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Geotechnical conditions for construction of bank revetment on the Sava amphitheatre area in Belgrade - Serbia

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Abstract. Within the project „Belgrade Waterfront“, regulation of the Sava River was predicted, which included the construction of a new bank revetment in a length of about 1800 m. In order to determine the existing situation and to make geotechnical maps for the new bank revetment, geotechnical investigations were performed during 2015. The paper presents the results of these investigations and the defining method of geotechnical models used for the stability analysis of the revetment depending on the extreme hydrological conditions. According to these models, seepage and geostatic calculations were performed, with the aim of illustrating the influence of the Sava River water level oscillations on the groundwater level. As a characteristic case, a 60-day flood wave was taken into account, which occurred in May and June of 2014. In order to simulate critical conditions during the duration of the flood wave, a further decline in the water level was assumed for another 12 days. Based on the performed geotechnical analysis, the stability of the revetment has been proved.

Keywords: Bank revetment, flood wave, geotechnical properties, seepage analysis, stability analysis

1 INTRODUCTION

The „Belgrade Waterfront“ project is located along the right bank of the Sava River, from the old railway bridge to the Brankov Bridge, on an area of about 90 ha. Construction of the facilities is planned for the entire area of the existing railway station, which by many urban planners is blocking Belgrade development, creating an ugly coastal environment. The whole complex is divided into several parts: a space reserved for luxury hotels, business zone, residential area, sports and recreation area, culture and art zone etc. (Figure 1).

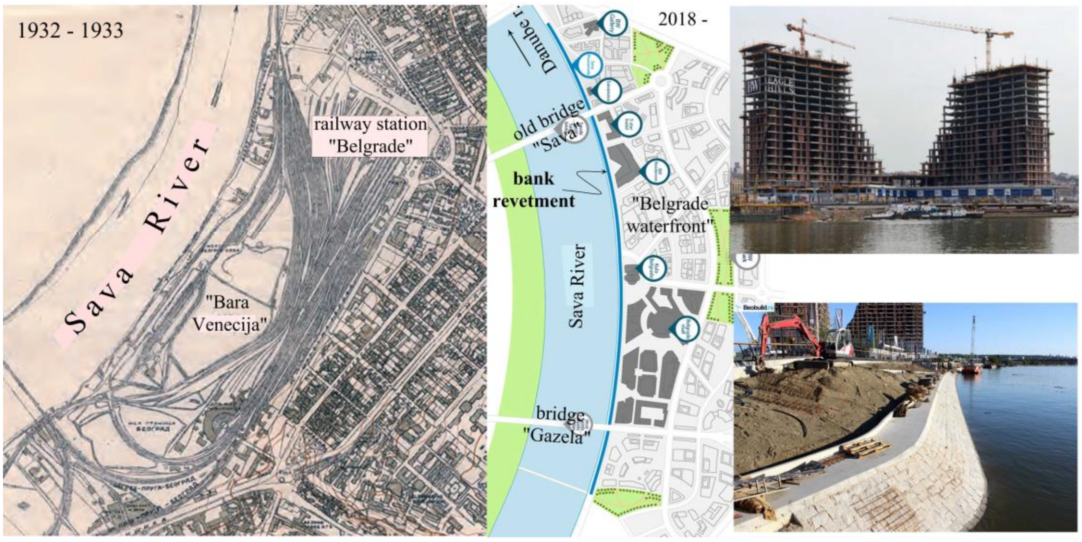

Figure 1. The “Bara Venecija” area in the period 1932-1933 and planned appearance with the revetment

The area on which is planned the construction was once covered with marshes, wetlands and numerous depressions caused by soil digging, so this part of the city is also known as „Bara Venecija“. In the second half of the XIX century filling work began, and the largest filling was performed during the construction of the railway station, at the end of the XIX century. Around 1930., „Bara Venecija“ was fully covered and the Belgrade Fair was built in one part of it. In parallel with the filling, flood embankments were built. They were made on several occasions, since they are characterized by certain zones in which bank regulation has been carried out. However, there were also parts of the bank which were not regulated or only partially regulated. The regulation was performed in different ways. Most often it was deposition of rock embankment in the riverbed on the right bank of the Sava River in combination with performation of the sloped quay of height over 2 m. With this filling of rock embankment, the river bank was stabilized and its erosion was prevented, because the river midstream was partially shifted to the left bank. Rock embankment of larger thickness was submerged in the surface sediments of the riverbed, while in some parts only surface filling of less than 2 m thickness was performed. Within the „Belgrade Waterfront“ project, regulation of the Sava River was predicted, which includes the construction of a new bank revetment in the length of about 1800 m.

2 BASIC GEOLOGICAL CHARACTERISTICS OF THE TERRAIN ALONG THE BANK REVETMENT

In order to determine the current situation and to make geotechnical maps for the new bank revetment, a remarkable number of field and laboratory investigations were performed during 2015. These investigations were performed in phases (three phases), and special Geotechnical Elaborates were made for each phase. All field investigations were performed in the narrow area of the right river bank and in the river itself, along previously defined profiles (the river bottom was previously surveyed geodetically). 93 boreholes were carried out, of which 31 in the river (1835 m of drilling), 200 SPT tests, 35 CPT tests and laboratory tests were performed on over 350 samples. Based on the study of deeper exploration boreholes, which were carried out for the construction of individual facilities within the „Belgrade Waterfront“ project, it was determined that complex subsurface structures are present in the exploration area (Figure 2).

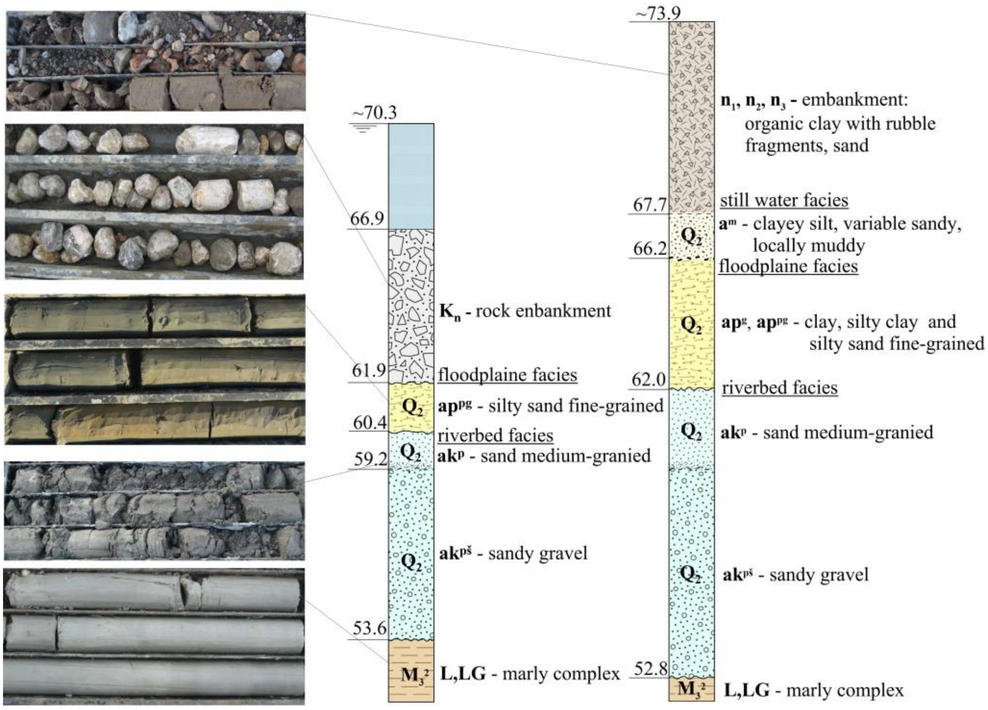

Figure 2. General stratigraphic column with core layout in the bank revetment area

By the depth of 60 m, the following geological units were determined:cretaceouss sediments (conglomerates and breccia limestones), sediments of middle and upper Miocene, quaternary formations and modern anthropogenic deposits. Sediments of the middle Miocene (M_2^2) are made of badenit limestones while the upper Miocene (M_3^2) is made of gray marls and marly clays. These Miocene sediments make the direct subsoil to the modern alluvial deposit of the Sava River. According to the age and genesis, only younger cycle of river sedimentation products (Q_2) was isolated within the alluvial deposits. Within quaternary sediments, riverbed facies sediments, floodplain facies sediments and occasionally sediments of still water were isolated. In the shelf part, terrain is predominantly built of coarse grained sediments (riverbed facies) represented by sands and gravelly sands (ak^p, $ak^{pš}$), which rhythmically shift with younger fine grained sediments in some zones (silty sands and silty clays). Sediments of floodplain and still water are built of gray-brown to gray clays and silty to sandy clays (ap^g, ap^{pg}, a^m). Content of organic matter gives them a dark gray color which indicates the presence of marshed deposit from the still water facies. Anthropogenic (or technogenic) deposits form surface cover over the entire space of investigation area (n_1, n_2, n_3), as well as the rock embankment in the riverbed itself (K_n). Surface embankment is formed of soil material mixed with other building materials (stone, brick, concrete, slag etc.). Its thickness is different and ranges from 2.0 m to over 11.0 m in local depressions. Rock embankments make the existing bank revetment, it has the irregular pyramidal shape of variable thickness, and in the riverbed, sloped tiled quay is locally carried out over the rock embankment in three levels of different height (from 0.5-3.0 m). One of characteristic geotechnical cross sections in bank revetment zone is presented in Figure 3.

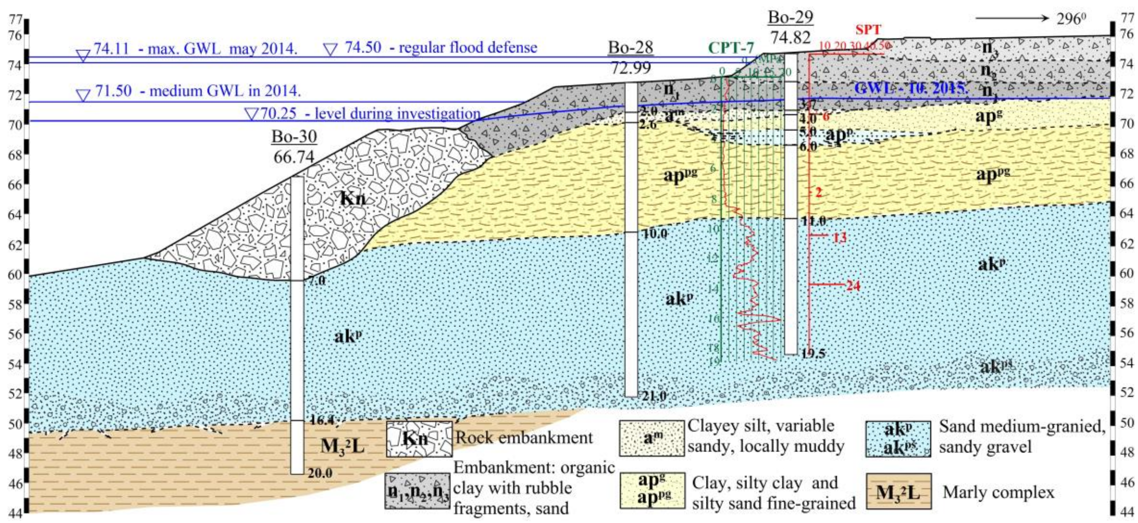

Figure 3. Characteristic geotechnical cross section of the terrain of the existing bank revetment

3 DEFINING OF GEOTECHNICAL CALCULATION MODELS

For the definition of physical-mechanical parameters of models, laboratory and many penetration test results were used (cone - CPT and standard - SPT penetration test). Regarding the results of standard penetration tests, correction of the number of a slide hammer blows was firstly made for 60 % of energy efficiency, according to the characteristic zones, which were previously defined by investigation phases (Figure 4). Regardless of the extreme results dissipation, for the fine grained sediments of floodplain facies (ap^g, ap^{pg}) and partially for clayed cover material, an estimation of consistenty state or undrained shear strength was performed. In adopting of relevant values of N and $(N_1)_{60}$, terrain zone was taken into account for which calculation model is being defined. Undrained shear strength from SPT test is defined based on term $c_u = f\,N$ (f depends on soil type and varies from 2 – 17.5, Stroud 1974, Sivrikaya and Togrol 2006), while from CPT test, undrained cohesion is defined based on term $c_u = q_c/N_k$ (N_k = 17-18 for poorly consolidated clay, i.e. N_k = 20 for hard and preconsolidated clay). The shear strength parameters for the sandy sediments of riverbed were also determined based on the results of cone and standard penetration tests. For normally consolidated sandy sediments based on the value of $(N_1)_{60}$, firstly was defined relative compaction D_R, which was used to determine effective internal friction angle (φ'). Similarly, the internal friction angle was obtained from the cone penetration test, but used relation was $\varphi'=28+2.5(q_c)^{0.5}$ (Mayerhof 1956). For the definition of physical-mechanical parameters, recommendations of EUROCODE 7 part 2 (EC-7) were also used.

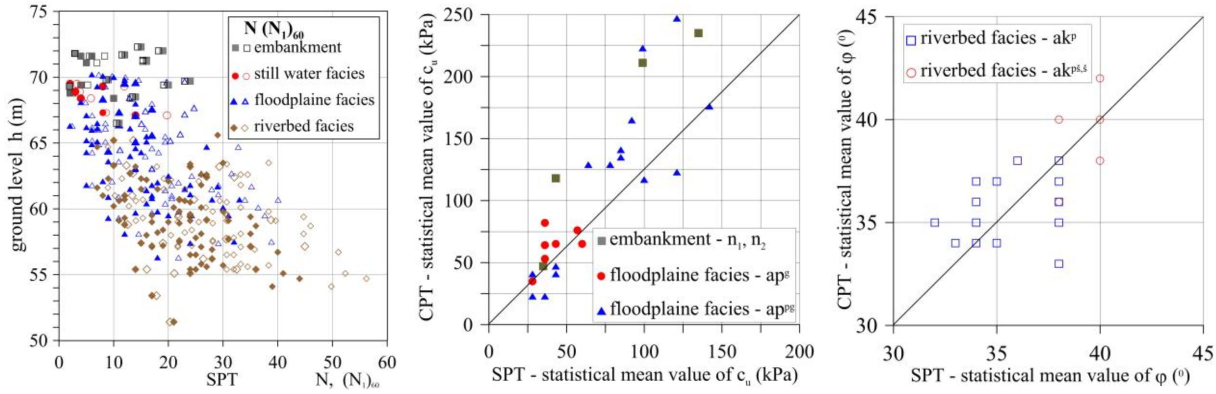

Figure 4. The interdependence of shear strength parameters obtained from SPT and CPT tests

Since it is the riverside part of the Sava River, filtration properties of the terrain were analyzed, where filtration coefficient value was defined based on the particle size distribution analysis. Adopted values of physical-mechanical properties for one of the characteristic geotechnical cross sections were presented in Table 1 (Rakić and Filipović 2015).

Table 1. Adopted values of physical-mechanical parameters for one characteristic geotechnical cross section

	Rock embankment K_n	Embankment $n_{1,2,3}$	Floodplain facies ap	Riverbed facies ak
Soil model - (Seep/W)	saturated	sat./unsat.	sat./unsat.	saturated
Soil model - (Slope/W)	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Unit weight γ (kN/m^3)	20.0	20.5	18.5	19.0
Internal friction angle φ' (°)	45	25	19	35
Cohesion c' (kN/m^2)	0	5	15	0
Filtration coefficient (in horizontal direction) k_x (m/day)	100	4.3×10^{-3}	1.7×10^{-3}	4.3

Based on the adopted values of physical-mechanical parameters, calculation models were defined (Figure 5), which were used for the seepage analysis and stability analysis of the bank revetment depending on extreme hydrological conditions. Certain simplifications (lithological and geometric) were made on models, which did not significantly affect the results.

4 GEOSTATIC AND SEEPAGE CALCULATIONS

Investigation area has direct contact with the Sava River on the west side, so the influence of the surface water is expressed by the direct action of flood waves on the terrain. This was particularly manifested in

1981, 2010 and 2006. during very high water level (16.04.2006. max. water level of the Sava 75. 66 m) which led to the flooding of the lowest parts of the terrain.

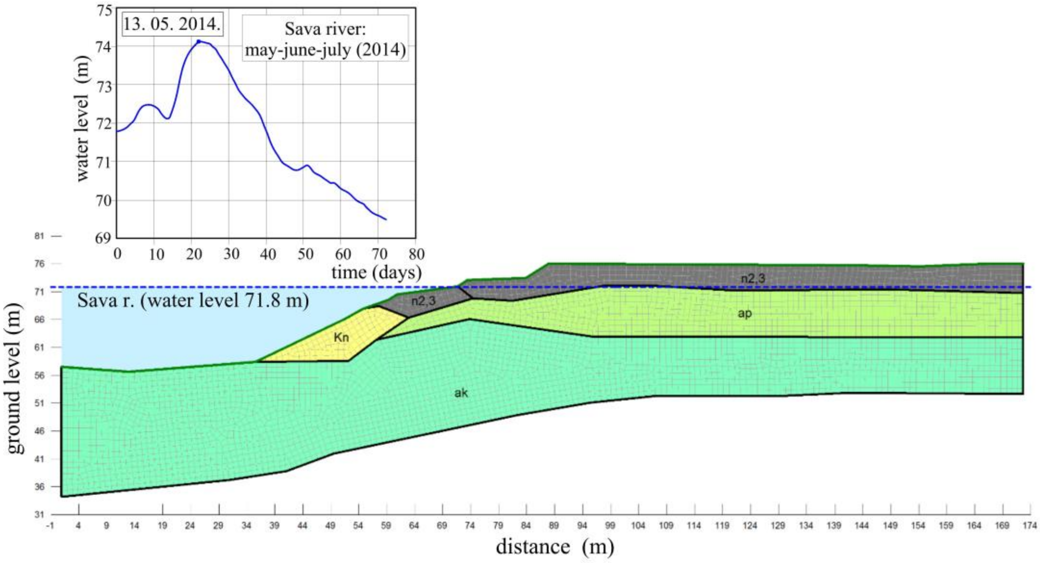

Figure 5. Layout of characteristic geotechnical model for the seepage analysis (cross section 3-3)

For these reasons seepage calculations were performed and in this regard, preliminary stability analysis of bank revetment depending on the extreme hydrological conditions. The analyzes were performed using GeoStudio 2007 software package i. e. modules Seep/W and Slope/W. Seepage analyses were performed using the finite element method, while the stability analysis calculation was performed using Morgenstern-Price limit equilibrium method. The initial analysis was performed for the water level in the Sava River at 71.8 m, assuming that the water level in the hinterland is the same as the water level in the river. Analysis were performed for a 60-day flood wave, which occurred during May and June of 2014. In order to simulate critical conditions of bank revetment stability during the flood wave duration, stability analysis for the falling of water level to 69.5 m in the next 12 days were performed. The aim of seepage calculation is to illustrate the influence of the Sava River water level oscillations on the grounwater level in the hinterland. Figure 6 presents the results of seepage calculations with the flow velocity vectors and contour diagram of piezometric pressures in the soil for one characteristic cross section, for a period of 7, 24, 45 and 72 days.

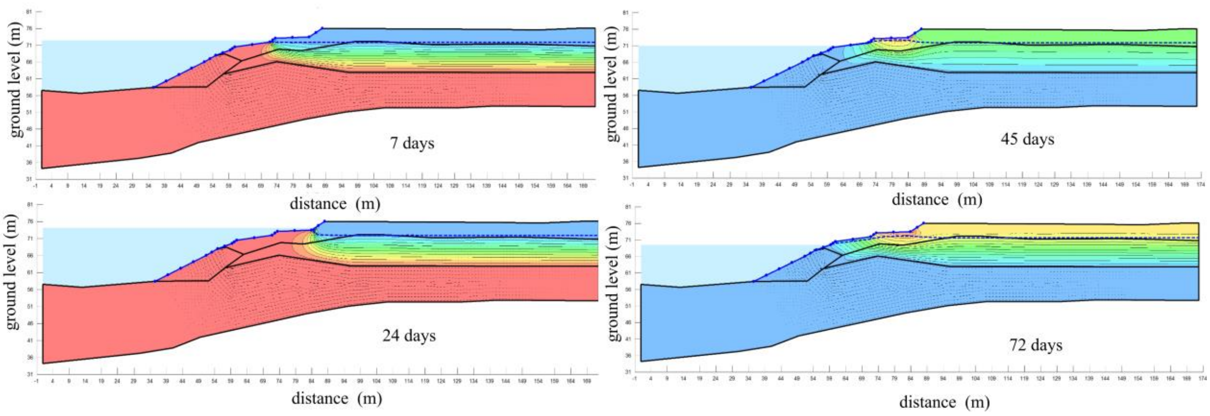

Figure 6. Seepage calculations of characteristic time intervals of 7, 24, 45 and 72 days

During the duration of the flood wave simulation, stability analysis of each calculation step were performed, with or without the influence of horizontal seismic acceleration expressed by a seismic coefficient (k_s=0.00 i 0.006). Cumulative calculation results for more characteristic cross sections and critical sliding surfaces are presented in Figure 7.

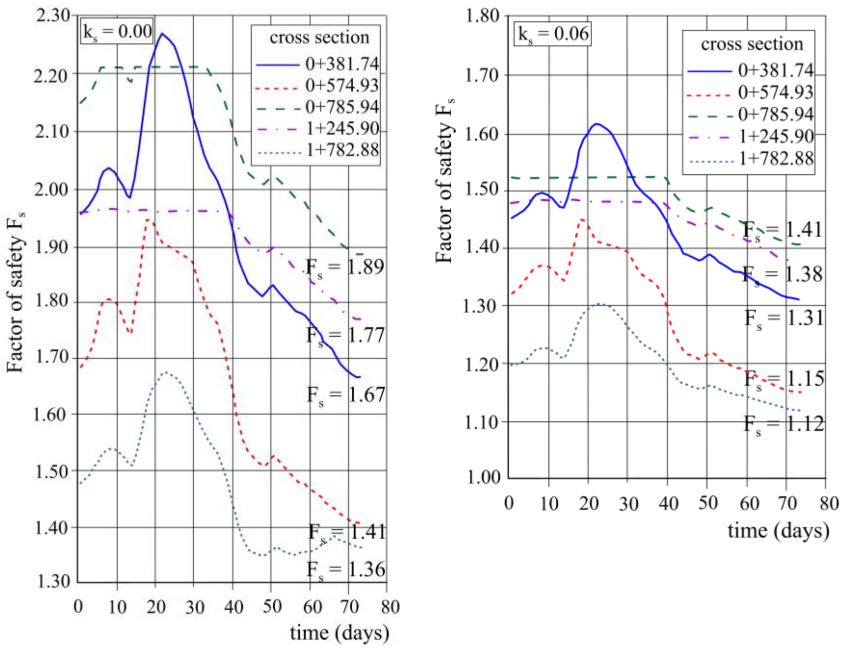

Figure 7. Safety factor change during the flood wave duration

5 CONCLUSION

The main aim of the bank revetment is the defense of the area from possible floods caused by the high water levels of the Sava River. In order to estimate flood waves influence on the change of pore pressures in the hinterland of the bank revetment, two dimensional hydrological models were formed and seepage calculation was performed in the software package Seep/W. On the basis of the obtained values of the pore pressures in the combination with field investigation results, geotechnical models were formed along the characteristic cross sections of the bank revetment and stability analysis were performed. Based on the these results it was shown that the sudden increase of water level in surface part of the terrain causes negative pore pressures and increase of the safety factor. After the withdrawal of the flood wave, safety factors decline rapidly, so that in certain conditions a critical period may occur. In the flood wave conditions which occurred during May and June of 2014., the analysis of characteristic cross sections of the bank revetment, proved its stability.

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