Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0968

XVII European Conference on Soil Mechanics and Geotechnical Engineering
ECSMGE 2019 Reykjavik

Foundation and soil improvements of the subsoil under St. Ivan Rilski university hospital bulding for the construction of a cyberknife system bunker

Fondation et à l'amélioration du sol du sous-sol dans la construction de l'hôpital universitaire St. Ivan Rilski pour la construction d'un bunker du système CyberKnife

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ABSTRACT:
Due to the construction of a unit for placing CyberKnife it is required that an RC bunker should be built in the existing building. A solution is proposed for a combined independent foundation with cast-in-place RC piles and a foundation slab, which jointly transfer the loads onto the subsoil. Additionally, due to the unexpected geological conditions, it was necessary to improve the subsoil using injections. The calculations and analyses performed during the design and construction phases are presented.

RÉSUMÉ: Dans le cadre de la construction d'un compartiment destiné au placement d'un CyberKnife il est nécessaire de construire un bunker en béton armé dans un bâtiment existant. Ci-dessous est présentée une solution pour fondation indépendante combinée avec pieux RC coulés sur place et une dalle de fondation, qui transfèrent conjointement les charges sur le sous-sol. En plus, en raison de la modification des conditions géotechniques, il était nécessaire de renforcer le sous-sol par des injections. Ci-dessous sont montrés les calculs et les analyses effectués pendant la conception et la construction.

Keywords: soil improvement, settlements, pile foundation,

1 INTRODUCTION

This paper considers problems arising in founding and strengthening of the subsoil related to building a room for placing a CyberKnife system in Block 3 of St. Ivan Rilski University Hospital, Sofia. The area of an existing pool is chosen as the most appropriate from a functional point of view thus requiring reconstruction and transformation of some parking areas and the basement (Fig. 1) into a room for placing the equipment. According to the requirements for ensuring radiation protection it is necessary that the walls, floor and ceilings be built with a minimum reinforced concrete thickness of 150 cm in some areas (Fig. 2.). Observing all requirements in building the room presupposes strengthening of the existing structure and constructing a new independent foundation.

2 GENERALINFORMATIONON THE EXICTING BUILDING

Block 3 of St. Ivan Rilski University Hospital is designed and used as a medical treatment center. According to the drawing provided, the working design was carried out in 1967. The building is two-storeyed with one installation basement underground and one semi-sunk floor (basement) – Fig 1. The structure is monolithic, skeleton-beam. The flooring consists of a system of unidirectional and crisscross reinforced fields resting on simple and continuous beams. The reinforcement of the slabs is made of straight and curved rods, which was typical of the period when the building was built. The columns have rectangular cross sections measuring from 25x25 cm to 40x70 cm. The collar beams are basically 60 m high. The basement RC walls, having a thickness of 40 cm, reach the ground level which is approximately in the middle of the basement floor.

The founding was carried out on subsoil with a design soil load of Ro=250 kPa. The solution was with single footings under the inner columns, single and strip footings under the peripheral columns and basement walls. The single columns are stepped with each step having a height of d=50 cm.

A pool is built in the slab above the installation basement measuring 5.00 x 5.50 m in plan view and 105 cm in depth. The pool structure rests on 120 cm high contour beams. The bottom slab is 15 cm thick.

Since the building operates under loads close to the specified ones and the construction was carried out 40 years ago, the existing structures have completely settled. The new additional CyberKnife structure had to be founded independently on a practically unyielding foundation.

Figure 1. Block 3 of St. Ivan Rilski University Hospital

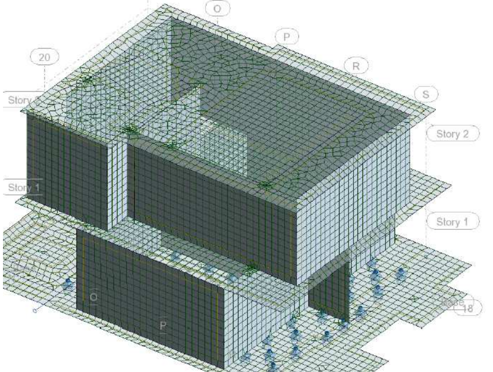

Figure 2.Monolithic bunker

3 A NEW STRUCTURE OF CYBERKNIFE

The new structure for CyberKnife is a RC monolithic bunker with geometrical dimensions determined by the condition for providing adequate radiation protection. The wall thickness varies between 40 and 175 cm. The floor slab is 80 cm thick. In the 62 cm ceiling slab, the thickness of the existing 18 cm RC slab is used to obtain the required 80 cm thickness. In addition, 24 cm and 10 cm thick protection steel plates are planned to be installed in the ceiling slab. The rebars in the structural elements fulfill the condition for minimum percentage of reinforcement in accordance with the high thickness of the sections. The mass of the building before the reconstruction was 4572 t. 100 t of concrete, 90 t of fill and flooring and 132 t of masonry infill were removed. The weight was reduced to 4250 t. 570 t of concrete were added (without the footings and piles), as well as 32 t of steel plates, 42 t of new flooring: a total of 4852 t. The difference in the masses before and after the reconstruction is 6.5% concentrated in the low basement levels. The masses of the two ground floors remained unchanged. The vertical loads from the bunker are transferred independently onto the subsoil by the newly built combined foundation system (piles + slab). The demolished brick walls were replaced by the stiffer RC structure thus allowing us to conclude that the seismic behavior of the building is not unfavorably affected by the current reconstruction.

A seismic analysis was performed to study in detail the interaction between the existing structure and the new one including the new bunker. The first mode of natural vibration has a period of T1=0.95 s in the Y direction (along the short side of the building). The second mode is rotational with a period of T2=0.78 s. The third mode is translational in the X direction (along the long side of the building) with a period of T3=0.72 s. The response in each direction is comparatively regular. The natural vibration periods have decreased resulting from the additional stiffness caused by the built-in bunker. The alteration of the stresses in the columns has been investigated which is caused by the seismic effect resulting from the changed dynamic characteristics of the system. A comparative analysis of the stresses in the columns shows a local increase in the bending moments of columns 321, 322, 331, 332 in the floor immediately above the bunker. These columns are planned to be strengthened between Level 1 and Level 2. The bending moments for all contour columns have decreased as a result of the concentration of loads in the stiffer area around the bunker.

4 ENGINEERING GEOLOGICAL CONDITIONS

A borehole investigation was carried out in the building yard to determine the engineering geological conditions on the site.

The subsequent borehole operations for driving the piles under the bunker show that the data obtained from the engineering geological investigation do not correspond to the real site conditions which are not constant even under the relatively small area of the bunker foundation.

Table 1. Characteristics of each type of soil

Soil	**γ kN/m3**	**E kPa**	**c kPa**	**φ deg**
Sand	18,6	22000	2	32
Clay 1	19,0	9600	14	18
Clay 2	17,5	18000	27	12

The different soil types are shown in Fig. 3. The soil layers according to the engineering geological investigation can be seen as well as those obtained during the borehole operations. All soils were studied under lab conditions for determining their strength and deformation characteristics (Table 1).

During the design phase the load bearing capacity of the piles was calculated based on the soil data obtained from the engineering geological report. After driving the piles and establishing the differences in the geological structure of the site, new calculations were performed as well as a load test of part of the driven piles. The results showed lower bearing capacities of the piles as compared with the design ones. That necessitated additional strengthening of the subsoil by injections.

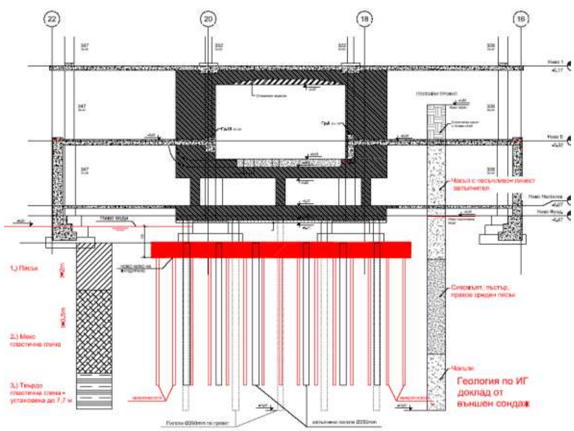

Figure 3. Engineering geological section with the bunker location

5 FOUNDING THE MONOLITHIC BUNKER

The foundation method is combined (pile-raft), i.e. borehole cast-in-situ piles and a foundation slab which jointly transfer the loads onto the subsoil. The piles have a diameter d=250 mm and a length of 8 m. The grillage is 60 cm thick. Basement walls of 40 cm thickness and 118 cm height rest on it, which together with the bunker floor slab form a rigid box-like section. The founding is planned to be carried out with cast-in-situ borehole piles passing through layers of gravelly and sandy soils and a foundation (grillage) slab resting on a layer of gravel according to the engineering geological report. The foundation is designed to limit the settlements caused by the specified load to 3 cm because of the sensitive apparatus. A maximum settlement of 1.5 cm was obtained in the analysis. It is required that the foundation structure should settle as a rigid body and there should be no considerable relative settlements in the area of the bunker bottom. A relative settlement of 0.12 cm/1550 cm ~ 0.08/1000 was obtained in the analysis. When using the combined foundation method, the piles are used mainly as elements which decrease the absolute and relative settlement, often operating under stresses higher than their bearing capacity.

A b orehole investigation was carried out in the building yard to determine the engineering geological conditions on the site.

6 ADDITIONAL STRENGTHENING OF FOUNDATION BASE

A difference was established in the geological varieties during the borehole operations for driving the piles. These varieties compose the soil profile under the building according to the engineering geological report used for the design. During the preparation of that report there was no possibility to drill under the existing pool in the area designed for future bases of the radiation surgery equipment. In that area it was found that the excavations for the construction of the existing building in the 1970s were performed with a common foundation pit which was backfilled to the pavement level.

The backfill has a varied composition of debris, organic soils and sandy sections. In this uppermost part large areas of contaminated soils can be observed resulting from leaks from the sewage system of the hospital over the years. It is impossible to place the main foundation base of the equipment in the backfill taking into account the loading and settlement limitations. The base of the new equipment is lowered to reaching solid subsoil which is not part of the backfill used during the construction of the existing building. The founding of the existing building on single and strip footings was carried out in a layer of silty to medium-sized sand. The layer is represented by light gray, grayish-yellow (with rusty spots) medium- to fine-grained silty sands. The sands are approx. 1.3-1.5 m thick below the foundation level of the existing building. Underneath the gravels described in the geological report were not uncovered on which it was planned to drive the piles for founding the equipment. Soft silty clay with a thickness of approx. 3.5 m was uncovered. The soft clays are underlain by gray, silty, hard-plastic to hard clays. The hard-plastic clays were not passed through during the driving of the piles.

Since it was impossible to drive deeper piles of larger diameter because of space limitations (a slab over the working site) and to use technologies in the existing hospital (small-size drills), it was necessary to use another technology for strengthening the subsoil.

The results obtained in August 2014 from testing performed on piles showed lower load-bearing capacity than that envisaged in the foundation design. A considerably lower bearing capacity of the order of 60-70 kN was obtained than the design 290 kN. The main reason for these results are the much weaker soil layers uncovered during the construction in the equipment foundation area.

After exploring the possibilities for strengthening the subsoil under the particular conditions (below ground level, limited height, operating hospital block, impossible introduction of heavy machinery, driven piles, etc.), the problem was solved by strengthening through injection (steel) micropiles (SA-97-070). The positioning of the piles in a plan view and depth is shown in Fig. 4a. The 153 piles were impact driven and positioned in an orthogonal grid with a spacing of 75/75 cm, avoiding positions with driven RC piles. Cement mortar with W/C ratio=0.65-0.75 was injected under low pressure (~2-5 atm) in the driven steel pipe. An absolute requirement is not to use high pressure in order to prevent destruction of the soil structure. The pipes have a diameter of 2”, their mouths are nicked and the possibilities for driving them are determined in situ. A lower W/C ratio should be used in the upper parts of the pipe. The proposed method of strengthening allows additional subsoil strengthening to be obtained as a result of the soil compaction during steel pipe driving (Fig. 36).

Two penetrations were carried out before and two after driving the piles in order to assess the quality of the subsoil strengthening operations. Geodetic monitoring is envisaged during the foundation works and construction of the superstructure for measuring the settlements that occurred.

7 COMPUTATIONAL MODEL

The following sequence of finite element solutions was used to solve the problem of determining the settlements under the particular geological conditions:

Model 1 – The soil properties were specified by this model using the deformation curves (Fig. 4) obtained from tests with piles (the so-called “back analysis”) and using the knowlage of 3D modelling based on (Tanev, 2012). The soil characteristics obtained were used to model the system ‘foundation slab-piles-subsoil’.

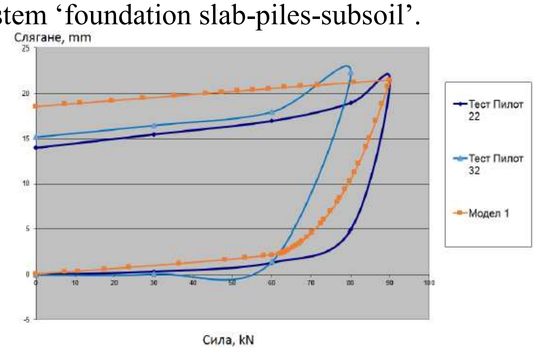

Figure 4. Deformation curves from pile testing

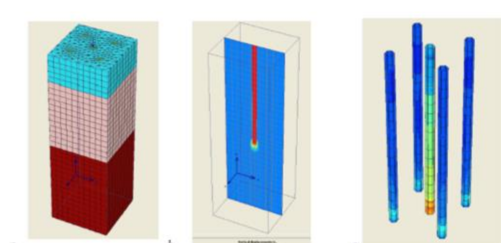

Figure 5. Model 1; a. General drawing with KE; b. Settlement caused by a load P=90kN -21.5 mm; c. Tangential stresses on the contact surface of the test pile τ_y=31kN/m^2

An area of 5 piles was used which simulated a larger common area. The central pile was loaded with a force of 90 kN. The subsoil characteristics shown in Table 1 were used. The results obtained are summarized in Fig. 5.

Model 2 – This partial model of the system ‘foundation slab-piles-subsoil’ was used to specify the spring constants of the piles and subsoil required for the analysis of a total spatial model of the structure, taking into account the interaction between the subsoil and the structure.

Soil properties specified in Model 1 were used. The 60 cm foundation slab of concrete class C30/37 was added. An evenly distributed load p=18095 kN /148 m^2 = 122 kPa was exerted on the foundation slab, which is equal to the load caused by specified loads on the main surface of the equipment. A settlement of 43.6 mm occurred which is higher than the maximum allowable of 30 mm. The results obtained are summarized in Fig. 6.

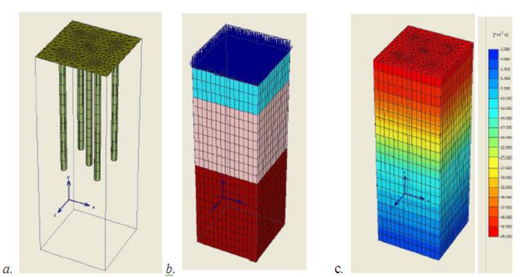

Figure 6. Model 2; a. Piles and foundation slab; b.General drawing with KE; c. Settlements caused by an evenly distributed load p=122 kPa: 43.6 mm.

Model 3 – This is a spatial model of the structure (Fig. 2), in which the geometrical dimensions of the structural elements and the loading caused by the existing building and the new structure are modeled in detail. The founding of the structure was modeled by using distributed and concentrated springs whose values were obtained in Model 2 (piles: Vp=3050 kN/m soil response: Vs=1380 kN/m3).

The results of the calculations showed higher values (40-46 mm) of settlements both in the partial Model 2 and in the complete Model 3. Therefore, in the uncovered geological layers it was necessary to carry out strengthening of the subsoil in order to decrease the settlements to acceptable values.

Model 4 – The filling micropiles were added to the foundation elements from Model 2. The subsoil strengthening was identified by an increase in the deformation and strength parameters of the layers 1 (sand) and 2 (soft clay) by 30%. The spring constants obtained were used for a complete spatial model of the structure, taking into account the interaction ‘strengthened subsoil-structure’.

Model 5 – – This is a spatial model of the structure, in which the geometrical dimensions of the structural elements and the loading caused by the existing building and the new structure are modeled in detail. The founding of the structure was modeled by using distributed and concentrated springs whose values were obtained in Model 2. The founding of the structure was modeled by using distributed and concentrated springs whose values were obtained in Model 4 (piles: Vp=5200 kN/m and soil response: Vs=2000 kN/m3) and reflect the strengthening of the subsoil.

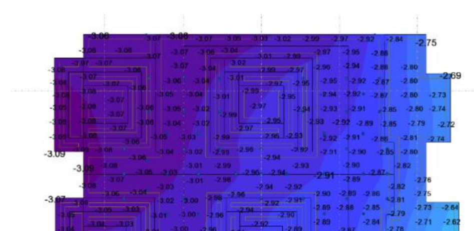

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Figure 7. Model 5 - Settlements caused by specified loads: 25-30 mm

The geometry and the loads on the structure were modeled in detail as well as the positioning of the pile, the foundation slab and the existing footings. The calculated settlement of 25-30 mm was close to that obtained from Model 4 and reflected more precisely the distribution of the loads and rigidities of the structural elements in the spatial model of the structure (Fig. 7).

The results of the application of the models with strengthened subsoil, Model 4 and Model 5, show settlements of the order of 25-30 mm. They are assumed to have allowable values. It should be noted that part of the settlements caused by the loading in the existing structure have already been realized and the actually measured ones on the site should have lower values than those calculated.

8 CONCLUSIONS

Measurements of the vertical deformations of the bunker were performed during the construction of the room for placing CyberKnife which was officially opened in September 2015. The results showed settlement within 5-8 mm which is considerably less than the design values and entirely within the allowable limits.

The discussed sequence of designing and the stages of modeling the system 'structure-subsoil' by using the most modern software products point out the significance of the input parameters and their influence on the results obtained. The use of the observation method presupposing a continuous connection between designer and contractor as well as the timely control over the strength-deformation parameters designed as input data allows the design solutions to be adapted during the construction process thus giving priorities to the geotechnical structures, especially in the reconstruction and strengthening of existing buildings.

9 REFERENCES

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