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DESIGN OF RC STRUCTURES OF MEDIUM-RISE APARTMENT COMPLEX ON SIGNIFICANTLY SLOPED TERRAIN IN MONTENEGRO

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Abstract

Design of structures in medium or extremely sloped terrains is a demanding and challenging engineering task. Depending on the depth of foundations of the future buildings, different methods of securing foundation pit sides are used. Extremely high vertical excavations cannot utilize the standard methods of securing ground stability (use of "L" segments) so somewhat more complicated and demanding solutions must be found. This paper shows the method of temporary securing of the vertical excavation during the building construction, using the prestressed geotechnical anchors in combination with the RC frame, on the example of the Apartment complex in Montenegro.

Key words: *Reinforced-Concrete Structure, Prestressed Anchors, Foundation Pit Support Structure, Retaining Walls*

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1. INTRODUCTION

The anchor bolt is widely used in support engineering because of its advantages of speedy installation and applicability to most types of rocks [1-4]. With the development and implementation of underground engineering, the characteristics of high ground stress, extremely broken surrounding rock and extra-large sections are becoming increasingly common, and the support of surrounding rock is also facing severe challenges [5-7]. Currently, prestressed anchor bolts are widely used as critical active support systems in different types of building structures involving high stresses and fractured surrounding rocks [8].

The stability of slopes of soil and rocks is important for designing and construction of various types of buildings: cuts and embankments of roads, hydraulic engineering buildings, landslide stabilization and other engineering buildings. At the moments when the shear stresses along the sliding plane reach or exceed the shear strength of the soil, there can occur the shear failure of the ground and large displacements of the ground mass above the sliding surface, i.e. the collapse of the slope. Practical consequences of the slope collapse can vary greatly, from the catastrophic ones (loss of human life and extensive material damage) to marginal. The causes of slope instability can be different in characters: a) excessively steep ground mass contours, b) high pore pressures, c) loads of surrounding structures, d) seismic inertial forces or e) high loads on the traffic infrastructure. In order to provide the slope stability various analytical and numerical methods are used, which guarantee sufficient security measures - safety factor. Calculation methods can mostly be divided into two groups: a) method of limit equilibrium – on whose basis the safety factor F_s is determined, which is used to assess the slope stability; b) Stress-strain analyses – where the stresses and strains in the slopes are calculated using numerical methods (finite element method) base on which the slope stability is evaluated.

According to Eurocode 7 when the slope stability analysis is conducted, it must be verified that the effects of the load E_d are lower than the resistance R_d. Calculated values of parameters are used. They are obtained by increasing the loads and soil parameter are reduced through implementation of the corresponding partial safety factors. Instead of the global safety factor F_s, Eurocode 7 introduces the implementation of partial safety factors and in this way the unreliability of input parameters is compensated. According to the National annex of Eurocode 7 (SRPS EN 1997-1) the design approach 3 is used as the proof of limit state in the slope stability.

Depending on the case which may occur in practice, different types of slope or vertical excavations stabilizations can be used: a) supporting structures, b) piles, c) passive measures, d) soil treatment in combination with drainage measures and others. In order to find appropriate solutions, main reasons for the predicted or observed instability must be identified so that the technical design would be economical and safe.

This paper presents the method of temporary securing of the vertical excavation during the building construction using prestressed geotechnical anchors in combination with the RC frame. Geotechnical anchors 5xØ15.7 (f_{pk}=1860N/mm^2) 20m and 22m long, and RC frame composed of vertical beams having cross-section 70/60cm and horizontal beams having cross-section 50/50cm were also used. Based on the obtained results, the vertical excavation satisfied the safety factor criterion.

The paper is divided in four sections: the first shows the introduction to the paper; general description of the apartment complex is shown in the second; the third deals with the implementation of securing of vertical excavations using prestressed geotechnical anchors, while the fourth section is the conclusion and discussion of the obtained results.

2. APARTMENT COMPLEX IN BEČIĆI – MONTENEGRO

Architectonic design of the apartment complex in Bečići was made by the company „Urbanist Projekt“ doo Budva, authored by the architect Uroš Urošević Bachelor with honors in architecture, hired by the investment fund „R.E.C.“ Limited Liability Company doo Budva.

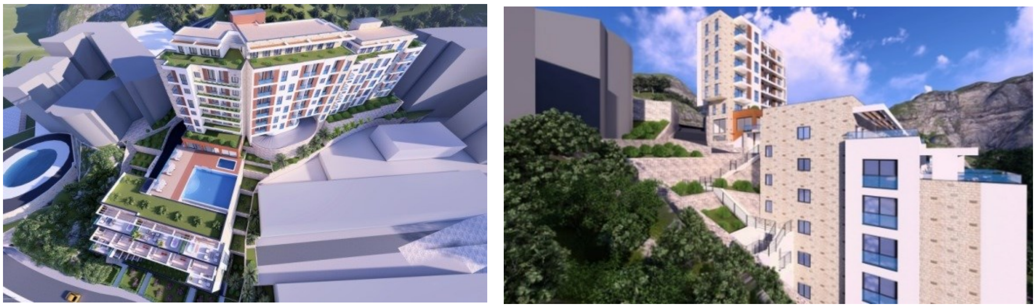

Figure 1. Apartment complex in Bečići - Montenegro

Apartment complex was design in the town planning block 105A, UP 105.1, on the cadastral lot 451/1, 453/7 and 453/8, cadastral municipality Bečići, DUP Bečići, Municipality of Budva. The complex consists of the buildings A, B, C and the garage G of the total surface area of around 22000,0 m^2. Buildings A, B and C have 9 and 10 floors, including the underground levels. Garage G has 4 floors with a swimming pool on the roof level (which can be clearly seen in figure 1). Building A is situated next to the principal road, seen frontally in figure 2. Immediately behind it (towards the rising side of the lot) the Garage G building was designed. Since the A building is dug almost 6 levels into the terrain on the rear side, it was necessary to provide the design to secure the side of the foundation pit for the 16m high vertical excavation.

The design of the supporting RC structure of apartment buildings was produced by the authors of this paper in cooperation with other engineers. In addition to the authors of the paper, Dragan Danilović, Bachelor with honors in Civil Engineering and Nikola Nikolić Bachelor with honors in Civil Engineering participated in the design of the support structure. The support structure consists of a vertical RC frame around 16 m high with prestressed anchors in the part of the lot behind the structure A. On the lateral sides, a system of perpendicular retaining walls was built (figure 1) which are not addressed in this paper. In addition to the previously mentioned support structures, on the top side of the apartment complex buildings B and C a support structure was designed, consisting of RC piles connected with the capping beam.

Figure 2. Apartment complex in Bečići – view from the highway

The focus of this paper is the use of prestressed anchors in the system with the RC frame for securing the vertical excavations, on the case study of the apartment complex in Bečići, Montenegro.

3. SECURING OF VERTICAL EXCAVATION USING PRESTRESSED ANCHORS

For the needs of the first phase of construction of apartment building – Building A, a staged excavation was planned, along with formation of multiple foundation pits for foundations designed buildings. Considering the spatial limitations imposed by the lot boundaries and existing infrastructural constructions, the foundation pit had to be constructed with verticals sides which, at extreme points were over 16m high.

The foundation pit is horizontal at the elevation of 10.80m and its approximate layout dimensions are 35x23m. The excavation is performed on a slope with a steady inclination between 31° and 35°, and the elevation from which the excavation starts is approximately 27.30mnm.

It is in agreement with the required dimensions of the foundation pit, defined contours of sides and geological conditions, the excavation of the foundation pit is secured with vertical RC beams having cross section of 70x60cm at an axial distance of 4m with three rows of horizontal beams having cross section of 50x50cm.

It is planned to construct prestressed geotechnical anchors at the locations where horizontal and vertical beams intersect. Anchors are arranged as beams in three rows with the following characteristics:

- Anchors at elevation 11.86asl (lowest level) 5xØ15.7mm, long 20m, with anchoring zone 10m long and anchoring zone cross section is 72mm;
- Anchors at elevations 19.11asl and 26.36asl (medium and upper level) 5xØ15.7mm, 22m long, with anchoring zone 10m long and anchoring zone cross section is 72mm;

The technical design of excavation and securing plans for the excavation in phases and securing of the foundation pit in the following phases:

- **Phase 1**:

In this phase the surface layer is removed from the entire slope, which, according to the available archeological data, is a potentially unstable wash. Simultaneously with the removal of this material, the decomposed diabase is excavated to the level 26.50asl, which is also the level from which the vertical excavation of the foundation pit starts. The slope in the decomposed diabase is constructed in the inclination 1:1. The design provides for the permanent geotechnical supervision, ground notch mapping and comparison of the rock mass with the parameters from the geological report on whose basis the stability analyses were conducted. In case of the considerable departure of the field working conditions, it was planned to attenuate the final slope using the jet grouting in a layer of 10cm reinforced with the single wire mesh Q188 and with the sporadic securing of potentially instable parts of the slope using rigid SN anchors made of reinforcement steel B500 B, having diameter Ø10mm and length 4m. The arrangement of the anchors is determined in situ, depending on the results of the IG mapping.

- **Phase 2**:

The second phase of construction provides for the excavation of the first level of the foundation pit to the elevation of 22.90asl, i.e. excavation 3.60m high. Excavation in this phase is performed in phases which prevents sudden unloading of the slope. After each stage of excavation in this phase, RC beams are cast and prestressed anchors are built in. Anchors are pretensioned to the force of 50kN. The geotechnical supervision defines all necessary parameters. In the case worse geotechnical conditions than those defined in the geological data are registered, it is necessary to secure the cut between the beams using the jet grouting 10cm thick and rigid SN anchors made of reinforcement iron B500 B, having diameter Ø10mm and length 4m.

- **Phase 3**:

After all the works of the second phase are finished, the third phase starts. As in the previous phase, the construction is performed in stages. The excavation is carried out to the elevation of the medium beams, beams are cast and anchors are installed. After formation of the entire vertical beam and installation of both anchors, the anchors are tensioned to the maximum force of 600kN.

- **Phase 4**:

This is the last phase, where in accordance with the planned phase work, the excavation in stages is performed along with securing the slope to the designed elevation of the future foundation pit of the building A. Figure 3 shows the schematic display of the final phase of securing the vertical excavation.

As shown in figure 3, during the excavation of phases 3 and 4, not all material is removed from the berm, but a part of the material is left as an additional ballast to secure the stability of the slope. This part of the ground is removed only after finishing all the excavation and securing works of the current excavation stage.

For the analysis of stability and for defining of securing measures, data from the previously executed site investigations were used. In terms of morphology a wider area of exploratory activities is the slope extending to the sea, immediately above the “Jadranska magistrala” principal road. The slope has a uniform inclination, to 300m, flat in extension. The elevation above sea level of the terrain which is being investigated is from 14.5asl at the level of the principal road below the location to around 45asl at the street above the location. In the geological composition of a wider area are present various sediments dated back to Triassic, Jurassic, Cretaceous and Cretaceous-Eocene and Quaternary times. A wider area of the location, in geological terms, is built of igneous-sedimentary series composed of igneous rocks, then tuff and tuffite, marlstone, sandstone and mostly of plate-like limestone. The location itself exclusively consists of igneous rocks, represented by porphyries and diabase, of massive textures, over which is a thin layer of sedimentary cover made of clayey and dusty debris.

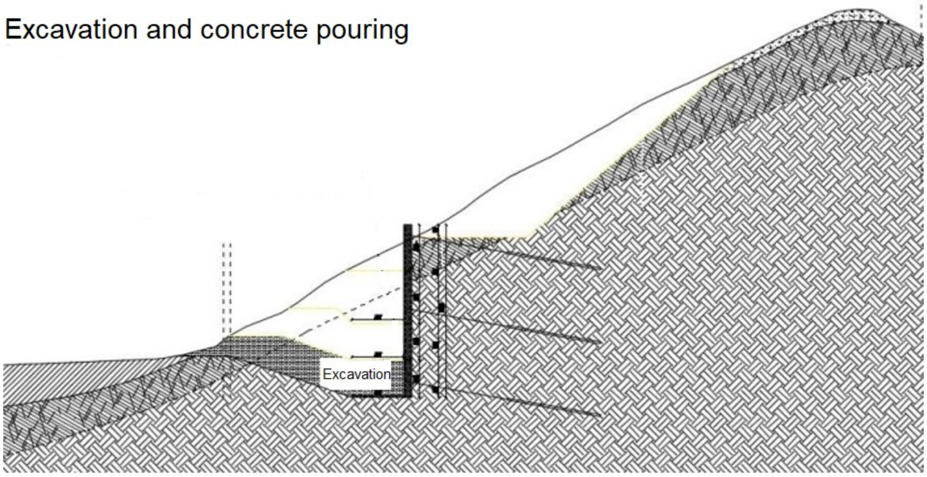

Figure 3. Final phase of excavation and securing of foundation pit sides

Table 1- Physico-mechanical properties of rock mass

Physico-mechanical properties	Sample			
	U-1	U-2	U-3	U-4
Lithological properties	Igneous-sedimentary formation			
Density (gr/cm^3)	2.440	2.444	2.455	2.512
Compressive strength (Mpa)	53.14	43.71	7.10	7.10
Shear strength (Mpa)	4.84	5.46	1.01	1.01

Hydrogeologic properties of terrain are in the function of the lithological composition of excavated ground. In, general, those are low water permeable and impermeable sediments. In the low water permeable rocks, is present fine and coarse detritus with a variable content of red clay, of sedimentary origin, having inter-granular porosity. Impermeable rocks feature igneous sedimentary series rocks such as: diabase and porphyry, tuff and tuffite, marlstone, sandstone and plate-like limestone.

The design of the slope stability and required security measures were done using the software package PHASE 2. Analyses were performed on a 2D model, based on the results of earlier survey – geomechanical report. The calculation of the slope stability was performed using the finite element method (FEM) and using the method based on the reduction of shear strength (Shear Strength Reduction - SSR).

Table 2- Physico-mechanical properties of separated medium

Medium	Parameter			
	γ (kN/m³)	φ (°)	C (Mpa)	D (Mpa)
Degraded igneous – sedimentary formation (medium 2)	22-24	22-27	0.05-0.10	50-100
Medium	Parameter			
	γ (kN/m³)	φ (°)	γ (kN/m³)	D (Mpa)
Igneous-sedimentary formation (medium 3)	23-25	30-40	0.30-0.60	300-500

The goal of SSR is to demonstrate what is the load bearing reserve of the rock. Shear strength reduction method makes it possible to determine the rock mass safety factor using the finite element method and appropriate material model.

- The procedure for determining the safety factor consists of:
- Reduction of failure envelope using the factor F,
- Determining material constants corresponding to the reduced envelope,
- New calculation with the same model of finite elements using the newly obtained estimated parameters,
- Safety factor is the lowest value of the reduction factor F for which the result is an instable slope.

The situation when the numerical calculation cannot converge to the solution is taken as the instability criterion (occurrence of failure).

The Mohr-Coulomb material model was applied

$$\tau = \sigma \cdot tg\varphi + c \quad (1)$$

If F is the shear strength reduction factor, the upper equation can be written in the following way:

$$\tau/_F = {}^{\sigma \cdot tg\varphi}/_F + {}^{c}/_F \quad (2)$$

$$\tau_{red} = {}^{\tau}/_F \quad (3)$$

$$c_{red} = {}^{c}/_F \quad (4)$$

$${}^{tg\varphi}/_F = tg\varphi_{red} \quad (5)$$

where c_{red} and φ_{red} are cohesions and the internal friction angle of the reduced failure envelope. Analogously, the value of the factor F at which the failure occurs, is assumed to be the global slope safety factor.

Analyses of the slope stability and calculation of securing measures were performed for the most critical cross – section, terrain profile at the middle of the slope where additional geological surveys were carried out, and for which there were the most reliable data on the terrain composition. The design profile was analyzed from the initial state.

Calculation of the stability was conducted for the following phases:

1. Initial state – natural slope,

2. Removal of the top layer of sediment and excavation of the first and second stage (sediment removal) to the elevation 26.50asl and formation of the slope with the inclination 1:1,

3. Excavation to the elevation 22.90mnm (phase 3 of the works),

4. Excavation to the bottom of the foundation pit.

The first calculation model was made as a case of the vertical excavation without additional elements of securing the slope stability (figure 4 left).

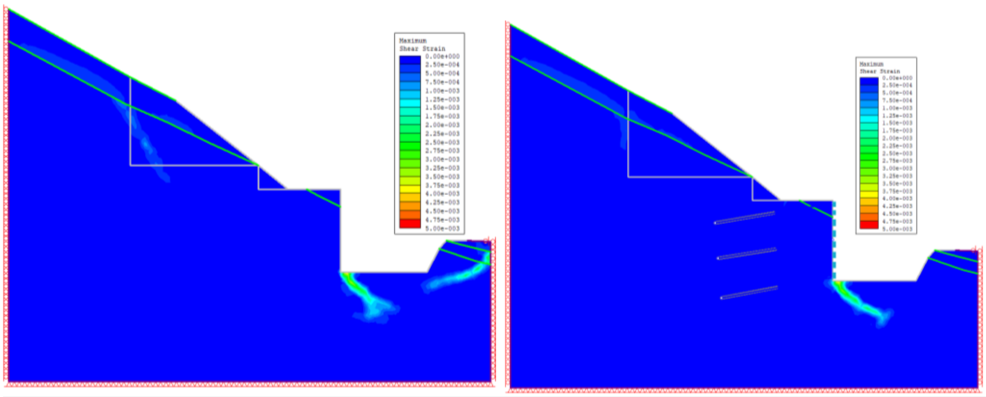

Figure 4. Left: Slope security factor without securing measures Fs=0.99<1.20; Right: Slope security factor with securing measures Fs=1.24>1.20

Considering that the slope safety factor is lower than the required one for the temporary slope (adopted $F_{s,min}$=1.20), further calculation of the slope was performed with the slope securing measures, assumed in the following way:

1. Prestressed anchors with prestressing force F=600kN,

2. AB vertical beams having cross-section 70x60cm,

3. If necessary, slope with the inclination 1:1 is secured using jet grouting 10cm thick reinforced with the reinforcement mesh Q188 and rigid SN anchors of reinforcement steel B500C Ø20 4 meter long.

Final excavation phase and support structure are shown in figure 4 right.

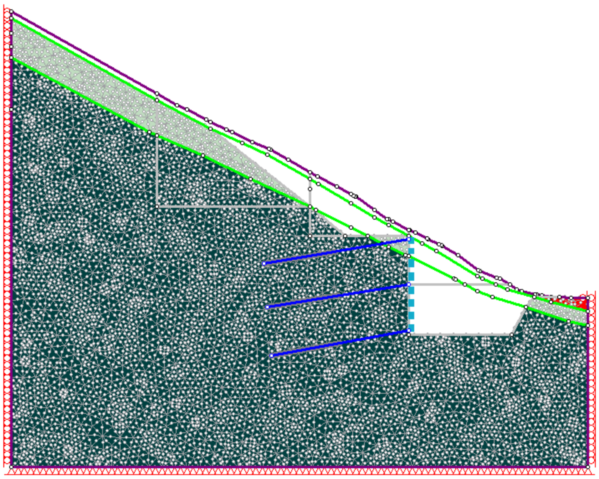

Figure 5. Final excavation phase and support structure

Based on the conducted calculation and analyses, for the vertical securing of the excavation, the use of the following anchors was planned:

- Geotechnical anchor 5xØ15.7 (f_{pk}=1860N/mm^2)

Based on the calculation of the required length of anchor (shear on the contact of steel and rock) the obtained lengths are 7.40m and 7.85m. The final adopted length of the anchoring zone is Ø72mm, L=10m.

The free length of the anchors on two upper levels is 12 meters, and of anchors on the lower level is 10 meters, so the total lengths of the anchors are L_1=22m and L_2=20m.

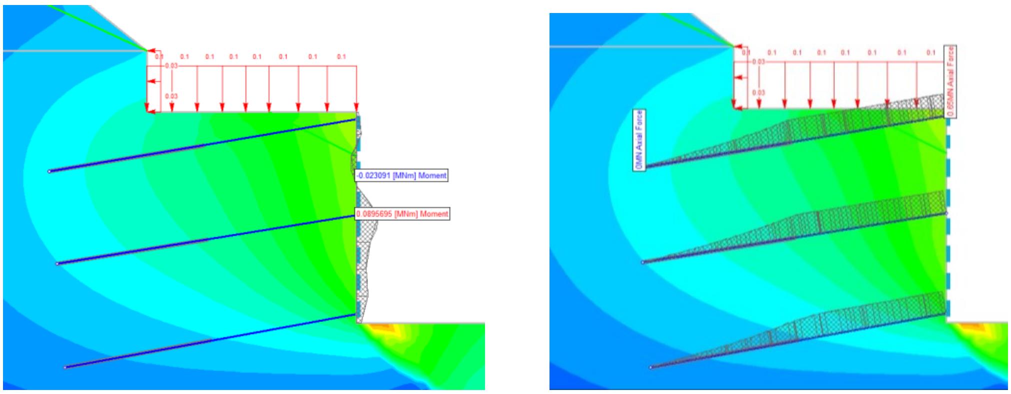

Figure 6. Left: Bending in the beam; Right: Maximum forces in anchors

After introducing the securing structure of the vertical excavation (anchors and RC frame), the safety factor obtained is higher than the minimum Fs=1.24>1.20 (figure 4 right). By calculating the maximum ground displacement, concentration at the bottom of the vertical excavation is obtained (figure 7). The value of maximum displacement is 7.0e-3 meters. In figure 6 right are shown the results of the obtained maximum forces in the anchors, on whose bases they were designed. While in the figure 6 left the obtained bending moments are necessary for designing RC vertical beams. Apart from the analyses shown in figure 5-7, models in the software package Tower were made, for two different phases. First phase in which vertical and horizontal beams are modeled for one characteristic span, and figures 12 and 13 where the modeling concept for the entire RC frame was implemented.

The securing structure, in addition to the prestressed anchors is composed of the RC frame designed from vertical and horizontal beams. Horizontal beams are mutually spaced 4m, while the horizontal beams were set in three levels at a distance of 0.5m, 8.25m and 15.5 meters from the top elevation of the ground. The support structure calculation was performed for the second and third phase of excavation. The static design was done in the Tower software package based on the finite element method (using linear finite elements). The adopted concrete class is C25/30 and reinforcement steel B500 B.

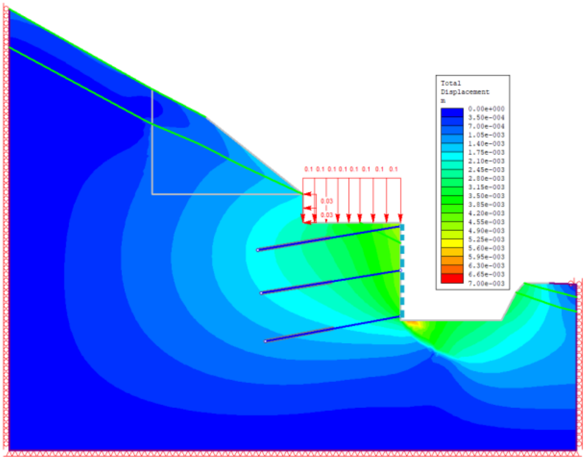

Figure 7. Total ground displacement

RC structure consisting of vertical and horizontal beams is analyzed in two phases. The first phase comprises one characteristic grid segment (two vertical and two horizontal beams), while the second phase comprises entire protective structure. In the first phase, beams have supports in anchor locations, while the load is equal to the reactive load of the rock of maximum force in anchors of 600 kN.

In the second phase the static structural system is the frame composed of vertical and horizontal beams in the entire volume. Beams in the places of anchors loaded with reactive load of 600kN, or 63.20kN/m. In addition, on the side of the safety, an incident load was considered, corresponding to the situation when the maximum permissible force in the anchor of 840kN is reached. In this case, the corresponding reactive load is 88.40kN/m.

Based on the analyzed phases of construction and design positions, the final reinforcement in the RC frame composed of vertical and horizontal beams was adopted. The results shown in figure 8 clearly demonstrate that the maximum required reinforcement in the beam grid is relevant for the first phase of construction, while above the support the maximum impact is recorded in the second phase of construction when the entire designed frame is formed.

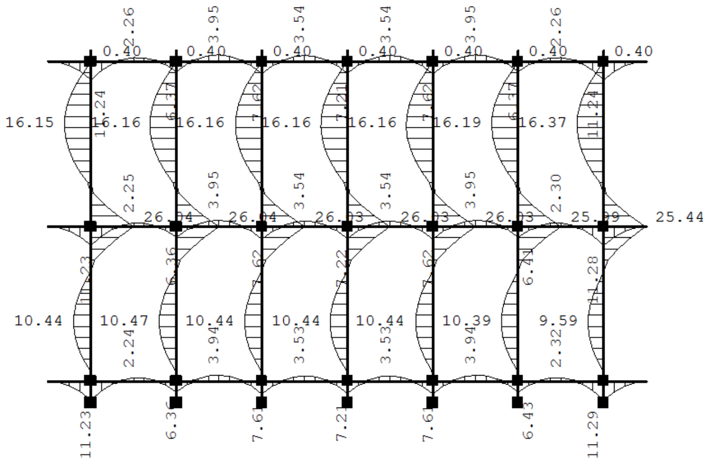

Figure 8. Required calculated reinforcement A_{a1}/A_{a2}

4. CONCLUSION

Designing of high-rise buildings on the lots with medium or high inclination require use of certain systems for securing foundation pit sides. Such systems can be made of “classical” RC tubs having walls 20-30cm thick walls and the foundation slab, which is a system for securing a maximum of two floors. However, if it is necessary to secure the vertical excavation for multiple floors it is necessary to construct somewhat more complex securing systems. It is usual to use the systems with piles and RC beams capping the piles. In the presented paper all the mentioned systems could not be used because of the excessive height of the vertical excavation (around 16m above ground). For these reasons, it was necessary to find such a solution to provide a safe stability of the vertical excavation but also to be economical The approach based on the use of prestressed geotechnical anchors 5xØ15.7 (f_{pk}=1860N/mm^2) in combination with RC frames made of vertical (70/60cm) and horizontal beams was used (50/50cm) was implemented.

In the first phase of the analysis, the case of a vertical excavation without any security measures was considered. The obtained slope safety factor was 0.99 which is lower than the recommended permissible safety factor of 1.20. After that, the slope stability was analyzed after the implementation of geotechnical anchors and RC frames. The conducted analysis demonstrated a higher safety factor than the minimum recommended one of 1.24>1.20, which provided the proof of slope stability.

The calculation of the RC frame was performed by analyzing two characteristic phases during the works execution. The first phase is when only one segment consisting of two vertical and horizontal RC beams and four geotechnical anchors are installed. The obtained results in this model were relevant for adopting the reinforcement in vertical beams in the grid segments. In the next phase, the entire RC frame was analyzed with all the installed geotechnical anchors in which the force in the anchor was: a) 600kN and b) 840kN. The other model provided relevant impacts above the support points.

The design presented in this paper was successfully implemented on the designed location. The presented design can be applied in relatively rocky areas. Considering the height of the vertical excavation, the design is extremely economical, relatively simple to construct and provides unobstructed construction of newly designed buildings

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