The accumulations of the coarse sands, sands with gravels and gravels, which were documented at the MAX locality (Hraničná street, Fig. 2a) could be related to the above mentioned sediments. The sediments may represent a channel fill of a meandering stream, but also the Pliocene to Pleistocene accumulations deposited after incision of the river into the older Miocene layers. Therefore, these coarser strata may not be related lithologically and genetically to the surrounded Neogene accumulations. In general, there is a stronger lateral lithological heterogeneity of the Volkovce Fm. opposite to the Beladice Fm., resulting from the nature of the depositional environment.

The south-east margin of the profile (the Slovnaft refinery area and the continuation of the profile towards the central Danube Basin) borders with an area, where predominantly coarse-grained river channel-fill succession could be observed immediately below the Quaternary deposits. Concerning lithology, these strata are represented by sands, sands with gravels, gravels and clays; they are classified lithostratigraphically to the sediments of the Kolárovo Fm. and are of Pliocene age and their thickness rises towards the central depression.

Elevation of the Neogene sediments surface declines irregularly in the south-east direction towards the basin's central part. The surface morphology is affected by the Malé Karpaty Mts. horst uplift, which was connected with the Plio-Pleistocene inversion of the basin (e.g. Horváth, 1995). Three different sections can be identified in the documented profile (Fig. 2a):

a) The north-west section, affected mainly by the Malé Karpaty Mts. crystalline elevation (buried slope approximately to the Račianska street with elevation of the Neogene surface at the interval ca. 145–130 m asl.);

b) The intermediate section with the surface of the pre-Quaternary base modelled especially by fluvial erosion of the Danube River flow in the Pleistocene (approximately to the Prievoz area with the level around 130–120 m asl.);

c) The south-east section, affected mainly by the normal faults towards the centre of the basin from the level ca 120 m asl. downwards.

The morphology of the Quaternary/Neogene boundary at the area of Bratislava was analysed in detail by Šujan (2011). According to the mentioned publication, the section a) can be correlated with the area of the higher Quaternary terraces; the section b) corresponds to the alluvial terrace of the Danube river formed during the latest Quaternary; the section c) is an area of accumulation in superposition during the Quaternary, which was affected by activity of normal faults (bounding the central depression of the basin) up to subrecent. The sections a) and b) are most likely separated by the marginal faults, delineating the Malé Karpaty Mts. horst towards the Danube Basin's filling. The boundary of the sections b) and c) corresponds to the course of some of the faults of lower order, corresponding to the Danube fault system (Čepek, 1938; Fusán et al., 1987). The mentioned boundary can be possibly explained also by the different thickness of the subjacent column of the Miocene sediments, while the difference of thicknesses led to different intensity of compaction and differential subsidence during the Pliocene and Quaternary.

3. INPUT DATA AND ANALYSIS

The mutually comparable exploration works, which verified the sufficient interval of the basement of the Quaternary alluvial prevailingly gravelly-sandy sediments, were selected for the analysis of the sedimentary composition. The quality documentation for the detailed grain size analysis and full core drilling with sufficient final diameter for taking the correct undisturbed subsoil samples for mechanical tests was the basic requirement. The boreholes with greater final depth were used preferentially for the analysis, as the proportional representation of individual classification of foundation soil types can be affected by the depth reach of the used exploration works and overall documented range (in metres) in the Neogene subsoils. The whole assessed set contains 429 foundation soil samples classified to the pre-Quaternary basement from all assessed localities, which are divided into the set of sediments of the Beladice Fm. from the Slovany and Nové Slovany localities ($\Sigma = 178$ samples) and the set of sediments of the Volkovce Fm. in the remaining part of the profile (Σ = 227 samples). A separate group is formed by 24 subsoil samples (the set P) of uncertain stratigraphical position from the interval between fluvial gravels base and clearly determined surface of the Neogene sediments from the MAX locality. Significant layers of predominantly sandy sediments from the basement of the Quaternary fluvial gravels at the Retro locality were classified to the Volkovce Fm. based on the lithological similarity. The Retro locality is not shown in the profile, as its position practically coincides with the MAX locality in its line. The data for the above foundation soils with high portion of sands were not included in the statistical processing. All data used in the analysis are included in the final reports Šujan (2007), Šujan & Blažo (2003, 2004, 2007), Šujan et al. (2005, 2007, 2008, 2009[a], 2009[b], 2010) and Pokorný et al. (2009).

3.1 Physical - descriptive properties of the Neogene subsoils

The all assessed samples of sediments were in terms of the standard classification principles (STN 72 1001) the foundation soils with majority of fine-grained subsoils above the sands. Their grain size distribution and in case of fine-grained subsoils the position in the plasticity diagram, respectively, is the basic classification feature of the studied foundation soils. The basic typology of subsoils divided into the set of subsoils of the Volkovce Fm. and the set of subsoils of the Beladice Fm. in the whole studied profile is expressed by the position of the individual samples in the triangle (ternary) diagram (sand/silt/clay) on Fig. 3a. The dependence of the grain size distribution of all foundation soil samples taken in the whole studied profile on the depth of sampling expressed in the triangle diagram is shown on Fig. 3b and for individual localities is presented on Fig. 4a–f. The results show a clear affinity of the Volkovce and Beladice fms. in terms of the grain size distribution – Fig. 3a. The subsoil samples do not show any significant differences even at the grain size distribution evaluation in dependence on the depth of sampling (Fig. 3b). The diagrams point to the predominance of the silty component in foundation soils and prevailing composition on the silt ↔ sand line, respectively. A minimum portion of the samples with significant predominance of clayey fraction is present in the set. These characteristics can be generalized for the whole studied set, the deviations among the localities reflect local differences in the sedimentation dynamics Fig. 4a–f.

Proportional representation of subsoils classified in terms of the STN standard is influenced by the criterion of the percentage content of the fine fraction (clay + silt), i.e. formally established threshold. The clays, less the silts and clays and sandy silts, are represented this way in the sets of the Volkovce and Beladice fms. (Fig. 5a). The clays with low and medium plasticity (F6/CL-CI; 26.7 % of the whole set of samples) and the clays with high and very high plasticity (F8/CH-CV; 14.6 %), formed the largest part of the clays. As regard the silts (loams), the silts with low and medium plasticity (F5/ML-MI; 13.1 %) prevailed, a smaller group was formed by the silts with high plasticity (F7/MH; 2.9 %). The other significant group, which represented 20.7 % of the whole set of samples, was formed by clayey sands (S5/SC), the other sands types formed a 7.4 % portion. The representation of the fine-grained sandy subsoils: sandy silts (F3/MS; 6.9 %) and sandy clays (F4/CS; 7.2 %) was smaller in the set. The sands (mainly clayey sands, sands with the fine-grained subsoil admixture and the silty sands) with more than 83 % portion of the set are highly predominating in the samples from the set of unclear stratigraphical position from the MAX and Retro localities (Fig. 5b). These sandy subsoils were not included into the statistical processing due to different classification features. The plasticity properties of the Neogene foundation soils samples were evaluated by the standard use of the Casagrande plasticity chart. The position of the subsoil samples of the whole evaluated set in the plasticity chart is shown on Fig. 6a. According to the position in the plasticity chart they are the clayey and silty subsoils with low to high plasticity, while the subsoils with

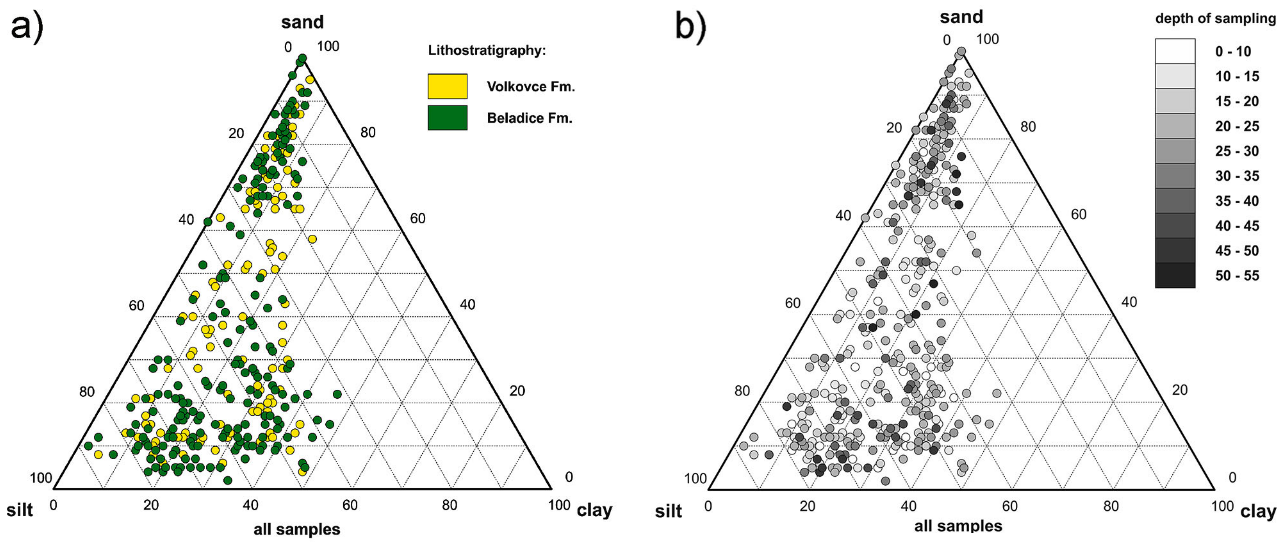

Fig. 3. a) Grain size distribution of soil samples – division according to lithostratigraphic position; b) Grain size distribution of soil samples – division according to the depth of soils occurrence.

medium plasticity prevail. Similar to the grain size distribution, also the plasticity properties of the foundation soils point to the relatedness of the Volkovce and Beladice fms. The above finding is confirmed also by the evaluation of the other physical properties expressed in dependence on depth of sampling together for the Volkovce and Beladice fms.: water content

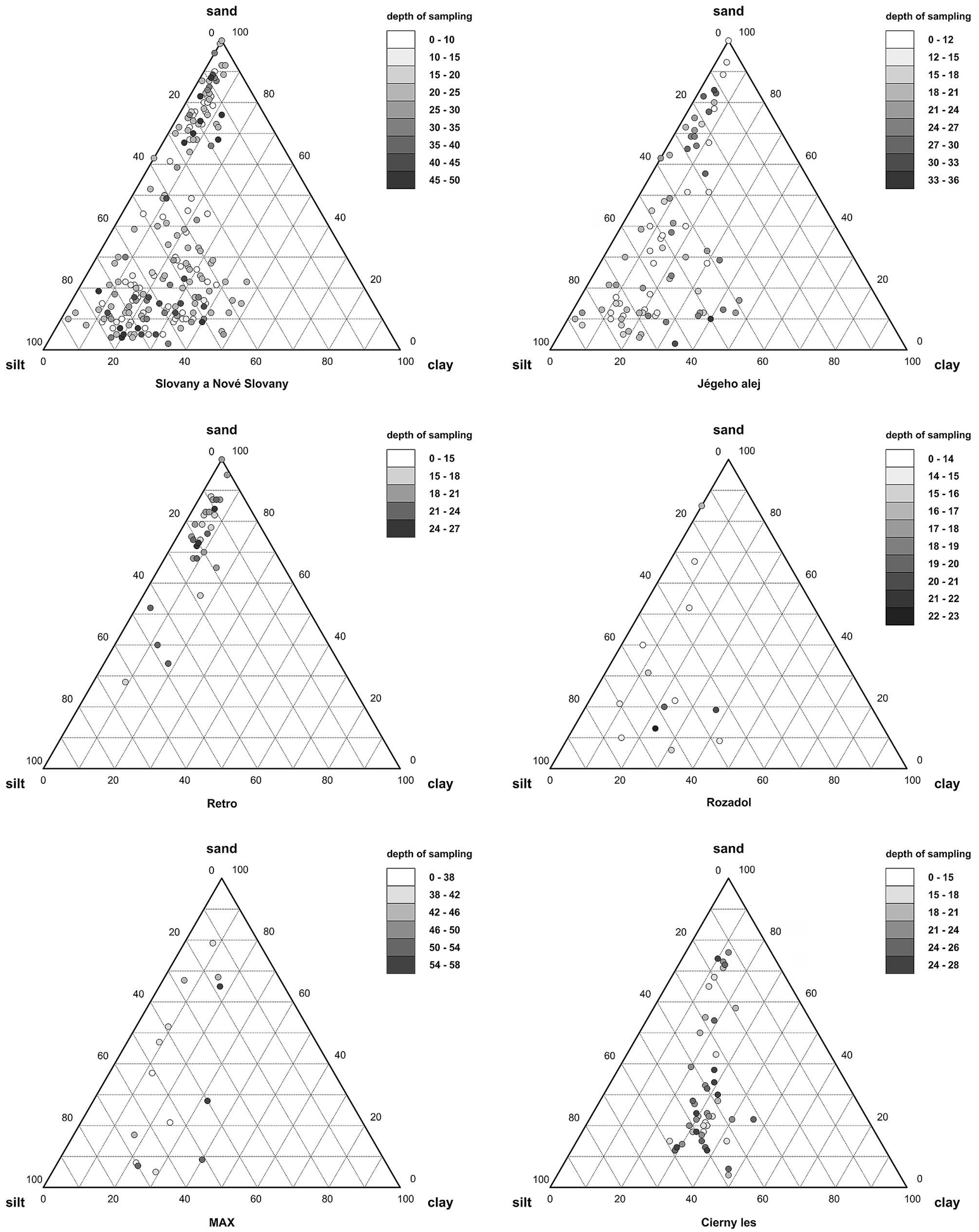

Fig. 4. Grain size distribution of soil samples – division according to the localities and depth.

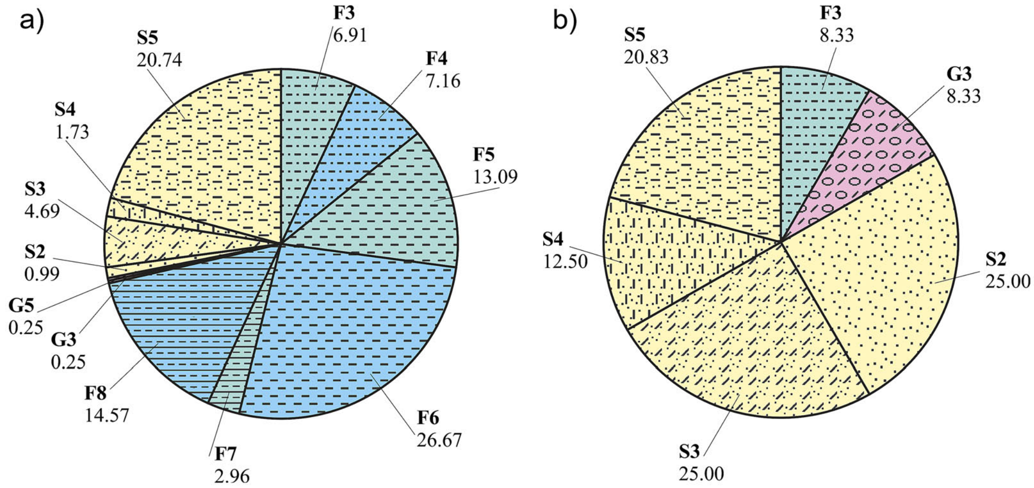

Fig. 5. a) Proportional representation of the classification soil types of the Volkovce and Beladice fms.; b) Proportional representation of the classification soil types of uncertain stratigraphical position.

w_n [%], liquid limit w_L [%], plasticity index I_P [%], consistency index I_C [-], porosity n [%], unit weight of subsoil (natural state) γ_n [kNm^{-3}] and the dry unit weight γ_d [$kN.m^{-3}$]. These characteristics are clearly shown in the diagrams on Figs. 6–7.

The variability assessment of the physical - descriptive foundation soils properties of the Volkovce and Beladice fms. in the whole selected profile was carried out on the basis of their statistical evaluation. Tab. 1 introduces the descriptive statistics consisting of numeric characteristics of the position and variance. The central value, around which the other values are less or more concentrated, is given by arithmetic mean x_m and median x_{me}. The variability of values is expressed by the variability characteristics: variance R_v = max – min, interquartile range $R_{iq} = u_{qv} - l_{qv}$, standard deviation s and the coefficient of variation c_v, which represents the relative rate of variability and enables the comparison

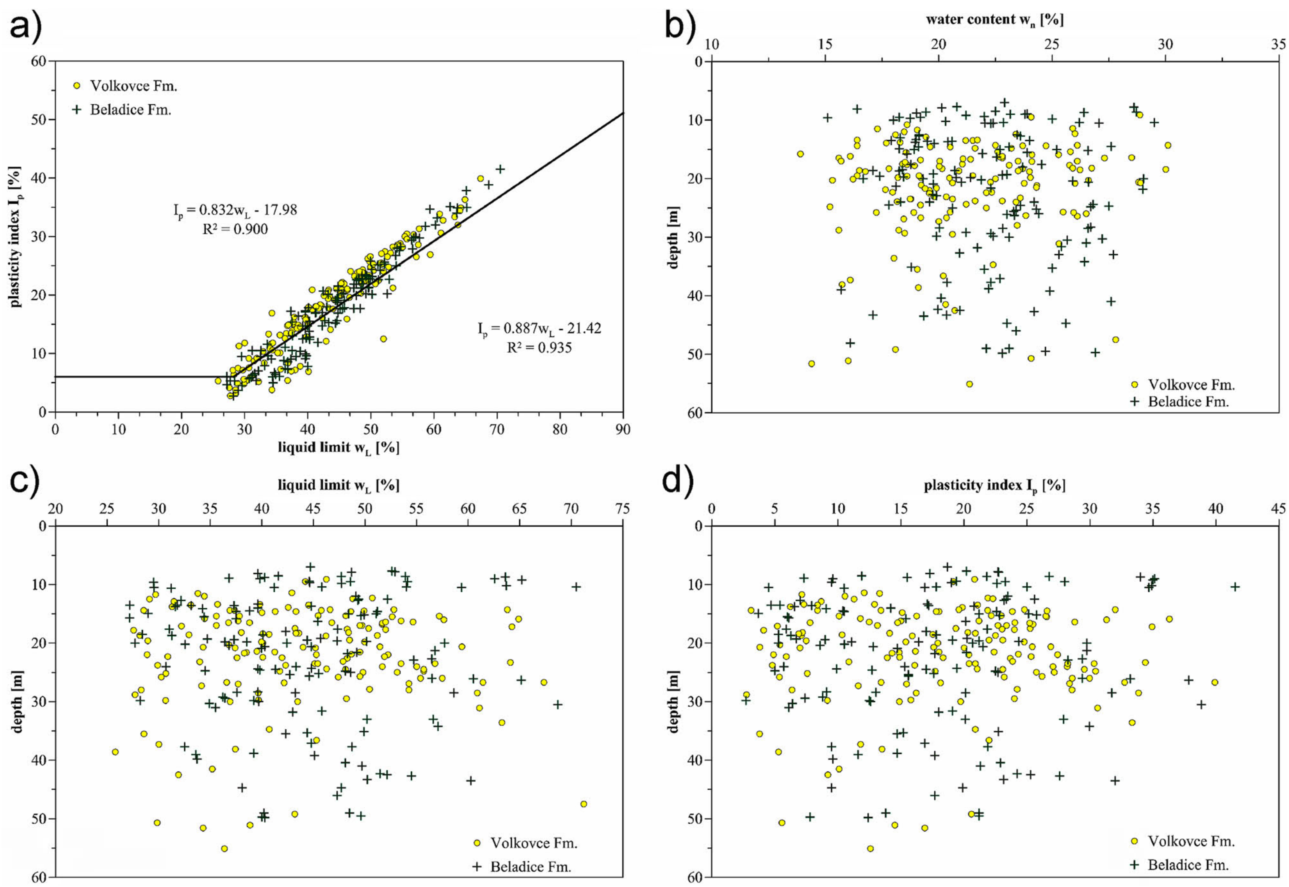

Fig. 6. a) Location of the soil samples in the plasticity chart; b) Water content of soils depending on depth (w_n); c) Liquid limit depending on depth (w_L); d) Plasticity index of soils depending on depth (I_P).

Tab. 1. Basic descriptive statistics of the sets of physical - descriptive properties of Neogene soils.

property	total number of samples	variance			interquartile range			mean	median	standard deviation	coefficient of variation
	n	min	max	R_v	l_{qv}	u_{qv}	R_{iq}	x_m	x_{me}	s	c_v
water content w_n [%]	288	12,6	30,26	17,66	19,4	24,1	4,97	21,68	21,45	3,57	0,165
unit weight γ_n [kNm^{-3}]	167	18,7	22	3,4	19,9	20,7	0,8	20,3	20,3	0,63	0,031
dry unit weight γ_d [kNm^{-3}]	167	14,9	18,8	3,9	16,2	17,1	0,9	16,7	16,5	0,86	0,052
porosity n [%]	167	30,9	44,7	13,8	36,8	40,5	3,7	38,3	38,7	3,3	0,086
void ratio e [–]	167	0,45	0,81	0,36	0,58	0,68	0,1	0,62	0,63	0,09	0,138
degree of saturation S_r [%]	167	67,5	100	32,5	89,6	99,6	10,1	93,3	95,8	7,7	0,083
liquid limit w_L [%]	290	25,8	71,2	45,4	37,3	49,9	12,6	44,1	44,1	9,6	0,217
plasticity index I_P [%]	289	2,7	41,5	38,8	11,3	23,5	12,2	18,1	18	8,5	0,466
consistency index I_C [–]	278	0,58	2,9	1,51	1,11	1,37	0,26	1,27	1,23	0,26	0,201

of variability among individual sets. The lower l_{qv} and upper u_{qv} quartile is specified by the interval, which covers 50 % of values, i.e. under the lower (25 %) and above the upper (75 %) quartile one quarter of the values occur. The interquartile range does not cover the extreme values (min and max), which can misrepresent the evaluation of the whole set.

The evaluation of the acceptability of the variability of the measured values and the sets homogeneity is possible on the basis of the coefficients of variation c_v introduced for individual geotechnical characteristics e.g. in Kulhawy & Phoon (2002), Meyerhof (1994), Réthátí (1988) or Schneider (1999). An overview of the typical values of the coefficients of variation for

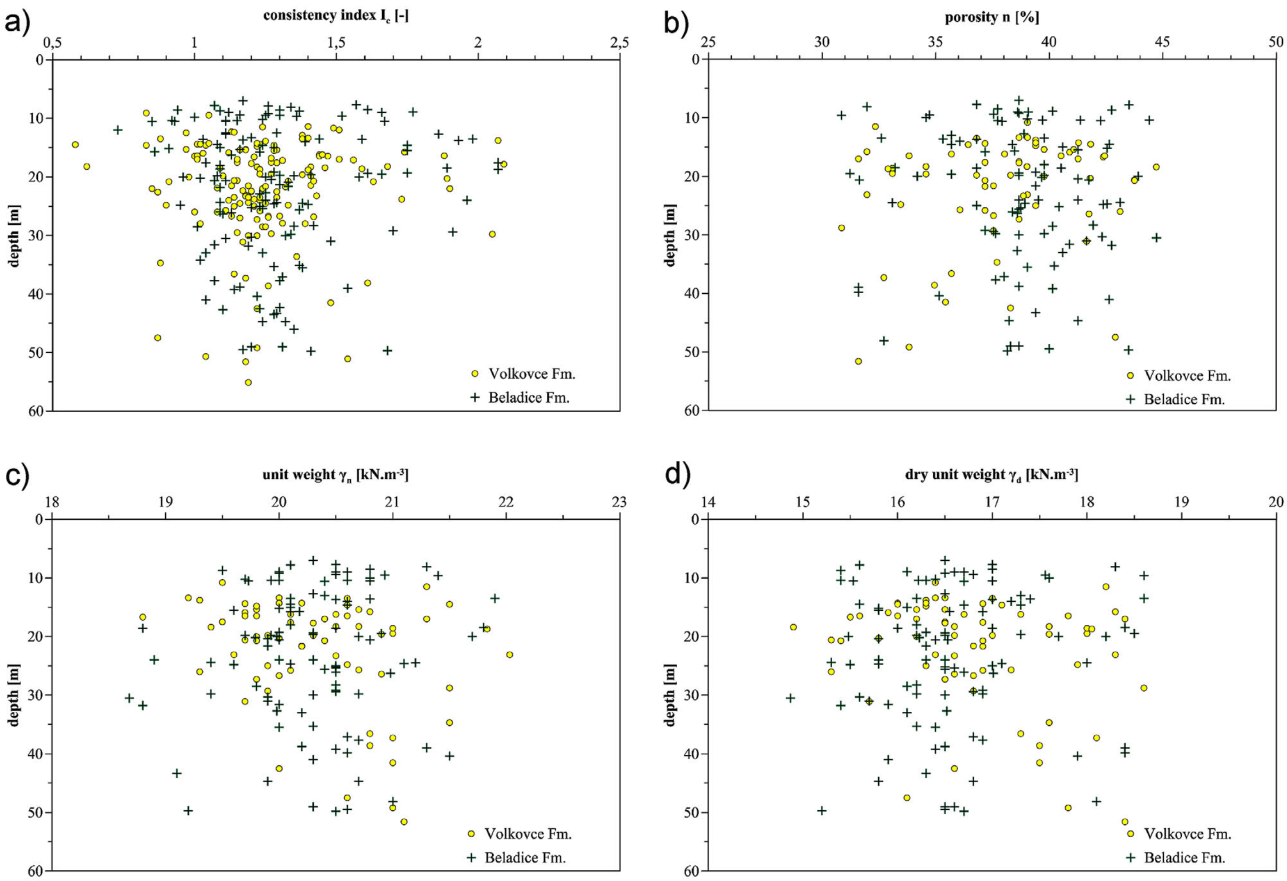

Fig. 7. a) Consistency index of soils depending on depth (I_C); b) Porosity of soils depending on depth (n); c) Unit weight of soils depending on depth (γ_n); d) Dry unit weight depending on depth (γ_d).

the physical-descriptive characteristics of subsoils introduces Tab. 2. Exceeding the typical value may indicate the need of a more detailed division of the set (lithostratigraphic unit or engineering geological unit) to reach a lower value of the coefficients of variation.

According to the comparison of the evaluated coefficients of variation (Tab. 1) with typical values (Tab. 2) it is clear, that the variability of the characteristics of physical state w_n, e, γ a I_C is relatively low, despite of the wide spectrum of geotechnical types of foundation soils with a very large range of the plasticity index ($c_v = 0.466$) and a big extent of the studied massif of the Neogene subsoils. For example, the coefficient of variation of water content wn ($c_v = 0.165$) is only a little higher than the criterion ($c_v = 0.150$) and at the void ratio e ($c_v = 0.138$) it occurs below the criterion threshold 0.150. The unit weights of the subsoils γ_n and the dry unit weight γ_d are characterized by the coefficients of variation $c_v = 0.031$ and 0.052, whereby they meet the required criterion. The whole Neogene complex appears to be very homogeneous in terms of foundation soil consistency (coefficient of variation of the consistency index $c_v = 0.201$), as the consistency state of subsoils is almost exclusively firm, very firm to hard. The occurrence of subsoils with soft and stiff consistency is sporadic, while it is generally bound to the contact and to the vicinity of the Quaternary-Neogene boundary. Small differences between the median x_{me} and arithmetic mean x_m indicate, that the evaluated sets do not show asymmetry, i.e. they have normal distribution of the probability of the values occurrence.

3.2 Mechanical properties of subsoils

The laboratory experimental measurements of shear strenght and compressibility were carried out within the individual explorations on selected samples of the Neogene foundation soils. The resulting effective parameters of shear strength of the Neogene subsoils (effective angle of internal friction φ_{ef} and effective cohesion c_{ef}) determined by the shear box tests served to the assessment of the ultimate limit state – the assessment of the bearing capacity of the foundation soil. The compressibility of the Neogene subsoils was verified by the oedometric tests and the resulting oedometric modules E_{oed} served to the assessment of the serviceability limit state – the assessment of the deformation of foundation soil. The foundation of the buildings in the selected profile was designed from the construction reasons in the considerable depths (2 to 4 underground storeys) and on large foundation constructions (slab foundation). The fulfilment of the condition of serviceability limit state – the limit state of deformation, is significantly more demanding in this case of the foundation. Therefore, the greater emphasis was put on the expression of the deformation characteristics of the Neogene foundation soils located in the basement of the buildings. The oedometric modules E_{oed} are the variable characteristics dependent on the state of stress in the subsoil, which may vary significantly during the construction. The foundation base is significantly unloaded by the excavation of a deep construction pit (at 2 to 4 underground storeys the depth of excavations is 7 to 15 m below the original terrain), while an uplift of the basement occurs. The oedometric modules from the unloading phase E_{oed}^{ul} were derived for this change of the stress condition. Subsequently, the realization of the foundation construction and the upper construction takes place. The load is transferred on the basement through the foundation construction, while its deformation takes place (consolidation). It is necessary in this phase to distinguish the oedometric modules for the pre-consolidation phase invoked by the reloading to the extent of the unloading by the excavation E_{oed}^{rl} from the oedometric modules for the consolidation phase by the overloading E_{oed}^{ol} (above the level of the pre-consolidation stress). The change of the stress condition reflecting the depth of excavation and the load intensity was analysed in detail in the basement of each building in the selected profile and taken into account in the design and the realization of experimental measurements of deformation characteristics of the Neogene foundation soils.

The evaluations of experimental measurements of the strength and deformation characteristics, expressed in dependence on depth of sampling below the terrain surface, are shown on Figs. 8–9 together for the subsoils corresponding to the Volkovce and Beladice fms.: the effective angle of internal friction φ_{ef} [°], effective cohesion c_{ef} [kPa], oedometric modulus of compressibility for the phase of reloading within the pre-consolidation E_{oed}^{rl} [MPa] and oedometer modulus for the phase of overloading E_{oed}^{ol} [MPa].

The likeness of foundation soils corresponding to both formations confirm also the strength and deformation characteristics of subsoils, evaluated in dependence on the depth of occurrence below the terrain surface (depth of sampling). Distribution of values of the experimentally verified strength and deformation characteristics within the whole depth range of the realized exploration works do not show any significant differences between the evaluated sets. The values of the shear strength parameters of the Neogene foundation soils do not show any dependence on depth of their occurrence. The opposite situation is in the assessment of the deformation parameters of the Neogene foundation soils, where there is an apparent trend of dependence (growth) of the value of the oedometric modules on depth. The impact of the depth of subsoil sampling on the value of oedometric modulus is confirmed by the fact, that the modulus is a variable characteristic, dependent on stress condition in the ground massif.

Tab. 2. Typical values of the coefficients of variation for selected physical - descriptive characteristics of soils.

property	range of typical values c_v
unit weight w_n	< 0.15
liquid limit w_L	0.09 ~ 0.28
plasticity index I_P	0.18 ~ 0.40
consistency index I_C	0.10 ~ 0.27
porosity n [%]	< 0.15
void ratio e	0.15 ~ 0.22
bulk (mass) density γ_n (ρ_n)	0.01 ~ 0.10

Similarly as for the assessment of variability of physical – descriptive properties of the Neogene foundation soils of the Volkovce and Beladice fms. in the whole evaluated profile, the assessment of variability of mechanical properties based on statistical evaluation was carried out, as well (Tab. 3). The typical coefficients of variation c_v for the assessment of the acceptability of variability of the measured values and homogeneity of the sets of mechanical properties introduces Tab. 4.

A comparison of the evaluated coefficients of variation (Tab. 3) with typical values (Tab. 4) clearly indicates, that the variability of the effective value of the angle of internal friction φ_{ef} ($c_v = 0.123$) and effective cohesion cef ($c_v = 0.462$), as well, is in the range of typical values of the coefficient of variation. Very high, however, are the values of the coefficients of variation of the sets of oedometric modules of compressibility E_{oed} ($c_v = 0.357$ to 0.721), which are far beyond the range of typical values of the coefficient of variation ($c_v = 0.20$ to 0.40). However, the considerable variability of values of the oedometric modules does not result from the inhomogeneity of the Neogene foundation soil massif of the pre-Quaternary basement. That phenomenon is caused by the fact, that the values of the oedometric Eoed were expressed for various ranges of the loading levels, which resulted from the specific requirements of the building. In case of the quantitatively identical loading levels applied in all experimental measurements, the variability of the values of oedometric modules would decrease significantly, as well. The high variability of values of the oedometric modules is influenced also by the trend of increasing values depending on depth, i. e. for the correct assessment of the variability it is necessary to split the set into zones according to the depth.

4. INTERPRETATION

4.1 Sedimentology

The Neogene sediments surface of the pre-Quaternary basement in the Bratislava area are generally clearly recognizable in the borehole profiles based on macroscopic features. A sharp transition from the coarse gravels of the river channel-fill facies classified to the Pleistocene into the silts and clays of the Upper Miocene is typical. The pre-Quaternary basal surface is on some places accompanied by the occurrence of the 0.2~0.4 m thick lithified layer, which can be generally designated as siltstone. The presence of the layer probably indicates a local incrustation by the media with deeper circulation (e.g. mineralized groundwater), the ascent of which can be possible through the faults, or by the effect of redox processes. The similar phenomenon was documented also inside the body of the Quaternary coarse-grained sediments (increases in the south-east direction, mainly south from the Slovnaft refinery), where the consolidated sediments and the rocks, even indicated as conglomerates, were described in the drill cores rarely.

Following criteria were used to distinguish the alluvial and lacustrine (including transitional - lagoonal, coastal and deltaic) sediments in case of the absence of a clear lithological contrast on the contact of fluvial gravels with pre-Quaternary basement: a) presence of laminae (and layers) of lignites and coal clays, b) the occurrence of the variegated fine-grained sediments, c) the presence of the layers of calcareous sand with a large proportion of clastic mica of variegated colours and d) the occurrence of thin sandy layers with an admixture of fine fraction alternating with variegated silts and clays.

Tab. 3. Basic descriptive statistics of the sets of mechanical properties of Neogene soils.

property	total number of samples		variance		interquartile range			mean	median	standard deviation	coefficient of variation
	n	min	max	R_v	l_{qv}	u_{qv}	R_{iq}	x_m	x_{me}	s	c_v
oedometric modulus E_{oed}^{ul} [MPa]	141	29	432,2	403,3	73,4	196,2	122,9	150,1	122,4	95,9	0,639
oedometric modulus E_{oed}^{rl} [MPa]	134	18,8	323,7	304,9	40,4	128	87,6	94	74,4	67,8	0,721
oedometric modulus E_{oed}^{ol} [MPa]	151	9,7	54,6	44,9	20	30,7	10,7	26,1	24,3	9,3	0,357
effective cohesion c_{ef} [kPa]	58	5,1	61,8	56,7	21,3	40,8	19,5	31,8	32,7	14,7	0,462
effective angle of internal friction φ_{ef} [°]	56	20,4	32,8	12,4	23,4	28,8	5,4	26,2	26,3	3,24	0,123

Tab. 4. Typical values of the coefficients of variation of mechanical characteristics of cohesive soils.

property	range of typical values c_v
angle of internal friction φ_{ef}	0.05 ~ 0.19
cohesion c_{ef}, cu	0.20 ~ 0.50
oedometric modulus E_{oed}	0.20 ~ 0.40

The situation is more complicated in the part of the model profile, as predominantly the sands and the sediments with significant portion of sands occur locally in the immediate basement of the Pleistocene alluvial sequence. The base of the coarse-grained fluvial sediments of the channel facies attributed to the Quaternary age can be identified in the profile based on the upward fining sequences commonly starting with boulders on their base. The stratigraphic position of that boundary may not be clear, especially in case of the MAX locality, where the sediments immediately below the gravels can be a part of the Quaternary unit, but they can be correlated also with the Kolárovo Fm. of the Pliocene age. The occurrences of sands in the profile continuation below the base of the Quaternary deposits are more common in the direction into the basin's central part. There exists a gradual trend of increase of the sandy proportion with transition to upper and younger lithostratigraphic levels, in the southward direction from the late Pannonian to the late Pliocene. Especially in the sediments of the Kolárovo Fm., stratigraphically classified to the late Pliocene, the sands, sands with gravel and "clean" gravels often occur, i.e. the studied boundary (base of the Quaternary sediments) may not be clearly contrasting.

A separate group in the pre-Quaternary foundation soils within the model profile are typical fluvial channel-fill facies strata on the MAX locality. Predominantly sands of different varieties were described in the immediate basement of the channel-fill facies of coarse gravels on the above mentioned locality, while the "clean" sands, classified as the sand poorly grained and the sand with an admixture of fine-grained fraction according to the STN, have significant proportion in the profile. A possible affiliation of these sands to the pre-Quaternary basement would be in terms of macroscopic description indicated especially by the sediment colour. However, their typical bedding is missing in contrast to the "normal" sandy facies in the immediate pre-Quaternary basement, the sediments were in general massive, with minimum interbeds with increased silt proportion. An occasional irregular admixture of fine gravel in the sands indicates a more dynamic sedimentation environment compared to the Neogene lacustrine to alluvial sediments of the pre-Quaternary basement. The character of the lower boundary of these sediments is substantial, as well, while it indicates erosive incision of the river bed without an apparent lateral migration (the ratio width/height of the body is ca. 30).

The sediment colouration may indicate a different depositional environment, the greenish colours indicate the presence of floodplain accumulation, the blue and grey colours may indicate input of sediment by erosion of the banks formed by the pre-existing Neogene sediments and their transport on a small distance. The occurrence of a wider spectrum of facies from the alluvial through the semi-transmissive ponds up to the oxbow lakes is possible in the overbank environment, what may correspond also with the macroscopic features of the sediments including colouration. These features led the authors to the classification of the predominantly sandy section in the direct basement of the fluvial gravels once again to the fluvial channel-fill sediments, however the stratigraphical classification is possible to derive only from their position in the profile. There is a very striking difference of the problematic section of the sands from their immediate basement at the MAX locality: the "typical" pre-Quaternary basement profile was documented from the 34.6 m depth below the terrain, in which the sands occur, too, however its proportion is significantly lower and all the macroscopic features determine the sediment as an alluvial one (pronounced bedding, laminations, alternation of the clays, silts and sands layers, organic interlayers etc.). Taking into account all the features of the mentioned section of sediments at the MAX locality, the most suitable solution is their correlation with the sediments of the Kolárovo Fm. of the Pliocene age. These deposits form here an isolated remnant survived locally, after most of the correlative succession was removed in the vicinity by the erosion of the Danube river during the Quaternary (Fig. 10).

The occurrences of the similar situations are according to the existing archive documentation spatially bound to the zone in the close proximity to the recent flow of the Danube river. Situation comparable to the Retro and MAX localities could be observed on the right bank, for example the Vienna Gate Residence (Janták, 2004). The formation of the analogous phenomena is most likely bound to the area of the alluvial terrace of the Danube river, the extent of which was determined by the decreasing activity of the Danube fault system in the Late Pleistocene. The margin of the alluvial terrace towards the basin is situated on the south-east profile termination at the Slovnaft refinery area. The territory, which follows in the further continuation towards the south-east, is partly influenced by the subsidence of the Danube Basin centre, which documents the onset of the sediments of the Kolárovo Fm. with gradual increase of their thickness. A considerable part of the subsidence is expected to be a result of the gradual compaction of the profile of the unconsolidated sediments of the Upper Miocene and Pliocene. The rate of subsidence is influenced by the height of the column of the unconsolidated sediments,

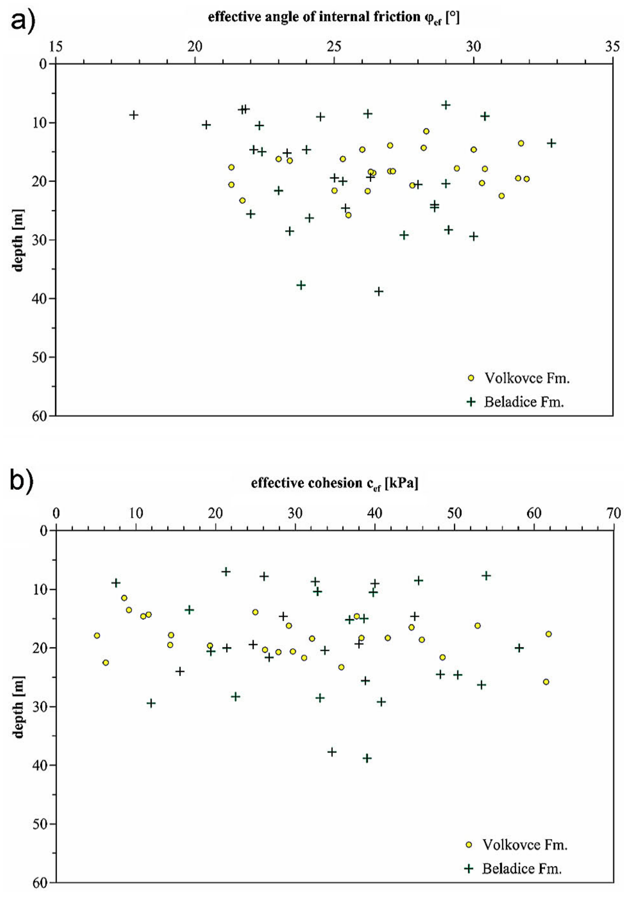

Fig. 8. a) Effective angle of internal friction depending on depth (φ_{ef}); b) Effective cohesion of soils depending on depth (c_{ef}).

i.e. by the inclination of the pre-Cenozoic basement surface in the direction from the Malé Karpaty Mts. into the basin. The delimitation of the alluvial terrace towards the basin´s central depression correlates well with the expected course of the marginal faults of the north-east direction, which limit the Malé Karpaty Mts. horst towards the Danube Basin (Fordinál, 1993; Bielik et al., 2002, Lenhardt et al., 2007).

The occurrence of the separate gravel layer with the fine-grained subsoil at a depth interval ~ 28.6–29.9 m below the terrain surface at the Retro locality belongs among the exotic phenomena. The gravels are by their sorting and maturity of the material similar to the Danube ones, however, they occur below the series of fine-grained and sandy sediments including a coal layer, which should be ranked according to the macroscopic features to the Upper Miocene. The gravel layer can be the basal part of the gradational interval in a sandy body of the meandering channel, or possibly sediment of a crevasse splay. Taking into account all the characteristics of the given section of predominantly sandy sediments, they were classified to the Volkovce Fm. The sediment was deposited in the proximity to a channel belt in contrast to the prevailing volume of the Volkovce Fm., formed by the clays and silts in the studied area, deposited in a less dynamic river floodplain.

A limited difference with possible genetic interpretation can be observed in terms of the facies and lithotypes grain size distribution in the Beladice and Volkovce fms. The lithotypes at the Slovany and Nové Slovany localities (Fig. 4a) show a relatively significant vertical variability on an areally not very large territory. However, the beds are in terms of lateral variability lithologically constant, the cyclical variations happen only in the vertical direction. There were lithologically slightly different localities documented in the Volkovce Fm. with the following possible interpretation: 1) the Retro locality – the transition river channel/alluvial plain (Fig. 4c); 2) the Jégého alej locality – the proximal alluvial plain with the occurrence of the crevasse splays (Fig. 4b) and 3) the Čierny les locality – proximal to distal alluvial plain with dominance of deposition from suspension and sporadic occurrence of the sediments of traction currents (crevasse splays) (Fig. 4f).

Considering the above discussed information, it can be assumed, that there will be a low lateral variability of the lithotypes with defined variance at the construction sites situated in the sediments environment of the Beladice Fm. The Volkovce Fm. is on the contrary lithologically laterally less constant and it is necessary to consider the possibility, that there will be intercepted a lateral transition of the lithologically different sediments in the construction pit (e.g. the Retro locality). Although the individual macroforms in the order channel – transition zone (e.g. levee, crevasse splay) – alluvial plain reach the size of hundreds of metres, and therefore the probability of the environments

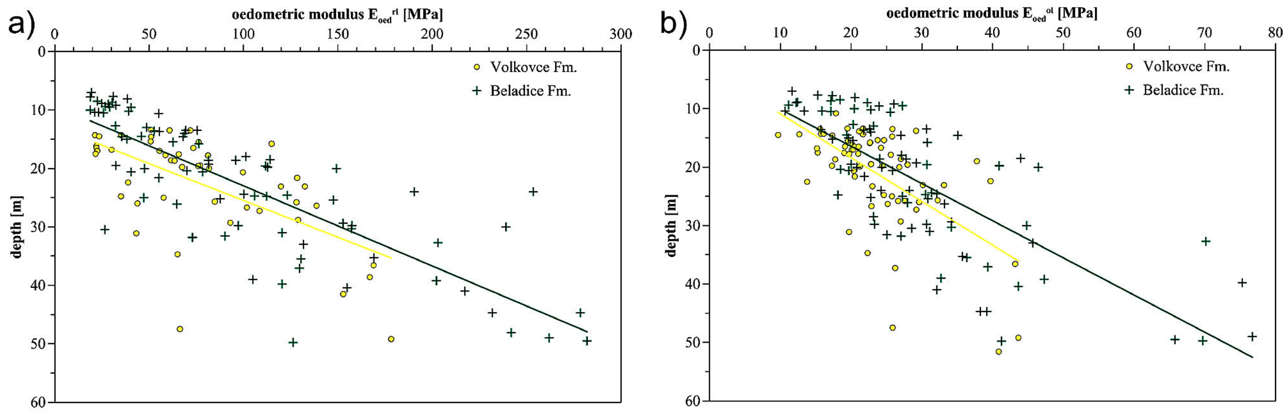

Fig. 9. a) Oedometric modules for the pre-consolidation phase (reloading) depending on depth (E_{oed}^{rl}); b) Oedometric modules for the phase of primary load (overloading) depending on depth (E_{oed}^{ol}).

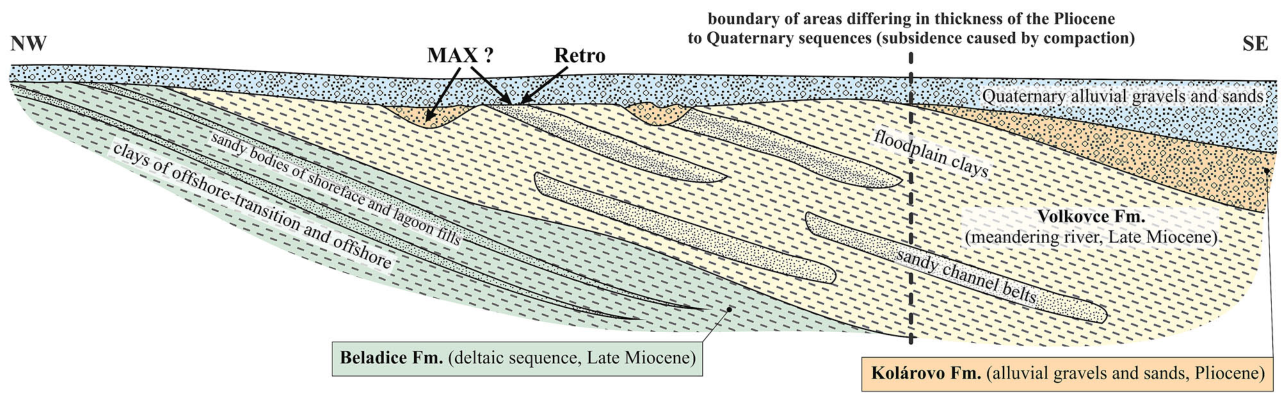

Fig. 10. Scheme of the expected sedimentary settings in the model profile.

boundary occurrence at the area of an individual construction site is low, however, the particular situation may occur.

4.2 Geotechnics

The pre-Quaternary basement of the Neogene age is formed in the model profile prevailingly by the fine-grained subsoils with a slight predominance of the silt fraction, what can be generalized for the foundation soils classified to both the Beladice Fm. and Volkovce Fm. The position of samples in the plasticity chart points to the similarity of the subsoil types in both lithostratigraphic units, while the shapes of the regression functions $I_p = f(w_L)$ are very similar for both sets. A similar statement may be given also for the all physical – descriptive (index) characteristics of the foundation soils of both studied sets. The position of samples in the individual diagrams (Figs. 6–7) points to very similar ranges of the individual evaluated parameters, at the considerable variance and the absence of any trend indication depending on the depth of occurrence. A certain indication of the difference of both sets is observable at the greater depths of occurrence, from ca. 30 to 40 m towards the depth: Liquid limit and the plasticity index reach lower values for the subsoils samples from the Volkovce Fm., on the contrary the unit weights are lower for the subsoils from the Beladice Fm. The only index characteristic, which shows a certain trend depending on depth, is the consistency index of foundation soils. The variance I_C decreases with the increasing depth of occurrence, while the subsoils classified to the Volkovce Fm. show rather lower values (a firm consistency predominantly) and the subsoils classified to the Beladice Fm. show rather higher values (very firm consistency).

The situation is similar with the shear strenght parameters when evaluating the mechanical properties of foundation soils of both sets. The values of the effective angle of shear strength and effective cohesion do not show any trend depending on depth of occurrence. The position of samples in the diagrams (Fig. 8) simultaneously covers approximately the same area for the samples from both, the Beladice and Volkovce fms. In case of the oedometric modules there is a visible increase of values depending on depth of the foundation soil occurrence, what is a standard property of the characteristic, dependent on the stress condition in the subgrade. In case of the model profile it is possible to state, that the oedometer modules for the preconsolidation phase (reloading) are very similar for both studied sets, while an orientation equation $E_{oed}{}^{rl} = 4 \times h - 10$ [MPa] can be derived for the dependence of the modulus value on depth. The subsoils classified to the Beladice Fm. show slightly higher values, when evaluating the modules for the phase of overloading, however, this difference is insignificant. Similarly, an orientation equation $E_{oed}{}^{ol} = 0.7 \times h + 9$ [MPa] can be introduced for the modules from the overloading. A further verification of the applicability of the similar dependences on bigger sets from the larger area of Bratislava is necessary.

The rate of geological pre-consolidation can be assumed based on the estimation of the sediments column thickness, by which the layers of the Neogene age, forming the immediate basement of the Quaternary sediments, were loaded. A rough estimation can be carried out based on the data of seismic section 556/82-83, oriented perpendicular to the Malé Karpaty Mts. horst (Hrušecký, 1999). Using the seismic section, a correlation was made with the basin central part, where is expected continuous deposition and upper boundary of the Late Miocene sequence is buried below the Pliocene to Quaternary succession. In the area of the Grob-1 borehole penetration (ca 5 km from the Malé Karpaty Mts. foothill and comparable to studied area), the missing column of the overlain sediments can be estimated to ca 160 m. These sediments were probably eroded away during the Pliocene and Quaternary. The Neogene sediments in the immediate basement of the Quaternary sequence are thus recently substantially less loaded in comparison to the depth of their burial during the latest Late Miocene.

5. CONCLUSIONS

The research is based on the complex analysis of the geotechnical parameters of the Neogene cohesive foundation soils of the pre-Quaternary basement, obtained at the model profile of the left bank of the Danube river in Bratislava (situated on the northwestern margin of the Danube Basin). The study based on analysis and comparison of sedimentological and geotechnical features of the Neogene subsoils led to following main conclusions:

(1) The Quaternary base with underlying Neogene formation soils is in the most of the area lithologically contrast and well traceable boundary, with sandy-gravelly strata overlying mostly clayey and silty subsoils.

(2) The pre-Quaternary basement is formed in the most of the study area by the deltaic Beladice and alluvial Volkovce formations, both of the Late Miocene age. Their transition below the Quaternary base is a result of overall inclination of the Late Miocene succession towards the central part of the Danube Basin and an angular unconformity towards the overlying Quaternary sequence.

(3) The Beladice and Volkovce formations differ in origin and in facies associations. This resulted in difference in lateral and vertical variability of facies. The alluvial Volkovce Fm. is typical by more frequent lateral changes in lithology, mainly on boundaries of sandy channel belts and fine grained floodplain strata. On the other side, the Beladice Fm. exhibits spatially less variable lithology. This is assumed as important in terms of exploration practise. At the construction sites located in the Volkovce Fm. subsoil complexes it is necessary to count with the possibility of the lateral transitions of various sedimentary facies. The similar situation is in the case of the Beladice Fm. very improbable.

(4) A significant relatedness of the subsoils corresponding to the Volkovce Fm. and Beladice Fm. in terms of their geotechnical properties could be stated. The likeness of the foundation soil complexes represented by the Beladice and Volkovce fms. is inferred from the results of the mutual comparison of their physical properties. A similar fact was confirmed also by the statistically evaluated parameters of the shear strength of

the Neogene foundation soils. As the parameters of the shear strength of the above mentioned subsoils are determined especially by their physical properties, the mutual similarity of both sets is logical.

(5) The effect of the geological pre-consolidation (influence of the long-term effect of the weight of the column of the overlying sediments, including the recently eroded sections), evidently overwhelms possible differences of the subsoils properties, which could result from differences in the facies associations. The overall thickness of the column of the overlain sediments, which were eroded during the Pliocene and Quaternary, can be roughly estimated on ca. 160 m. The history of the foundation soils loading significantly influences (in this case reduces) the differences in the deformation characteristics. Stress condition resulting from the position of the sample in the depth profile (geostatic stress) during its burial and the pre-consolidation of foundation soils (technical and/or geological pre-consolidation) affected the deformation properties. The superposition of the Volkovce Fm. above the Beladice Fm. might resulted in slightly higher values of the oedometric modules of the Beladice Fm., which was buried deeper and the pre-consolidation was more intense in its case. Based on the mentioned facts, variability of the determined geotechnical characteristics of the subsoils is affected in very low degree by the grain size composition, physical properties and origin of the sediment.

(6) Significantly different characteristics of foundation soils, forming the direct basement of the Quaternary gravelly fluvial accumulation, were indicated in the part of the model profile at the MAX and Retro localities. The subsoils with a large proportion of sand in that section is very likely possible to correlate with the sediments of the Kolárovo Fm. of the Pliocene age. As they are the subsoils with significantly different classification features, they were not included into the comparison, which is oriented on the cohesive foundation soils of the pre-Quaternary basement. The possibility of occurrence of the prevailingly sandy sediments of the Kolárovo Fm. in the immediate Quaternary basement is further necessary to take into account towards the centre of the basin. This fact may have a significant impact on the proposals for the drainage of the construction pits, especially in terms of the probability of filtration anomalies occurrence.

(7) The foundation soil complexes of the Beladice and Volkovce fms. can be in terms of the analysed physical properties considered as very similar and their mutual dividing line only for the palaeo-environmental boundary The results of the experimental verifications of the physical-descriptive properties of the Neogene foundation soils of the Beladice and Volkovce fms. give a real possibility of introducing an assumption, that both formations can be connected into one quasi homogeneous block. In this case, the set of statistically analyzed parameters of the subsoils samples, taken in the model profile, could be extended by the further set of experimental measurements realized on subsoils of the Neogene complex from a larger area of Bratislava (similar attempt is expected to continue the research). In practical terms, it would be useful to realize the regression analysis of the relationship between the physical and mechanical properties of the Neogene foundation soils and in view of the applicable Eurocode 7 also the expression of the characteristic values of physical and mechanical properties of the Neogene foundation soils. This procedure was applied by the authors as a standard at the individual construction sites and there exist a real assumption for an attempt for similar correlations also for a larger study area. The sediments of the Kolárovo Fm. will require a separate analysis, namely in terms of their spatial distribution, as well, as in terms of their geotechnical properties.

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