Europe Tower Sofia Optimised Pile-Raft Foundation Design under Earthquake Impacts and High Static Loads

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Summary

Bulgaria's highest structure and future landmark, the Europe Tower Sofia ETS, is a major project of the ECE Hamburg. This paper deals after explaining and discussing the important aspects and facts of the project and the subsoil and seismic conditions with the foundation analysis, optimisation and the resulting pile-raft foundation design.

1 Introduction

The Europe Tower Sofia ETS, located 3 km away from the historic Sofia city centre is concerning foundation a project of the geotechnical category 3 (highest requirements). The subsoil and groundwater conditions have been determined by the LGA/ GCO Poland. ELE Frankfurt/Rhein-Main has developed the pile-raft-foundation design geotechnically. For the structural design IDN Duisburg in cooperation with RSP Frankfurt is responsible. HPP Düsseldorf is the responsible architect.

Figure 1: Europe Tower Sofia

The ETS has in the foundation level a rectangular floor plan with dimensions of approximately 74 and 54 m (approximately 4000 m²). According to current planning it has 3 under storeys and 40 upper storeys. The total height is above foundation raft 187.60 m, plus the raft thickness it is over 190 m high. The foundation bottom is about 15 m below ground level, so that a corresponding deep excavation is required. The average ground level is about +572 m a.s.l. (Building Reference Level +572,7 m a.s.l.).

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As Sofia is located in an earthquake risk area the foundation has been optimised geotechnically considering the geotechnical reports, earthquake impacts and extremely high, eccentric acting static loads of the tower foundation system of up to approx. 2000 MN.

2 Subsoil, groundwater and seismic conditions

The subsoil at the project site is comparable to typical local soil conditions at Sofia area. The ground profile can be subdivided into **two major units**. There is an upper zone of quite heterogeneous composition containing fill, gravel, sand, silt and clay. Underneath this upper zone clay deposit follows about 15 m to 17 m depth from the ground surface, reaching down to about 60 m. At greater depth, there are alternating sand and clay layers. The dense sand layers dominate the geotechnical properties below 60 m. Altogether, **9 soil types** can be distinguished.

Near the ground surface, anthropogenic fill, designated soil type 1, dominates. Soil type 2 consists of black silty clay to silty-sandy clay of low to medium plasticity with soft to stiff consistency. Different from soil type 2 in colour, but otherwise somewhat comparable is soil type 3, brown silty clay of medium plasticity with some gravel. Together, **soil types 1 to 3** belong to the class of **cohesive soils**. Sandy, partly clayey gravel with variable clay content is designated soil type 4. Grey-yellow medium sand is designated soil type 5. Soil type 6 consists also of sand, but while the soils of types 4 and 5 belong to the Quaternary, the sand of soil type 6 belongs to the Pliocene. It occurs in individual layers of variable thickness or in thin lenses interspersed within clay layers of soil type 7. The **soil types 4; 5 and 6** belong to the class of **none cohesive soils**, although they contain some clay and silt.

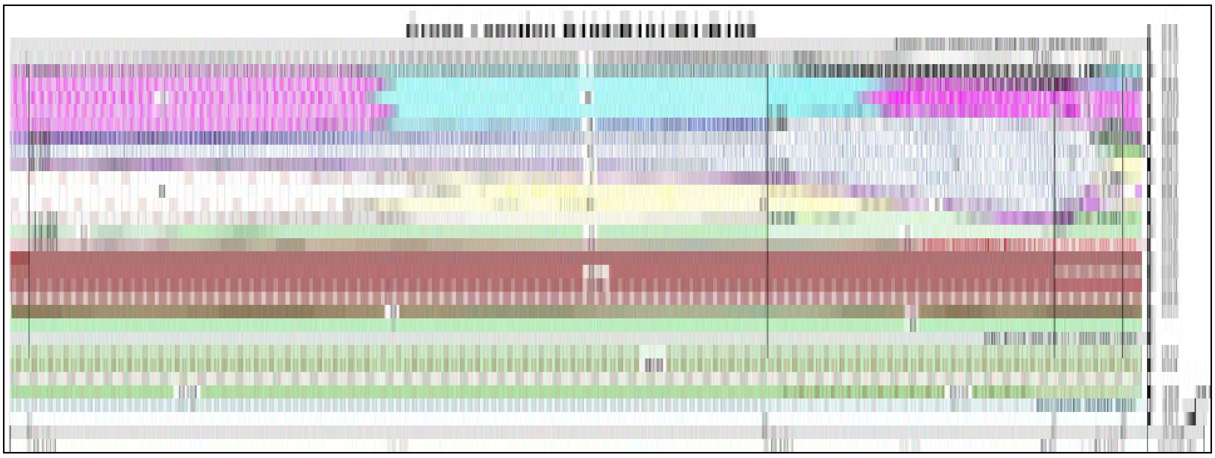

Figure 2: Subsoil cross-section B104-B101-B1-B102

There are two different types of **Pliocene clays**. The upper layer, **soil type 7**, is essentially a clay of medium **CM** to high plasticity **CH**, medium plasticity dominating. At depths below about 15 to 17 m **soil type 8**, a grey–green to grey–blue clay of high plasticity **CH** which shows transitions towards organic clay of high plasticity **OC** was found in all borings. It contains integrated lenses of shell fragments and organic matter (lignite). Sand lenses may also occur erratically. Fissures and ancient slip surfaces are encountered at some locations. The water content of soil type 8 decreases with depth and the consistency increases accordingly. In some borings at a depth up to 20 m approximately, the water content of the clay was relatively high. This zone of the clay deposit with generally stiff consistency deserves special attention and has been specified as soil type 8a. Water saturated **fine to medium sand** of grey–green colour in a very dense state, designated **soil type 9**, dominates below 60 m. Clay layers of soil type 8 occur together with the sand of soil type 9 between 60 and 90 m.

Figure 2 shows a subsoil cross-section in the ETS area as example acc. to [LGA/GCO 2007/ 2008], where the subsoil conditions are described in detail.

The piezometric **groundwater** table is encountered at about 6 to 7 m below ground surface. The **design water level** of the Tower is suggested to be 568 m a.s.l. (about 4 m below ground level). The cohesive soil types 1; 2; 3; 7 and 8 have low to very low hydraulic **conductivity** ($k = 1*10^{-6}$ to $1*10^{-11}$ m/s). They may be subject to elevated piezometric pressure. The cohesionless soil types 4; 5; 6 and 9 are regarded as aquifers with high to medium, partially low hydraulic conductivity ($k = 1*10^{-3}$ to $1*10^{-6}$ m/s). The groundwater is exhibiting **no attack on concrete and steel**.

Due to the subsoil conditions and the **seismic** characteristics of the site area detailed investigations have been performed concerning soil liquefaction risk (relevant soil layer 6).

The Sofia valley has an earthquake zone with the seismic intensity IX acc. to the XII-stage concerned scale MSK Medvedev-Sponheuer-Karnik. According to the European and local regulations an acceleration level of **0,378 g** has to be considered in the structure and foundation design.

Figure 3 shows the first 6 natural frequencies of the Tower as analysed by [IDN 2007/ 2008] due to possible earthquake impacts.

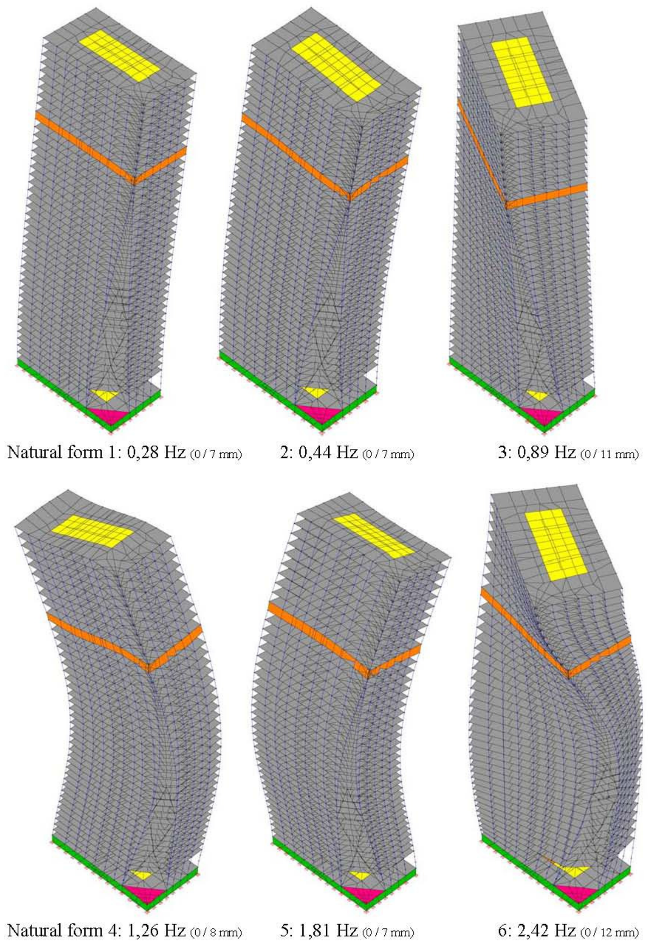

Figure 3: Natural frequencies

3 Foundation Analysis

3.1 Basics of the foundation analysis

Due to the soil properties of the ground immediately below the foundation slab, a combined **Pile-Raft Foundation** was recommended. Bored, cast in place concrete piles are considered as adequate members of the foundation concept. Due to the non-uniform soil composition inside the formation strata soil improvement will be necessary partially beneath the foundation raft. Simplified soil profiles have been used for the foundation analysis.

Acc. to the **pile design** values (skin friction and base resistance) based on [LGA/GCO 2007/ 2008]; following piles with settlements of about 13 to 15 cm have been analysed by [ELE 2008]:
Ø 1,3m-Piles: about 6 MN on 45 m, 10 MN on 50 m, 13,5 MN on 60 m pile length
Ø 1,5m-Piles: about 7 MN on 45 m, 12 MN on 50 m, 16 MN on 60 m pile length
To smooth settlements and in particular **to minimize differential and surrounding settlements** based on the current static load high ultimate pile loads are required. Due to soil conditions a sufficient pile embedding (pile length greater than 45 m) and use of piles of 1.3 m in diameter, also because of the pile spacing, have been chosen embedding the foundation piles sufficient and effective in the bearing mixed ground layer 8/9.

The decisive **foundation loads** acc. to [RSP and IDN 2007/ and 2008] are at top of the foundation raft with permanent (dead) load G, variable (traffic) load Q, earthquake load (E), distributed load g = 1,0 kN/m², q = 3,5 kN/m². The vertical load situation in the foundation base looks as follows (figures rounded):

- Dead load (without foundation raft): 1.310 MN ≅ 327,5 kN/m²
- Dead load of the foundation raft: 410 MN ≅ 102,5 kN/m²
- Dead load G total: 1.720 MN ≅ 430 kN/m²
- Traffic load Q: 230 MN ≅ 60 kN/m²
- Structure load G+Q: 1.950 MN ≅ 490 kN/m²
- Settlement producing load (G + Q/3): 1.800 MN ≅ 450 kN/m²
  (The foundation geotechnical analysis carried out mainly for this **load combination**)
- Additionally earthquake impacts act on tower foundation system of up to approximately 100 MN horizontal load and 12000 MNm moment.

Concrete quality C30/37 and **steel** quality S500 are foreseen to be used. Because of earthquake risk steel with highest ductility has been recommended.

The calculations underlying **FE net** has an average element size of 2,46 m in the area (22 x 30 = 660 elements and 23 x 31 = 713 nodes) and 2,5 m in depth (38 elements and 39 nodes). That leads to the analysis system of totally 25.080 volumetric elements and 27.417 nodes considering the foundation area (54,1 m x 73,8 m) and the soil conditions down to 95 m below ground level (80 m below foundation raft).

Further important criteria for the foundation analysis are the **compatibility** of the deformations occurring (settlement, tilting) and the best utilization respect. **efficiency** of the foundation components (piles, raft).

3.2 Results of the foundation analysis

The tower foundation is a geotechnically-economically **optimised combined Pile-Raft Foundation**. The structure load will be transferred to the subsoil by raft and piles. 64 vertical bored piles which are, acc. Figure 4 [ELE 2008], essentially purposeful distributed underneath the core zone and the major columns of the high rise effect together with the foundation raft – compared with a raft foundation (without piles) – significant minimised settlements and tiltings. The results are subject to verification according to the results of foreseen pile tests.

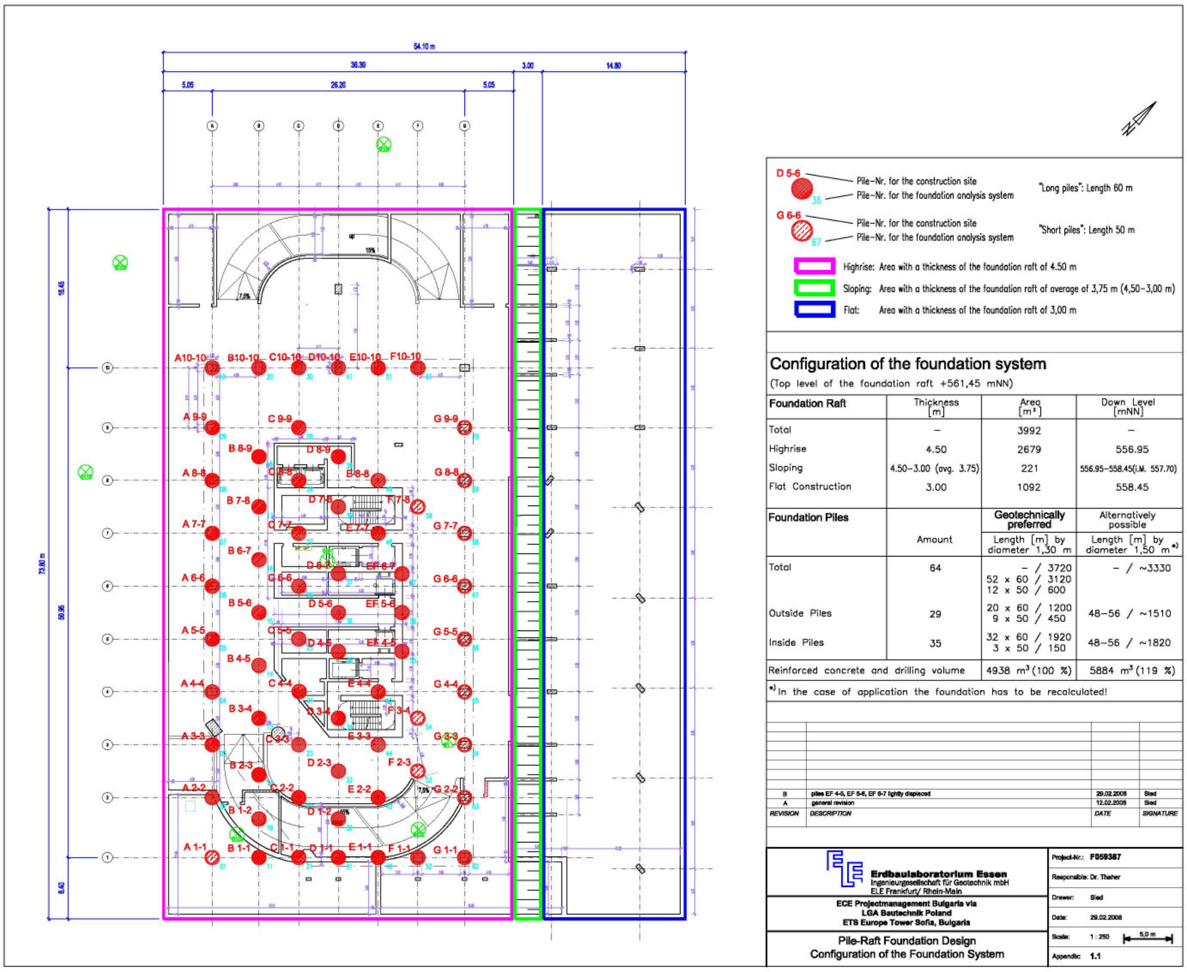

Figure 4: Configuration of the foundation system

- Foundation raft
  - – ca. 3992 m² total foundation area
  - – ca. 2679 m² with **4,5 m** thickness in the high rise area,
  - – ca. 1092 m² with **3,0 m** thickness in the flat construction area
  - – ca. 221 m² with **4,5 m to 3,0 m** (i.a. 3,75 m) thickness in the sloping area
- Foundation piles
  - – 64 bored piles (acc. DIN EN 1536/ DIN 4014) in the high rise area 52 **long piles** a' **60** m and 12 **short piles** a' **50** m, Fig. 5 left

- Diameter 1,3 m
- 29 outside piles, 20 long piles and 9 short piles
- 35 inside piles, 32 long piles and 3 short piles
- arithmetic load (load combination G+Q/3) about **13,5 MN** (long piles) respect. **10 MN** (short piles), Fig. 5 left acc. to [ELE 2008]
- arithmetic **total pile load** about **822 MN** (**pile load portion**)

From the structure load **G+Q ≈ 1950 MN** respect. **G+Q/3 ≈ 1800 MN** the piles transfer arithmetically a **pile load portion** of **822 MN**, also about **45%** of the total structure load to the subsoil. The remaining structure load will be transferred to the subsoil by contact pressure of the foundation raft. With this pile-raft coefficient the compatibility of deformations have been achieved economically. The **raft load portion** amounts to be about **1130 respect. 980 MN**, also about **55%** of the total structure load.

The **arithmetical** (probable) **settlement**s has been determined to a maximum of approximately (Fig. 5 right acc. to [ELE 2008])

- 130 mm in the central area of the high rise
- 110 mm at the foundation west border of the foundation area
- 90 mm at the foundation east border of the foundation area
- 70 mm at the foundation south border of the foundation area
- 50 mm at the foundation north border of the foundation area

In comparison using a **raft foundation** without piles would lead to arithmetical settlements of about **500 mm** with correspondingly large tiltings.

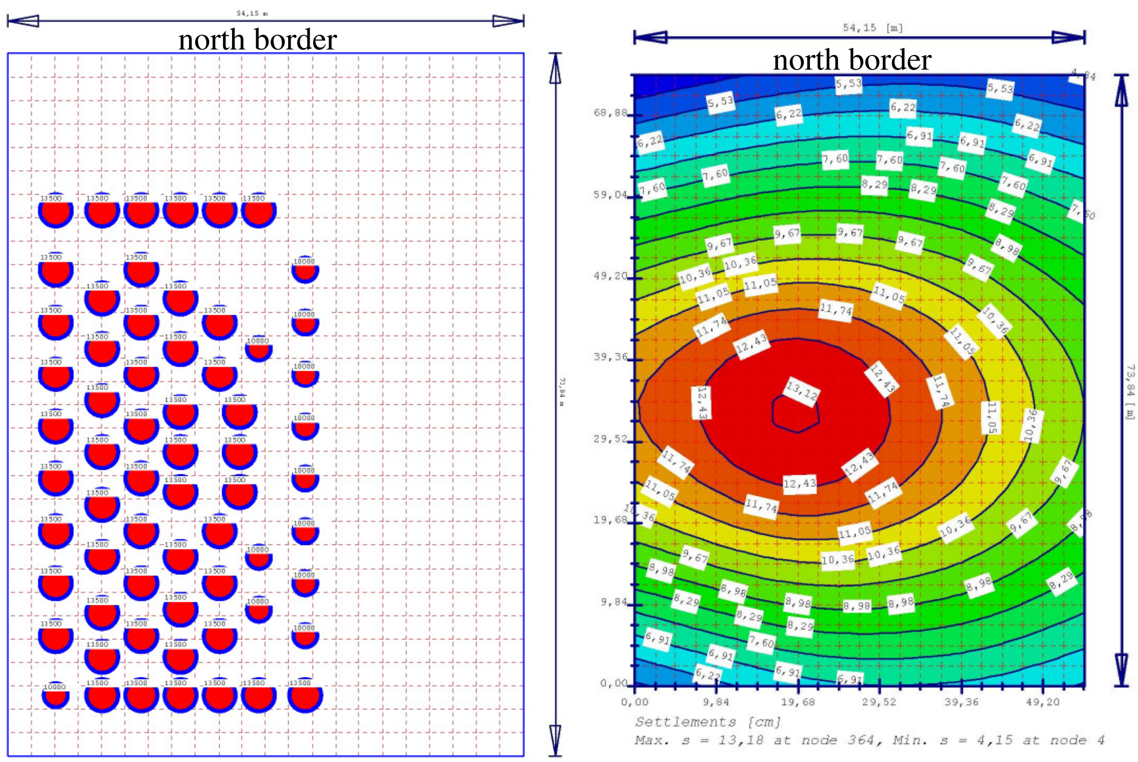

Figure 5: Pile load distribution (left) und settlement behaviour (right) in cross-section

4 Serviceability evidence

In **local matter** (Tower) the serviceability evidence is given due to the foundation configuration. Within a distance of two adjacent columns of about 5 to 7 m probable differential settlements computationally arise up to about 16 mm at tray shaped bearing and practically no deformations at saddle shaped bearing.

In global matter (Tower) the serviceability evidence is given as well due to the foundation configuration. For visually ensured verticality, function of the elevators, etc., the tilting angle of the foundation subgrade respectively of the vertical axis has been arithmetically limited to a permissible extent. The probable (ca. 10 mm) and possible differential settlements (up to 30 mm) in the tower area amount arithmetically maximal 1/3600 respect. 1/1200. That would lead to an arithmetic subsoil caused top deflection of the tower of about 5 respectively 15 cm in maximum. These fulfil the global serviceability evidence acc. to DIN 4019 for example.

Based on the a.m. settlements and experiences the **surrounding settlements** can be expected to be approx. 30 to 70 mm. Considering the consolidation behaviour of the Sofia clay surrounding settlements of approx. 20 to 50 mm might occur until the end of the construction time, and 10 to 20 mm after that. These deformations occur intensively close to the foundation area and decrease with increasing distance to it. In a distance of 30 to 50 m of the foundation borders the deformations are expected to be few mm only.

The a.m. deformations can not be excluded. They have been brought by the chosen foundation configuration to an **unavoidable minimum**. They have to be considered in the further planning and construction progress. It is desirable that additional deformations by the construction process itself have to be prevented or minimised as far as possible.

5 Characteristic values for structural foundation design

Due to the selected raft configuration and arrangement of the foundation piles, the bending stress of the foundation raft is influenced positively and the serviceability of the tower and the neighbouring buildings are evidenced. All significant boundary conditions are considered.

For the structural raft design the **subgrade reaction modulus k_s** (bedding modulus) has been assessed on the basis of the performed foundation computations, to be as follows:

Field area:	k_s = 1,0 to 1,25 MN/m³
Border areas:	k_s = 2,0 to 2,5 MN/m³
Corner areas:	k_s = 6,0 MN/m³

The foundation piles have to be structurally designed acc. to statical requirements and additionally 2 times (γ_{global}) of the outer ultimate load minimum (statical conditions). When simulating the piles by **pile spring constants c_F**, these has been assessed for the preliminary design to be

c_F = 90 to 150 MN/m $\quad$ c_F acc. to a determined pile spring stiffness distribution

The results of the indispensable and foreseen field **pile tests** will provide reliable design parameters for further geotechnical and structural design stages of the Pile-Raft Foundation.

For the application for **dynamic considerations** the dynamic subgrade reaction and pile spring stiffness were suggested to be up to 3 times higher than the statical values in a first step.

Concerning Pile-Raft Foundation Systems the application of the observational method is necessary. The foundation system has obligatory to be observed geotechnically during the construction time and after it. Thus a corresponding **observation** concept will be developed timely. In particular and in the sense of **quality assurance** the geotechnical foundation works will be controlled continuously (acceptance procedure and tests for subgrade and piles).

6 Final remarks

The foundation piles have been suggested to be activated as earth energy piles strengthening the use of earth energy as renewable energy. That makes the foundation system as well optimised ecologically making the foundation finally to an optimal one concerning safety, serviceability, ecology and economy.

It is projected to begin the excavation and foundation works in summer 2008 and to finish all structural activities within about 2 years building time.

The authors would like to thank the ECE Hamburg for permitting this paper and for the support given. They wish for the project success in progress and result. They hope to be able to report about further developments of the very interesting and challenging tower foundation.

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