Engineering geology of the Bucharest city area, Romania

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Abstract: The aim of the paper is to present briefly the geotechnical and geological conditions of Bucharest city.

The paper includes five sections covering: geological and geomorphological conditions; the lithological succession from the surface to a depth of about 250 m; the hydrogeological characteristics of the main geological units; their geotechnical properties and the dynamic properties of the soil layers. The last section emphasises the seismic characteristics of the lithological layers using information obtained from measurements taken during the earthquakes of 1977 and 1986 and also from experimental tests using geophysical methods.

Bucharest city is located on a plain with micro-relief resulting from erosion and sedimentary processes which extended along the valleys of the Dambovita River to the south and the Colentina River to the north. The city is located in the axial area of a syncline where the thickness of the sedimentary deposits is greatest (1000m). Subsidence features, oriented NE-SW, are caused by neotectonic movements that affect Neogene and Quaternary deposits. The area represents a seismic risk due to the lack of solid rocks at surface.

The geotechnical part of the paper utilises geotechnical data used in the design of the metro.

Résumé: Le but de cet ouvrage este de présenter brièvement les conditions géotechniques et géologiques de la ville de Bucarest. L'ouvrage contient cinq sections couvrant: les conditions géologiques et géomorphologiques, la succession lithologique à partir de la surface jusqu'à une profondeur d'environ 250 m, les conditions hydrogéologiques concernant l'aquifère phréatique et sous pression spécifique à la zone de Bucarest, les conditions géotechniques comprenant des détails de la base de données qui inclut les valeurs des paramètres spécifiques - physiques et mécaniques - des unités lithologiques et les propriétés dynamiques des couches du sol. Cette section met l'accent sur les caractéristiques séismiques des couches du sol. Cette information a été obtenue par les mesurages faites pendant les tremblements de terre de 1977 et 1986 et aussi par des tests expérimentaux utilisant des méthodes géophysiques.

Quelques-unes des conclusions présentées dans l'ouvrage sont: du point de vue géographique, morphologique et hydrographique, la ville de Bucarest est située dans une plaine ayant un micro-relief résulté de l'érosion et des processus de sédimentation développés au long de deux vallées: la vallée de la Dambovita au sud et la vallée de la Colentina au nord. Du point de vue géologique, le cadre structurel spécifique à la Plaine Roumaine est un synclinal avec des caractéristiques de subsidence, ayant une orientation sud-ouest/nord-est. La subsidence est causée par des mouvements néotectoniques qui influencent les depôts du Néogène et Quaternaire.

Bucarest est situé dans la zone axiale du synclinal où l'épaisseur des depôts sédimentaires est la plus grande (1000 m). Cette zone présente un risque séismique à cause de l'absence des roches solides à la surface.

La section géotechnique de cet ouvrage utilise des dates géotechniques employées dans la conception du métro pour le calcul de résistance structurale pour des tunnels circulaires et rectangulaires.

Cet ouvrage inclut des plans et sections géologiques et hydrogéologiques.

Keywords: aquifers, bearing capacity, clay, geology of cities, porosity, silt

INTRODUCTION

Bucharest, the capital of Romania is situated in the south-east of the country, 64 km north of the River Danube, 100 km south of the Eastern Carpathian Mountains and 250 km west of the Black Sea.

The city enjoys a temperate - continental climate with very cold winters and hot summers (Table 1). Spring and summer are the wettest months. The prevailing winds are predominantly from the north-east and south-west (Table 2) but easterly and westerly components are also significant.

Table 1. Air temperature- monthly and annual average (Bucharest-Baneasa metereological station)

Months												Annual
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Monthly and annual average /°C												
-3,0	-9,0	4,5	11,0	16,4	20,1	22,4	21,6	17,5	11,1	5,1	2,0	10,4

Table 2. Wind frequency (%) by seasons and directions

Season	Winter	Spring	Summer	Autumn
Direction				
N	1,6	3,0	5,5	3,9
NE	19,7	20,8	13,6	16,9
E	8,3	14,5	10,1	9,3
SE	1,1	2,2	2,4	1,1
S	0,8	1,8	1,8	1,4
SW	19,8	10,7	7,1	11,8
W	11,0	9,0	8,3	8,2
NW	1,4	2,3	4,0	1,7
Calm	36,3	35,7	47,2	45,7

The city of Bucharest is a built along the rivers Colentina and Dambovita, which drain south-eastwards across the low relief, Romanian plain. The rivers follow meandering courses, flanked by low-lying marshy depressions, which have been drained.

The geomorphology of the city comprises:

1) the lower alluvial floodplain meadows on the riversides.
2) the interfluve areas with altitudes up to 90 m in the north-west and 75 m (above the Black Sea level) in the south-east.
3) the higher plains, extending towards the north and south.

The commercial centre of Bucharest is largely located on the interfluve areas.

GEOLOGICAL OUTLINE

Geologically, Bucharest is situated above a north-east-south-west-trending Neogene sedimentary basin developed in the central part of the Moesic Platform. Following a long period of erosion during the Palaeogene, subsidence in Miocene times led to the accumulation of deep water deposits of clay and clayey marl within the Sarmatian Sea. During the Pliocene, shallower water facies, predominantly of sand and gravel, accumulated as connection to the Sarmartian Sea was periodically interrupted. Stratigraphic breaks in the Pliocene succession mark periods when sediment supply exceeded subsidence. Around Bucharest, the Pliocene has a thickness of around 700m.

By the end of the Pliocene, basin infilling was complete and the Quaternary development of the Romanian Plain commenced. The Quaternary sequence, totalling 250 m in thickness, comprises fluvial, lacustrine and wind-blown deposits.

Lithological details

The pre-Quaternary succession beneath Bucharest is made of alternating complexes of non-cohesive soil (sand and/or gravel) and cohesive clays. The Quaternary comprises an older loessic cover and younger floodplain deposits (river alluvium, lacustrine deposits, alluvial cones and terraces).

Based on geotechnical information from over 2000 borings, and a classification developed from a review of the technical literature, the deposits have been classified as follows:

Type 1 : Recent sediments: organic soil and clay-rich lithologies, with a thickness locally reaching 15 m.

Type 2: Upper Sandy-Clayey Complex: constituted partly of loessic deposits, often moisture sensitive, and including sand layers. This unit ranges in thickness from 16 m in the north to less than 1 m on the riverside.

Research into the structure of these deposits reveals two lithofacies: ‘field deposits’ and ‘meadow deposits’, which differ in thickness, structure and mode of origin.

The ‘field deposits’ comprise loess and loess-loam deposits. The loess deposits are characterised by an upper darker (yellow brown) layer that has been leached by meteoric waters and a lower white-yellow layer, incorporating a dense network of calcareous veinlets, together with disseminated and concretionary carbonate. Particle size is in the silty clay range (20% clay: 50% silt).

The loess-loams are greyish brown and generally plastic. They are non-calcareous, contain black iron-manganese pigmentations and grains, and have a higher clay fraction than the loess.

The two types described above occur inter-stratified over the fields on the left bank of Colentina River, over the Dambovita – Colentina interfluve and on the right bank of Dambovita River. The loessic deposits are regarded as aeolian in origin, whereas the loess-loams are considered to have formed in a lacustrine environment.

The ‘meadow deposits’, in contrast, consist of alluvial deposits of grey or black, silty or sandy organic-rich, clays, and grey, fine-grained, micaceous sands with a clay matrix.

Type 3 Colentina Gravel Complex: up to 20 m thick and made up of poorly sorted, cross-stratified sand and gravel with interbedded clayey layers. The structure of the gravels indicates a high energy environment of deposition.

Type 4 Intermediate Clay Complex: up to 23 m of alternating brown and grey clays, with sandy intercalations, and abundant disseminated carbonate and limonite. The thickness of the unit decreases southwards until it eventually dies out. The unit is believed to be of lacustrine origin.

Type 5 Mostistea Sand Complex: from 10 to 15 m thick, a partially confined water-bearing layer made up of grey, fine-grained sands with lenticular intercalations of clay. The unit is present as a continuous layer beneath Bucharest city.

Type 6 Lacustrine Complex: 10-60 m of clay and silty clay, with lenticular sandy layers, most located at the top of the complex. The grey colour and carbonate content are indicative of a lacustrine origin.

Type 7 Fratesti Sands Complex is the deepest founding stratum with a thickness of 100 to 180 m. It includes A, B and C Fratesti levels. It is made up of sands and gravel, from which water for industrial and drinking purposes is abstracted.

HYDROGEOLOGY

The units that are important hydrogeologically are classified as follows:

Colentina Gravel Complex: commonly water bearing, with a variable watertable ranging from 1.5 to 14.00 m below ground level. The specific average permeability coefficient of this aquifer is between 50 m and 250 m per day.

Intermediate Clay Complex: a laterally impersistent aquiclude with saturated sand intercalations

Mostistea Sand Complex: a partially confined water-bearing layer. In areas where the overlying Intermediate Clay Complex is thin or absent there is hydraulic continuity between this unit and the Colentina Gravel Complex above.

Lacustrine Complex: an aquiclude

Fratesti Sands Complex: a major aquifer from which water for industrial and drinking purposes is abstracted.

Measured groundwater levels taken over a 26-year period from over 300 piezometers show a maximum watertable variation of 1 m in areas unaffected by pumping. Modelling research used to optimise the design of dewatering systems for underground engineering projects (planned or under construction) suggest hydraulic conductivities values as follows:

- 50-100m/day for gravels with sands;
- 5-10m/day for sand;
- 1m/day maximum for clayey and silty sands

GEOTECHNICAL CHARACTERISATION

The geotechnical conditions for the Bucharest area are known from site investigation data held by METROUL S.A. and by other companies who have been close collaborators with our group for many years. The data provide a useful regional overview of the geotechnical properties of the near-surface layers to the maximum drilling depth of 70 m.

This section summarises the geotechnical conditions in three representative areas of the city:

- Plains area, from north of Colentina River to south of Dambovita River,
- Interfluve area
- Meadow area

Plains area (South of Dambovita River and North of Colentina River)

In this area, drilling revealed a uniform sequence consisting of:

Type 1: Recent sediments: The natural sediments have largely been replaced by backfill resulting from building demolition. This man-made layer is typically 0.50-4.00 m thick.

Type 2: Upper Sandy-Clayey Complex. This unit varies between 9.00 and 20.00 m in thickness. In the south- west of the city, the sequence comprises two or three zoned sedimentary cycles comprising in upwards sequence:

Cycle 1 (B1,C1) Cycle 2 (B2,C2) and Cycle 3 (B,C). The top of the lower unit is marked by a buried soil horizon.

The cycles are differentiated on the basis of:

- Carbonate content - B, B1 and B2 layers generally contain a high content of iron oxides but no carbonate, whereas C, C1, and C2 layers contain abundant carbonate disseminations
- Colour and grain size. B, B1, B2 layers are typically dark grey and red silty clays whereas C, C1, C2 layers are mainly yellow-brown to whitish yellow clayey silts
- Structure - Layer C preserves some of its original loessic structure and is macroporous

In geotechnical terms, the physical and mechanical properties of individual layers are similar and the deposits can be considered, therefore, as a single unit.

Particle size analyses show the deposits fall on the boundary between clays and clayey silts (average: sand 13%, silt 48%, clay 39%). Distribution diagrams confirm the vertical and lateral homogeneity and uniformity of the loam packet.

Plasticity index values range from 19 to 39% (average 28%). However, B layers have a higher plasticity, due probably to the higher clay content and presence of organic material.

Moisture content varies within small limits, 12-26% (average 19%). Consistency index is from 0.80 to 1.00 (average 0.90) which classifies them as plastic, stiff and hard.

Porosity varies between 36 and 47% (average 40%) for layer B and 38 to 48% (average 44%) for layer C.

The difference in averages between the two layers can be attributed to the macroporous structure of layer C. Compressibility tests by oedometer confirm that character and indicate a specific settlement coefficient of 12mm/m to 45mm/m (average 27mm/m) for B layers and 12 to 41mm/m (average 38mm/m) for C layers.

The values for porosity (n=46-51%) obtained from some samples indicate a high macroporosity and sensitivity to moisture of carbonate layers.

The main characteristic of brown clays from surface is their high shrink-swell potential under seasonal variations of temperature and humidity.

Local maximum values for shrink-swell phenomenon (about 24%) impose restrictions on construction and foundation design.

Table 3. Geotechnical data for selected sequences, North Plain and South Plain

Physic-mechanical features	**NORTH PLAIN**		**SOUTH PLAIN**	
	Loam layer - B	**Loam layer - C**	**Loam layer - B**	**Loam layer - C**
- Sand (%)	12	14	10	13
- Silt (%)	47	50	49	52
- Clay(%	41	36	41	35
- Ip (%)	24-37	14 - 29	26 – 39	30 -50
- W (%	14-24	14 - 23	14 – 23	14 - 23
- Ic (-)	0,75-1,00	0,70 – 1,05	0,75 - 1,00	0,75– 1,00
- γ_W (t/mc)	1,80 -2,05	1,65 – 2,00	1,84 – 2,07	1,70 – 2,02
- n (%)	36-42	39 - 45	36 - 43	39 - 45
- M_{2-3} (KPa)	8000 -14300	5000 - 12500	8000 - 22000	7000 - 13000
- ep_2 (mm/m)	11 - 35	14 - 35	14 – 35	15 – 36
- ep_3 (mm/m)		24 - 68		30- 82
- φ (^{0})	14 - 28	18 - 31	17 - 27	20 - 30
- c (KPa)	40 - 65	30 -50	35 - 70	30 -65

* γ_W - natural unit weight,
n – porosity,
M_{2-3} – compression modulus
φ - angle of shear friction,
C - cohesion and Un is non-uniformity coefficient.
ep_2 – settlement index
ep_3 – specific settlement to humidity
W – moisture content
Ip– plasticity index
Ic – consistency index

Type 3 : Colentina Gravels Complex. To the south and south-west of Dambovita River, Type 2 lithologies pass down through a transitional layer of grey or yellow clayey or sandy silt layers into the Colentina Gravels complex. This latter consists of fine, medium and coarse-grained sand with rare gravel. The particle size distribution averages: silt 8%, fine-grained sand 11%, medium-grained sand 25%, coarse-grained sand 30%, and gravel 26%.

Non-uniformity coefficient, Un, is about 2-15.

Over the remainder of the North Plain area, the Colentina Gravels Complex and underlying units (4, 5 and 6) show little geotechnical variation and the geotechnical properties are given in the next section.

Type 4: Intermediate Clay Complex comprises cohesive soils ranging in lithology from clayey sands to more widely occurring clays. The preponderance of yellow-brown clays containing disseminated carbonate and black coaly streaks and inclusions is characteristic. The thickness varies from 3 to 7 m. Permeable, fine to medium-grained sand laminations and thicker beds are found locally. In areas where the Colentina sands and gravels are absent, the unit is overlain by Type 1 deposits.

Type 5: Mostistea Sands Complex is made of grey medium- and coarse-grained sands, between 3 and 8 m thick. The unit is normally encountered at a depth of 25 to 30 m.

Type 6 : Lacustrine Complex is characterized by very consolidated marls with fine clayey sands, and some cemented sands.

In conclusion, drilling performed on the plains to the north and south of the Dambovita river, proved essentially the same successions. The only difference found was in the south-west of the area, where the loam package was around 20.00 m thick and made of two, or sometimes three B and C layers, whereas in the interfluve area it has a maximum thickness of 5.00 m and represented by single B and C layers.

Dambovita - Colentina interfluve

The succession is similar to that of the plain but the units differ in thickness.

Type 1: Recent sediments: backfill soil with brick fragments (around 0.50-3 m, locally 6-7 m). Only very rarely does this unit include organic soil.

Type 2: Upper Sandy-Clayey Complex: brown silty clay (layer B) overlying yellow-brown clayey silt with carbonate veins and concretions (layer C). Thicknesses are normally in the range 0.50 and 3.00 m, locally reaching a maximum of 5 m.

Table 4. Physical and mechanical properties of loam layers (Type 2)

Physic-mechanical features	**Loams layer - B**	**Loams layer - C**
- Sand (%)	17	26
- Silt(%)	46	43
- Clay (%	37	31
- Ip (%)	20-38	15 - 27
- W (%	14 – 26	12 - 22
- Ic (-)	0,80 – 1,10	0,74 – 1,10
- γ_W (KN/mc)	18,5 -21,0	17,5– 20,0
- n (%)	35-41	36 - 45
- M_{2-3} (KPa)	7000 -16500	6500 - 14000
- ep, (mm/m)	12 - 30	17 - 40
- φ (^{0})	11 - 20	16 - 22
- c (KPa)	40 - 75	28 - 50

Type 3: Colentina Gravel Complex: The contact between type 2 and type 3 deposits is locally transitional over 1-3 m of strata comprising silty clay lenses and silty sandy clays.

Particle size analysis gives an average grading of:

- Fine-grained sand 8%
- Medium-grained sand 12%
- Coarse-grained sand 20%
- Gravel 60%

Other geotechnical properties are:

γ_W = 20.00 KN/m^3,
n = 34%-46%,
M_{2-3} =25000-50000 (KPa),
$\varphi = 28^0 - 36^0$,
C =0KPa,
Un = 2,5 – 15

Type 4 Intermediate Clay Complex

Table 5. Physical and mechanical properties of silty clay deposits (Type 4)

Physic-mechanical features	**Silty clay deposits**
Sand (%)	17
Silt (%)	40
Clay (%	43
Ip (%)	24 - 45
W (%	18– 29
Ic (-)	0.74 – 0.95
γ_W (KN/mc)	18.5 - 20.50
- n (%)	36 - 40
- M_{2-3} (KPa)	9000 - 25000
- ep, (mm/m)	12 - 22
- φ (^{0})	10 - 18
- c (KPa)	60 - 90

Type 5: Mostistea Sands Complex Deposits thicker than on the plain, typically in the range 15-20 m.

Table 6. Physical and mechanical properties of sandy deposits (Type 5)

Physic-mechanical features	**Sandy deposits**
- Silt (%)	18 - 20
- Fine-grained sand (%)	10 - 25
- Medium-grained sand (%)	43
- Coarse-grained sand (%)	29 - 55
- γ_w (KN/mc)	19.50 - 21.00
- n (%)	20,0
- M_{2-3} (KPa)	10000 - 25000
- φ (^{0})	23 - 27
- c (KPa)	0 - 5
- Un	2 - 10

This complex includes also clayey, silty sub-units, with thicknesses of 1-2 m.

Type 6: Lacustrine Complex

Table 7. Physical and mechanical properties of clayey layers (Type 6)

Physic-mechanical features	**Silty clays deposits**
- Sand (%)	8
- Silt (%)	42
- Clay (%	50
- Ip (%)	14 - 36
- W (%	18– 20
- Ic (-)	0,74 – 1,20
- γ_w (KN/mc)	19,0 - 21,0
- n (%)	34- 39
- M_{2-3} (KPa)	15000 - 35000
- ep_2 (mm/m)	2 - 8
- φ (^{0})	8 - 30
- c (KPa)	20 - 90

The meadow area

Drilling of the meadow area revealed the following stratification:

Type 1: Recent sediments Backfill made of brick fragments, debris, and rubbish 0.5-3.5 m thick

Type 2: Alluvial deposits 5-8 m of clayey and silty soils. Some variation from organic clays to sands depending on whether the drilling was performed in former marshes or swamps or in abandoned river channels of the Dambovita and its tributaries. The alluvial deposits are poorly consolidated and more highly compressible than the Type 4 loams of other areas.

Table 8. Physic-mechanical features silty clayey deposits or sandy silty deposits (Type 2)

Physic-mechanical features	**Silty clayey deposits**	**Sandy silty deposits**
- Sand (%)	17	44
- Silt (%)	36	21
- Clay (%	46	30
- Ip (%)	15 - 45	14 - 30
- W (%	15 – 22	13 - 18
- Ic (-)	0,40 – 0,85	0,30 – 0,80
- γ_w (KN/mc)	15,40 - 21,00	17,70 - 19,50
- n (%)	36 - 42	38- 44
- M_{2-3} (KPa)	4000 - 12000	4700 - 10000
- ep_2 (mm/m)	15- 90	16 - 65
- φ (^{0})	14 -20	12 -25
- c (KPa)	30 - 70	10 - 50

Type 3 : Colentina gravel complex Fine- and medium-grained sands passing down into medium and coarse-grained sand with silty pockets and fine- to medium-grained gravel. The base of the unit was found at 10-15 m depth.

The succession beneath the Type 3 deposits is similar to that beneath the plain and interfluve areas.

DYNAMIC PROPERTIES OF THE SOIL LAYERS

The control of local geology on seismic effects in Bucharest was observed during the 1977 Vrancea earthquake. The effect on ground motion of the sedimentary cover was analysed by comparing frequency records from the 1986 earthquake accelerograms with the corresponding soil profiles at the recording sites (component soil layers, dynamic characteristics of the soil layers, the soil profile depth above bedrock, etc.). The soil condition information in Bucharest is known from soil profiles located near the sites of seismic stations, and along geological sections aligned NW- SE, SSW-NNE, W-E and N-S. Of particular interest is the intermediate clay unit which, during the 1986 and 1977 earthquakes, seemed to be associated with long period seismicity.

Although, the total depth of the soil profile at the sites studied, varies from 140 m to 180 m (the base of the profile is formed by a gravel complex), only the uppermost 50 - 60 m are crucial in defining the dynamic characteristics of the soil at different sites in the city. As an example in eastern Bucharest, in the uppermost 50 m of strata, 30 m consist of clay (control period of response spectra T_c = 1.26 s, Aug. 30, 1986).

The seismic coefficient (Ks) for Bucharest city is 0.20 in accordance with Romanian norms.

The shear wave velocities determined in 1997 in eastern Bucharest are characterized an average velocity (in the uppermost 70 m) of V_s = 315 m/s. At the same site, for the intermediate clay deposits (18 m depth) the shear wave velocity and the longitudinal wave velocity were determined as: V_s = 236 m/s and, V_p = 715 m/s, respectively.

Following the Romanian-German collaboration on seismic effects of the Vrancea earthquake in Bucharest, based on CRC-461, a requirement to study shear wave velocities for different soil layers was identified. The aim was to acquire representative information for the whole city area. As a result shear wave velocities were determined by the Vertical Seismic Profiling method (VSP) for different depth intervals in selected boreholes throughout Bucharest.

From these measured velocities, characteristic vs. - values for each of the main soil layers in the subsurface were deduced. Using these data in conjunction with previously determined velocity and density data, a velocity /density model for the Quaternary layers in Bucharest was established.

Table 9. Velocity/density model.

Geologic layer no.	**Depth of the upper limit of the geologic layer (m)**	**Averaged density (g/cm^3)**	**Averaged v_s (m/s)**	
1 Backfill	0	1.10	Lungu et al 102	
2 Upper Clay Layer	0.50-5.00	1.75	Lungu et al 302	CPT 234-380
3 Colentina Aquifer (sand+gravel)	5.00-12.00	1.99	Lungu et al 335	CPT 255-280
4 Intermediate Clay Layer	10.00-20.00	2.07	378	
5 Mostistea Aquifer (fine to medium sand)	15.00-30.00	2.00	400	
6 Lacustrine Layer	35.00-50.00	2.14	442	
7 Fratesti aquifer A (sand+gravel)	100.00-180.00	2.05	500	

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