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DYNAMIC ANALYSIS AND THE SOIL IMPACT ON THE PILED RAFT FOUNDATION OF A TALL OFFICE BUILDING (I)

BY

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Abstract. The research presented starts from an extensive laboratory analysis of foundation soil and concludes by performing a dynamic analysis through a geotechnical computer program. The paper aims to show the undisguised design stages *prior* to a foundation project: investigation, design and determining the efficiency through verification. This study, presented in two parts, aims to highlight the influence of soil type during earthquake upon piled raft foundations (piles with large diameter – columns) of a high civil building. The analysis is performed on two types of earths indigenous to the area of Iaşi city, Romania. Foundation system is designed considering the influence of ground type in terms of sizing and behaviour over time, which means that the piles are computed as friction piles (with lateral friction) which are crossing through a homogeneous layer of earth. The entire structural system is made of reinforced concrete devised at superstructure with frames (columns, beams, plates) and structural walls. The foundation mediums taken into consideration are earths sensitive to moisture and earths with large swellings and shrinkages. The purpose of this research is to obtain a system that supports loads from the normal service of the building and from seismic forces without any major

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settlements of any kind. This should be possible by adaptation to the environment of foundation soil and by providing safety against quakes.

Key words: piled raft foundation; different soils; geotechnical investigations; PSU, PUCM.

1. Introduction

The investigation seeks to outline the differences of a foundation system raft on piles in different homogeneous mediums. Also is intended to see if the system is capable to ensure the superstructure safety and implicitly of the occupants on seismic events. Entire structure is designed of reinforced concrete.

Piles are computed in accordance with Eurocode 7 and NP 123/2010 (Romanian Standard regarding geotechnical design of foundations on piles, which is adapted to Eurocode 7).

Superstructure is designed in accordance with Eurocode 8 and P100/2011 (Romanian seismic design code, which is adapted to Eurocode 8). The structural system is of reinforced concrete frames which is composed of columns, beams and plates. In order to ensure good behaviour and safety had been adopted structural walls. They are placed in accordance with European Norm to ensure maximum safety at accidental actions on the construction and not only.

The types of soils which are the subject of this study occupies a relatively large surface of Romanian territory. The first one, earth's sensitive to moisture, abbreviated PSU, occupies about 17% and they are examined in Romanian Norm NP 125/2010 (Norm regarding the foundation on earth sensitive to moisture). The second one, earths with large swellings and shrinkages, abbreviated PUCM, occupies about 19% and they are examined in Romanian Norm NP 126/2010 (Norm regarding the foundation on earths with large swelling and shrinkages). These norms are based on Eurocode 7 and 8.

2. Geotechnical Investigation

Investigations are considered to be made in Iaşi, Romania. The borehole is made in both situations to a depth of 120 m and the earth from the site is entirely homogeneous.

2.1. Framing the Soil from First Site

According to geotechnical investigations the ground of first site is a loess soil, as per particle size distribution diagram. By grain size composition on Ternary Diagram, the earth is identified as clayey silt and it belongs to the category of earths sensitive to moisture.

a) *Pursuant to Norm NP 125/2010 soil must fulfil one condition from the following criteria*

Further will be presented only the criteria satisfied by targeted earth according to Romanian standard for designing foundations on earths sensitive to moisture.

a) Criteria relating to the composition and physical properties. First two are determined for cohesive soils in natural state and third is by index *I*:

a1) saturation degree ($S_r < 0.8$): 0.326 – real value;

a2) porosity ($n > 40\%$): 45 % – real value;

a3) index *I* is determined depending on porosity index and on plasticity index I_p: for $I_p = 21 \rightarrow I = 0.24$ – real value;

b) Criteria relating to mechanical behaviour:

b1) additional specific compaction index by moisture under the step of 300 kPa, $i_{m300} \geq 2$ cm/m = 2%, $i_{m300} \geq 4.2$ cm/m = 4.2%.

It can be seen from above that the examined earth fulfils at least two criteria linked to the composition, physical properties and mechanical behaviour.

b) *standard values of geotechnical parameters for loess soils from romania according to NP 125/2010*

The PSU soils are unsaturated macro porous cohesive earths, which in contact with water suffers suddenly and irreversible changes of the internal structure, reflected by additional settlements with a collapsing nature and decreases of geotechnical parameters of mechanical behaviour.

Table 1
Limits of Variance in Natural State and Values of Analysed Soil

Characteristic name	Symbol	Typical values	Real values
Density of solid particles, [g/cm^3]	ρ_s	2.52...2.67	2.67
Unit weight of soil, [kN/cm^3]	γ	12.0...18.0	16.15
Unit weight of dry soil, [kN/cm^3]	γ_d	11.0...16.0	14.68
Water content, [%]	w	6...15	10
Porosity, [%]	n	40...55	45
Liquid limit, [%]	w_L	12...30	30
Plastic limit, [%]	w_p	9...18	9
Plasticity index, [%]	I_p	5...22	21
Swelling pressure, [kPa]	p_u	0...10	0
Hydraulic conductivity coefficient, [m/s]	k	$10^{-4}...10^{-6}$	10^{-5}
Supplementary settlement σ = 100 kPa, [%]	i_{m100}	0...0.6	0.6
Supplementary settlement σ = 200 kPa, [%]	i_{m200}	1...4	1.1
Supplementary settlement σ = 300 kPa, [%]	i_{m300}	2...14	4.2
Oedometric modulus, [kPa]	$E_{oed200\text{-}300}$	5,000...15,000	7,692
Angle of internal friction, [degrees]	Φ	5 - 25	10
Cohesion, [kPa]	c	10...30	24

In Table 1 are presented the characteristic values and the values obtained from laboratory analysis for first site earth.

2.2. Framing the Soil from Second Site

From geotechnical investigations it has been observed that the ground of second site is mostly composed of clay, as per particle size distribution diagram. By grain size composition on Ternary Diagram, the earth is identified as fat clay and it belongs to the category of earths with large swellings and shrinkages.

a) *Identification of soil according to NP 126/2010*

The Norm 126 provides a series of tables with values of geotechnical parameters for the classification of soils with large swellings and shrinkages depending on the activity degree and on the earth nature. These features will be shown below in Table 2.

Also to obtain the activity index it can be done the Soils Stamp (Fig. 1) which is characteristic for this type of earths.

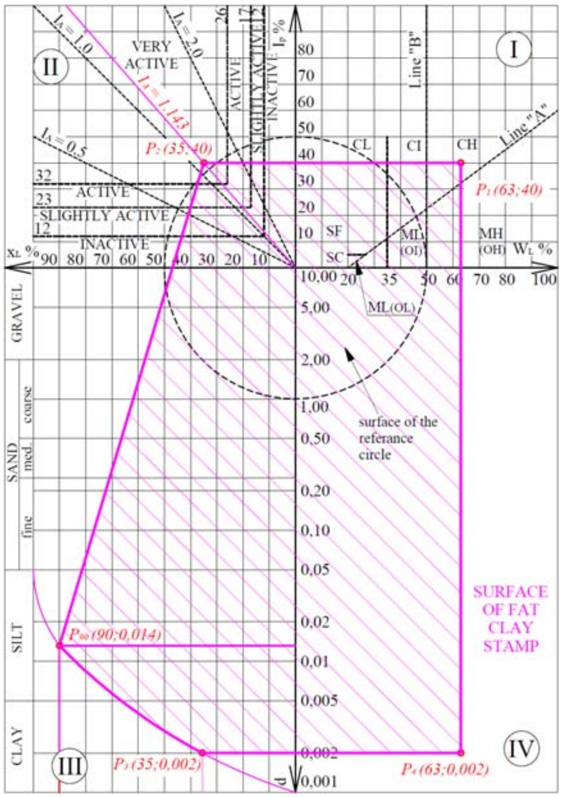


Fig. 1 – Fat clay stamp, characteristic for PUCM earth activity.

b) *Standard values of geotechnical parameters for clays from romania according to NP 126/2010*

The PUCM soils, also known as contractile earths, expansive or active, these are clayey soils which have the property of sensitive modifications of the volume at the humidity variations.

In Table 2 are presented the characteristic values and the values obtained from laboratory analysis for second site earth.

Table 2
Characteristics and Activity Level of Analysed Soil

Characteristic name	Symbol	Real values	Determination of activity
Fraction grains to ≤ 0.002 mm, [%]	A_{2u}	35	very active
Plasticity index, [%]	I_p	40	very active
Activity index	I_A	1.15	active
Plasticity criterion	C_p	28	$I_p \geq C_p$
Free swelling coefficient, [%]	U_L	110	active
Shrinkage limit, [%]	w_s	12.5	active
Coefficient of shrinkage volume - disturbed, [%]	C_v	85	active
Coefficient of shrinkage volume - undisturbed, [%]	C_u	30	active
Heat of immersion, [J/g]	$q_{u\,\max}$	40	very active
Corresponding suction moisture at 15 bar, [%]	w_{15}	20	very active
Swelling pressure, [kPa]	p_u	9	very active

2.3. Comparison Between the Main Characteristics of Soils

In Table 3 is presented the comparison between the PSU earth and PUCM earth.

Table 3
The Main Differences Between Properties of Soils Analysed

Characteristic name	Symbol	PSU earth	PUCM earth
Unit weight of solid particles, [%]	γ_s	26.7	27.7
Porosity, [%]	n	45.0	41.5
Void ratio, [%]	e	81.8	70.9
Unit weight of soil, [kN/m^3]	γ	16.15	20.20
Unit weight of dry soil, [kN/m^3]	γ_d	14.68	16.20
Plastic limit, [%]	w_p	9	23
Liquid limit, [%]	w_L	30	63
Water content, [%]	w	10	24.7
Plasticity index, [%]	I_p	21	40
Consistency index, [%]	I_c	0.950	0.957
Degree of saturation	S_r	0.326	0.390

2.4. Determination of Soil Characteristics Depending on Grain Size

In Fig. 2 is presented the identification of the soils in ternary diagram and in Fig 3 is presented the grain-size distribution.

a) *Ternary diagram*

In this way is possible to identify and classify the soil by assigning it a name based on silt, clay and sand composition. The PSU (earth sensitive to moisture) is identified as clayey silt (red) and PUCM (earth with large swellings and shrinkages) is identified as fat clay (magenta).

PSU earth: C (clay) = 25%; M (silt) = 72%; S (sand) = 3%.

PUCM earth: C (clay) = 83%; M (silt) = 17%; S (sand) = 0%.

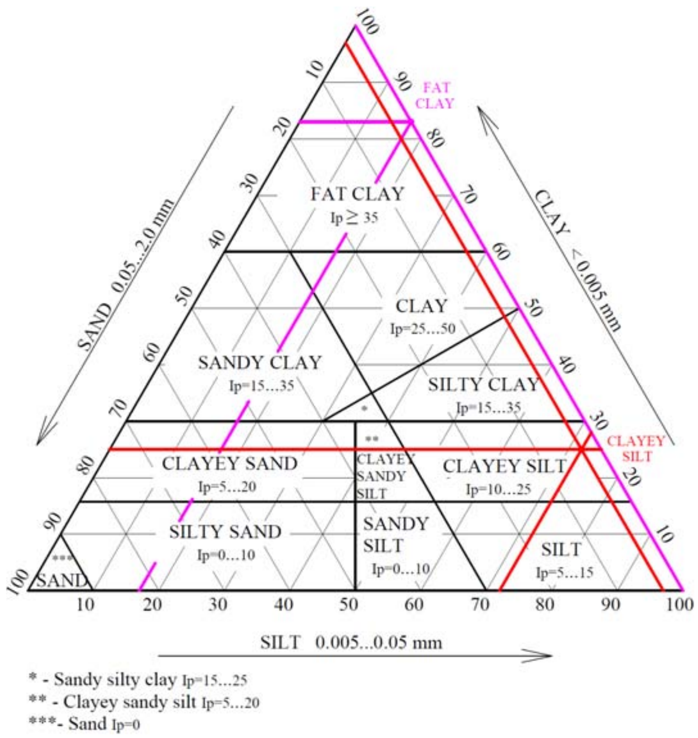


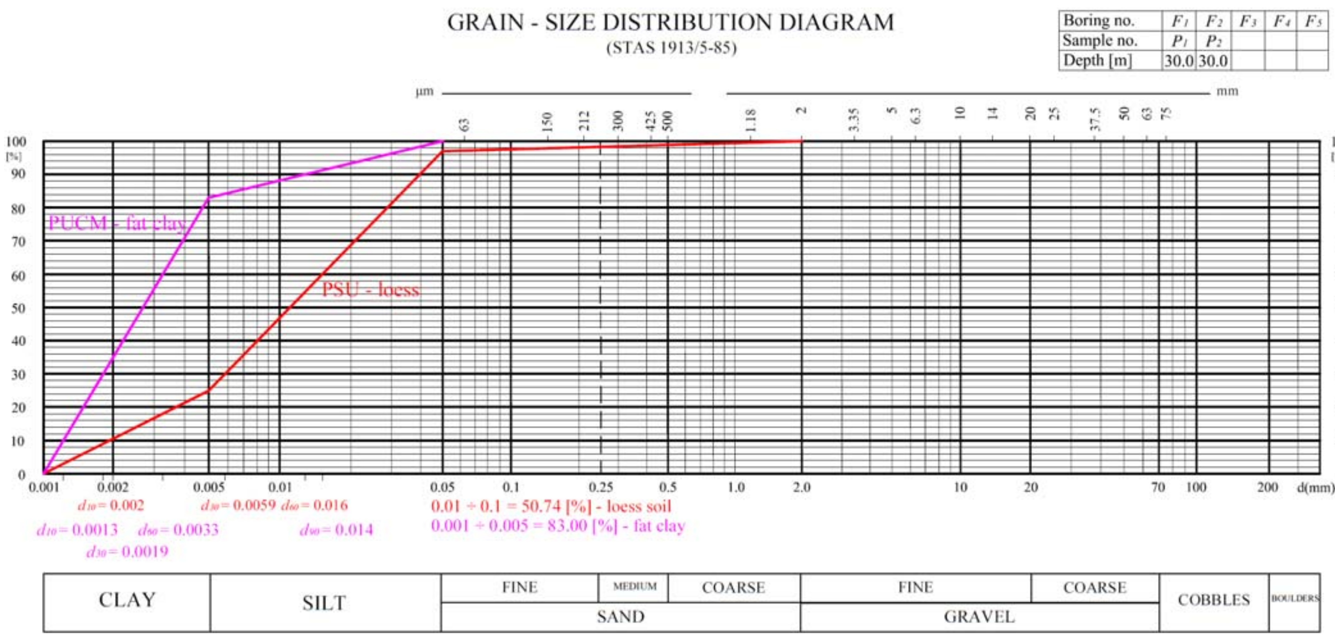
Fig. 2 – Identification of analysed earths in Ternary Diagram.

b) *Grain-size distribution diagram*

The method is used to determine the relation between the percentages of grain size fraction distribution and grains diameter.

The grain diameter is plotted on the logarithmic scale and the finer percentage is plotted on the arithmetic scale.

The d_{10} , d_{30} and d_{60} are the diameters corresponding to percentage 10, 30 and, respectively, 60.



Sample number	P_1	P_2	P_3	P_4	P_5	
d<0.002 mm	10	35				% clay (colloidal)
0.002<d<0.005 mm	15	48				% clay
0.005<d<0.05 mm	72	17				% silt
0.05<d<0.25 mm	1.5	0				% fine sand

Sample number	P_1	P_2	P_3	P_4	P_5	
0.25<d<0.5 mm	0.6	0				% medium sand
0.50<d<2 mm	0.9	0				% coarse sand
0.2<d<20 mm	0	0				% fine gravel
20<d<70 mm	0	0				% coarse gravel

Sample number	P_1	P_2	P_3	P_4	P_5	
70<d<200 mm	0	0				% cobbles
d>200 mm	0	0				% boulders
Un=d60/d10	7.75	2.54				uniform granulometry

Coefficient of gradation: $Cv = d_{30}^2/(d_{10} \cdot d_{60}) = 1.09$ - PSU earth

Coefficient of gradation: $Cv = d_{30}^2/(d_{10} \cdot d_{60}) = 0.84$ - PUCM earth

Fig. 3 – Earths representation in Grain-size Distribution Diagram.

3. Considerations Regarding the Piled Raft Foundation

Builders in time of the Romans certainly understood the need for an adequate foundation because many of the structures from that time remained unyielding for centuries and some of them being found standing even today. In this idea builders realized the need for stable foundations since structures began rising above ground. Nowadays the geologist uses a variety of tools to study the earth, in gaining information on a variety of matters to help him in the foundation design process.

Maintaining this principle of creating a sustainable and safe foundation, the purpose of this study is to investigate the behaviour of a piled raft foundation system under the load of a 48 m high office building during earthquake.

The foundation engineer is obligated to consider effects on the structure that could occur with time. Examples are settlement due to consolidation of clays, settlement due to compaction of sand by vibration, movement of a foundation due to swelling and shrinkage of a clay and the adverse effects of time related erosion.

Primarily the use of this foundation was chosen due to the nature of the ground, to weak comparable with the vertical loads from the building.

Deep foundations have a number of different use, but in this case is to sustain axial loading by side resistance and to improve the stability of construction. In other words in this case piles are designed to distribute the axial load through the stratum by skin friction along the pile shaft.

The engineer's confidence in computing the axial capacity of a pile and the load–settlement curve can be greatly enhanced by the results of field tests of piles under axial load in soils that exist at the site and installed with methods to be used in production. The other method used to calculate the load–settlement curve for an axially loaded pile may be called *the load-transfer method* (commonly referred to as the *t–z* method).

The analysis and design of a pile under lateral loading requires the solution of a nonlinear problem in soil–structure interaction. The ability to make detailed analyses and a successful design of a pile to sustain lateral loading depends principally on the prediction of the response of the soil with appropriate accuracy.

4. Presentation of the Results Obtained at the Foundation Level From the Superstructure Analyse

The construction is a 48 m high office building with the base of 30 x 30 m. The structural system is designed with frames and structural walls according to Euronorms.

The superstructure analyse was performed with the program SAP 2000 v15.0.0 to obtain the efforts at the foundation level in fundamental combination (static analysis) and seismic combination (dynamic analysis). The earthquake action is specified according to Eurocode 8 and Romanian norm P100/2011. In accordance with the criterion adopted in EN 1998-3 for checking of the various performance requirements, the seismic action to be performed is the elastic response spectrum method as shown in Fig. 4 and Tables 4,...,6.

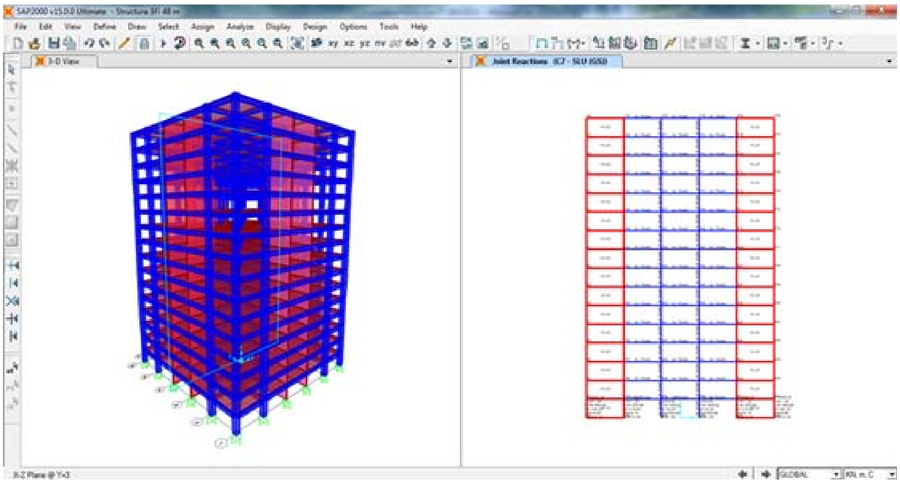


Fig. 4 – Representation of the superstructure in SAP2000 program.

Table 4
Biggest Efforts From The Marginal Columns

Fundamental combination		Seismic combination	
$V_{y,Ed}$ = 54.08 kN	$M_{y,Ed}$ = 10.53 kN·m	$V_{y,Ed}$ = 72.65 kN	$M_{y,Ed}$ = 6.32 kN·m
$V_{x,Ed}$ = 11.30 kN	$M_{x,Ed}$ = 197.79 kN·m	$V_{x,Ed}$ = 11.62 kN	$M_{x,Ed}$ = 293.64 kN·m
N_{Ed} = 3,245.4 kN	$M_{z,Ed}$ = 0.65 kN·m	N_{Ed} = 2,450.5 kN	$M_{z,Ed}$ = 1.07 kN·m

Table 5
Biggest Efforts from the Central Columns

Fundamental combination		Seismic combination	
$V_{y,Ed}$ = 73.47 kN	$M_{y,Ed}$ = 0.02 kN·m	$V_{y,Ed}$ = 113.13 kN	$M_{y,Ed}$ = 2.45 kN·m
$V_{x,Ed}$ = 1.46 kN	$M_{x,Ed}$ = 222.08 kN·m	$V_{x,Ed}$ = 2.62 kN	$M_{x,Ed}$ = 339.99 kN·m
N_{Ed} = 2,989.8 kN	$M_{z,Ed}$ = 1.03 kN·m	N_{Ed} = 1,345.4 kN	$M_{z,Ed}$ = 1.66 kN·m

Table 6
Biggest Efforts from the Structural Walls

Fundamental combination		Seismic combination	
$V_{y,Ed}$ = 308.23 kN	$M_{y,Ed}$ = 16.33 kN·m	$V_{y,Ed}$ = 444.02 kN	$M_{y,Ed}$ = 20.25 kN·m
$V_{x,Ed}$ = 4.18 kN	$M_{x,Ed}$ = 0.06 kN·m	$V_{x,Ed}$ = 1.04 kN	$M_{x,Ed}$ = 0.06 kN·m
N_{Ed} = 2,222.81 kN	$M_{z,Ed}$ = 20.17 kN·m	N_{Ed} = 1,850.06 kN	$M_{z,Ed}$ = 33.25 kN·m

Based on these results was dimensioned the piled raft foundation system. Also these efforts were used in the infrastructure modelling presented in second part of the present research

5. Presentation of Designed Foundation System

In piled raft foundations are sometime used instruments to observe the performance or to gain information's on the distributions of loading to the various elements and to keep the settlements under observation.

In this way the work of the geologist engineering is important in the design and construction of deep foundations (Figs. 5 and 6), and also in the investigations made after the construction was finished.

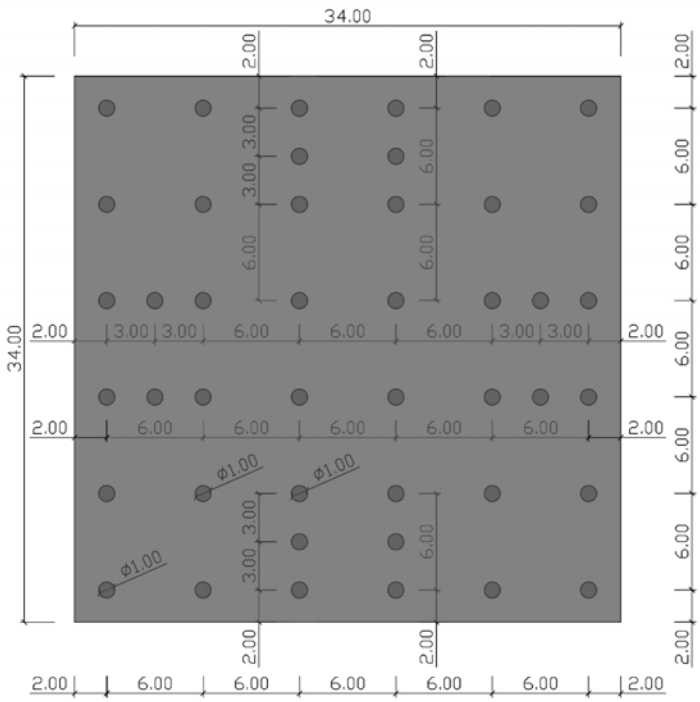


Fig. 5 – Distribution of piles in raft plan.

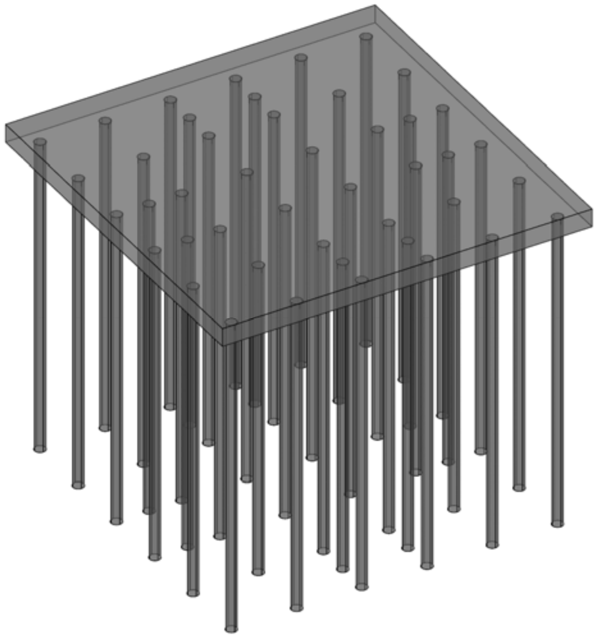


Fig. 6 – 3-D view of the piled raft foundation system.

5. Conclusions

A comprehensive subsurface investigation program might include both conventional borings and other specialized field investigations or testing methods.

Therefore, close communication between the engineer and driller is essential. The results of preliminary borings should be reviewed as soon as possible so that additional borings and *in situ* testing, if necessary, can be performed without remobilization and with a minimum loss of time.

Once all explorations and testing have been completed, the geotechnical engineer must organize and analyse all existing data and provide design recommendations. The scope of the analysis will of course depend upon the scope of the project and the soils involved.

Upon completion of the subsurface investigation and analysis, the information, which has been obtained, must be compiled in a format, which will present to others the results of the work, which has been performed.

Considering the nature of the analysed earths and the descriptions from national norms it have to be take account that: the raft from location with earths sensitive to moisture have to enter at least 1.50 m into the ground and the raft from location characterized by the presence of earths with large swellings and shrinkages have to enter 2.00 m into the ground.

Considering the recommendations from norms, the typology of ground and the characteristics of analysed soils it resulted that the depth of foundation for slab to be at 2.00 m for both construction sites. The raft will have 1.70 m height. After the construction is finished the ground floor level will be the same with the sidewalk surrounding the building.

The piles have the length of 29.00 m for first construction site and 28.00 m for second construction site, and in both locations the piles will have the diameter of 1.00 m.

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ANALIZA DINAMICĂ ŞI IMPACTUL PĂMÂNTULUI ASUPRA FUNDAŢIEI RADIER PE PILOŢI A UNEI CLĂDIRI DE BIROURI ÎNALTE (I)

(Rezumat)

Cercetarea porneşte de la o amplă analiză de laborator a terenului de fundare şi se concluzionează prin efectuarea unei analize dinamice prin intermediul unui program de calcul geotehnic. Acest articol urmăreşte etapele fireşti premergătoare realizării unui proiect de fundaţii: investigare, proiectare şi determinarea eficienţei prin verificare. Studiul urmăreşte să evidenţieze influenţa pe care o are tipul de pământ în timpul seismelor asupra fundaţiei radier pe piloţi (piloţi de diametru mare – coloane) a unei clădiri civile înalte. Analiza este efectuată pe două tipuri de pământuri originare din zona oraşului Iaşi, România. Sistemul de fundare este proiectat luând în considerare influenţa tipului de pământ în termeni de dimensionare şi comportare în timp. Acesta a determinat proiectarea piloţilor ca piloţi flotanţi (cu frecare laterală) ce străbat un strat de pământ omogen. Întregul sistem structural este realizat din beton armat conceput la suprastructură prin cadre de beton armat (stâlpi, grinzi, planşee) şi pereţi structurali. Mediile de fundare luate în considerare sunt pământurile sensibile la umezire şi pământurile cu umflări şi contracţii mari. Prin adaptarea optimă a construcţiei la terenul de fundare se urmăreşte realizarea unui sistem constructiv viabil care să asigure exploatarea în condiţii normale şi excepţionale atât pe domeniul static cât şi pe domeniul seismic a structurii proiectate.